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Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants

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ABSTRACT

Field measurements and data investigations were conducted for developing an emission factor database for inventories of atmospheric pollutants from Chinese coal-fired power plants. Gaseous pollutants and particulate matter (PM) of different size fractions were measured using a gas analyzer and an electric low-pressure impactor (ELPI), respectively, for ten units in eight coal-fired power plants across the country. Combining results of field tests and literature surveys, emission factors with 95% confidence intervals (CIs) were calculated by boiler type, fuel quality, and emission control devices using bootstrap and Monte Carlo simulations. The emission factor of uncontrolled SO_2 from pulverized combustion (PC) boilers burning bituminous or anthracite coal was estimated to be 18.0S $kg\,t^{-1}$ (i.e., 18.0 × the percentage sulfur content of coal, S) with a 95% CI of 17.2S–18.5S. NO_X emission factors for pulverized-coal boilers ranged from 4.0 to 11.2 $kg\,t^{-1}$, with uncertainties of 14–45% for different unit types. The emission factors of uncontrolled $PM_{2.5}$, PM_{10}, and total PM emitted by PC boilers were estimated to be 0.4A (where A is the percentage ash content of coal), 1.5A and 6.9A $kg\,t^{-1}$, respectively, with 95% CIs of 0.3A–0.5A, 1.1A–1.9A and 5.8A–7.9A. The analogous PM values for emissions with electrostatic precipitator (ESP) controls were 0.032A (95% CI: 0.021A–0.046A), 0.065A (0.039A–0.092A) and 0.094A (0.0656A–0.132A) $kg\,t^{-1}$, and 0.0147A (0.0092–0.0225A), 0.0210A (0.0129A–0.0317A), and 0.0231A (0.0142A–0.0348A) for those with both ESP and wet flue-gas desulfurization (wet-FGD). SO_2 and NO_X emission factors for Chinese power plants were smaller than those of U.S. EPA AP-42 database, due mainly to lower heating values of coals in China. PM emission factors for units with ESP, however, were generally larger than AP-42 values, because of poorer removal efficiencies of Chinese dust collectors. For units with advanced emission control technologies, more field measurements are needed to reduce emission factor uncertainties.

1. Introduction

As the largest coal-consuming sector in China, electric power generation has been considered the most important source of atmospheric pollutants and regional air pollution. A series of emission inventory studies on China has been conducted since the year 2000, indicating that the power sector accounts for 31–59% of national anthropogenic emissions of SO_2 (Streets et al., 2003; Cofala et al., 2007; Ohara et al., 2007; Zhao et al., 2008; Zhang et al., 2009), 21–44% of NO_X (Hao et al., 2002; Streets et al., 2003; Cofala et al., 2007; Ohara et al., 2007; Zhang et al., 2007a, 2009; Zhao et al., 2008), and 9% of particulate matter, PM (Zhang et al., 2007b; Zhao et al., 2008).

The level of an emission factor, expressed as the mass of emitted pollutant per unit fuel consumption or per unit industrial production, is closely associated with source characteristics. The widely used AP-42 database divides emission factors of coal-fired boilers into different categories according to boiler type, coal quality, burner pattern, emission control technology, and the time when the power plant goes into operation (USEPA, 1999). Most of these parameters are likewise considered in the European database for power sector emission factors, although unit location (indicated by country) and unit size are also included and the operation time is excluded (EEA, 2002). Statistical methods like bootstrap simulation have been applied to evaluate the uncertainty and variability of emission factors (Rhodes and Frey, 1997; Frey and Zheng, 2002). In China, an emission factor database was published by the State Environmental Protection Administration (SEPA, the predecessor of Ministry of Environmental Protection, MEP), providing only SO_2 and total PM emission factors for the power sector (SEPA, 1996). However, there is no integrated

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database for Chinese coal-fired power plants that includes emission factor levels and uncertainties for different technologies. Considering power generation as a single sector in the emission inventory framework, most existing studies either apply uniform emission factors for the entire sector, or refer to domestic emission standards instead of actual performance. The uncertainties of those estimates are thus difficult to evaluate.

Recently the Chinese power sector has experienced the fastest development pace of the past three decades. Due to high energy consumption and emissions, the Chinese government has set the power sector as the most important target for the emission control until 2010, particularly for SO_2. Several regulations have been enforced: small units with low combustion efficiency, totaling over 50 GW, should be gradually shut down; newly-built power units (not including combined heat and power units, CHP) must be larger than 300 MW; and all newly-built units as well as most existing ones must install flue-gas desulfurization (FGD) systems. With increasing nitrogen pollution, new measures to control NO_X emissions of power sector may be implemented after 2010. Therefore an emission factor database for units with high combustion efficiency and advanced emission control technology is needed to aid in assessment of the effects of emission control polices. Although domestic tests have recently been conducted to determine emission characteristics of Chinese coal-fired power plants, particularly for NO_X (Bi and Chen, 2004; Zhu et al., 2004; CRAES, 2006) and size-fractionated PM (Yi et al., 2006, 2008; Qi, 2006; Sui, 2006; Gao, 2006), these results have seldom been incorporated in emission databases or emission inventory studies.

In this study, field measurements of SO_2, NO_X and PM emission characteristics were first carried out in selected coal-fired power plants. Based on these test results and published data, an emission factor database for the Chinese coal-fired power sector was established describing different emission levels by unit type. To better understand the uncertainty when using the database to estimate emissions, bootstrap and Monte Carlo simulations were applied to provide the variance and statistical distribution for given emission factors.

2. Field experiments

2.1. Sampling methods

As shown in Table 1, gaseous pollutant and PM emissions were measured for ten units at eight coal-fired power plants across China, covering most unit types in terms of boiler variety, burner pattern, fuel quality, and emission control device. During the test period, all of the power units were operating under normal conditions.

Sampling positions were located at both the inlet and outlet of specific emission control devices for corresponding pollutants in order to obtain the emission levels and removal efficiencies of control devices, e.g., PM emissions were measured before and after the dust collectors as well as after wet-FGD systems (if applicable). Chinese national regulation (GB/T16157-1996) was followed during the sampling procedures.

Gaseous pollutants (SO_2 and NO_X) as well as O_2 were measured with the KANE 9106 Gas Analyzer (http://www.keison.co.uk/kane_9106.shtml). For comparisons with other test results, the measured pollutant concentrations were converted to values based on an O_2 level of 6%. The total PM was collected by a filter drum using the WJ-60B parallel dust sampling meter. The emission concentration of total PM was calculated from the weight difference of the filter drum before and after the sampling.

The size distributions of PM_{10} were measured by an electrical low-pressure impactor (ELPI, http://www.dekati.com/cms/elpi) , an instrument designed for real-time monitoring of airborne particle size distribution. It operates in the size range of 0.03–10 μm, with 12 stages. The ELPI has three major operating processes: particle charging with a unipolar corona charger, size classification by a cascade impactor, and electrical detection with sensitive electrometers. Without particle charging and electrical detection, the ELPI can also be used for gravimetric measurement and chemical analysis as by a low-pressure impactor (LPI).

A series of measurements have been conducted on the particle size distribution from combustion sources using ELPIs or LPIs both in China and abroad (Moisio et al., 1998; Lind et al., 2003; Yi et al., 2006;

Table 1
Operational parameters and gaseous pollutant concentrations (converted to the value at $O_2 = 6\%$) for the tested power plants.

No.	Unit #	Size (MWe)	Fuel	S[a] (%)	A[b] (%)	Boiler type	Burner pattern	Control device	SO_2 (mg Nm^{-3})	NO_X (mg Nm^{-3})
1	2	200	Bituminous	1.33	16.2	PC	Tangential	LNB[d]; ESP[e]	3043	374
	3	200		1.33	16.2	PC	Tangential	ESP	2663	547
2	5	50	Lignite	0.15	21.7	PC	Wall	ESP	307	456
3	2	50	Lignite	0.18	21.7	PC	Wall	ESP	486	945
	4	100		0.18	21.7	PC	Wall	ESP	462	862
4	4	200	Bituminous	3.84	22.3	PC	Tangential	ESP;	8228[h]	726
								Wet-FGD	334[i]	
5	1	125	Bituminous	0.61	20.4	PC	Tangential	ESP	1379	792
6	2	29	Bituminous	0.77	20.4	Grate	–	Simple-FGD;	1711[h]	437
								Wet scrubber	1410[i]	
	8	58		0.77	20.4	CFB	–	ESP	1278	237
7	2	165	Anthracite	0.44	7.7	PC	W-flame[c]	SCR[f]; ESP;	837[h]	351[j]
								Wet-FGD	47[i]	180[k]
8	1	100	Bituminous	2.01	30.6	PC	Tangential	ESP;	4593[h]	635
								CFB-dry-FGD; FF[g]	976[i]	

[a] Sulfur content of the coal (as-received basis).
[b] Ash content of the coal (as-received basis).
[c] Designed mainly for anthracite combustion: the use of a double-arch furnace with down-shot firing burners results in a "W-flame", which provides sufficient residence time for the anthracite combustion.
[d] Low-NO_X burner.
[e] Electrostatic precipitator.
[f] Selective catalytic reduction.
[g] Fabric filter.
[h] Pre-FGD control.
[i] Post-FGD control.
[j] Pre-SCR control.
[k] Post-SCR control.

Sui, 2006). In this study, PM_{10} was sampled with gravimetric methods, using the combination of ELPI and a two-stage dilution system (Moisio 1999). The sampling system consisted of an isokinetic sampler probe, precut cyclone with cutoff diameter at 10 μm, dilution system, the ELPI, and the sampling pump. Flue gas was first pumped at the stable rate of 10 $L\,min^{-1}$ into the precut cyclone, where the PM larger than 10 μm was removed. It was then mixed and diluted with clean and dry pressurized airflow in dilution system. The dilution air was generated by an air compressor and purified through an oil filter, silica gel dryer, and particle filter. To prevent coagulation and condensation due to a temperature drop during the dilution process, the two-stage diluter was applied in the measurements, i.e., the flue gas was heated and kept at the stack temperature in the first-stage diluter, and it was then cooled down to the ELPI-tolerant temperature ($<60\,^{\circ}C$) with dilution air in the second-stage diluter. The total dilution ratio was 1:85. Finally the sampled particles were drawn into the ELPI and were collected in the different impactor stages inertial classification according to their aerodynamic diameters through. A teflon filter membrane was used at each stage to capture the particles. The concentrations of PM at specific size categories were calculated as the weight differences of the corresponding filters before and after the sampling.

2.2. *Measurement results*

The SO_2 and NO_X emission levels of measured power units are listed in Table 1. The concentrations of combustion-generated SO_2 were very closely related to sulfur content ($R^2 = 0.994$). Compared with pulverized combustion (PC) boilers, the SO_2 emission from a circulating fluidized bed (CFB) boiler (Unit 6-#8) was around 25% lower. Substantial variations in the effectiveness of SO_2 control were found for the tested FGD technologies. Wet-FGD had the highest removal efficiency, above 90% (Unit 4-#1 and Unit 7-#2), followed by CFB-dry-FGD, close to 80% (Unit 8-#1). The removal efficiency of the tested simple-FGD (Unit 6-#2) was merely 18%, even lower than that of the CFB boiler alone.

Regarding NO_X, the emission levels were highly affected by the coal quality, burner pattern, and emission control device, and more results are thus needed to draw strong conclusions. During the tests, the lowest emission level was found for the CFB boiler (Unit 6-#8) without further de- NO_X technologies. Selective catalytic reduction (SCR) reduced the NO_X level by 43% (Unit 7-#2), while the low-NO_X burner (LNB) reduced it by 27%. Since the dosage of NH_3 did not reach the maximum during the test, the removal efficiency of SCR obtained in this study was much lower than the typical value for full-operated SCR devices.

The PM_{10} mass size distributions before and after dust collectors are shown in Fig. 1. It is widely reported that PM generated from coal combustion displays a bimodal size distribution, i.e., a submicron mode in which particles are formed through vaporization, condensation, and nucleation of inorganic constituents, and a coarse mode in which particles are formed through fragmentation and coalescence of surface ash droplets (Ylatalo and Hautanen, 1998; Buhre et al., 2005; Yi et al., 2006). In this study a submicron mode peak around 0.2–0.3 μm was observed in the flue gases of all of the tested power units before the dust collectors, while the coarse mode peak was missed due to the limit of the ELPI measurement range. In the flue gases after dust collectors, the bimodal size distribution was observed at all units, with peaks for submicron and coarse modes at 0.2–0.3 and 2.0–3.0 μm, respectively.

The calculated mass size fractions of PM_{10} before and after dust collectors (and wet-FGD, if applicable) are shown in Fig. 2. Before dust collectors, the fine-mode particles ($PM_{2.5}$) accounted for only 23–35% of the PM_{10} mass, and the shares of $PM_{1.0}$ to total PM_{10} were less than 10% at all the tested units. After dust collectors, the percentages of $PM_{2.5}$ to PM_{10} and $PM_{1.0}$ to PM_{10} increased to 38–60% and 14–28%, respectively, confirming that the removal efficiencies of dust collectors for finer particles were poorer than those for larger ones. The effect of dust collectors on fine-particle share was smallest for Unit 6-#2, in which wet scrubbing instead of electrostatic precipitator (ESP) was applied. The side-effect of PM control was also found in wet-FGD technologies, particularly for large particles. After wet-FGD systems, the percentages of $PM_{2.5}$ to PM_{10} and $PM_{1.0}$ to PM_{10} rose beyond 60% and 30%, respectively, in both Units 4-#4 and 7-#2.

The removal efficiencies for different particle sizes can be calculated by comparing PM levels before and after the dust collectors. The measured removal efficiencies of ESPs in this study (not including Unit 8-#1, for reasons noted below) were 98.08–99.53% for total PM, 93.25–98.78% for PM_{10}, and 90.88–97.86% for $PM_{2.5}$. This is much

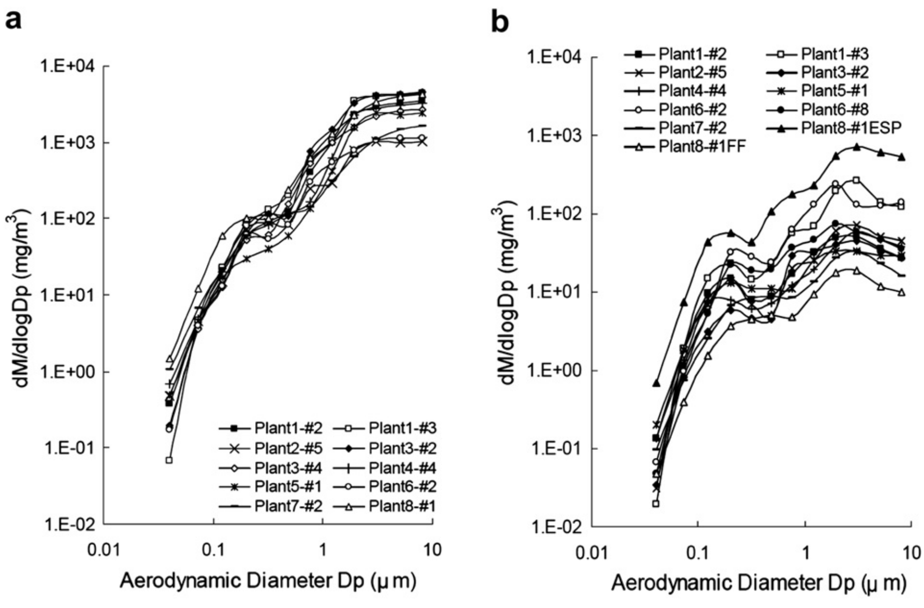

Fig. 1. The PM_{10} mass size distributions for the tested power units. (a) Before dust collectors; (b) after dust collectors.

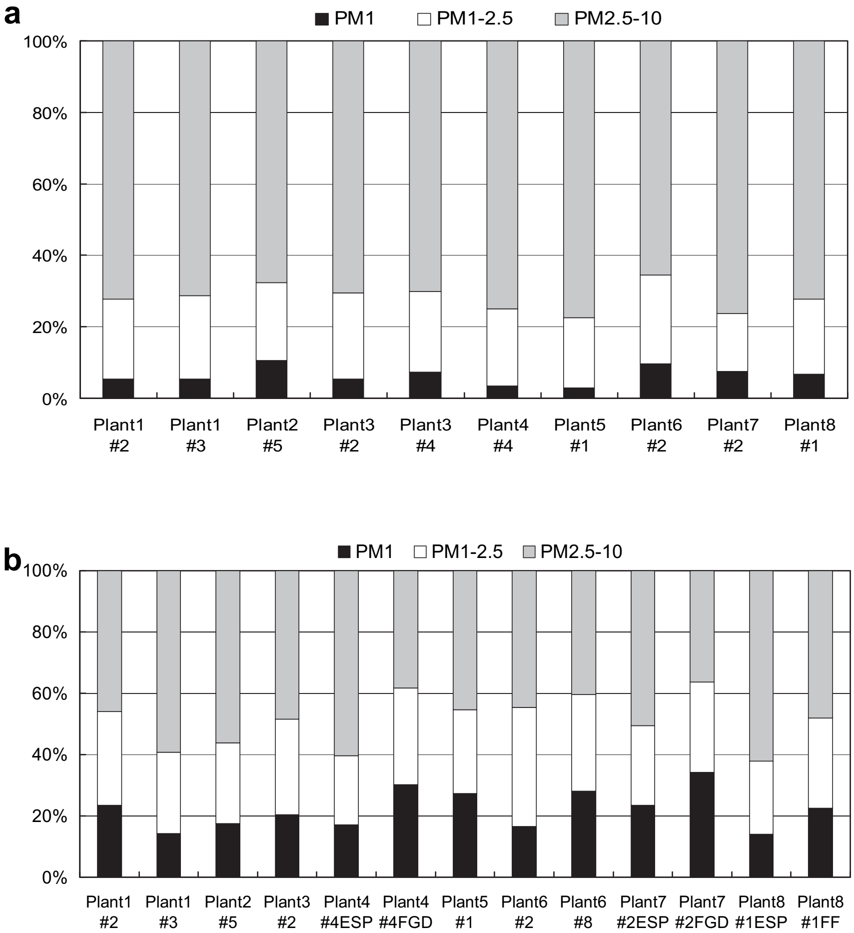

Fig. 2. The PM_{10} composition by size for the tested power units. (a) Pre-dust control; (b) post-dust control and desulfurization.

higher than those of the tested wet scrubber (Unit 6-#2), at 94.08%, 82.37%, and 71.73%, respectively. Since the ESP of Unit 8-#1 was used for dust removal prior to the CFB-dry-FGD and applied only two electric fields (as opposed to 3–5 fields in typical Chinese ESPs), its removal efficiencies were lower than those of other ESPs, at 89.44%, 81.12%, and 74.27% for total PM, PM_{10}, and $PM_{2.5}$, respectively. Combining ESP and wet-FGD (Units 4-#4 and 7-#2), the total PM removal rate could reach 99.8%. Fig. 3 shows the penetration of PM_{10} through the dust collectors and wet-FGDs. In accord with previous studies, the highest penetrations were found at the particle size range of 0.1–1.0 μm for all of the emission control devices (Helble 2000; Yi et al., 2006).

3. Emission factor database

3.1. Method and data collection

Emissions factors of SO_2, NO_X, and PM from coal-fired power plants can be calculated with Eqs. (1)–(3), respectively.

$$EF_{SO_2} = 10 \times S \times (1 - \mathrm{Sr}) \times (1 - \eta) \times 2 \quad (1)$$

$$EF_{NO_x} = C_{NO_x} \times V/1000 \quad (2)$$

$$EF_{PM,y} = 10 \times A \times (1 - \mathrm{ar}) \times f_y \times (1 - \eta_y) \quad (3)$$

where EF is the emission factor (kg t^{-1}); S is the sulfur content of fuel (%); Sr is the sulfur retention ratio of ash; η is removal efficiency of the emission control technology (%); C is the pollutant concentration in the flue gas (mg Nm^{-3}); V is volume of flue gas per unit of fuel consumption (m^3 kg^{-1}); A is the ash content of fuel (%); ar is the ratio of bottom ash to total ash; f is the particulate mass fraction by size; and y is the particulate size.

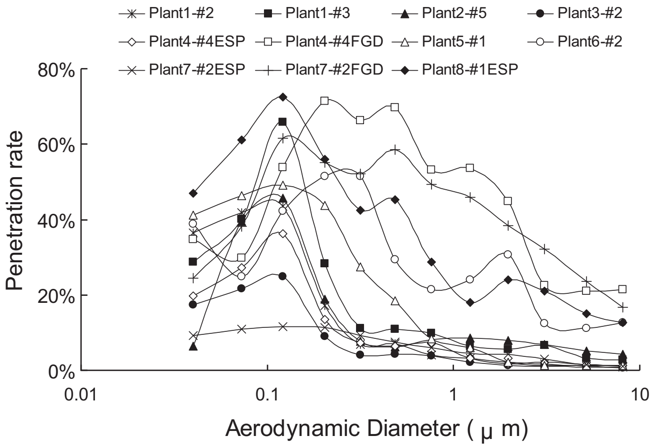

Fig. 3. The PM_{10} penetration by size for the tested dust collectors.

The flue-gas volume per unit of fuel consumption is mainly affected by the lower heating value of coals, and can be calculated with Eqs. (4)–(5).

$$V = 1.04 \times Q_L/4187 + 0.77 + 1.0161 \times (\alpha - 1) \times V_0 \tag{4}$$

$$V_0 = \begin{cases} 0.251 \times Q_L/1000 + 0.278 & \text{(Bituminous)} \\ Q_L/4140 + 0.606 & \text{(Anthracite)} \end{cases} \tag{5}$$

where Q_L is the lower heating value (kJ kg^{-1}), V_0 is the theoretical air volume (m^3 kg^{-1}), and α is the excess air coefficient (The ratio 1.4 was applied in this study according to national emission standard of air pollutants for thermal power plants, GB13223-2003).

Parameters of Eqs. (1)–(5) were collected and classified for emission factor calculation according to the boiler/burner types, coal qualities, and emission control devices. Among all of the pollutants, SO_2 is believed to be most certain (Streets et al., 2003), and thereby only the measured data described in Section 2 were used to develop the database for it.

NO_X formation during combustion is associated with the temperature and degree of oxygen enrichment, which can be significantly influenced by the unit capacity, burner, and fuel type. To better understand the NO_X emission characteristics, data for NO_X concentrations in flue gases were collected from many sources, including the field measurements of this study and other published results. The Chinese Journal Full-text Database (CJFD) was thoroughly searched for published data on NO_X emissions from coal-fired power plants since 2000 for inclusion. This study also included field measurements by other research institutes referenced in additional literature (Tian, 2003; Yi et al., 2006; CRAES, 2006) and CEMS (Continuous Emission Monitoring Systems) data when available. The statistics of the obtained NO_X concentrations by unit type are shown in Fig. 4. The Q_L values for different types of steam coals were taken from statistics (Jin 2001).

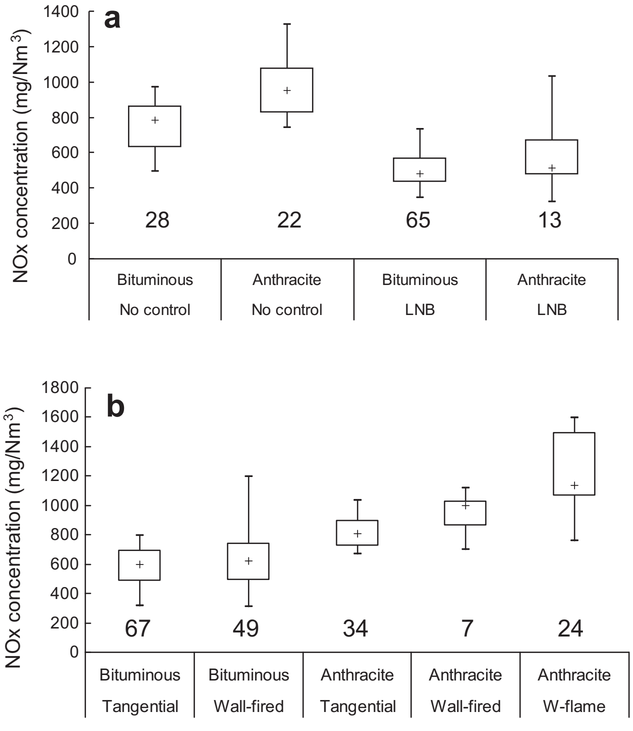

Fig. 4. 95%, 75%, 50%, 25%, and 5% percentiles of the surveyed NO_X concentrations, by unit type. The numbers in the figures are the sample sizes. (a) Units smaller than 300 MW; (b) units larger than or equal to 300 MW, all of which have LNBs.

Regarding PM emission factors, field measurements of emission characteristics by size class have been conducted by several other domestic research teams (Yi et al., 2006; Qi, 2006; Sui, 2006; Gao, 2006). As summarized in Tables S1 and S2 in the Supplementary Information, ratios of bottom ash, particulate mass fractions by size, and size-specific removal efficiencies for different dust collectors were taken from those studies as well as from the results described in Section 2. In addition to dust collectors, wet-FGD systems are increasingly common and their benefits to PM control were also considered in the emission factor estimate.

The probability distributions of these parameters were calculated using a bootstrap simulation method (Frey and Zheng, 2002). Statistical tests were used to fit observed datasets of each parameter to preliminary distributions of either normal, lognormal, beta, gamma, or Weibull forms. Synthetic datasets of the same sample sizes as the original datasets were then generated from the assumed probability distribution using random Monte Carlo sampling. This sampling was conducted 1000 times for each parameter. Finally the probability distribution for each parameter was determined by fitting the mean values of the 1000 datasets. To calculate the emission factor for each unit type, relevant parameters with corresponding statistical distributions were placed in a Monte Carlo framework, and 100,000 simulations were performed. This yielded the mean value, distribution, and 95% confidence interval (CI) for each emission factor.

3.2. *Results*

Due to the article length limit, only one example of probability distribution bands is shown in Fig. 5, for the $PM_{2.5}$ emission factor of PC boilers with ESP. Through the bootstrap simulation, the mean values of the ash release ratio, $PM_{2.5}$ mass fraction of uncontrolled PM emissions, and removal efficiency of ESP for $PM_{2.5}$ were estimated to be 0.69, 0.06, and 92.31%, with beta, lognormal, and lognormal probability distributions, respectively. Based on these results, the uncontrolled and controlled $PM_{2.5}$ emission factors were calculated to be 0.41A (95% CI: 0.29A–0.59A) and 0.032A (95% CI: 0.021A–0.046A) respectively, as shown in Fig. 6.

The SO_2, NO_X, and PM emission factors of Chinese coal-fired power plants are summarized in Table 2. For the unit types widely used in China, emission factors with 95% CI are provided. For other rarely used unit types (e.g., grate boilers, CFBC, and units with wet scrubber dust collectors), values are given tentatively, without uncertainty estimates, due to limited data.

The uncontrolled SO_2 emission factor for PC boilers combusting bituminous or anthracite coal, the most common unit type and fuels, was estimated to be 18.0S kg t^{-1}. This represents a sulfur retention ratio of roughly 0.10, which is lower than the value of 0.15 used in previous official estimates. Acknowledging the uncertainty, wet-FGD (e.g., technology using limestone/gypsum sorbents), currently installed in over 50% of Chinese coal-fired units, showed satisfactory SO_2 removal efficiency (95%). The control effects of other FGD systems that are mostly applied in relatively small units were poorer.

As China is now implementing a policy retiring small units and requiring newly-built units to equal or exceed 300 MW in capacity, this size is used as a threshold between small and large units for classifying NO_X emission factors. With a higher burning temperature point, combustion of coal with low volatile matter content (e.g., anthracite) reliably generates higher NO_X emissions, and vice versa. In this study, the NO_X emission factors were generally 30–40% lower for units burning bituminous and lignite coals than those fired by anthracite. Regarding burner type, wall-fired boilers were subject to 10–15% higher emissions than tangentially-fired boilers, while W-flame boilers, which are mainly designed for anthracite combustion, had the highest emission factor, 11.2 kg t^{-1}. Widely applied in large units, the NO_X control efficiency of LNB was estimated to be

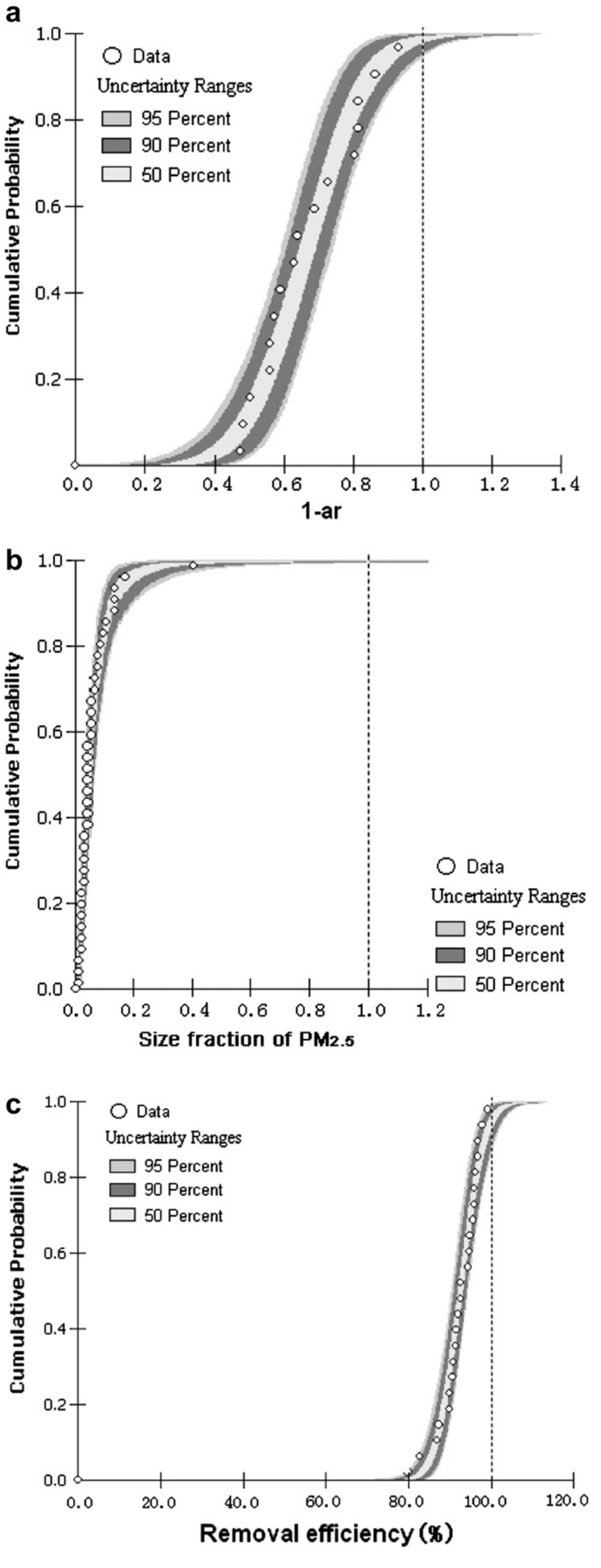

Fig. 5. Probability distribution bands of three parameters of the emission factor for $PM_{2.5}$ from PC boilers with ESPs. The dashed lines indicate the actual maximum values of parameters. (a) Ash release ratio (1-ar); (b) mass fraction of $PM_{2.5}$ in uncontrolled PM emissions; (c) removal efficiency of ESPs for $PM_{2.5}$.

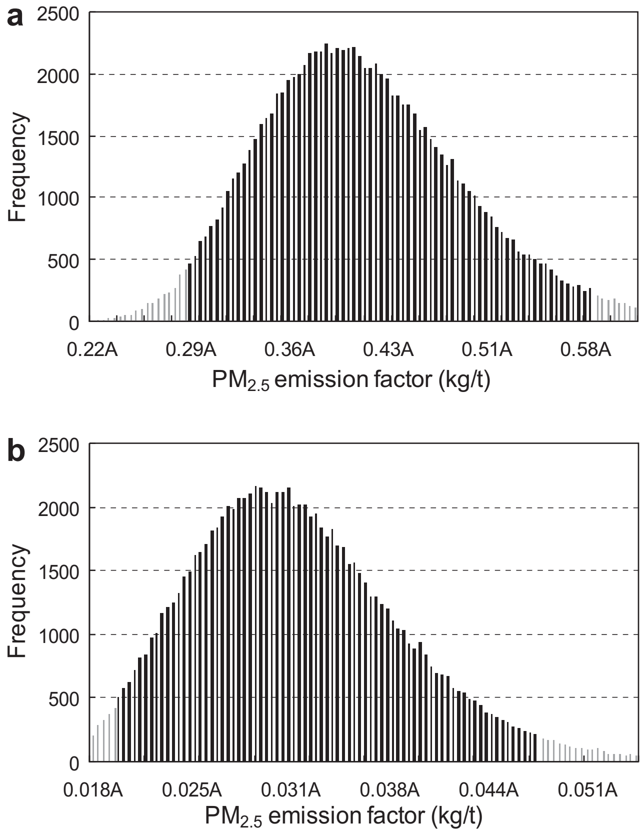

Fig. 6. Probability distribution of $PM_{2.5}$ emission factor for PC boilers with ESP. "A" indicates the ash content of coal (%). The grey bars are out of the 95% CI. (a) Uncontrolled; (b) controlled.

30–40%. Since use of SCR is only incipient in China and few measurements exist, its control effect was not evaluated in this study.

Regarding PM emission factors, PC boilers with ESP and wet-FGD systems are the most widely used configurations. The share of fine particles ($PM_{2.5}$) of the total uncontrolled emissions was estimated to be 5.8%, and increased to 34.0% and 63.6% with addition of ESPs, and ESP combined wet-FGD systems, respectively. Currently the market share of fabric filter systems (FF), a dust collector with higher PM removal efficiency than ESP, is rising and is expected to approach 10% in 2010. Noting large uncertainty, the controlled PM emission factor of units using FF was calculated to be 0.0042A, 82% lower than that of ESP combined with wet-FGD, indicating the huge benefits of this technology.

4. Discussion

The objective of this study is to establish an integrated emission factor database particularly for the development of emission inventories of Chinese coal-fired power plants. A difference of the results of this study and AP-42, the widely used emission factor database for the U.S., should be noted. For SO_2, the emission factors for bituminous and lignite combustion in AP-42 are 19.0S and 17.5S $kg\ t^{-1}$, respectively, higher than those obtained here (18.0S and 15.0S $kg\ t^{-1}$). The value for anthracite in AP-42 is even higher, reaching 19.5S $kg\ t^{-1}$. As shown in Fig. 7(a), NO_X emission factors in AP-42 are 4–19% higher than those of corresponding units ($\geq$300 MW) in this study. For tangentially-fired burners burning anthracite, the AP-42 value is even beyond the upper limit of the 95% CI of this study. However the discrepancy is significantly reduced for the emission factors per unit of energy input (Fig. 7(b)). The emission

Table 2

Emission factor database for Chinese coal-fired power plants (kg t^{-1}). The numbers in the brackets indicate the 95% CIs. For those without 95% CIs, considerable uncertainty can be expected due to small sample sizes, and these emission factors should be regarded as tentative.

(a) SO_2

Boiler	Coal	Uncontrolled	Controlled		
			Wet-FGD	Dry-FGD	Simple-FGD
PC and grate boiler	Bituminous and anthracite	18.0S[a] (17.2S–18.5S)	0.9S	3.6S	15.0S
	Lignite	15.0S		N/A[b]	
CFBC	–	13.0S[c]		N/A	

(b) NO_X

Boiler	Capacity	Coal	Control	Burner	Emission factor
PC and grate boiler	<300 MW	Bituminous and lignite	No	–	6.1 (5.3–7.1)
		Anthracite	No	–	9.0 (8.1–9.9)
		Bituminous and lignite	LNB	–	4.0 (3.5–4.6)
		Anthracite	LNB	–	5.5 (4.3–6.8)
	≥300 MW	Bituminous and lignite	LNB	Tangential	4.7 (4.1–5.4)
		Bituminous and lignite	LNB	Wall-fired	5.2 (4.4–6.1)
		Anthracite	LNB	Tangential	7.6 (7.1–8.1)
		Anthracite	LNB	Wall-fired	8.6 (7.4–9.9)
		Anthracite	LNB	W-flame	11.2 (9.9–12.5)
CFBC	–	–	–	–	1.5

(c) PM

		Uncontrolled	Controlled			
			ESP	Wet scrubber	FF	ESP + wet-FGD
PC	$PM_{2.5}$	0.4A[d] (0.3A–0.5A)	0.032A (0.021A–0.046A)	0.135A	0.0019A	0.0147A (0.0092A–0.0225A)
	PM_{10}	1.5A (1.1A–1.9A)	0.065A (0.039A–0.092A)	0.291A	0.0034A	0.0210A (0.0129A–0.0317A)
	PM	6.9A (5.8A–7.9A)	0.094A (0.065A–0.132A)	0.479A	0.0042A	0.0231A (0.0142A–0.0348A)
Grate	$PM_{2.5}$	0.10A	0.008A	0.032A	N/A	N/A
	PM_{10}	0.26A	0.012A	0.054A	N/A	N/A
	PM	1.50A	0.019A	0.098A	N/A	N/A
CFB	$PM_{2.5}$	0.45A	0.034A	N/A	N/A	N/A
	PM_{10}	1.54A	0.067A	N/A	N/A	N/A
	PM	4.80A	0.085A	N/A	N/A	N/A

[a] In all cases, S is the sulfur content, in percent, of the coal as fired.

[b] Due to low sulfur content (usually less than 0.2%), FGD systems are not generally installed.

[c] Result from a single field test. It is generally believed that the SO_2 emission of CFBC systems is closely related both with the sulfur content and the calcium-to-sulfur ratio.

[d] In all cases, A is the ash content, in percent, of the coal as fired.

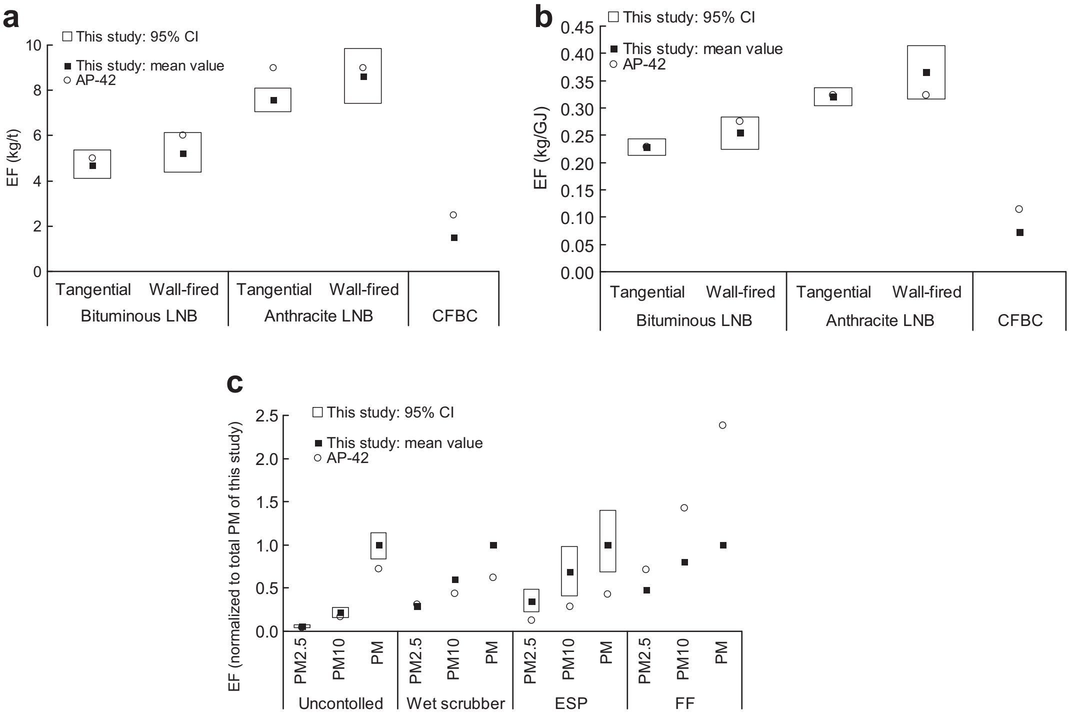

Fig. 7. Comparison of emission factors from this study with those of the U.S. EPA AP-42. (a) NO_X (kg t^{-1}). With the exception of CFBC, the plotted emission factors of this study are for units larger than or equal to 300 MW; (b) Same as (a), but the unit for the emission factors is kg GJ^{-1}; (c) PM. The emission factors of each control category are normalized to that estimated in this study for total PM.

factor for wall-fired boilers burning anthracite in AP-42 is even lower than that obtained in this study. Therefore the difference between the AP-42 and this study's NO_x emission factors (with the unit of $kg\,t^{-1}$) can be largely explained by the difference in coal heating values between the two countries. The average heating values for bituminous and anthracite in US are around 24.4 and 27.9 $MJ\,kg^{-1}$ respectively, more than 10% higher than those in China (USEPA, 1999; Jin, 2001). Regarding PM, the emission factors are normalized to the total PM levels for all of the uncontrolled and controlled technology types as shown in Fig. 7(c). For uncontrolled, wet-scrubber-controlled, and ESP-controlled groups, the AP-42 emission factors of different size fractions are respectively found to be 25–28%, 28–38%, and 58–62% lower than those of this study (except for wet-scrubber-controlled $PM_{2.5,}$ which is 7.1% higher). This implies that the removal efficiencies of wet scrubbers and ESPs in the U.S. are higher than those in China. The AP-42 emission factors for FF control of PM, however, are significantly higher than those of this study, with the caution that this is far less conclusive due to the small sample size, only two field tests, of the current study.

The quantitative uncertainties of the emission factors were calculated by dividing the differences between the upper and lower limits of the 95% CIs by the mean values. The contributions of different parameters to the emission factor variance were provided through Monte Carlo simulations described in Section 3.1. Ignoring the sulfur content variation, the uncertainty for uncontrolled SO_2 from PC boilers was estimated to be 7% in this study. For NO_X and PM, the uncertainties with the variance contributions of the various parameters are shown in Fig. 8. The uncertainties of NO_X emission factors for different unit types varied from 14% to 45%. The emission factor variances for only three out of the listed nine unit types were dominated by the uncertainty of fuel heating value, while the remaining six were dominated by the uncertainty of NO_X concentrations, particularly for units combusting anthracite. As shown in Fig. 8(b), the uncertainties of PM emission factors generally increased from large to fine particles. The emission factors for units with ESP and wet-FGD systems had uncertainties over 80% for all of the size fractions, much higher than those for SO_2 and NO_X. Regarding the contributions of parameters to the variances, the ash release ratio contributed more than mass fraction by size for large particles of uncontrolled emission factors (78% vs. 22%, respectively, for particles larger than 10 μm), but the opposite was true for small particles (8% vs. 92% for $PM_{2.5}$). For post-control emission factors, the contributions to variance of the ash

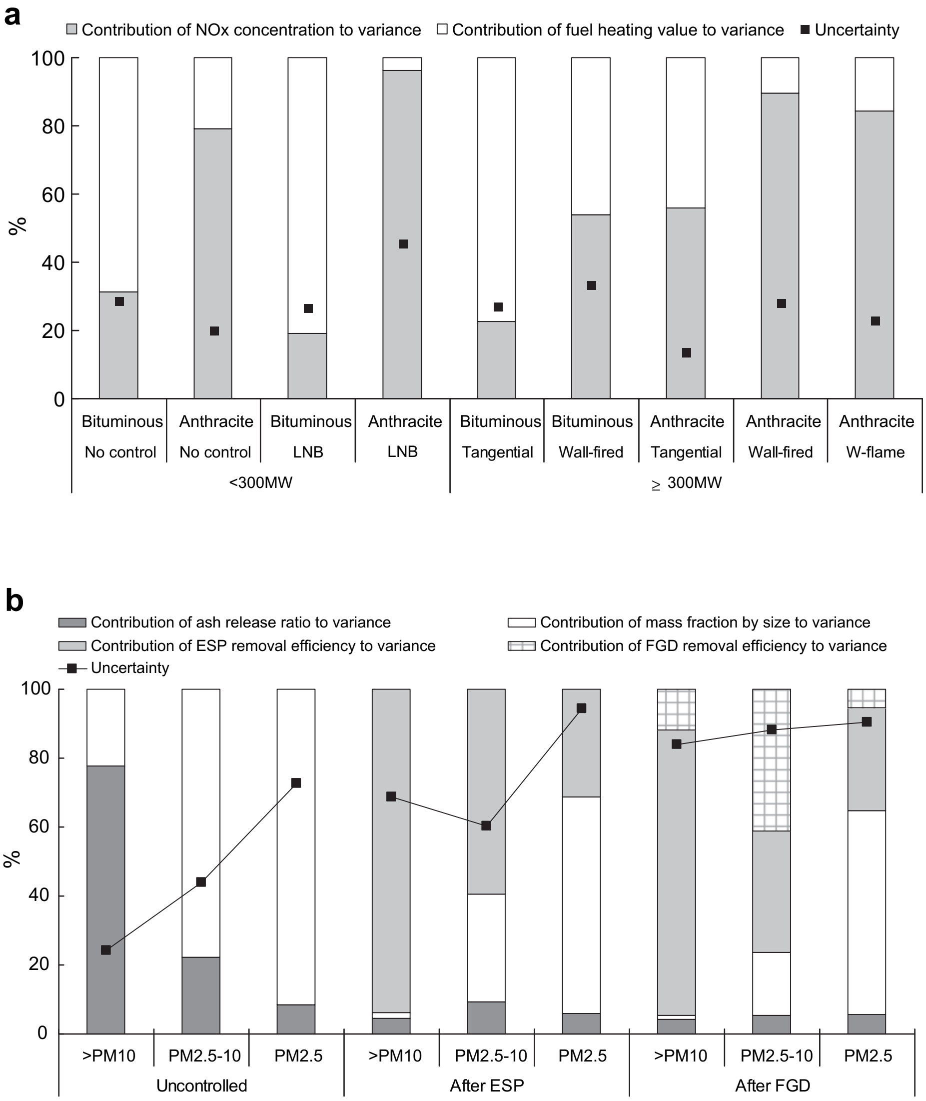

Fig. 8. Uncertainty analyses of emission factors. (a) NO_X; (b) PM.

release ratio decreased substantially, to less than 10%. ESP removal efficiencies played very important roles for the variances of all size fractions, particularly for large particles (more than 80% for particles larger than 10 μm), while the mass fraction still contributed around 60% to the uncertainties of $PM_{2.5}$. To reduce the uncertainties of PM emission factors, studies of mass fractions of fine particles and ESP removal efficiencies are still needed.

Limitations of this study should be acknowledged. Besides boiler types, fuel qualities, and emission control devices, emission levels can also be influenced by the operating parameters of power units like boiler load, coal fineness, oxygen enrichment, and dust collector rapping cycles (Bi and Chen, 2004; Yi et al., 2006; Liu et al., 2006). Although all the emission data in this study were obtained during normal working conditions, those operating conditions were hardly identical. The testing instruments used by various studies were also different and thus subject to different sensitivity levels. Accordingly the uncertainties of emission factors could possibly be even larger than estimated here. At present, the penetration of advanced technologies into the Chinese power sector is increasing quickly, including ultra-super critical boilers (600–1000 MW) with wet-FGD, SCR, and FF systems. To date few field measurements have been taken and published on these units. Moreover, the removal efficiencies of FGD and SCR can vary considerably depending on the quantities of sorbent used, e.g., the actual national average removal efficiency of FGD for SO_2 were currently believed only 70–80% according to a recent survey by MEP.[1] Therefore the emission factors obtained for these units should be applied with caution.

5. Conclusions

An integrated emission factor database for the Chinese coal-fired power sector was developed based on field tests and thorough data surveys. With 95% CIs for emission factor estimates, the database can support improved emission inventories and uncertainty analyses for different types of power units and fuels. Although advanced emission control devices are increasingly used, their actual performance varies significantly due to lack of specific policies and regulatory incentives, particularly for NO_X and PM control. Along with better-targeted policy and improved regulatory implementation, more field tests for those devices are recommended and more accurate emission factors can be expected in the future.

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Appendix. Supplementary information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2010.01.017.

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[1] Personal communication from MEP officer.