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Temporal Trends in Airborne Dust Concentrations at a Large Chrysotile Mine and its Asbestos-enrichment Factories in the Russian Federation During 1951–2001

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Abstract

Objectives: Mining and processing of chrysotile, an established carcinogen, has been undertaken in Asbest, Russian Federation since the late 1800s. Dust concentrations were routinely recorded at the open-pit mine and its asbestos-enrichment factories. We examined the temporal trends in these dust concentrations from 1951 to 2001.
Methods: Analyses included 89 290 monthly averaged gravimetric dust concentrations in six factories (1951–2001) and 1457 monthly averaged concentrations in the mine (1964–2001). Annual percent changes (APC) in geometric mean dust concentrations were estimated for each factory and the mine separately from linear mixed models of the logarithmic-transformed monthly averaged concentrations.
Results: Dust concentrations declined significantly in the mine [APC: −1.6%; 95% confidence interval (CI): −3.0 to −0.2] and Factories 1–5 but not 6. Overall factory APCs ranged from −30.4% (95% CI: −51.9 to −8.9; Factory 1: 1951–1955) to −0.6% (95% CI: −1.5 to 0.2; Factory 6: 1969–2001). Factory trends varied across decades, with the steepest declines observed before 1960 [APCs: −21.5% (Factory 2) and −17.4% (Factory 3)], more moderate declines in the 1960s and 1970s [APCs from −10% in Factory 2

(1960s) to –0.3% (not statistically significant) in Factory 4 (1970s)], and little change thereafter. Mine dust concentrations increased in the 1960s (APC: +9.7%; 95% CI: 3.6 to 15.9), decreased in the 1990s (APC: –5.8%; 95% CI: –8.1 to –3.5) and were stable in between.

Conclusions: In this analysis of >90 000 dust concentrations, factory dust concentrations declined between 1951 and 1979 and then stabilized. In the mine, dust levels increased in the 1960s, declined in the 1990s and were unchanged in the interim.

Keywords: asbestos; chrysotile; dust measurement; Russian Federation

Introduction

Chrysotile asbestos is carcinogenic to humans (IARC Group 1) (IARC, 2012). The Joint Stock Company Uralasbest ('Uralasbest'), situated in Asbest, Russian Federation operates the world's largest open-pit chrysotile mine. Currently, it produces ~20% of the world's chrysotile. Mining and processing of raw chrysotile-containing ore have been undertaken at this site since the late 19th century (Zorina and Kashansky, 1999).

At Uralasbest's open-pit mine, chrysotile is mined through a mechanized process of drilling and blasting (Kashansky *et al.*, 2001). At present time, the mine covers an area of 12 km^2 and is 325 meters deep. The average asbestos content of the ore mined at Uralasbest is 2.3% (Kashansky *et al.*, 2001) and has a low amphibole content. In an autopsy study of 47 former residents of Asbest, approximately half of whom had known occupational exposure to asbestos, chrysotile accounted for 90% of inorganic fibers in lung tissue, tremolite/anthophyllite contributed 5%, and there was no indication of crocidolite or amosite (Tossavainen *et al.*, 2000). Since the late 1800s, there have been seven asbestos-enrichment factories operated by Uralasbest. All factories used the dry milling technique, which consists of repeated cycles of crushing the raw ore, drying and then screening through vibrating screeners so that asbestos fibers rise to the surface and are removed by vacuum suction. Over time, the degree of mechanization advanced and technology improved, permitting the enrichment of ore with lower chrysotile content, material of which would have been previously disposed. The majority of production today is of 50-kg packages of chrysotile, graded for use in textiles, pipes, slate, and fillers.

To further characterize cancer mortality risks associated with exposure to chrysotile, a historical cohort study of over 30 000 workers employed at Uralasbest, *The Asbest Study*, has been initiated. As described in the study overview and rationale paper (Schüz *et al.*, 2013), retrospective assessment of occupational exposures of the cohort members will rely heavily on historical measurements of airborne dust concentrations. There are extensive records of gravimetric dust concentrations which were systematically collected per standard practice at Uralasbest. Previous reports, made prior to the initiation of *The Asbest Study*, provided a brief overview of the dust measurement collection methods and presented descriptive results of these dust data in the mine and factories (Elovskaya *et al.*, 1998; Scherbakov *et al.*, 1998; Tossavainen *et al.*, 1999; Kashansky *et al.*, 2001; Shcherbakov *et al.*, 2001). The objective of this paper is 2-fold: (i) to provide a comprehensive characterization of the dust data collection methods and measurements available for analysis in the on-going cohort study and (ii) to examine the temporal trends in the dust concentrations in the mine and asbestos-enrichment factories over a 50-year period, from 1951 to 2001.

Methods

Ethics

The historical cohort study of which this work is a part was approved by the IARC Ethics Committee (IEC No. 12–22, September 2012). The present investigation does not include participant-level data.

Dust measurement sampling

Paper records of dust concentrations from routine sampling in the factories conducted by the company's Central Laboratory for Production Control (CL) are available beginning in the early 1950s (excluding the years 1956–1958 because flooding destroyed the records). From 1964 to 2001, routine dust measurements in the mine were made by the Paramilitary Mine Rescue Unit (Mine Rescue), a division of the Russian Federation Emergencies Ministry. Along with the Mine Rescue, the CL conducted periodic measurements in the mine beginning in the 1970s.

All measurements were taken at stationary sampling points in areas corresponding to the breathing zone of workers, or as close as possible. The number of measurements taken in each factory or the mine and the location of these sampling points depended on factors such as its size, including the number of units within each, as well as the amount of equipment and number of workers in different units. Sampling procedures for total dust (summarized in Table 1) followed Russian government standards for monitoring air quality in workplaces (GOST, 1988; Russian Federation Oversight Committee for Sanitation and Epidemiology, 2005). Factory measurements were taken at each sampling point either once per month or every 10 days (i.e., 2–3 times per month), depending on the time period. In the mine, measurements were taken approximately once every 3 months with fewer measurements taken in January, April, July, or October than in other months.

Measurement equipment and procedures for estimating gravimetric concentrations were consistent across factories and the mine, and over time. Dust was collected on 10 or 20 cm^2 AFA VP filters ('AFA VP 10', 'AFA VP 20') using stationary samplers placed 1.5 meters off the floor with concave sampling heads with an opening diameter of either 55 mm or 73 mm. The smaller head and filter were used in less dusty areas, whereas the larger head and filter were used in dustier areas. Air pumps were typically operated at 20 l min^{-1} or 70 l min^{-1} for a duration of 15 to 30 minutes, with the lower sampling

Table 1. Description of sampling methods, frequency of sampling, and availability of dust measurement data from the Uralasbest asbestos-enrichment factories and mine: 1951–2001.

A. Dust measurement database

	Monthly averaged concentrations per sampling point based on multiple measurements taken on one day per month[a]	**Monthly averaged concentrations per sampling point based on multiple measurements taken 2–3 days per month**[b]	**Multiple individual measurements from which unit-level monthly average estimated**
		Years of data available	
Factory (years of operation)[c]			
Factory 0 (1896–1956)		1955	
Factory 1 (1924–1955)	1951–1954	1955	
Factory 2 (1930–1980)	1951–1954	1955, 1959–1980	
Factory 3 (1936–1977)	1951–1954	1955, 1959–1977	
Factory 4 (1956–2010)	1981–2001	1959–1980	
Factory 5 (1955–1997)	1981–1997	1955, 1959–1980	
Factory 6 (1969–present)	1989–2001	1969–1988	
Mine (1896 to present)			
Source: Mine Rescue			1964–2001
Source: CL			Periodic measurements from 1970s

B. Sampling information provided by Central Laboratory

Samplers	Аспиратор для отбора проб воздуха, модель 822 Аспиратор для отбора проб воздуха, АПВ-4-220В-40, АПВ-4-12В-40 Приборы для отбора проб воздуха ПА-20м-1, ПА-20м-3
Filters	1 to 5 filters placed at each sampling point on each day of measurement 10 or 20 cm^2 AFA VP filters on concave sampling heads with opening diameter of 55 mm or 73 mm.
Typical sampling duration	15–30 minutes, reduced in areas of very high dust to prevent overloading of filter, increased in areas of low dust to permit sufficient collection on filter
Typical suction rate	20 l min^{-1} or 70 l min^{-1}, with lower speeds used in areas of higher dust levels.

Abbreviations: CL = Central Laboratory for Production Control; Mine Rescue = Paramilitary Mine Rescue Committee.

[a] Multiple measurements taken at each sampling point on one day of the month. Arithmetic mean of the day's measurements reported in the database.

[b] Multiple measurements taken at each sampling point taken on 2–3 days per month, with multiple measurements taken on each occasion. Arithmetic mean of the daily arithmetic means recorded in the database.

[c] All factory measurements taken by CL.

rate and shorter duration used in areas of higher dust levels to avoid overloading the filters, and higher speed and longer duration in less dusty areas. On each day of sampling, between 1 and 5 measurements were taken at each sampling point. Filters were weighed before and after dust collection (minimum and maximum detectable weights of 0.01 mg and 200 g, respectively) and the gravimetric dust concentration (mg m^{-3}) was calculated as: [($\text{weight}_{\text{post-sampling in mg}}$ – $\text{weight}_{\text{pre-sampling in mg}}$)/volume (l) of air collected] × 1000. Photos of the sampling heads and filters are provided in Supplementary Material 1 in the online edition (available at *Annals of Work Exposures and Health*).

Dust measurement database and classification of measurements

The CL transferred dust concentrations from original paper records to an electronic database. Concentrations in the database are indexed by factory number or mine, month, year, and sampling point number. In the factories, each number refers to a distinct location. In the mine, stationary measurements from like equipment or processes (e.g., excavator cabins) within a production unit have the same sampling point number.

For analysis, sampling point numbers were grouped into production units (described in Supplementary Table 1 in the online edition, available at *Annals of Work Exposures and Health*) based on documentation in the original dust measurement journals and official company work orders. Factory units were classified as 'crushing and sorting—main; crushing and sorting—drying and boiler; crushing and sorting—dust chamber/bag house filter; dry ore warehouse; enrichment—main; enrichment—dust chamber/bag house filter; enrichment—dust/waste bunker; dust chamber; final product (packaging); mosaic tile (a unit which only existed in Factory 6)' and 'other'. Mine units were classified as 'mining—borehole drilling; mining—excavators; mining—dump transport; drilling—drilling station; mine dump—excavators; mine dump—background'; and 'other'. In the factories and mine, the category of 'other' includes measurements taken in areas of maintenance, engineering, laboratory, and quality control. In the mine, this group also includes rail transport activity.

For each sampling point number in the factories, the CL transferred the corresponding monthly averaged concentrations [average of the (multiple) daily arithmetic means] as recorded in their paper records, indexed by month and year, into the database. Supplementary Table 2 in the online edition (available at *Annals of Work Exposures and Health*) shows the number of stationary sampling points per unit per year in the factories and the breakdown of units within each factory over time. Occasionally, there were multiple measurements per month for a given spot (<3% of the records) due to duplicate data entry or measurements that were not averaged by the CL. We took the arithmetic mean of these values and retained one record per sampling point per month. After excluding measurements with the missing month (n = 17), there were 89 397 monthly averaged concentrations from Factories 0 to 6. The numbers of monthly averaged concentrations per factory, unit, and year are shown in Supplementary Table 3 in the online edition (available at *Annals of Work Exposures and Health*).

For the mine, the CL entered all measurements within a production unit from the Mine Rescue's routine measurements as well as the CL's own periodic measurements into the database. After excluding five measurements with missing month, we calculated unit-level monthly averages, stratified by source (n = 1457 from Mine Rescue, 87 from CL). The number of monthly averaged concentrations per unit and year are shown in Supplementary Table 4 in the online edition (available at *Annals of Work Exposures and Health*).

Although the chrysotile enrichment process was similar over time, the naming and structure of units varied across and within factories over the years (illustrated in Supplementary Tables 2–4, available at *Annals of Work Exposures and Health*). Furthermore, within a factory or the mine, there were units for which measurements were not available in every calendar year. This likely reflects changes in the factory structure over time (e.g., the bag house filter chamber in the crushing and sorting unit was only installed in Factory 4 in 1978) as well as variability in the level of detail in the original dust measurement journals.

Quality control

We performed an independent double entry for a convenience sample of 1991 monthly averaged concentrations from paper dust measurement records and found a high level of agreement (98.9%) between the means entered in the database and those recorded on paper. Additional details are provided in Supplementary Material 2 online (available at *Annals of Work Exposures and Health*).

Statistical analysis

For all analyses, we used the log-transformed (natural logarithm) sampling point-level monthly averaged concentrations for the factory data (n = 89 290 from Factories 1 to 6) due to a strong right skewness of the distribution (Supplementary Material 3 in the online edition, available at *Annals of Work Exposures and Health*). Main trend analyses excluded the 107 monthly averaged concentrations from Factory 0 because data were limited to 1 year (1955) but these data are presented in the online Supplementary Tables (available at *Annals of Work Exposures and Health*). Primary analyses in the mine used the log-transformed unit-level monthly averaged concentrations taken by the Mine Rescue (*n* = 1457). The 87 monthly averaged concentrations taken by the CL in the mine (shown in Supplementary Table 4 in the online edition, available at *Annals of Work Exposures and Health*), were only included in sensitivity analyses.

Descriptive analyses of dust concentrations were undertaken using Stata version 13 (College Station, TX) to examine temporal patterns in dust concentrations in the factories and mine. Geometric means (exponential of the arithmetic mean of the log-transformed monthly averaged concentrations) of monthly averaged dust concentrations were estimated by factory, unit, and time period (year or decade).

We used linear mixed models of the log-transformed monthly averaged concentrations to estimate the annual percent change (APC) in the geometric mean dust concentration (SAS mixed procedure, v9.3, Cary, NC). A priori it was decided to fit separate models for the mine and each factory (1 to 6). We fitted models with a fixed effect for calendar year (continuous) and a random intercept and slope for calendar year (continuous) by unit. From the fixed component of the slope in the model, we obtained a factory- or mine-specific overall temporal trend [and corresponding 95% confidence interval (CI)] in the geometric mean dust concentration. In addition, unit-specific trends and 95% CIs were obtained from the Best Linear Unbiased Predictors (BLUPS) of the random component of the slope. In addition to modelling time trends over all calendar years, we examined the trends within decades by adding a fixed effect for decade (categorical) and the interaction between decade and the fixed component of calendar year (continuous) to our main model. All *P* values reported are two-sided.

In sensitivity analyses, we compared trend estimates from the models described above to models adjusted for calendar month of measurement by adding month (categorical) as a fixed effect to the time trend models. We also conducted a sensitivity analysis in the mine including the 87 monthly averaged concentrations from the periodic CL measurements.

Results

Descriptive analyses of geometric annual mean dust concentrations in the factories and mine

Geometric annual mean dust concentrations decreased over time in all factories and the mine (Fig. 1A) but the contrast between levels in the first and last years of available measurements was greater for Factories 1 (192.2 to 34.6 mg m^{-3}), 2 (134.9 to 4.6 mg m^{-3}), and 3 (83.8 to 5.7 mg m^{-3}) than Factories 4 (5.1 to 4.0 mg m^{-3}), 5 (6.5 to 3.6 mg m^{-3}), 6 (5.0 to 2.8 mg m^{-3}), or the mine (2.7 to 2.0 mg m^{-3}). The corresponding number of monthly averaged dust concentrations contributing to the annual estimates are shown in Supplementary Tables 3 and 4 in the online edition (available at *Annals of Work Exposures and Health*).

Examining Fig. 1A in more detail, the highest dust concentration levels were observed in Factories 1–3 in the early 1950s; in Factories 1 and 2, the geometric annual means exceeded 100 mg m^{-3} in 1951. By 1959, there were four factories in operation (Factories 2–5) with annual dust concentrations ranging from 16.1 mg m^{-3} in Factory 3 to 5.1 mg m^{-3} in Factory 4. Throughout the 1960s, dust concentrations further decreased across the four factories. In 1969, the geometric annual mean dust concentrations ranged from ~5 (Factories 4, 5, and the newly opened Factory 6) to 10 mg m^{-3} (Factory 3). Annual estimates of the factory dust levels continued to decrease through the 1970s, ranging from 3 to 4 mg m^{-3} in 1979 in Factories 2, 4, 5, and 6 (Factory 3 closed in 1977). Throughout the 1960s and 1970s, annual mean dust levels were 1.5- to 3-fold higher in Factories 2 and 3, which opened in the 1930s than in Factories 4 and 5, which opened in the mid-1950s. Geometric annual mean dust levels ranged from 2.5 to 4 mg m^{-3} in the three factories (4–6) which were open throughout the 1980s and 1990s.

In the mine, the annual mean dust concentration increased from 2.7 mg m^{-3} in 1964 to 7.8 mg m^{-3} in 1966 and then decreased to 4 mg m^{-3} in 1969 (Fig. 1A). Annual mine dust concentrations ranged from 2.5 to 4.7 mg m^{-3} in the 1970s and early 1980s with no clear pattern of increasing or decreasing levels. There were overall decreases from the mid-1980s to the end of the 1990s and early 2000s with annual mean dust concentrations in these later years ranging from 1.8 to 2.2 mg m^{-3}. Geometric means by decade are reported in Supplementary Tables 5 and 6 in the online edition (available at *Annals of Work Exposures and Health*) for the factories and mine, respectively.

The calendar year patterns observed at the unit level in the factories (Fig. 1B, all factories combined) and mine (Fig. 1C) paralleled those observed overall (Fig. 1A). The figures further illustrate the marked variability (at times exceeding 10-fold) in the dust levels across the units in the factories and mine. In the factories, the highest levels were observed in the 'dust chamber, enrichment—dust chamber/bag house filter, enrichment—dust/waste

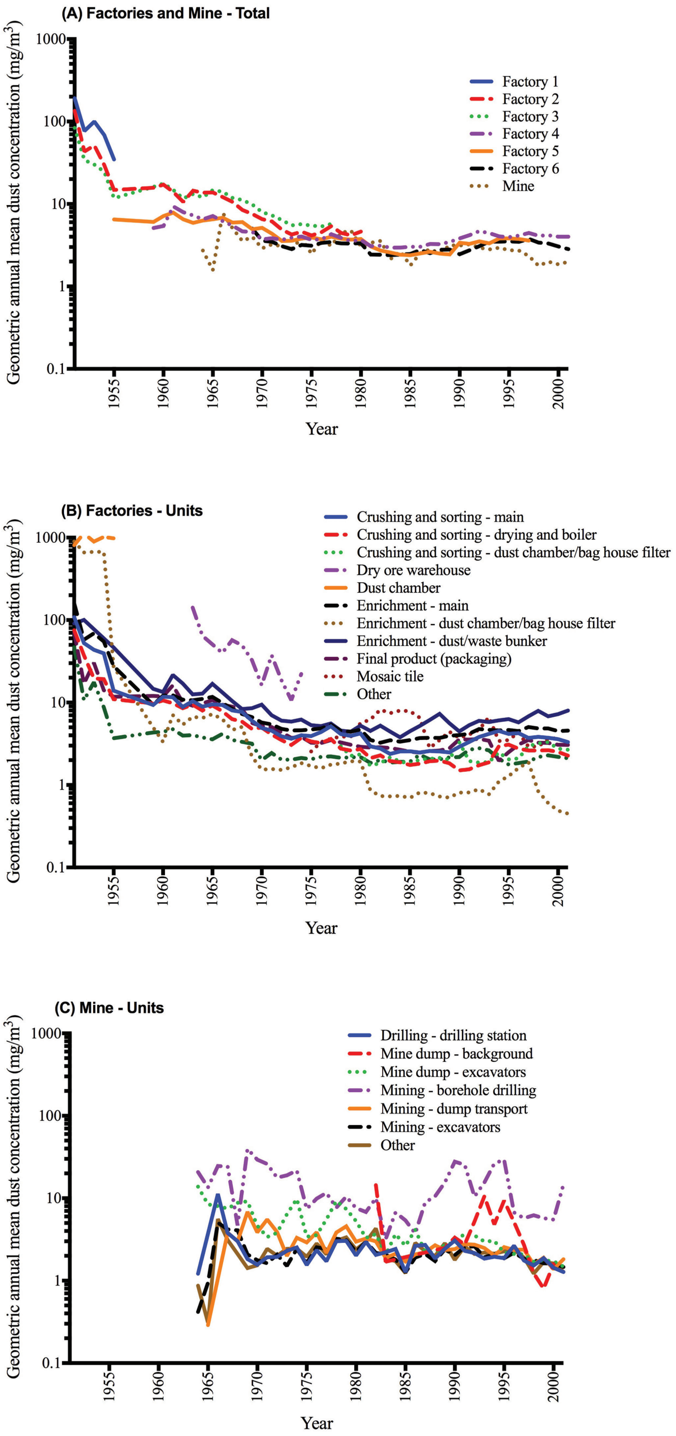

Figure 1. Geometric annual means of the monthly averaged dust concentrations in the Uralasbest asbestos-enrichment factories and the mine: (A) by factory (1951–2001) and the mine (1964–2001); (B) by factory unit for all factories combined (1951–2001); (C) by mine unit (1964–2001).

bunker', and 'dry ore warehouse'. In the mine, annual mean dust levels were consistently highest in the 'mining—borehole drilling unit'.

Modelled APCs of dust concentrations

Statistically significant negative overall APCs, consistent with a downward trend in dust concentration levels, were observed for Factories 1–5, ranging in magnitude from −30.4% (95% CI: −51.9 to −8.9) in Factory 1 to −1.4% (95% CI: −1.9 to −1.0) in Factory 4, and −1.6% in the mine (95% CI: −3.0 to −0.2; Table 2). In Factory 6, the overall trend was not statistically significant (APC: −0.6%; 95% CI: −1.5 to 0.2). Unit-specific APCs within a factory or the mine tended to follow similar patterns as the overall factory- or mine-specific trend although the magnitude varied. In Factory 2, for example, the APC was −6.6% (95% CI: −7.0 to −6.2) in 'crushing and sorting—main' and −22.9% (95% CI: −23.9 to −21.9) in 'enrichment—dust chamber/bag house filter'. In Factory 6, however, APCs varied in direction as well as magnitude. Contrary to the non-significant decrease observed at the factory level, dust concentrations in the 'enrichment—main' unit increased over time (APC: 0.5%; 95% CI: 0.4 to 0.6), whereas they decreased in the 'enrichment—dust chamber/bag house filter' (APC: −1.9%; 95% CI: −2.2 to −1.5) and 'other' (APC: −1.8%; 95% CI: −2.3 to −1.3) units.

Within each factory and the mine, there was significant heterogeneity in the calendar year trends by decade (*P* values <0.001 for the interaction between decade and the fixed component of calendar year; Table 3). The most rapid declines in dust concentration levels were observed before 1960 (APCs of −21.5%; 95% CI: −26.6 to −16.5 in Factory 2 and −17.4%; 95% CI: −20.4 to −14.3 in Factory 3). This was followed by continued but more moderate declines in the 1960s (factory-specific APCs ranged from −2.0% to −10%). Statistically significant decreasing trends continued into the 1970s (APCs estimates −1.2% to −6.2%) in Factories 3, 5, and 6 but not in Factories 2 or 4. In 1980s and 1990s, APCs were consistent with stable dust levels for Factories 4 and 6 whereas in the third factory operational during this period, Factory 5, the levels continued to decrease in the 1980s by 2.9% (95% CI: −4.0 to −1.9) per year but then increased in 1990s by 2% (95% CI: 0.7 to 3.2) per year. In the mine, dust levels increased in the 1960s [APC: 9.7%; 95% CI: (3.6 to 15.9)] and decreased in the period of 1990 to 2001 [APC: −5.8%; 95% CI: (−8.1 to −3.5)]. During the interim two decades, dust levels were stable with non-statistically significant APCs of 1.7% and −1.4% estimated for the 1970s and 1980s, respectively.

Supplementary Material 4 in the online edition (available at *Annals of Work Exposures and Health*) shows the comparison of the raw unit-specific annual geometric means with the predicted values, for the models used in Tables 2 and 3. The Akaike information criterion values (AIC) from the two models as well as the AIC from a model with no calendar year trend are also shown. Across the factories and the mine, lower AIC values, indicative of improved model fit, were obtained by modeling separate trends by decade (i.e., model used in Table 3).

Sensitivity analyses

Inclusion of month as a fixed effect did not materially change the trend estimates reported in Tables 2 and 3 although month was significantly associated with dust levels in the factories (*P* values <0.001) but not in the mine (*P* = 0.65). The overall mine APC changed from −1.6% (95% CI: −3.0 to −0.2) to −2.3% (95% CI: −4.0 to −0.6) when including the sporadic CL measurements, the majority of which were taken in the 'mine dump—background' and 'other' units but the patterns across units and calendar time were consistent with the main results (data not shown).

Discussion

Key findings

This analysis of the time trends in gravimetric dust concentrations at Uralasbest is based on over 90 000 dust measurements collected across six factories and a mine covering a period of five decades. As such, it constitutes the largest evidence base of its kind for a single asbestos-producing company. Over the full period, statistically significant decreased in the geometric annual mean dust concentrations were observed in the mine (−1.6% per year) and in Factories 1–5 (ranging from −30.4% to −1.4% per year) but not in the most recently built factory (Factory 6). Overall, unit-specific trends largely followed those of their factory or mine although they varied in magnitude. Decade-specific time trends revealed substantial heterogeneity in the temporal patterns across decades, both within and between the factories and the mine. The steepest declines occurred where dust levels were initially highest, in Factories 1–3 and for calendar year periods prior to 1970. In the 1970s, significant downward trends were observed for Factories 3, 5, and 6 but not in Factories 2 or 4. Dust levels were stable in Factories 4 and 6 in the 1980s and 1990s. In Factory 5, levels continued to decrease in the 1980s and subsequently increased in the 1990s. In contrast to the factories, dust levels increased sharply (9.7% per year) in 1960s in the mine, decreased in the 1990s (−5.8% per year), and were stable in the interim.

Table 2. Annual percent change of geometric mean dust concentrations in six Uralasbest asbestos-enrichment factories and the mine, overall and by unit: 1951–2001.

Annual percent change (95% confidence intervals)[a]

A. Factory (years[b])	Overall	Crushing and sorting—main	Crushing and sorting—drying and boiler	Crushing and sorting—dust chamber/bag house filter	Dry ore warehouse	Enrichment—main	Enrichment—dust chamber/bag house filter	Enrich-ment—dust/waste bunker	Final product	Other[c]
Factory 1 (1951–1955)	−30.4 (−51.9, −8.9)	−33.4 (−41.1, −25.7)	−29.8 (−57.1, −2.4)			−25.0 (−33.4, −16.6)			−43.8 (−55.7, −31.9)	−50.3 (−63. 1, −37.5)
Factory 2 (1951–1955, 1959–1980)	−9.5 (−14.3, −4.8)	−6.6 (−7.0, −6.2)	−7.6 (−8.2, −7.1)		−6.7 (−12.3, −1.1)	−10.3 (−10.6, −10.0)	**−22.9** **(−23.9, −21.9)**	−7.8 (−8.8, −6.8)	−7.9 (−8.6, −7.2)	−6.4 (−7.1, −5.7)
Factory 3 (1951–1955, 1959–1977)	−8.9 (−12.1, −5.8)	−9.1 (−9.8, −8.4)	−6.8 (−7.5, −6.0)		**−14.7** **(−18.9, 10.5)**	−6.9 (−7.4, −6.4)	**−13.0** **(−14.2, −11.8)**	**−5.6** **(−6.6, −4.7)**	−8.8 (−9.5, −8.0)	−6.6 (−7.5, −5.7)
Factory 4 (1959–2001)	−1.4 (−1.9, −1.0)	−1.8 (−2.0, −1.6)	−1.5 (−1.8, −1.2)	−0.9 (−1.8, 0.0)		**−0.9** **(−1.0, −0.8)**	−1.3 (−1.7, −1.0)	**−2.2** **(−2.6, −1.8)**	−1.4 (−1.5, −1.2)	−1.4 (−1.6, −1.1)
Factory 5 (1955, 1959–1997)	−2.4 (−3.3, −1.5)	−2.8 (−3.0, −2.5)	**−4.1** **(−4.3, −3.8)**	−2.2 (−4.0, −0.3)		**−1.4** **(−1.5, −1.2)**	−1.9 (−2.3, −1.5)	−1.7 (−2.1, −1.2)	**−3.6** **(−3.9, −3.3)**	−1.6 (−2.1, −1.1)
Factory 6 (1969–2001)	−0.6 (−1.5, 0.2)	−0.3 (−0.5, −0.2)	−1.4 (−2.1, −0.7)	0.0 (−2.3, 2.3)		**0.5** **(0.4, 0.6)**	**−1.9** **(−2.2, −1.5)**	−0.0 (−0.4, 0.4)	−0.1 (−0.5, 0.4)	**−1.8** **(−2.3, −1.3)**

B. Mine[d] **(1964–200[b])**	Overall	Mining—borehole drilling	Mining—excavators	Mining—dump transport	Drilling—drilling station	Mine dump—excavators	Mine dump—background	Other[c]
	−1.6 (−3.0, −0.2)	−2.0 (−3.1, −0.9)	−0.6 (−1.4, 0.2)	−1.4 (−2.4, −0.5)	−1.2 (−2.1, −0.3)	**−3.9** **(−4.9, −2.9)**	−1.8 (−4.8, 1.2)	−0.4 (−1.2, 0.4)

[a] Annual percent change (APC) and 95% confidence intervals estimated from linear mixed models of the log of the monthly averaged dust concentrations. Each factory and the mine were modeled separately with a fixed effect for calendar year (continuous) and a random intercept and slope for calendar year (continuous) by unit. Factory 1 'Dust Chamber' unit [APC: −0.0 (95% CI: −14.2 to 14.1)] and Factory 6 'Mosaic tile' unit [APC: −0.8 (95% CI: −1.7 to 0.2)] not shown in table due to space constraints. Bolded values: unit-specific APC significantly different (two-sided *P* value < 0.05) than the overall trend for that factory (A) or mine (B).

[b] Years for which data available.

[c] Includes maintenance, engineering, laboratory, and quality control units.

[d] Based on routine measurement data from Mine Rescue.

Table 3. Annual percent change of geometric mean dust concentrations by decade in five Uralasbest asbestos-enrichment factories and the mine: 1951–2001.

Annual percent change (95% confidence intervals)[a]					
Factory or mine (years[b])	**1951–1955, 1959**	**1960–1969**	**1970–1979**	**1980–1989**	**1990–2001**
Factory 2 (1951–1955, 1959–1980)	−21.5 (−26.6, −16.5)	−10.0 (−15.0, −5.1)	−2.7 (−7.6, 2.3)[c]		
Factory 3 (1951–1955, 1959–1977)	−17.4 (−20.4, −14.3)	−7.2 (−9.7, −4.7)	−6.2 (−8.8, −3.6)		
Factory 4 (1959–2001)		−6.5 (−7.2, −5.8)[d]	−0.3 (−1.0, 0.3)	−0.0 (−0.8, 0.7)	−0.1 (−0.8, 0.5)
Factory 5 (1955, 1959–1997)		−2.0 (−3.0, −1.0)[e]	−2.0 (−3.1, −0.9)	−2.9 (−4.0, −1.9)	2.0 (0.7, 3.2)
Factory 6 (1969–2001)			−1.2 (−2.1, −0.3)[f]	−0.7 (−1.6, 0.2)	0.2 (−0.6, 1.1)
Mine (1964–2001)[g]		9.7 (3.6, 15.9)	1.7 (−1.1, 4.4)	−1.4 (−4.2, 1.5)	−5.8 (−8.1, −3.5)

[a] Annual percent change (APC) and 95% confidence interval estimated from linear mixed models of the log of the monthly averaged dust concentrations. Each factory and the mine were modeled separately with fixed effects for calendar year (continuous), decade (categorical), and the interaction between the two, and a random intercept and slope for calendar year (continuous) by unit.

[b] Years for which data available

[c] Includes 1980.

[d] Includes 1959.

[e] Includes 1955, 1959.

[f] Includes 1969.

[g] Based on routine measurement data from Mine Rescue Committee.

Potential factors contributing to observed trends

Our study expands upon previous descriptive reports of the dust measurements at the Uralasbest mine and factories (Elovskaya *et al.*, 1998; Scherbakov *et al.*, 1998; Kashansky *et al.*, 2001; Shcherbakov *et al.*, 2001) by providing a more detailed description of the data sources and by modelling the temporal trends over five decades in each factory and the mine separately, overall and by unit. These previous studies cited several factors that could explain the observed declines in the dust concentrations during the 1950s and 1960s in the factories and the generally lower levels in more recently constructed factories. These include specific technological improvements such as modernization of the ventilation systems, replacement of rollers with pressurized belt conveyors, and improved sealing of equipment to contain dust (Shcherbakov *et al.*, 2001), as well as measures taken to reduce dust levels at workplaces in the mine that included pressurization and ventilation of truck cabins and the practice of injecting water to control dust levels during drilling (Kashansky *et al.*, 2001; Shcherbakov *et al.*, 2001). Improvements in the mine, however, largely occurred in the mid-1950s and would thus seem unlikely to explain either the positive trend in the 1960s or the downward trend in the 1990s. Time trends in the mine may in part reflect changes in the activity in the mine. From the mid-1960s to mid-1970s, there was a rapid increase in the amount of ore extracted per year. After peaking in the mid-1970s, production declined from the early 1990s to mid-1990s (Elovskaya *et al.*, 1998; Scherbakov *et al.*, 1998; Shcherbakov *et al.*, 2001). The increasing trend observed in the 1960s in the mine should, however, be interpreted cautiously as routine dust measurements were only available for part of the decade. Although factory activity also slowed down in the 1990s, dust levels in the factories were either stable (Factories 4 and 6) or increasing (Factory 5). Any reductions in dust levels driven by lower activity in the 1990s may have been offset by the lack of resources to repair machines and invest in new ones or to install and maintain control measures during the economic crisis which occurred after the collapse of the Soviet Union. Serious deteriorations in occupational health and safety in some non-governmental sectors have been documented during the politico-economic reforms of the 1990s (Dudarev *et al.*, 2013; Dudarev and Odland, 2013).

Comparison of temporal trends with literature

We identified a limited number of studies that reported temporal patterns of dust levels in asbestos mines and their processing factories. Although different measurement methods make it difficult to compare the absolute levels across studies, the overall downward trend of dust concentration observed here is consistent with the patterns observed elsewhere. Gibbs *et al.* reported substantial declines in the annual dust concentrations between 1948 and 1966 based on 4152 measurements taken in multiple chrysotile mills (i.e., factories) and mines in Quebec, Canada (Gibbs and Lachance, 1972). Measurements were primarily taken in the mills with a limited number in the underground mines. During that time, the average dust levels decreased by more than 7-fold from ~75 to <10 million particles per cubic foot. This is comparable to the decreases observed in the Uralasbest factories between the early 1950s and mid-1960s. Technological changes thought to contribute to the improved conditions in the Quebec study included improved ventilation systems and the switch from manual to machine packing of the final product (particularly pressure packing; Gibbs and Lachance, 1972). In a Chinese chrysotile mine and associated factories, Wang *et al.* reported extremely high concentrations in the 1980s (800 mg m^{-3}) reduced 5- to 6-fold to 140 mg m^{-3} in the 1990s (Wang *et al.*, 2013).

Previous publications of occupational asbestos exposure trends, including but not restricted to asbestos mining and enrichment settings, are largely based on analyses of fiber concentrations (Coble *et al.*, 2001; Paustenbach *et al.*, 2003; Bagatin *et al.*, 2005; Hagemeyer *et al.*, 2006; Kauppinen *et al.*, 2013; Peters *et al.*, 2016). Fiber concentration is generally the preferred metric for assessing health outcomes from asbestos exposure because dust encompasses other airborne materials in addition to asbestos fibers (Harries, 1971; Dement *et al.*, 2008). A limited number of parallel dust and fiber measurements available for *The Asbest Study* have been used to derive dust-to-fiber conversion factors that may be applied to estimate fiber levels for the planned risk analyses (Feletto *et al.*, 2017). In Brazil, Bagatin *et al.* (2005) reported the annual fiber concentrations throughout a chrysotile asbestos mine and mills between 1977 and 1993. In that study, fiber levels were stable following a sharp drop in the earliest period (before 1980). Most recently, Peters *et al.* (2016) estimated a decrease of 10.7% per year (~3-fold reduction per decade) of asbestos fiber levels across a wide range of industries in Europe and Canada prior to the introduction of asbestos bans, with no further decline after the implementation of the bans. Decreasing trends within established industrial countries, attributed to a combination of changes in occupational safety standards and regulations, technological changes in factory processes, improved ventilation, as well as bans and other regulatory measures on the use of substances, have been more broadly reported for occupational exposures to aerosols, gases, vapours, and fibers (Creely *et al.*, 2007).

Strengths and limitations

The large amount of dust measurement data, systematically collected using consistent measurement procedures and equipment over a long time period, is unique and a key strength of this study. Although the frequency of measurements varied over time in the factories (i.e., once per month versus 2–3 times per month), measurements were taken at each sampling point at least once per month in the factories. The mine data are more limited in terms of the range of calendar years for which data are available but still cover a period of nearly 4 decades. The frequency of measurements per year in each unit of the mine was also more limited than in the factories and thus fewer measurements contribute to annual averages.

Although each factory conducted all stages of chrysotile enrichment, from the initial crushing of the ore received from the mine to the packaging of chrysotile for sale, there is variability in the unit classifications across factories. Furthermore, within a factory or the mine, there were units for which measurements were not available in every calendar year. As discussed in the Methods, this is likely a function of changes in the factories over time but also the level of detail in the original dust measurement journals. The results of unit-level trends must, therefore, be interpreted cautiously. For example, the trend for Factory 2's 'enrichment—dust chamber/bag house filter' unit is based on measurements from 1951 to 1955 and again from 1975 to 1980. In the mine, there are few measurements for the 'mine dump—background' between 1964 and 1988 and thus the trend for that unit is driven by measurements in the later years.

Conclusions

The large database of dust concentrations in the asbestos-enrichment factories and mine of Uralasbest has allowed for a detailed, rigorous statistical analysis of temporal trends in asbestos-containing dust between 1951 and 2001. Factory data are consistent with strong downward trends in the 1950s and 1960s which then slowed down and flattened off in more recent decades suggesting that dust levels were no longer declining after the 1970s, although there was some suggestion of an increase in the 1990s for one of three factories operational at the time. A different pattern emerged for the mine, where dust levels rose in the 1960s, declined in the 1990s and were relatively unchanged in the interim.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Competing Interests

In relation to the Declarations of Interests from the Russian collaborators from SRIOH (Dr Evgeny Kovalevskiy; EK) and the Yekaterinburg Medical Research Center (Dr Sergey Kashansky; SK), the following conflicts of interest were declared: EK and SK reported receiving, on behalf of their institutes and personally through consulting firms, payments from companies to evaluate exposure to asbestos and risk of asbestos-related disease in those workplaces. EK and SK reported attending meetings organized by the International Chrysotile Association and reported that all expenses for attendance were paid by their respective institutes. EK reported participation as an occupational and environmental health expert as part of the delegation of the Russian Ministry of Health at multiple World Health Assembly meetings as well as at the Conference of the Parties to the Basel and Rotterdam Conventions. All other authors have no competing interests to declare.

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