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Refuse Incinerator Particulate Emissions and Combustion Residues for New York City during the 20th Century

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Refuse incineration data for New York City (NYC) have been compiled as a function of time during the 20th century to assess the historical significance of this pollutant source in a densely populated area. Thirty-two municipal and 17 000 apartment house refuse incinerators were identified. Approximately 1.1×10^8 t of refuse (wet weight) were combusted in NYC incinerators between 1908 and 1993, producing 3.4×10^7 t (dry weight) of combustion residue disposed in local landfills. Refuse incinerators were operated for most of this period without air pollution control and emitted 1.0×10^6 t of particles (a total of 120 mg for each cm^2 of land in NYC). Incinerator particle emission (PE) rates per unit area of land were highest in Manhattan (equivalent total deposition of 530 mg cm^{-2}). Incinerator PE exceeded 1.2×10^4 t yr^{-1} between 1930 and 1975, with maximum emission rates ($> 2.2 \times 10^4$ t yr^{-1}) in the late 1930s and 1960s. These and other factors support the conclusion that refuse incineration without air pollution control was an important source of airborne, respirable pollutants in NYC for many decades during the 20th century. Rates of particle emissions from Manhattan incinerators estimated here correlate strongly with Pb accumulation rates as a function of depth (time) in Central Park Lake sediments, consistent with refuse incineration emitting large amounts of atmospheric lead in NYC for many decades after the 1920s.

Introduction

Incineration of municipal refuse began to be substantial in the United States in the late 19th century (*1*). During the periods 1885−1910 and 1911−1935, approximately 180 and 500 new municipal incinerators, respectively, are reported to have been built (*2*). Construction peaked in the 1920s (*3*), and by the late 1930s, municipal incinerator (combustor) use was reported in 600−700 U.S. cities (*4*). After reduction in municipal waste combustor (MWC) use during World War II, surveys conducted during the mid-1950s indicate increased use of MWC and a trend toward construction of facilities with higher daily combustion capacity, especially in large North American cities (including Baltimore; Buffalo; Chicago; Cleveland; Detroit; Miami; New York; Philadelphia; St. Louis; Washington, DC; Montreal; and Toronto) (*5*−*7*). Prior to about 1950, air pollution controls (APC) in MWC were limited to dry expansion chambers, baffle walls, or elongated flues with low (<30%) particle mass retention. These early MWC were usually batch-feed furnaces that utilized manual stoking on stationary grates. Turbulence, temperature variations due to batch processing, and over-charging of furnaces relative to plant design capacity contributed to high particle emission (PE) rates. In the 1950s, continuous-feed of refuse, mechanized stoking on moving grates, and water-based APC systems became common (*8*), although the latter were only minimally effective (30−60% particle mass retention, *9*). Use of advanced APC in refuse incinerators, such as electrostatic precipitation (EP) and fabric filters, emerged in the early 1970s in response to new Federal laws mandating lower PE rates. Studies of refuse incinerator PE in the mid-1970s demonstrated high metals content of emitted particles (e.g., 8.1% Pb by mass, Table 1), suggesting that incinerators could be an important source of metals in some urban areas (*12, 13*). High costs for advanced APC inhibited new incinerator construction and led to the progressive closure of existing facilities (*15*). Operating MWC in the United States declined from 289 in 1965 (*8*) to 114 in 1974 (*15*), with selective retention of larger plants equipped with advanced APC. In New York City (NYC), the high cost of advanced APC led to the end of construction of new MWC in the mid-1960s (*16*), followed by closure of 8 of 11 plants between 1969 and 1981 (*17*−*19*). Electrostatic precipitation was installed at three remaining MWC between 1980 and 1984 (*17*) and continued to operate until closure of all facilities in the early 1990s (*20*).

Nonmunicipal refuse incinerators were first reported in NYC in hospitals in 1890 (*21*), but apartment house use of incineration apparently became common somewhat later (ca. 1910). By the 1920s, apartment house incinerators (multi-dwelling domestic waste combustors, DWC) were widely distributed in U.S. cities (*22*), and by 1958, more than 19 000 were in use (*23*) with a large majority in NYC. By 1960, NYC had more than 11 000 DWC (*24*), almost all with uncontrolled PE (*25*). These incinerators were a chronic source of particles (*26, 27*) due to inexperienced operators, low and variable combustion temperatures, refuse charging during combustion, infrequent cleaning, excessive combustion air intake rates, and overcharging (*22, 25*). Although all new DWC built in NYC after 1962 were required to have simple APC (*25*), failure to maintain APC devices was common (*27*). More restrictive PE limits led to a decline in the use of DWC in NYC beginning in the late 1960s (*28*). Single-family domestic incinerators, open burning, and other types of refuse incineration have also been commonly used in the United States. For example, in Los Angeles, 1.5×10^6 backyard incinerators were reported in use in the early 1950s (*29*) while Chicago area sales of domestic gas-fired incinerators exceeded 9×10^4 by 1955 (*30*).

Extensive past use of refuse incinerators in urban areas, relatively recent installation of effective APC devices, and high metals content in incinerator PE, all indicate that examination of refuse incinerators as an important historical particle source in urban areas is warranted. We are aware of no previous study that has attempted to quantify refuse incinerator PE in an urban area over many decades. Here we estimate PE and residue (ash) production from refuse

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TABLE 1. Comparison of Selected Elemental Content in Earth's Crust and Coal Fly Ash to Products of Municipal Refuse Incineration[a]

element	crust (*10*) (μg/g)	coal fly ash (*11*) (μg/g)	incinerator particles emitted (*12*) avg (μg/g)	incinerator particles emitted (*12*) 1σ (μg/g)	incinerator particles retained (fly ash) (*13*) avg (μg/g)	incinerator particles retained (fly ash) (*13*) 1σ (μg/g)	incinerator residue (*14*) avg (μg/g)	incinerator residue (*14*) 1σ (μg/g)
As	1.7	110	240	60	40	13		
Cd	0.1	8	1500	400	42	24		
Cl			200000	70000	8000	2100		
			20%	7%				
Cr	70	300	490	380	1330	170	400	
Cu	30	140	1700	300	980	440	3500	1500
Hg	0.03	0.05						
Ni	44	207	150	60	740	100	100	
Pb	15	80	81000	11000	4000	1300	5000	1700
			8.1%	1.1%				
Sb	0.2	12	2100	500	270	140		
Se		25	37	13	304	1.9		
Sn	3		11500	1200	1430	260	450	220
Ti	4700	5980	2400	1600	32000	4000	12000	
					3.2%		1.2%	
V		440			135	18		
Zn	60	740	120000	10000	10800	1400	4800	2300
			12%	1%	1.1%			

[a] Values in μg g^{-1} and % where noted. Incinerator particles emitted (particles not retained by APC and emitted from stack) from tests of three MWC (*12*) with an average PE rate of 2.43 kg of PE (t of refuse combusted)$^{-1}$. Incinerator fly ash (particles retained by APC) from one MWC (*13*) with a PE rate of 2.8 kg of PE (t of refuse combusted)$^{-1}$. Incinerator residue (bottom ash) is from tests performed on six incinerators (*14*). Substantial metal enrichment is evident in incinerator products (particularly Pb, Cd, Sb, Sn, and Zn), especially for emitted particles.

incineration in NYC as a function of time during the 20th century and examine its historical importance as a pollutant source in this densely populated urban area.

Methods

Historical literature and municipal refuse management records were examined to quantify annual and total mass of refuse incineration in NYC as well as operating conditions for individual MWC plants, including their locations, periods of operation, design process capacities, APC, and incineration rates. Total refuse mass incinerated in all MWC was compiled for most years. Data for each individual MWC were obtained for a number of years: 1934, 1946−1947, 1952−1971, 1973, and 1980. Thus about one-half of the total reported refuse mass incinerated in MWC can be assigned to specific plants. For other years, individual plant estimates were derived as the product of the total annual incinerated refuse mass (all facilities) and the proportion of the design combustion capacity of each MWC relative to the total design combustion capacity of all operating plants for that year. Complete records for 1934 (*16*) indicate that MWC in New York County (Manhattan) operated at substantially greater than design capacity (110−150%) while plants in other NYC counties had average throughputs relative to design capacity that were appreciably less (90%). This operating practice probably resulted from higher population density and waste generation rates for Manhattan. The method used here would thus tend to underestimate incineration rates in Manhattan MWC relative to the rest of NYC prior to 1952. After 1973, progressively fewer MWC operated, and the absolute magnitude of errors in particle emissions was reduced accordingly. Data for Queens and Richmond Counties were not reported in records available for the period prior to 1930, and MWC combustion rates in those counties have been estimated here as 90% of reported plant process capacity (based on 1934 records, *16*).

TABLE 2. Particulate Emission Factors (PEF) for Six Incinerator/APC Classes Reflecting Improvement in Furnace Operation and APC over Time[a]

incinerator plant/APC class	average APC efficiency (% retained)	average PEF (kg of PE/t)	lower bound APC efficiency (% retained)	lower bound PEF (kg of PE/t)
MWC-1	0	12	15	10.2
MWC-2	20	9.6	30	8.4
MWC-3	45	6.6	60	4.8
MWC-4	98	0.23	99	0.12
DWC-1		15		12
DWC-2		6		4.8

[a] MWC-1, batch-feed with manual stoke and no APC; all constructed before 1920. MWC-2, batch feed, manual-stoke and continuous-feed, mechanical stoke with dry expansion chamber and baffles for APC; all constructed 1920−1950. MWC-3, continuous-feed with mechanical stoke, and dry combustion chamber with and without wetted bottoms, wetted baffles, and sprays for APC; all constructed 1950−1962. MWC-4, continuous-feed with mechanical stoke and electrostatic precipitation for APC; all APC upgraded after 1980. DWC-1, flue-feed with no APC; all constructed before 1963. DWC-2, flue-feed with multiple chambers for APC; all constructed 1963−1968. For MWC, PEF were calculated as the product of average furnace PE (12 kg (t of refuse combusted)$^{-1}$; *41*) and 1 minus APC capture efficiency fraction (shown). Air pollution control efficiency for MWC reported as mass % of furnace PE retained by APC. All efficiencies are from ref *9* except MWC-4 average, which was calculated from reported stack PE tests of NYC MWC with EP (*43*). The PEF (particle emission factors) for DWC are from ref *9*. The class appropriate for each MWC is listed in Table 3.

Much useful information on design and operation of NYC MWC was reported in engineering periodicals contemporaneous with their use (*1, 31*−*38*). Although historical details are not available for all MWC, municipal records tended to highlight MWC that deviated from the most common designs used in each period, enabling unambiguous classification of individual NYC plants with respect to APC. Detailed description of APC equipment is not presented here but is available elsewhere (*39, 40*). Four MWC/APC classifications were established to aggregate MWC emissions representing progressive improvements in design and fraction of particles captured over time (Table 2). To quantify incinerator PE mass, each of the four MWC/APC classes was assigned a PE factor (kg of PE (t of refuse combusted)$^{-1}$) calculated as the product of the furnace PE rate and 1 minus the fraction of particle capture by APC in each class (i.e., fraction of furnace particle mass emitted by APC). A refuse furnace emission rate of 12 kg t^{-1} was used for all four MWC/APC classes based on mean furnace emissions from 183 incinerator tests (*41*; tests were performed on furnaces from 50 MWC during the 1960s). Findings elsewhere for furnace emissions from U.S. MWC are higher (17.5 kg t^{-1}, *42*; 15 kg t^{-1}, *9*), and the rate used here is probably biased toward a low value for most NYC MWC, especially for incinerators constructed prior to 1950 that used batch-feed and manual-stoked furnaces. Two PE factors were used for each MWC class to approximate the mean and minimum (lower bound) PE as discussed below and shown in Table 2. Particle capture efficiency fraction for most MWC/APC classes were derived from compiled ranges reported by the U.S. EPA (*9*). Midpoint values in reported ranges were used to calculate the mean PE factor for all MWC/APC classes except MWC-4, where reported average results from several years of emissions tests of NYC MWC with EP were used (*43*). Maximum PE capture percentages in reported ranges were used to calculate lower bound PE factors. Results of PE tests conducted on individual MWC in NYC are available for post-1950 MWC/APC classes (*25, 44*−*47*) and are consistent with the mean PE factors reported in Table 2.

The mass of particles discharged annually by each MWC was then calculated as the product of the total mass of refuse

TABLE 3. 32 Municipal Refuse Incinerators That Operated at 24 Locations in New York City during the 20th Century[a]

incinerator	county	design combustion (t/day)	year opened	year closed	incinerator APC class	refuse combusted (kt)	particles emitted (kt)
1, 56th Street	NY	272	1924	1936	MWC-2	6254	60.0
	NY	680	1937	1969	MWC-2		
2, 73rd Street	NY	290	1927	1953	MWC-2	4508	35.4
	NY	599	1957	1972	MWC-3		
3, 139th Street	NY	290	1925	1958	MWC-2	2693	25.9
4, W 215th Street	NY	680	1934	1970	MWC-2	6042	58.0
5, Gansevoort	NY	907	1953	1979	MWC-3	5341	35.3
6, W 8h Street	K	91	1924	1937	MWC-2	383	3.7
7, Georgia Avenue	K	91	1924	1937	MWC-2	381	3.7
8, Hamilton Avenue	K	454	1929	1962	MWC-2	7938	64.1
	K	907	1962	1981	MWC-3		
9, Greenpoint	K	454	1929	1959	MWC-2	10013	64.1
	K	907	1959	1994	MWC-3,4		
10, Flatlands	K	454	1929	1958[b]	MWC-2	3340	32.1
11, South Shore	K	907	1954	1978	MWC-3	5394	35.6
12, SW Brooklyn	K	907[c]	1961	1991	MWC-3,4	5535	26.7
13, Maspeth	Q	91	1916	1937	MWC-1	553	6.6
14, Ravenswood	Q	336[d]	1918	1950	MWC-1	2003	24
15, Arverne	Q	63[e]	1918	1937	MWC-1	87	1
16, Flushing	Q	63	1919	1935	MWC-1	2645	22.9
	Q	272	1936	1955	MWC-2		
	Q	599	1957	1969	MWC-2		
17, Jamaica	Q	91	1921	1937	MWC-2	444	4.3
18, Hammels	Q	136	1925	1938	MWC-2	554	5.3
19, Bergen Landing	Q	136	1924	1938	MWC-2	613	5.9
20, Betts Avenue	Q	136	1926	1938	MWC-2	7766	42.9
	Q	907[f]	1950	1993	MWC-3,4		
21, Zerega Street	B	680	1934	1969	MWC-2	5488	52.7
22, W New Brighton	R	54	1908	1938	MWC-1	1765	17.5
	R	136	1924[g]	1958	MWC-2		
23, Clifton	R	82	1913	1934	MWC-1	709	7.4
24, Great Kills	R	136	1927	1947	MWC-2	712	6.8
total: 20th century						81163	642

[a] Incinerator numbers in left column identify map locations (Figure 1). Counties: NY, New York (Manhattan); K, Kings (Brooklyn); Q, Queens; B, Bronx, and R, Richmond (Staten Island). Design combustion rates and operational periods are listed for each MWC. Incinerator/APC classes are outlined in Table 2. Multiple class listing indicate APC upgrade during operational period. Total mass estimates of refuse combusted and particles emitted for all MWC operated at each location are also shown. [b] Did not operate in 1946. [c] Decreases to 680 t d^{-1} in 1974. [d] 91 t d^{-1} furnace closed in 1937. [e] Operated summer only. [f] 725 t d^{-1} 1950−1957; closed April 1984−July 1986. [g] Year opened only approximate.

combusted in each facility and its assigned PE factor. Records of residue (ash) measurements from individual MWC are also available for 1961−1969, 1971, and 1973 (113 one-year plant records, *48*), indicating an average (nonweighted) dry residue production of 26.5% (± 5.2**%)** of initial refuse mass. This "average" factor was used to estimate residue production for each year for which measurements were not reported.

Available data for PE from DWC in NYC are limited to the number of operating incinerators and total mass of refuse combusted for selected years. Incineration rates were estimated as the product of the number of operating DWC and the average process rate for DWC for each year. Linear interpolation was used to estimate annual incineration rates for years between those reported. A relatively simple design history appears to be representative for APC used in DWC in NYC, and only two separate PE factors have been used (Table 2) to estimate particulate emissions from this source. Residue from DWC is estimated as 37.3% (± 5.2%) based on tests performed in NYC by Kaiser et al. (*25*). Average bottom ash output from DRI was about 40% higher than MWC, indicating less efficient refuse combustion.

Results and Discussion

Thirty-two MWC were constructed in NYC at 24 locations between 1908 and 1962 (Table 3; Figure 1). Approximately 8.1×10^7 t of refuse was combusted in MWC between 1908 and 1993 (Table SI-1 in Supporting Information). Approximately 17 000 DWC were installed in NYC apartment buildings between about 1910 and 1968 and combusted approximately 3.3×10^7 t of refuse between 1910 and 1993 (Tables SI-1 and SI-2 in Supporting Information). Collectively, these incinerators combusted about 1.1×10^8 t of refuse between 1908 and 1993 (71% in MWC) and produced 3.4×10^7 t of residue (63% by MWC; Table SI-1 in Supporting Information). Municipal incinerator usage in NYC exhibited a bimodal pattern as a function of time during the 20th century (Figure 2) with maximum rates in the late 1930s and the mid-1960s ($>2 \times 10^6$ t yr^{-1}) following two periods of intensive incinerator construction. Available data indicate that use of DWC increased progressively from about 1910 until 1971, when a maximum of 1.3×10^6 t yr^{-1} was combusted.

Collectively, NYC refuse incinerators emitted 1.0×10^6 t of PE to the atmosphere (Table SI-1 in Supporting Information). Estimated rates of PE from NYC refuse incinerators greater than 1.2×10^4 t yr^{-1} occurred throughout the period between 1930 and 1975 (Figure 3). The total mass of PE during the 20th century from MWC and DWC in NYC is estimated to be 6.4×10^5 and 3.7×10^5 t, respectively (lower bound: 5.3×10^5 and 2.9×10^5 t, respectively). Total PE for MWC and DWC are equivalent to 0.79% and 1.1% of refuse combusted, respectively. Emissions from MWC exhibited a bimodal pattern coincident with MWC usage (Figure 3). The large decline in relative PE rates from MWC after 1980 was due to use of high-capture-efficiency EP in the three remaining facilities. The rate of PE from DWC exhibited a progressive

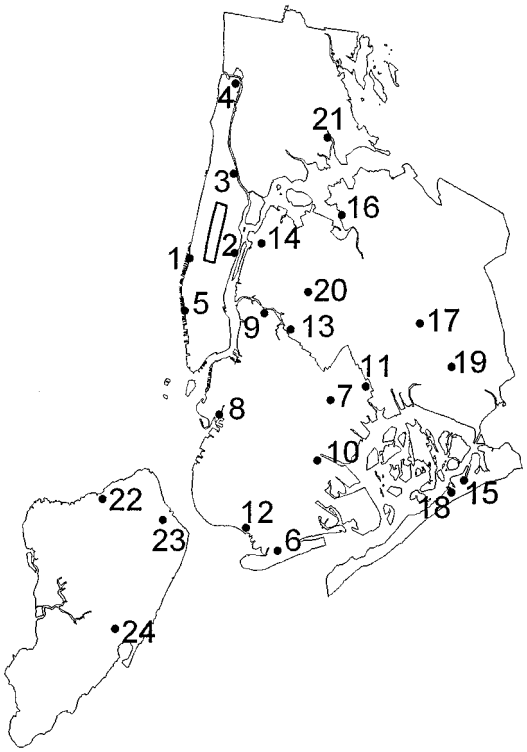

FIGURE 1. Map of New York City showing locations of MWC operated during the 20th century; 32 municipal incinerators were constructed at these 24 locations between 1908 and 1962. Incinerator location numbers refer to Table 3. Central Park is indicated as a rectangle.

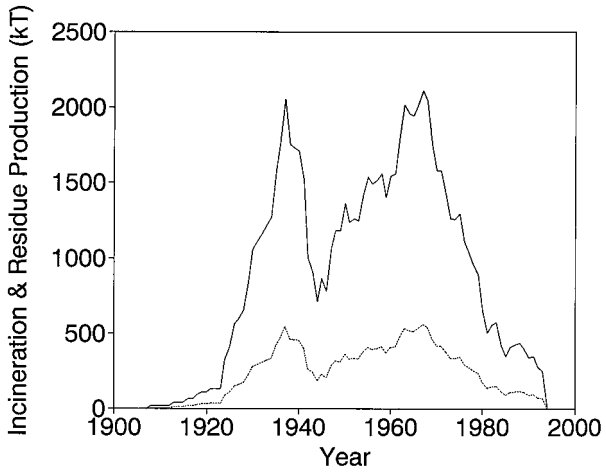

FIGURE 2. Mass of refuse combusted in MWC in New York City as a function of year (upper) and the mass of residue generated (lower). Annual data are reported in Table SI-1 in Supporting Information.

rise during much of the century with peak emissions in 1971 (Figure 3). Total (MWC and DWC) incinerator PE is equivalent to 120 mg cm^{-2} if accumulated uniformly throughout NYC (831.4 km^2). Approximately 32% (3.3×10^5 t) of the total for NYC was emitted in Manhattan (61.4 km^2; 7% of NYC land area). This is equivalent to 530 mg cm^{-2} of particle deposition, assuming that all emissions from Manhattan were accumulated uniformly on its land surface. Incinerator particle emissions were substantially greater per unit land surface area in the most densely populated urban core as compared to the rest of NYC.

Refuse incineration was reported to account for only 2.2% of the total particle mass emitted in the United States in 1970

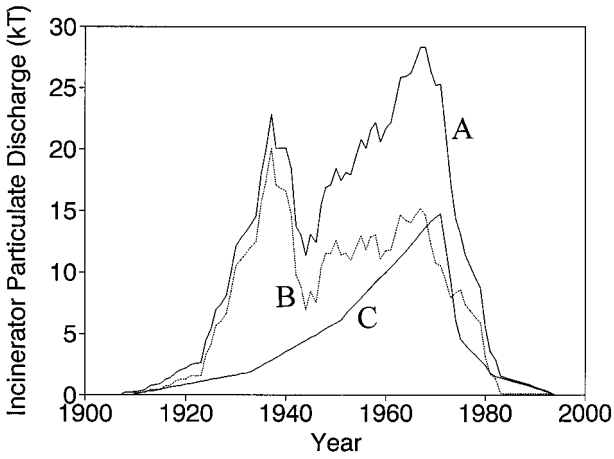

FIGURE 3. Mass of total particle emissions from both types of refuse incinerators (MWC and DWC) in New York City as a function of year (A) and particle emission by source type from MWC (B) and DWC (C). Annual data are reported in Table SI-1 in Supporting Information. Municipal incinerators released 71% of total PE.

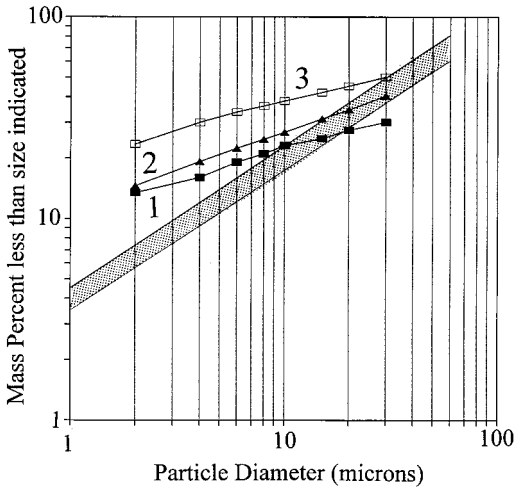

FIGURE 4. Size distribution (by mass) of particles discharged from furnaces of three MWC (numbered lines, *56*) and a range of MWC furnace PE from multiple tests (shaded area, *42*). All tests performed on MWC in the United States in the 1960s. Lines 1 and 2 were from 125 t d^{-1} MWC. Line 3 includes data for a 60 t d^{-1} MWC. A range of 5−24% of furnace PE by mass less than 2 μm is shown.

(*52*, excluding open burning). However, refuse incineration appears to have been the largest single PE source category in NYC in 1967 (*53*) and 1974 (*54*), accounting for 36% and 38% of total atmospheric PE, respectively. The disparity in these findings reflects the heavy reliance on incinerators in NYC (and some other large cities) for combusting solid wastes as compared to the United States as a whole.

Particle size and chemical content play an important role in the potential impact of particles on human health. Small particles (<2.5 μm) have the greatest health impact because they tend to be deposited more readily in the lungs where they can be absorbed (*55*). The size of particles released from a refuse furnace is dependent on many factors, such as the type of refuse, furnace design, and furnace operation (*40*, *42*); data on the size distribution of PE released from refuse furnaces is limited (*40*). However, available data on the PE size distribution for MWC comparable to those operated in NYC (i.e., high-capacity MWC built before 1965 without APC) indicate a range of 5−24% PE by mass less than 2 μm (Figure 4; *42*, *56*). In a study of a MWC with low-capture-efficiency APC (similar to most NYC MWC), Bush et al. (*57*) reported a PE rate of 1.4×10^{17} particles (t of refuse combusted)$^{-1}$,

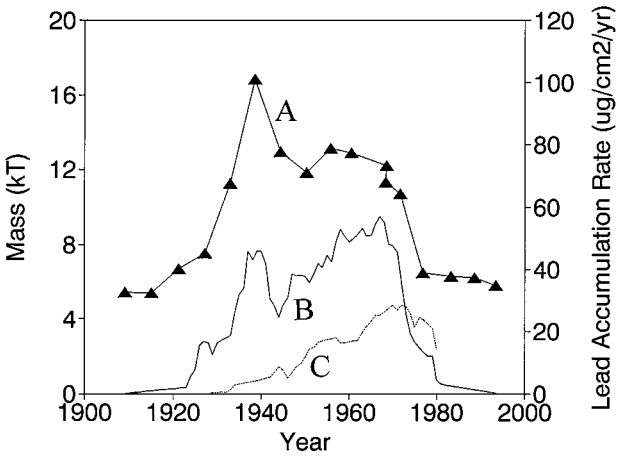

FIGURE 5. Comparison of normalized Pb accumulation rates in dated sediment cores from Central Park Lake (A, right scale; *59*) with particle emissions from all refuse incinerators in Manhattan (B, left scale) and total production of Pb for gasoline additive in the United States (C; *60, 61*; left scale $\times 40$). See Figure 1 for locations of MWC and Central Park.

with a geometric mean particle size (by *number*) of 0.12 μm. In another study, a range of 95−99.7% of particles was reported to be less than 0.1 μm (*58*) with a mean particle size (by *number*) of 0.05 μm. Due to the components of refuse typical of a North American city, trace metals tend to be concentrated in refuse incinerator PE (Table 1). Metals in refuse incinerator PE are associated predominately with respirable particles (*12, 13*) that are relatively soluble in water or dilute acids (*13*). For instance, Greenberg et al. (*12*) reported Pb concentrations of PE from a Chicago area MWC in the mid-1970s of 6.9% (±1%), with more than 95% of Pb mass in PE occurring in particles less than 2 μm. Comparably high total lead concentrations in PE (7.7% and 9.7%) were reported at two MWC in the Washington, DC, area (*13*). Probable emission of a substantial percentage of incinerator PE (by mass and number) in the respirable (<2.5 μm) size range and enrichment of metals on respirable particles (when combined with sustained, high rates of refuse combustion and high rates of particle emissions due to absence of APC and other factors, such as concentrated incinerator use in densely populated areas) are consistent with the conclusion that refuse incineration was an important source of airborne, respirable pollutants and a possible source of health impact in NYC for many decades of the 20th century.

The temporal pattern of estimated PE rates of refuse incinerators operated in Manhattan has strong similarities to annual accumulation rates of Pb as a function of depth (time) in dated layers of sediment in cores collected from Central Park Lake (*59*; Figure 5). A rapid increase in annual Pb deposition in lake sediments after approximately 1920 was evident, reaching maximum 20th century values in the late 1930s. This temporal pattern of Pb accumulation is quite similar to the history of Manhattan refuse incinerator emissions but is appreciably different from that for Pb emission from automobile exhaust. Extensive open burning and use of some MWC (*62, 63*) have been reported in adjacent counties in New Jersey and could have also contributed slightly to refuse-derived PE to Central Park Lake sediments.

Estimated Pb emissions from automobile exhaust and refuse incinerator PE in NYC and Manhattan for 1967 are shown in Table 4. Quantitation assumes total PE of 28.3 kt (Table SI-1 in Supporting Information) and 9.5 kt for NYC and Manhattan, respectively, and the Pb content of emitted and retained particulate reported in Table 1. The average PE factor for all incinerators in NYC in 1967 (8.8 kg of PE t^{-1}) was higher than the average for incinerators represented in Table 1 (2.43 kg of PE t^{-1}), probably due to improved APC used on the units tested in Table 1 in the 1970s as compared to those used in NYC in 1967. To account for this difference, 27.6% (2.43/8.8) of incinerator PE in NYC in 1967 was assumed to have the Pb content of emitted particles in Table 1 and 72.4% the Pb content of retained particles. Computations of automotive Pb emission to the atmosphere assumes total automotive travel distance of 2.53×10^9 km (Manhattan; *64*) and 1.74×10^{10} km (NYC; *64*); automotive fuel consumption rate of 4.25 km L^{-1} (*64*; 10 mi gal^{-1}); leaded gas content of 0.52 g L^{-1} (*65*; 2 g gal^{-1}) of which 80% is assumed to be released to the atmosphere. On the basis of this calculation, refuse incinerators accounted for approximately 29% and 49% of the combined atmospheric Pb emissions by these sources in NYC and Manhattan, respectively. Temporal trends in the ratios of Pb, Zn, and Sn accumulation in Central Park Lake sediments (*59*) suggest that refuse incineration accounts for an even greater fraction of the atmospheric deposition of Pb in Manhattan. Sustained high rates of incinerator PE after 1930 and high Pb content of combustible refuse reported as early as 1908 (0.3%, *66*) are additional factors supporting our general conclusion that refuse incineration was a major historical source of atmospheric Pb and several other metals in NYC during the 20th century, particularly in Manhattan.

TABLE 4. Comparison of Pb Emissions by Automotive Exhaust and Refuse Incineration in New York City and Manhattan for 1967[a]

location	automotive exhaust Pb	incineration Pb	incineration (% of total)
NYC			
mass (t/yr)	1725	602−827	26−32
(μg cm^{-2} yr^{-1})	207	72−99	
Manhattan			
mass (t/yr)	250	203−278	45−53
(μg cm^{-2} yr^{-1})	407	330−453	

[a] Equivalent Pb deposition rates assume that all Pb was uniformly deposited in NYC (831 km^2) and Manhattan (61 km^2), respectively.

Enrichment of metals has also been observed in the ash residue produced by refuse incinerators (Table 1). Residue from NYC incinerators was routinely disposed in landfills located throughout NYC (*16*), and such refuse landfills probably now account for as much as 10% of the NYC land surface area (*67*).

Data summarized here represent the most comprehensive attempt to estimate particle emissions as a function of time from refuse incinerators in a major urban area of which we are aware. Due to high refuse combustion rates and the absence of air pollution controls, refuse incineration produced high rates of particulate emissions to the NYC atmosphere for many decades during the 20th century and appears to have been an important source of air-borne, respirable pollutants. Use of advanced APC after 1980 resulted in large reductions in the relative rate of particle emissions from municipal incinerators. High concentrations of metals and other contaminants in incinerator particles and residues indicate that deposits of these materials may continue to play an important role in exposure to toxic materials within the NYC environment, through resuspension, leaching and redistribution of surface soils, and sediment transport in the adjacent Hudson River estuary. For example, Pb concentrations in sediment layers deposited in Central Park Lake between approximately 1930 and 1970, the period of peak incinerator particle emission, range from about 850 to 1260 mg kg^{-1}, 30−50 times higher than uncontaminated fine grained sediments (*59*). Temporal patterns of incinerator usage similar to NYC have been reported for other large U.S. cities, suggesting that incinerator particulate emissions may

also have been significant elsewhere. Recognition of past practices of refuse incineration without air pollution control as an important historical pollutant source in urban areas has been generally underappreciated. This may be explained by a lack of awareness of the extent of incinerator operations in the United States during the first 7 decades of the century, nonuniform incinerator use in U.S. cities, relatively late use of APC with very high-particle-capture efficiency in refuse incinerators, and a large decline in the number of operating incinerators before detailed studies of their particle emissions were performed.

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Supporting Information Available

Two tables that report data on annual mass of refuse combusted, residue produced, and particles emitted from municipal and domestic incinerators in NYC for the period 1907−1994 (Table SI-1); reported rates of domestic incinerator usage in NYC (Table SI-2). This material is available free of charge via the Internet at http://pubs.acs.org.

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