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Comparisons of the Dust/Smoke Particulate that Settled Inside the Surrounding Buildings and Outside on the Streets of Southern New York City after the Collapse of the World Trade Center, September 11, 2001

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ABSTRACT

The collapse of the World Trade Center (WTC) on September 11, 2001, generated large amounts of dust and smoke that settled in the surrounding indoor and outdoor environments in southern Manhattan. Sixteen dust samples were collected from undisturbed locations inside two uncleaned buildings that were adjacent to Ground Zero. These samples were analyzed for morphology, metals, and organic compounds, and the results were compared with the previously reported outdoor WTC dust/smoke results. We also analyzed seven additional dust samples provided by residents in the local neighborhoods. The morphologic analyses showed that the indoor WTC dust/smoke samples were similar to the outdoor WTC dust/smoke samples in composition and characteristics but with more than 50% mass in the <53-μm size fraction. This was in contrast to the outdoor samples that contained >50% of mass above >53 μm. Elemental analyses also showed the similarities, but at lower concentrations. Organic compounds present in the outdoor samples were also detected in the indoor samples. Conversely, the resident-provided

IMPLICATIONS

Dust and smoke generated by the pulverization of the WTC buildings on September 11, 2001, heavily contaminated many surrounding indoor and outdoor locations. In addition to outdoor dust/smoke, indoor dust/smoke samples were collected and analyzed for composition and characteristics. The comparison between the indoor and outdoor WTC dust/smoke indicates similarities and differences, which can be useful when conducting exposure assessment and source identification and evaluating health impact caused by indoor or outdoor exposures.

convenience dust samples were different from either the WTC indoor or outdoor samples in composition and pH, indicating that they were not WTC-affected locations. In summary, the indoor dust/smoke was similar in concentration to the outdoor dust/smoke but had a greater percentage of mass <53 μm in diameter.

INTRODUCTION

On September 11, 2001, the explosion and collapse of the World Trade Center (WTC) twin towers and adjacent buildings generated a huge plume of dust and smoke that was dispersed and then settled in all directions outdoors and indoors in southern Manhattan. For the first 12–18 hr, the winds transported the plume to the east and then the southeast toward Brooklyn, NY.[1,2] The amount of bulk mass deposited from the air was inches thick in some locations. Several days after the disaster, three outdoor dust and smoke samples were collected by Lioy et al.[1] from undisturbed sites in streets adjacent to the WTC site and in the downwind direction. Those were analyzed to characterize the dust/smoke composition and, subsequently, to assess the impact of the dust/smoke on the rescue and recovery workers and residents. Results from the analysis of the outdoor samples found significant percentages of inhalable and larger particles and <2% for respirable particles (<2.5 μm in diameter). Those samples were composed of a variety of construction materials that included elements (e.g., heavy metals), polycyclic aromatic hydrocarbons (PAHs), volatile/semi-volatile organic compounds (VOCs/SVOCs), and other organic compounds.

The dust and smoke generated during the collapse immediately penetrated and contaminated the interior of apartments and office buildings in southern Manhattan. Dust surface loadings, up to (and at times greater than) 3 cm thick, were deposited on indoor surfaces, from visual assessment. The patterns and extent of deposition throughout the rooms sampled indicated that the dust was deposited during the collapse of the building. To provide a basis for evaluating the potential health risk for returning residents and indoor workers, 16 indoor WTC dust/smoke samples were collected by staff of New York University (NYU) and the Environmental and Occupational Health Sciences Institute (EOHSI) on November 19, 2001, from two uncleaned buildings. After the terrorist attack, access to the WTC site was very restricted, and permission was obtained through the efforts of the U.S. Environmental Protection Agency (EPA) and the New York City Department of Health. Further, because of access and safety issues for individual buildings, samples could only be taken from two buildings close to Ground Zero: one was located on Liberty Street and the other was on Trinity Place. Access was only allowed on the day of sampling; therefore, the sampling design needed to be augmented based upon the conditions encountered in each building on that day. These samples were analyzed using the same methods previously described by Lioy et al.[1] for the outdoor samples to determine the chemical and physical composition and, thereby, would have a direct link to the information needed about characterization of indoor/outdoor dust. The similarities and differences of indoor and outdoor sample results are discussed in this manuscript. A few indoor dust samples that were provided to EOHSI by apartment residents (i.e., North Moore Street, South End Avenue, Liberty Street) were also analyzed. These resident-provided convenience samples provided data on loading of contaminants for a variety of locations that may or may not have been thoroughly cleaned before receipt of samples. Because people spend most of their day indoors, these indoor data and comparisons with the outdoor concentrations are valuable for identifying the presence of post-cleanup residential WTC dust and the potential for continued exposure to the WTC dust/smoke.

METHODS

The 16 indoor bulk (total deposited mass) settled WTC dust/smoke samples were collected from the two adjacent buildings using protocols similar to those developed to collect surface dust in previous studies.[3,4] There was some attempt to obtain samples from different floors in each building. Access to the different floors was based upon safety consideration in each building (e.g., damaged ceilings or under reconstruction). Because large amounts of the dust/smoke were deposited on surfaces, the sampling team, with gloves, respirators, and goggles on, used either a sample container (e.g., vial, jar) to pick the dust up or a brush to gently sweep the dust into a container. Samples were collected from all safe and accessible locations on different floors throughout the two buildings. Despite a large variability in sample dust quantity (<1 g ~ >100 g) caused by proximity to the WTC site, broken or open windows at the time of the collapse, the dust was collected at each sampling location in quantities for multi-analyses. Five resident-provided dust samples, collected by residents themselves either after cleanup or to address a resident's concern, were sent to EOHSI for analysis. These samples, collected with unknown methods, however, were to find out whether their residence contained the WTC dust/smoke. The sampling sites in Lower Manhattan are illustrated in Figure 1. Upon reception, all

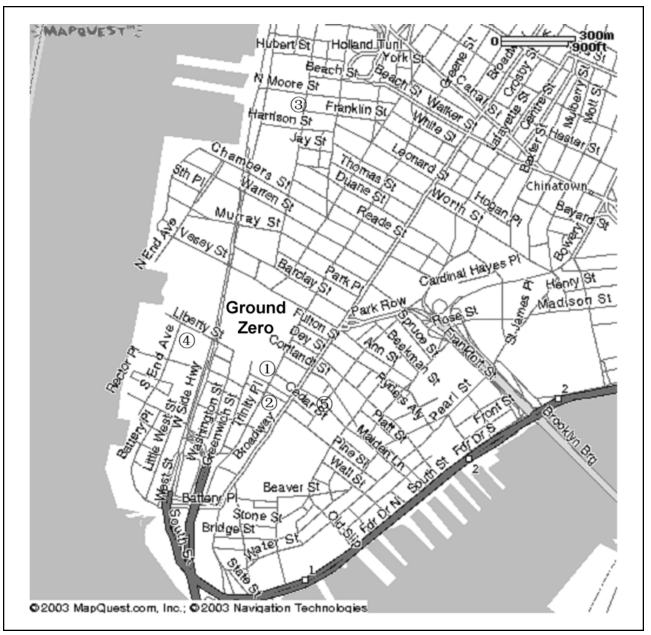

Figure 1. Indoor sampling sites around the WTC. Collected by NYU/EOHSI at (1) Liberty Street and (2) Trinity Place. Provided by residents at (3) North Moore Street, (4) South End Avenue, and (5) Liberty Street (courtesy of Mapquest.com).

samples were stored at 4 °C before delivery of sub-fractions to laboratories for analyses.

Because of limitations in the mass available for analysis from individual samples, samples were selected for specific analyses based on sample mass and the desire to obtain measurements for a variety of horizontal and vertical sampling locations (see Table 1). The samples selected for morphologic and gravimetric analyses were sieved using standard 4-in. diameter brass sieves (U.S. Standard Sieve Mesh 18 and 270) for the following fractions: >1000, 53–1000 μm, and <53 μm. Polarized light microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM) were used to examine the physical composition of the dust. Dust samples were also separated aerodynamically into four size fractions: >53 μm, 10–53 μm, 2.5–10 μm, and <2.5 μm. Details of the morphologic and gravimetric procedures have been reported previously.[1]

Samples for elemental analysis were microwave-digested (MDS 2000, CEM) with concentrated nitric acid and analyzed by inductively coupled plasma–mass spectrometry (ICP-MS). VOCs that were adsorbed to dust were analyzed using thermal desorption and a gas chromatograph (GC)/MS detector. Two thermal desorption temperatures were used, 75 °C for 2 min and 150 °C for 2 min. The lower temperature was used to examine the presence of the lightest compounds (<C8), while the higher temperature was used for heavier hydrocarbons. SVOCs other than PAHs were measured using microwave-assisted solvent extraction followed by GC/ion trap mass spectrometer. Solvents of methylene chloride and acetone (1:1, v/v) were used for extraction in the CEM microwave system. The PAH analyses found in the indoor samples have been described in an article by Offenberg et al.[2] Dioxin and furan analyses were completed using the EPA-certified Method 1613 and RCRA SW846 Method 8290. Toluene was used with an extraction thimble to extract dioxins and furans from samples. All other details of equipment and procedures used to collect and analyze the sampled dust/smoke have been reported in the manuscript by Lioy et al.[1]

RESULTS

Morphologic Analyses

Nine of the indoor WTC dust/smoke samples collected from the two uncleaned buildings, and two of the resident-provided dust samples were assigned for morphological analyses. Eight of the nine WTC samples had the same appearance: gray/tan powdered dust with consolidated fibrous aggregates (see Figure 2a). The one exception was Sample ID 17 (see Figure 2b). It had some large white and gray consolidated chunks of debris, which added to the general appearance. The samples shared many characteristics that were similar to the WTC outdoor samples collected from Cortlandt, Market, and Cherry Streets.[1] Each was primarily composed of construction debris (e.g., glass fibers, vermiculite, perlite, diatoms, plaster, glass fragments, paint particles, calcite grains, and paper fragments) and low-temperature combustion materials (e.g., charred woody fragments). The samples were also texturally and elementally similar to the results obtained from dust collected from New York Harbor sediments after the attack.[5] Quartz grains, cotton fibers, hair, starch, tarry particles, rust/metal flakes, and some skin cells were also observed in the nine WTC indoor samples. Some of these materials were not seen on the outdoor samples and probably caused by other sources of residential dust.[6] Chrysolite asbestos fibers were found in all indoor samples and estimated to comprise less than 1% by volume (see Figure 3a). SEM and TEM found glass fibers (see Figure 4a), cement particles, chrysolite asbestos fibers, lead paint fragments (see Figure 5), and soot (see Figure 6a) in the <53-μm particle size fraction of each WTC indoor dust/smoke sample. Previously, chrysolite fibers (see Figure 3b), glass fibers (see Figure 4b), and soot (see Figure 6b) were found in the WTC outdoor dust/smoke. An yttrium particle was found in Sample ID 09, Liberty Street. It was possibly released from a broken television or computer monitor. Cadmium (Cd), chromium (Cr), or mercury was not found in any of the particles examined in the nine WTC indoor samples.

Table 1. Summary of indoor settled dust and smoke sample collection and analysis.

ID	Address	Location Description	Date Collected	Morphological Analysis	Elemental Analysis	VOC Analysis	SVOC Analysis	Dioxin/Furan Analysis
124[a]	Liberty Street	F1 8A, dust from living room and bedroom	Nov 19, 2001	√	√	√	√	
5	Liberty Street	F1 5A, library, under bookshelves	Nov 19, 2001		√		√	√
6	Liberty Street	F1 5A, hall, shelf	Nov 19, 2001	√	√	√	√	√
7	Liberty Street	F1 5A, baseboard	Nov 19, 2001		√			
8	Liberty Street	F1 4A, floor	Nov 19, 2001	√	√	√	√	√
9	Liberty Street	F1 4A, hall and living room, baseboard	Nov 19, 2001	√	√		√	
10	Liberty Street	F1 4A, table of child highchair	Nov 19, 2001	√	√	√	√	√
11	Liberty Street	F1 4A, bedroom, baseboard	Nov 19, 2001		√			
12	Liberty Street	F1 2A, front room, atop 3 boxes	Nov 19, 2001	√	√	√	√	√
13	Liberty Street	F1 2A, front room, windowsill	Nov 19, 2001		√			√
14	Liberty Street	F1 2A, entryway, edge above elevator door	Nov 19, 2001	√	√	√	√	
16	Trinity Place	F1 8, kitchen, top of 3 counters	Nov 19, 2001		√			
17	Trinity Place	F1 7, walkway, radiator	Nov 19, 2001	√	√	√	√	√
15	Trinity Place	F1 10, top of file cabinet	Nov 19, 2001		√			
18	Trinity Place	F1 10, office facing WTC site, table	Nov 19, 2001	√	√	√	√	√
19	Trinity Place	F1 10, office facing WTC site, windowsills	Nov 19, 2001		√	√	√	√
20	North Moore Street	air filter	March/April 2002	√				
21	South End Avenue (R)	dust from vacuum cleaner	April 22, 2002		√			
22	South End Avenue (R)	HEPA prefilter from children's room	May 6, 2002	√	√			
23	South End Avenue (R)	dust out of kitchen vent	May 16, 2002		√			
24	Liberty Street (R)	outside windowsill on the 11th floor	Sept 2001–June 2002		√			

Note: (R) = residential; [a]Mixed sample from originally separate Samples 1, 2, and 4.

Other micrographs of particles will be posted on a Web site (e.g., EOHSI, MVA, and Air & Waste Management Association.)

In contrast to the alkaline pH of the nine WTC indoor samples collected by NYU and EOHSI, the two samples provided by residents and analyzed for morphology were acidic (pH <7; see Table 2), and their appearance was different than either the WTC indoor or outdoor samples (see Figure 2c). The morphologic analyses showed that the resident-provided samples contained skin cells, plant material, cotton fibers, starch (see Figure 7), and diatoms, indicating that the dust shared the common characteristics of house dust.[6] Particles composed of fungal materials, synthetic fibers, hair, and paint were also present in the resident-provided samples. No chrysolite asbestos fibers, cement particles, or glass fibers were found in these samples, indicating that these samples did not contain the WTC dust/smoke. Cd, Cr, and mercury were not detected in any of these samples.

Despite the morphologic similarities between the WTC indoor and outdoor dust, the nine indoor samples displayed a different pattern of aerodynamically separated size distribution from that found in the previously collected WTC outdoor dust. Most of the indoor dust samples had >50% of the mass in the 10–53 μm size fraction, with some having greater than 70% of the mass in this fraction (see Table 2). In contrast, the outdoor WTC dust samples had only 30–40% mass in this size fraction, with a majority of dust/smoke mass in the >53-μm particle size fraction.[1] This result is consistent with the data of Offenberg et al.,[2] which indicated that an indoor dust sample collected from a building on Broadway had a majority of mass in the 10–53 μm size fraction. Similar to the outdoor dust/smoke, the indoor samples only had 2–3% mass in the fraction <10 μm (see Table 2). The shift to a smaller size range for the indoor dust suggests a discrimination against some of the larger size particles when the dust/smoke was transferred and penetrated indoors.

Elemental Analyses

All the indoor dust/smoke samples collected by NYU/EOHSI staff from inside the two buildings had an element profile similar to those found in the three WTC outdoor dust/smoke samples. For example, both inside and outside samples had the elements which are normally found in building materials (e.g., Cr, manganese [Mn], barium [Ba]). In contrast, concentrations of the measured elements found in the indoor samples (on a mass fraction basis) were 50–67% lower than values obtained from the

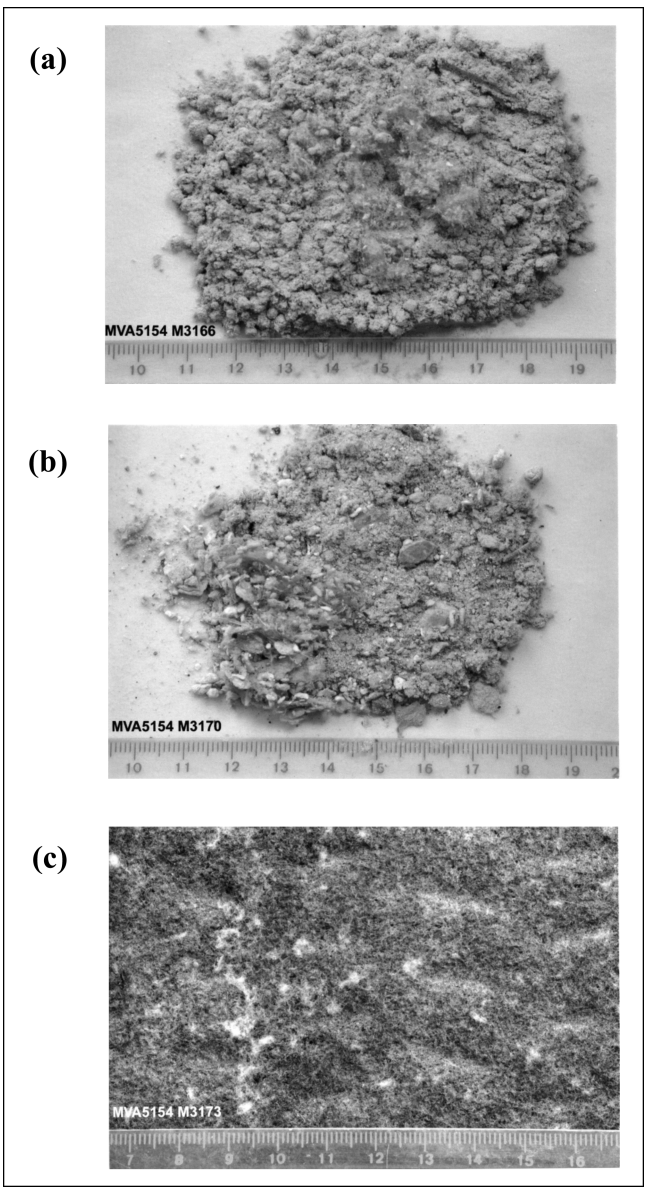

Figure 2. Appearance of the indoor dust collected from (a) Liberty Street, (b) Trinity Place, and (c) South End Avenue (HEPA pre-filter). Other WTC samples were similar in appearance to (a). Magnification = 1.5×.

outdoor samples (see Table 3). For example, the average lead (Pb) concentration for the outdoor samples was ~305 μg/g or ppm, while the indoor samples ranged from only 112 to 246 μg/g. An even lower elemental concentration was measured in Sample ID 17, which contained more large chunks of debris than other samples and had a Pb concentration of only 52 μg/g.

The resident-provided dust samples had elemental profiles that were different from either the WTC indoor or outdoor dust/smoke samples (see Table 3). For instance, Pb was not detected in any of the resident-provided samples, whereas it was commonly found in all three WTC outdoor dust/smoke samples, and ranged from 150 to 500 μg/g. In contrast, the dust sample collected by a resident from an outside windowsill of a residential building on Liberty Street (Sample ID 24) more closely matched the WTC dust elemental concentrations than the others but had a high concentration of thallium (Tl). The similar elemental concentrations could be expected because of its proximity to Ground Zero. Sample ID 23, collected from a kitchen vent, also had an extremely high Tl concentration of 1370 μg/g, which is 1000 times higher than that in the WTC dust/smoke. The high Tl concentrations may have been caused by a former use of thallium sulfate, a household insecticide/rodenticide that has been banned in the United States since 1975.

Analyses of Organic Compounds

Previous qualitative analyses of the WTC outdoor dust by thermal desorption GC/MS showed the presence of straight-chain and branched alkanes along with PAHs.[1] The alkanes have been reported to be major components of jet fuel,[7] while the latter are products of incomplete combustion. Only small quantities (<0.01 μg/g) of straight chain or branched alkanes with less than eight carbons were found in the indoor samples after thermal desorption at 75 °C. Similarly, minimal quantities of

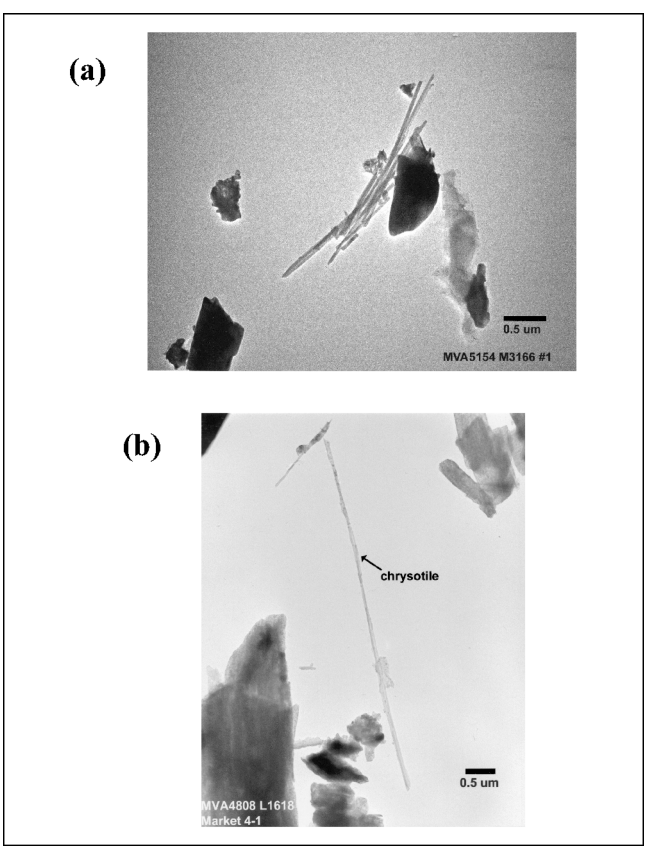

Figure 3. TEM image of chrysotile asbestos in Sample ID 9 (a) and in outdoor Market Street sample (b).

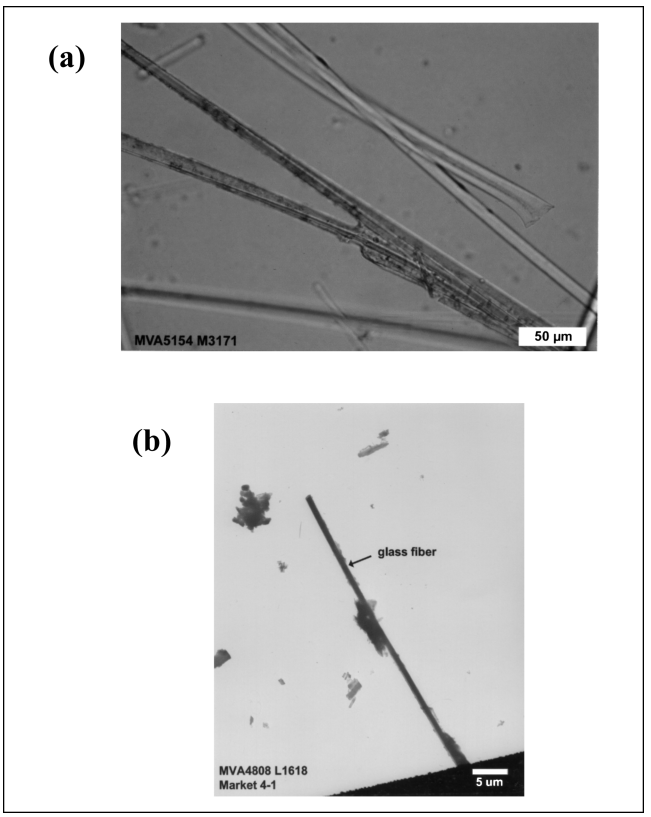

Figure 4. Light microscope image of filamentous glass fibers in Sample ID 18 (a); TEM image of glass fiber found in outdoor Market Street Sample (b). (Reprinted from Lioy et al.[1])

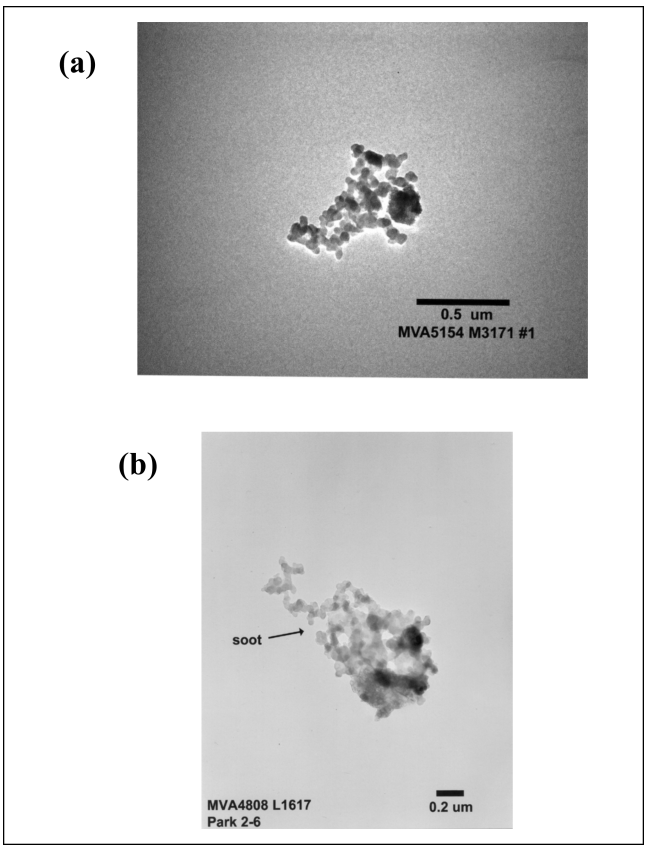

Figure 6. TEM image of indoor soot in Sample ID 18 (a) and in an outdoor sample (b). (Reprinted from Lioy et al.[1])

benzene, toluene, xylene, or ethyl benzene, usually below the level of quantitation, were present in the samples, indicating that VOC concentrations in the residential indoor samples were lower than those observed in the outdoor samples. The latter had been collected and analyzed 2 months earlier and 6 months earlier, respectively.

To quantify the higher-molecular-weight n-alkanes and naphthalene, a second analysis was conducted at a desorption temperature of 150 °C for 2 min. The concentrations of the n-alkanes series, representative of the higher-molecular-weight jet fuel components, and naphthalene are shown in Table 4. The presence of the 7-carbon through 15-carbon n-alkanes, consistently found at levels of tenths to low ppm, were considered to be residue of jet fuel because these organic compounds in this molecular size range comprise 30–50% of jet fuel by mass. The naphthalene concentrations were detected in the low ppm range, indicating the presence of products of incomplete combustion in the indoor dust/smoke samples. A GC chromatogram for one of the indoor samples shows peaks of alkanes, benzene derivatives, and PAHs (see Figure 8).

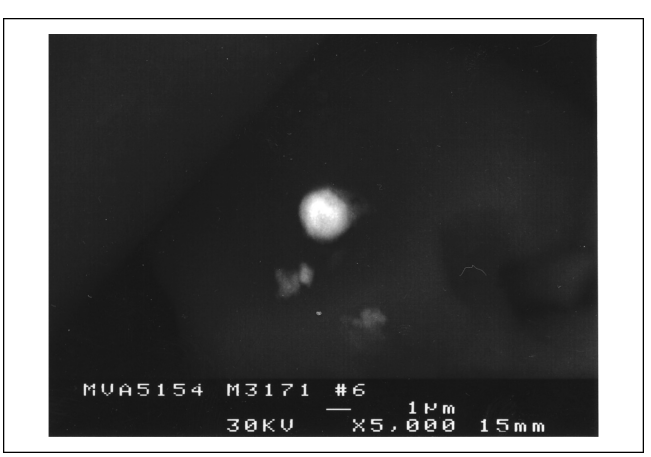

Figure 5. SEM image of a leaded particle in an indoor sample.

The SVOC analyses found products of incomplete combustion in most of the WTC indoor dust samples. The compounds included phthalate esters and PAHs (e.g., naphthalene derivatives, anthracene, fluoranthene, fluorene, pyrene; see Table 5a). PAHs in indoor dust are typically derived for both indoor sources, such as combustion from heating, cooking, and smoking, and outdoor combustion sources through track-in of soil and infiltration of airborne particles, which then settle indoors.[6] A similar series of PAH compounds has been reported in house dust, with most being in the smallest size fractions (<4 μm or 4–25 μm) with an individual

Table 2. General characteristics of settled dust and smoke samples in indoor environments of buildings surrounding the WTC.

Address	**Liberty Street**											**Trinity Place**			**North Moore Street**	**South End Avenue**
Floor	**8**	**5**			**4**				**2**			**7**	**10**		**—**	**—**
Sample ID	**124**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**17**	**18**	**19**	**20**	**22**
Location	**LR & BR**	**Library**	**Hall**	**Baseboard**	**Floor**	**Hall & LR**	**High Chair**	**BR**	**Front Room**	**Front Room**	**Entryway**	**Walkway**	**Office**	**Office Window**	**Air Filter**	**HEPA Prefilter**
Color	gray/tan	N/A	gray/tan	N/A	gray/tan	gray/tan	tan	N/A	tan	N/A	gray/tan	gray/tan	gray/tan	N/A	gray/white	gray
pH	11	N/A	11	N/A	11	11	11	N/A	11	N/A	11	8	10	N/A	5–6	5
Chrysotile fibers (% volume)	<1	N/A	<1	N/A	<1	<1	<1	N/A	<1	N/A	<1	<1	<1	N/A	ND	ND
Sieved sample (% mass)																
>1000 μm	1	N/A	1	N/A	2	1	3	N/A	6	N/A	1	28	5	N/A	insufficient	insufficient
53–1000 μm	72	N/A	73	N/A	69	67	74	N/A	72	N/A	69	59	67	N/A	insufficient	insufficient
<53 μm	27	N/A	27	N/A	28	33	23	N/A	22	N/A	31	13	28	N/A	insufficient	insufficient
Aerodynamically separated sample (% mass)																
<2.5 μm	0.6	0.4	0.7	0.4	0.8	0.8	0.6	0.6	0.5	0.5	0.6	0.2	0.7	0.6	N/A	N/A
2.5–10 μm	1.3	1.2	2.3	1.4	1.5	2	1.8	2	1.5	1.8	2.2	0.5	1.6	1.5	N/A	N/A
10–53 μm	78.5	51.4	64.7	60.6	63	72.1	59	61.4	50.9	42.4	71.6	20.1	58.2	56.3	N/A	N/A
>53 μm	19.6	47	32.3	37.6	34.7	25.2	38.6	36	47.1	55.3	25.3	79.1	39.5	41.3	N/A	N/A

Note: LR = living room; BR = bedroom; N/A = not applicable; ND = not detected.

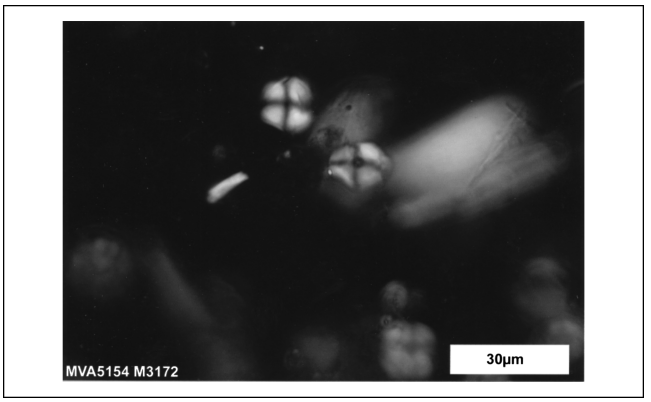

Figure 7. Light microscope image of starch grains in North Moore Street (indoors).

compound concentration of 1–5 μg/g,[8] which is in contrast to the exposure with the WTC samples.[1,2]

Phthalate esters were present at relatively low concentrations, with the highest being 50 μg/g in Sample ID 6 (from the Liberty Street building), as compared with the reported total phthalate ester concentrations in an outdoor sample collected on Market Street (>100 μg/g).[1] Phthalate esters have been measured in indoor air, and their source is typically from indoor off-gassing of plasticizers used in consumer products and furnishings, with indoor concentration generally greatly exceeding outdoor concentrations.[9,10] The vapor phase has been reported to be greater than particulate. It is likely that the loadings measured in the dust were from the large amount of plasticizers present in the furnishings and office materials in WTC. Except for the PAH compounds and the phthalate esters, there was a large degree of variability in the concentrations measured for specific SVOCs found in the WTC indoor dust/smoke samples. The levels of these uncommonly found SVOCs were not very significant, and most concentrations were only slightly above the detection limits (e.g., 5 ppm; see Table 5b).

The indoor levels of polychlorinated dibenzo-*p*-dioxins (PCDDs) and dibenzofurans (PCDFs) were similar to those found in the outdoor WTC dust samples (see Table 6). All the indoor samples collected from inside the Liberty Street building had PCDD and PCDF equivalents in dust that were similar to those derived from the WTC outdoor dust/smoke samples and Ground Zero pile (~100 ng/kg).[1] However, two exceptions were found for the dust collected from inside the Trinity Place building: a low concentration (~40 ng/kg) on Floor 7 and a

Table 3. Concentrations (ng/g dry weight) of elements found in the indoor dust and smoke samples.

Address	Liberty Street				Trinity Place			South End Avenue			Liberty Street (Residential)	Street[a]
Floor	8	5	4	2	7	8	10	—	—	—	11	Outdoor
Sample ID[b]	124	5, 6, 7	8, 9, 10, 11	12, 13, 14	17	16	15, 18, 19	21	22	23	24	Cortlandt, Cherry, Market
Li	16,900	15,800	13,000	ND	12,200	10,200	15,900	ND	ND	ND	16,800	26,300
Be	1,900	1,690	2,140	1,490	ND	ND	1,500	ND	ND	ND	ND	3,230
Ti	1,120,000	1,000,000	850,000	945,000	971,000	834,000	1,010,000	36,600	20,800	1,680,000	1,170,000	1,670,000
V	20,300	21,100	16,700	16,200	13,800	24,400	18,500	1,650	778	469,000	21,100	39,000
Cr	79,700	82,300	60,300	55,000	60,100	51,900	66,500	308,000	2,130	382,000	85,500	165,000
Mn	654,000	573,000	446,000	499,000	570,000	415,000	565,000	23,100	20,700	875,000	691,000	725,000
Co	3,780	4,560	3,680	3,560	3,040	4,120	3,350	ND	372	44,200	3,710	8,670
Cu	172,000	162,000	99,100	94,000	348,000	236,000	139,000	27,800	13,700	2,460,000	109,000	265,000
Ga	9,470	9,710	7,770	7,890	6,780	6,960	8,850	ND	ND	ND	9,330	30,500
As	2,330	3,380	3,290	3,490	2,600	3,790	2,450	ND	1,390	34,100	2,050	2,620
Rb	10,500	10,400	8,380	9,310	9,480	7,960	9,640	1,810	10,600	39,400	12,000	20,600
Sr	562,000	490,000	368,000	416,000	433,000	442,000	479,000	16,400	11,100	744,000	534,000	630,000
Ag	1,600	1,080	1,550	956	153	1,570	781	689	138,000	499,000	1,420	2,250
Cd	4,060	3,230	3,120	5,300	3,130	5,340	5,400	ND	ND	43,400	4,370	7,200
Cs	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1,190
Ba	222,000	212,000	170,000	178,000	149,000	166,000	219,000	14,600	8,120	1,230,000	238,000	381,000
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tl	ND	ND	ND	ND	ND	ND	ND	9,880	1,520	1,370,000	99,300	1,380
Pb	158,000	174,000	112,000	126,000	51,600	246,000	187,000	ND	ND	ND	ND	305,000
Bi	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1,320
U	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	16,800	4,080

Note: ND = not detected; [a]Data were derived from Lioy et al.[1]; [b]Average is shown for multiple sample IDs.

Table 4. Concentrations (μg/g or ppm) of selected volatile organic compounds in the indoor dust and smoke samples.

Address	Liberty Street												Trinity Place					
Floor	8		5		4				2				7		10			
Sample ID	124		6		8		10		12		14		17		18		19	
Desorption Method	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only	75–150	150 Only
2-Methylpentane	ND	ND	0.36	0.49	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.13	ND	ND
n-Heptane	0.32	ND	ND	ND	ND	ND	0.25	ND	0.31	10.22	ND	ND	ND	ND	ND	ND	0.27	ND
Toluene	0.15	ND	0.13	ND	0.11	0.11	0.15	0.13	0.13	ND	0.1	4.35	0.1	ND	0.1	ND	0.16	ND
n-Octane	0.37	0.18	0.15	0.19	0.29	0.25	0.11	0.66	0.41	0.11	0.23	0.11	0.21	0.11	0.28	0.18	0.24	0.18
p-Xylene	0.33	0.33	0.28	ND	0.32	ND	0.38	0.4	0.31	0.28	0.31	0.34	ND	ND	0.32	0.35	0.37	0.33
Propylbenzene	0.14	0.14	0.11	0.14	0.13	0.16	0.15	ND	0.13	0.11	0.13	ND	ND	0.14	0.13	ND	ND	0.14
n-Decane	0.18	0.21	0.08	0.27	0.45	0.19	0.19	0.2	0.18	0.12	0.18	0.26	0.14	0.2	0.06	0.16	0.19	0.21
Butylbenzene	ND	0.21	0.14	0.19	0.17	0.24	0.22	ND	0.21	0.14	0.16	0.2	ND	0.21	0.16	0.21	ND	0.21
n-Dodecane	0.19	0.1	ND	0.13	0.08	0.12	NA	0.09	0.38	0.06	ND	0.1	ND	0.07	0.07	0.1	ND	0.1
n-Tridecane	0.13	0.12	0.06	0.1	0.38	0.37	0.12	0.04	0.34	0.09	0.09	0.2	0.28	0.2	0.2	0.25	0.07	0.12
n-Tetradecane	0.57	0.36	0.67	0.49	0.91	0.26	0.32	0.68	0.08	0.2	0.68	0.47	0.49	0.28	0.65	0.38	0.81	0.36
n-Pentadecane	2.03	0.14	1.79	0.03	2.7	1.67	0.23	1.59	0.13	0.05	1.39	0.15	1.35	0.43	1.55	1.51	1.49	0.14
Styrene	0.36	ND	0.27	0.06	0.14	0.1	0.17	0.08	0.52	0.03	0.09	ND	0.04	ND	0.23	0.1	0.44	0.06
Butylbenzene	ND	ND	ND	ND	ND	0.04	ND	ND	ND	ND	ND	0.07	ND	0.13	ND	0.05	ND	ND
Naphthalene	2.69	1.07	4.91	3.92	4.87	3.11	24.3	45.8	0.91	2.37	7.18	3.66	0.73	0.33	12.9	2.34	2.86	4.26

Note: ND = not detected; NA = unresolved GC peak.

high concentration (~300 ng/kg) on Floor 10. The low-concentration sample was the one (Sample ID 17) that had large chunks of debris and little powder-like dust. The sample also had the low Pb concentration. The high-concentration dust/smoke samples, Numbers 18 and 19, had levels of PCDDs and PCDFs that were 3 times greater than any other WTC indoor sample. These values were similar to the observed maximum total equivalents found in the WTC outdoor samples.[1]

DISCUSSION

The physical characteristics and chemical composition of the 16 WTC indoor dust/smoke samples were examined after collection in November 2001, ~2 months

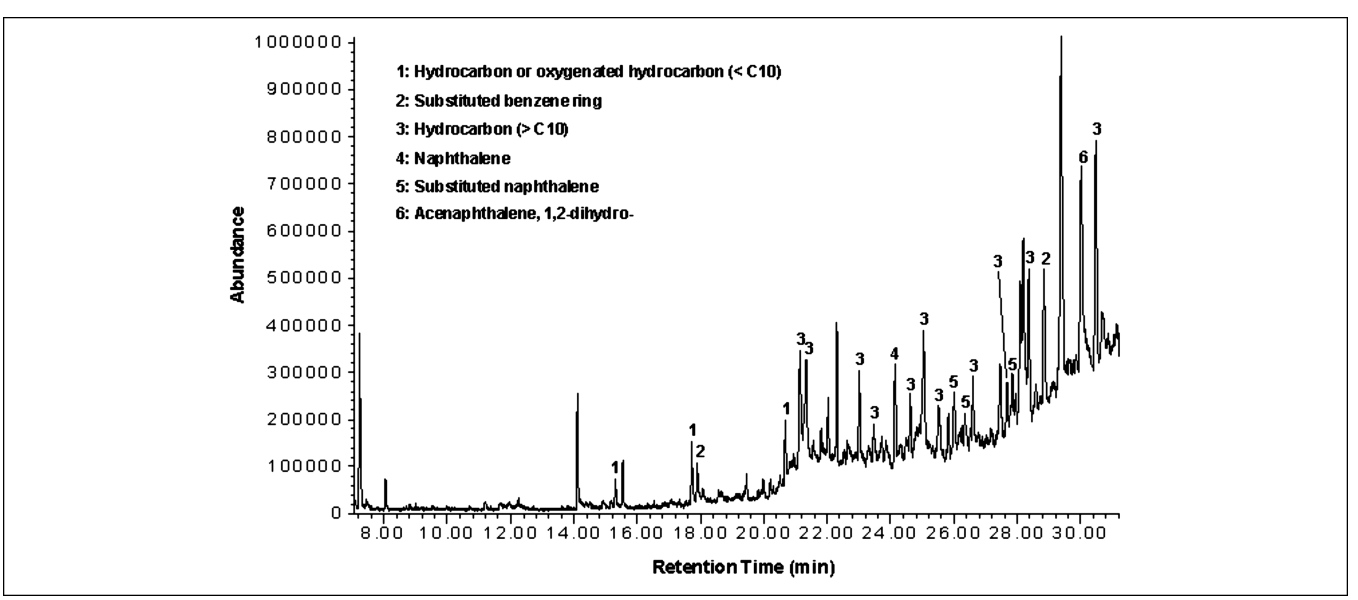

Figure 8. GC/MS analysis of the Trinity Place (Fl 10) sample and the compounds detected that are components of jet fuel.

Table 5a. Concentrations (μg/g) of the most frequently found semivolatile hydrocarbons in the indoor dust and smoke samples.

		Sample ID										
Compound Name	**CAS No.**	**124**	**5**	**6**	**8**	**9**	**10**	**12**	**14**	**17**	**18**	**19**
1-Decanol, 2-hexyl-	2425-77-6	ND	3.07	3.99	ND	1.9	3.09	ND	ND	ND	ND	ND
Acenaphthene	83-32-9	ND	3.41	ND	0.1–5	5.23	4.06	ND	0.1–5	17	ND	ND
Anthracene	120-12-7	ND	ND	9.17	0.1–5	20.4	16.2	2.25	1.76	13.7	1.82	0.09
Benz(c)acridine	225-51-4	ND	ND	ND	ND	ND	ND	0.41	0.38	4.72	0.05	ND
Benz(a)acridine	225-11-6	ND	4.97	3.28	ND	ND	11.8	ND	14.1	ND	ND	ND
Benzo(a)pyrene	50-32-8	ND	5.04	5.48	ND	7.68	3.62	ND	13.5	ND	1.88	0.05
Benzoic acid, p-tert butyl	98-73-7	2.68	2.73	20.2	0.1–5	2.5	1.8	ND	0.1–5	86.9	ND	ND
Benzyl butyl phthalate	85-68-7	ND	9.43	9.89	ND	8.94	ND	1.53	ND	30.3	ND	ND
Carbazole	86-74-8	ND	0.77	0.94	ND	2.02	0.77	ND	0.1–5	ND	ND	ND
Dibenzofuran	132-64-9	ND	1.97	2.13	0.1–5	2.81	2.44	ND	0.1–5	20.3	ND	ND
Dibutyl phthalate	84-74-2	1.75	0.29	22.9	ND	9.52	1.47	0.85	ND	8.32	3.99	0.1
Diethyl phthalate	84-66-2	ND	ND	2.85	ND	3.43	ND	ND	0.1–5	ND	1.61	0.03
Fluoranthene	206-44-0	ND	15.7	9.15	ND	30.9	11	ND	ND	23.1	ND	0.18
Fluorene	86-73-7	ND	2.89	2.66	ND	4.52	2.33	0.1–5	0.1–5	18.2	ND	ND
Phenanthrene	85-01-8	ND	ND	9.17	0.1–5	2.99	2.5	ND	2.62	7.02	1.82	ND
Pyrene	129-00-0	ND	ND	14.2	ND	22.5	ND	1.66	11.6	11.3	ND	ND
Thebenidine	194-03-6	ND	21	4.56	0.1–5	ND	23.9	0.1–5	25.9	ND	2.13	0.08

Note: ND = not detected.

post-September 11, 2001. The samples were obtained from undisturbed locations inside the buildings near Ground Zero and determined to be similar in composition and physical appearance to those of the outdoor dust previously collected during the days immediately after the catastrophic event. The indoor dust samples, collected by EOHSI/NYU, were primarily composed of construction materials (e.g., cement) and had a pH >7. Two indoor dust samples provided by residents from North Moore Street (0.5 mi north) and South End Street (0.2 mi southwest) showed pH values lower than 7, indicating a distinctly different composition from the WTC dust/smoke. The SEM and TEM analyses for these two resident-provided samples found biological materials and no glass fibers; the latter was determined to be a significant component of the total WTC dust/smoke. The elemental analyses of these resident-provided samples also yielded different elemental profiles (e.g., high Tl concentrations, Pb concentrations below the detection limit) and from those found in the WTC dust/smoke (e.g., low to nondetectable Tl concentrations, high Pb concentrations). Thus, the two resident-provided dust samples did not have reportable levels of the WTC dust/smoke. The two residences may have been cleaned effectively before the sample collection, or the WTC pulverization may not have severely polluted the indoor environments of the two houses. The outside windowsill dust, collected by the resident in a housing unit on Liberty Street (0.3 mi southeast) after cleanup, appeared to contain a significant amount of the WTC dust based on the similar elemental profile and its location in the major impact zone. Unfortunately, no direct morphological measurement was made on this sample because it did not contain enough dust for the analysis. The windowsill sample disclosed a potential problem that outside parts of the building also needed cleanup because residents could be exposed to such uncleaned WTC dust/smoke deposited outside when windows were open.

Most WTC indoor dust samples had more than 50% of the mass in particle size <53 μm in aerodynamic diameter; the result was different from the particle size categories identified for the outdoor samples. The latter had a majority of the particles present in the >53-μm fraction.[1] When the pulverization of the WTC buildings occurred, particles of all sizes were instantly generated and scattered throughout the surrounding areas, and because of gravity, larger (aerodynamic diameter) particles settled faster than the smaller particles. Thus, only a portion of larger particles that could penetrate a building via open or broken windows and doors during the pulverization could settle indoors. The largest particles would have been filtered out by buildings' walls and smaller openings around unbroken windows. Smaller particles, which stayed airborne longer, would have a greater penetration efficiency than larger particles. These would have had a greater possibility of entering and settling inside buildings. Because of relatively small quantities of larger particles

Table 5b. Concentrations (μg/g) of rarely found semivolatile hydrocarbons in the indoor dust and smoke samples.

Compound Name	CAS No.	No. of Sample	Concentration Range
1,2-Benzenedicarboxylic acid, diheptyl ester	3648-21-3	1	4.61
1,2-Dihydrobenzo[b]fluoranthene	N/A	3	2.31–9.88
1,2-Oxathiane,6-dodecyl-2,2-dioxide	15224-88-1	1	4.32
1,3-Butanedione, 2-methyl-1-phenyl-	6668-24-2	1	1.85
1,3-Cyclohexadiene	592-57-4	1	21.5
1,4,7,10,13,16-Hexaoxacyclooctadecane	17455-13-9	1	2.76
1,4-Naphthalenedione, 3-acetyl-2,5,7-trihydroxy-	54725-01-8	1	16.2
10[1′,2′]-Benzenoanthracene,9,10-dihydro-	477-75-8	1	2.12
1-Butanol,3-methyl-,benzoate	94-46-2	1	1.01
1-Hexene, 3,4,5-Trimethyl-	N/A	1	3.81
1H-Indene, 1-ethylidene-	2471-83-2	1	1.26
1H-Indene, 1-methylene-	2471-84-3	1	1.69
1-Pentacontanol	40710-43-8	2	2.12–3.85
1-Pentadecanol	629-76-5	1	0.1–5
2,3-dihydro-1,1-dioxide	19446-96-9	1	66.4
2-Bromo-3′-nitroacetophenone	2227-64-7	1	6.07
2-Cyclopropen-1-one,2,3-diphenyl	886-38-4	1	2.15
2-Ethyl-1-dodecanol	19780-33-7	1	5.01
2-Phenyl-6,7-dimethylquinoxaline	71897-07-9	1	2.11
3,6-Phenanthrenedicarbonitrile	18930-78-4	1	7.97
3-Hexene,2,2,3,4,5,5-hexamethyl-(E)-	54290-40-3	1	6.24
5-Methylpyrimido[3,4-a]indole	89-02-2	1	0.87
9(10H)-Acridinone	13161-83-6	1	1.46
9,10-Anthracenedione	84-65-1	3	1.11–1.76
9,10-Phenanthraquinone	N/A	1	1.39
9H-Fluorene,9-Methylene	4425-82-5	3	0.23–15.1
Anthracene,2-Methyl-	613-12-7	3	0.75–0.81
Benzamide, N-acetyl-	1575-95-7	1	2.71
Benzamide, N-propyl	10546-70-0	1	1.54
Benzene, 1-ethenyl-4-methoxy-	637-69-4	1	23.3
Benzeneacetic acid	37148-65-5	1	0.33
Benzenedicarboxylic acid, isopropyl ester	131-16-8	1	3.69
Benzo butyl phthalate	85-68-7	1	0.14
Benzo(b)carbazole	243-28-7	2	1.65–2.28
Benzo(b)fluoranthene	205-99-2	2	3.41–5.03
Benzo(c)acridine	225-51-4	1	5.53
Benzo(c)carbazole	34777-33-8	2	1.6–4.06
Benzo(k)fluoranthene	207-08-9	3	0.86–15.3
Benzo[b]fluoranthene	205-99-2	1	42.2
Benzoic acid, 1-methylethyl ester	939-48-0	1	1.46
Benzoic acid, 2-benzoyl-1,2-dimethyl hydrazide	1226-43-3	1	4.17
Bicyclo[4,2,0]octa-1,3,5-triene-7,8-dione	6383-11-5	3	0.6–23.4
Butanedioic acid, 1-cyclohexen-1-yl-, 1-ethyl ester	82546-67-6	1	1.99
Butyl phthalate, Benzyl	85-68-7	1	6.38
Butylated Hydroxytoluene	128-37-0	2	0.1–5
Chrysene	218-01-9	1	17.1
Cyclodecanone	830-13-7	1	4.81
Cyclododecanemethanol	1892-12-2	2	1.04–1.8
Cyclohexane, methyl-	108-87-2	1	5.85
Cyclopentaphenanthrene	203-64-5	2	0.91–1.05
Cyclotetradecane	295-17-0	1	2.05
Decanedioic acid, didecyl ester	2432-89-5	2	0.1–5
Decanoic acid	N/A	1	5.08
Decanoic acid, didecyl ester	2432-89-5	1	6.43
Dibenothiophene	132-65-0	1	0.82
Dibenzo(B,def)carbazole	104313-09-9	2	0.87–0.99
Dibenzothiophene	132-65-0	3	0.1–5
Didecyl phthalate	84-77-5	1	2.09
Di-n-octyl phthalate	117-84-0	3	0.1–21.5
Dodecanoic acid	143-07-7	1	15.9
Ethanedione, diphenyl-	134-81-6	1	24.7
Ethanol,2-(tetradecyloxy)-	2136-70-1	1	2.23
Ethanone, 2-(formyloxy)1-phenyl-	55153-12-3	1	1.8
Fluorene, 9-ethylidene-	7151-64-6	1	0.57
Heptanedioic acid, 4-(ethoxycarbonylmethylene)-, diethyl ester	N/A	1	3.5
Hexyl octyl ether	17071-54-4	3	1.29–30.6
Isoquinoline,1-phenyl-	3297-72-1	1	2.59
Methanone, phenyl (5-phenyl-1,3-oxathiol-2-yl)	50742-77-3	1	1.78
Methyl 2-ethylhexyl phthalate	56166-83-7	1	0.54
Naphthalene, 1-phenyl-	605-02-7	1	0.23
Naphthalene, 2-phenyl-	612-94-2	1	0.3
Octyl ether, hexyl	N/A	1	2.13
Pentachlorophenol	87-86-5	1	2.9
Phenanthrene, 1-methyl-	832-69-9	1	1.41
Phenol, 2,3,4,5-tetrachloro-	4901-51-3	1	13.1
Phenol, 4,4′-(1-methylethylidene)bis-	80-05-7	1	1.66
Phosphonic acid, dioctadecyl ester	19047-85-9	1	7.43
Phthalic acid, butyl ester	85-70-1	1	4.58
Quinoline,2-phenyl-	612-96-4	1	0.36
Sulfamethazine	57-68-1	1	4.48
Xanthene	92-83-1	1	0.1–5

Table 6. Concentrations (ng/g dry weight) of dioxins/furans found in the indoor dust and smoke samples.

Address	Liberty Street			Trinity Place		Street[a]
Floor	5	4	2	7	10	Outdoor
Sample ID[b]	5, 6	8, 10	12, 13	17	18, 19	Cortlandt, Cherry, Market
Dioxin (ng/kg)						
2,3,7,8-Tetrachlorodibenzo-p-dioxin	9.6	8.9	7.4	3	20	6.4
1,2,3,7,8-Pentachlorodibenzo-p-dioxin	37.2	24.9	19.1	5	30.6	14.2
1,2,3,4,7,8-Hexachlorodibenzo-p-dioxin	37.2	24.9	16.7	5	15	14
1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	37.2	24.9	23.2	7	35.7	23.2
1,2,3,7,8,9-Hexachlorodibenzo-p-dioxin	37.2	24.9	28.2	9.1	55.7	25.4
1,2,3,4,6,7,8-Heptachlorodibenzo-p-dioxin	334	385	313	242	500	262
1,2,3,4,6,7,8,9-Octachlorodibenzo-p-dioxin	3755	5375	3630	2620	3765	2,830
Furan (ng/kg)						
2,3,7,8-Tetrachlorodibenzo-p-furan	261	331	278	123	1119	164
1,2,3,7,8-Pentachlorodibenzo-p-furan	50.1	46	38.3	14.9	117	40.8
2,3,4,7,8-Pentachlorodibenzo-p-furan	80.2	72.3	56.5	26.4	158	72.3
1,2,3,4,7,8-Hexachlorodibenzo-p-furan	50.8	50.4	53.1	20.4	89.4	49.9
1,2,3,6,7,8-Hexachlorodibenzo-p-furan	49.4	45.8	37.9	15.9	25	46.7
1,2,3,7,8,9-Hexachlorodibenzo-p-furan	37.2	24.9	15.1	5	8.2	19.4
2,3,4,6,7,8-Hexachlorodibenzo-p-furan	47.5	38.5	37.1	13.8	84.4	38.1
1,2,3,4,6,7,8-Heptachlorodibenzo-p-furan	199	204	157	68.8	342	147
1,2,3,4,7,8,9-Heptachlorodibenzo-p-furan	41.5	29.9	27.6	5	54.9	34.4
1,2,3,4,6,7,8,9-Octachlorodibenzo-p-furan	223	275	184	78.1	278	157
2,3,7,8-Dioxin Total Equivalents	96.5	100	87.3	39.3	293	101

[a]Data were derived from Lioy et al.[1]; [b]Average is shown for multiple sample IDs.

entering buildings, the WTC indoor dust/smoke contained more than 50% particles <53 μm in diameter.

A vertical deposition pattern by size could not be found for the WTC indoor settled dust. One of the reasons may have resulted from the heterogeneity of the WTC dust, as suggested in the previous WTC paper;[1] another reason may have been the scale of vertical sampling: only 10 stories. The collapse and pulverization of the two towers generated millions of tons of material so that sampling within a nearby 10-story building did not provide a sufficient gradient to develop a vertical pattern of deposition.

The majority of WTC indoor dust was in the size fraction of <53 μm and had high alkalinity and numerous glass fibers and, therefore, could be irritating to nose, eyes, and upper respiratory tract. Many of the rescue workers and firefighters have been diagnosed as having different levels of respiratory problems, from bronchial responsiveness to severe cough, caused by the exposures to the WTC dust/smoke.[11] A study that assessed the characteristics of material-induced sputum on the WTC firefighters found that the firefighters were exposed to particles ranging from 1 to 50 μm, and the particles contained cement and other construction materials.[12] Given the result from the current study, the WTC indoor dust had a composition similar to the outdoor dust/smoke but contained a greater percentage of the mass of <53-μm particles that may have caused the WTC cough in rescue workers and firefighters. It also would be of concern for residents who returned to their houses before cleanup or for indoor cleanup workers who did not wear respirators.

Several other WTC studies have focused on health effects of respirable particles (<2.5 μm). A study analyzing the chemical composition of the WTC fine dust (<2.5 μm) has found that two major components are calcium sulfate (gypsum) and calcium carbonate (calcite),[13] which are known to cause irritation of the mucus membranes of the eyes and respiratory tract.[14] Another study testing effects of the fine dust (<2.5 μm) on mice has found that those particles could cause respiratory tract hyperresponsiveness and pulmonary inflammation.[15] Although the fine particulate (<2.5 μm) was present in a small amount of the sampled WTC indoor dust (<1%), they should not be neglected because these particles can stay airborne for a long time or be resuspended from the large amounts of dust in some uncleaned residences or other commercial buildings.

The WTC indoor dust/smoke contained more than 50% mass in the <53-μm particle size fraction, unlike the outdoor dust/smoke that had the majority of particles in the >53-μm fraction. The difference in composition between the WTC indoor and outdoor dust/smoke may be the reason that the indoor samples had the lower concentrations in heavy metals despite sharing similar elemental profiles. Most <53-μm particles released from the collapse and pulverization of the WTC buildings were considered construction materials (i.e., cement),[12,14] which primarily consisted of calcium, silicon, magnesium, aluminum, and iron, not the heavy metals listed in Table 3. Thus, the WTC indoor dust/smoke contained more construction materials with fewer heavy metals and led to lower concentrations in heavy metals than the outdoor dust/smoke. The only exception was Sample ID 17, which contained more mass in the >53-μm particle fraction but had low concentrations in heavy metals similar to the other WTC indoor dust/smoke. This is because the large chunks of debris in the sample altered the particle size distribution, and they probably did not contain significant amounts of heavy metals.

Very little of the lightest jet fuel hydrocarbons were found in the WTC indoor dust/smoke samples, despite the detection of significant levels of heavy hydrocarbons that would be present in jet fuel. The light VOCs would have evaporated from the indoor dust, because ~2 months elapsed before the dust was collected by the NYU/EOHSI team. Several indoor and outdoor dust samples in regular New Jersey homes were collected and analyzed as background dust. These New Jersey samples were found to have considerably lower quantities of these alkanes, a different ratio pattern across the molecular weight range, and different alkane isomers than the WTC indoor samples, supporting the point that the alkanes observed in the WTC dust would be from the jet fuel.

The SVOC analysis identified products of incomplete combustion (e.g., phthalates, PAHs) and other varieties of organic compounds. The variability in the identified SVOCs reflected combustion of a variety of materials that would have been present inside the WTC buildings. Most SVOCs, including commonly found PAHs, had levels lower than 50 ppm, which were similar to the previously reported PAH result of WTC-settled dust.[2] Although the levels were as low as those found in the outdoor WTC dust, the significance of many exposures experienced by workers or residents remains unclear. The levels of PCDDs and PCDFs in the WTC indoor samples were also found to be similar to those of the outdoor dust. As described by EPA,[16] as well as the previous results from the WTC outdoor dust, these PCDDs and PCDFs in dust do not exceed the background values.

CONCLUSIONS

The indoor settled dust from the collapse of the WTC buildings was physically and chemically similar to the outdoor settled dust. However, the samples contained more inhalable dust particles (<53 μm) than did the outdoor dust. Because of the size and continued high alkalinity and the presence of fibrous particles, the WTC indoor dust/smoke would lead to exposures that influence residents' and others' respiratory health in cases where they returned to uncleaned homes and did not wear respiratory protection. The levels of organic components of the dust were found at relatively low concentrations in the indoor samples as compared with the outdoor samples. However, the health effects caused by this complex set of organic compounds mostly remain unknown. The indoor dust samples collected and provided by the residents showed no presence of the WTC dust/smoke, indicating that these specific residences were not affected by the WTC dust/smoke or cleanup was successfully completed. The outside windowsill sample result suggests that uncleaned outside parts of a building may remain a source of residential exposure to the WTC dust/smoke.

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