

# MITIGATION OF ULAANBAATAR CITY'S AIR POLLUTION – FROM SOURCE APORTIONMENT TO ULTRA-LOW EMISSION LIGNITE BURNING STOVES

S Lodoyasamba<sup>1</sup> and C Pemberton-Pigott<sup>2</sup>

<sup>1</sup>Nuclear Research Center, National University of Mongolia, P.O.Box-46A-202, Ulaanbaatar, Mongolia

[lodoysamba@num.edu.mn](mailto:lodoysamba@num.edu.mn); [lodoysamba@yahoo.co.uk](mailto:lodoysamba@yahoo.co.uk)

<sup>2</sup>SeTAR Center, Department of Geography, Environmental Management and Energy Studies,

University of Johannesburg, P.O Box 524, Auckland Park 2006, South Africa

[crispin@newdawn.sz](mailto:crispin@newdawn.sz)

## ABSTRACT

Mongolia has an extreme continental climate with long, cold winters lasting 7 to 8 months. Monthly average temperatures are typically -20°C in January and February, dropping to -40°C at night. The urgent need for space heating in traditional *gers* (yurts) results in very high ambient particulate matter (PM) concentrations, largely the result of burning high moisture, high volatiles lignite in a sheet-metal wood-burning stove.

A study conducted in 2008-2009 found the annual average ambient PM level of Ulaanbaatar city is 150 µg m<sup>-3</sup> for PM<sub>2.5</sub> and 300 µg/m<sup>3</sup> for PM<sub>10</sub> in the city centre. In the coal burning poor districts it is 300-620 µg m<sup>-3</sup> for PM<sub>2.5</sub> and 350-900 µg m<sup>-3</sup> for PM<sub>10</sub>. The main sources are wind-blown soil, coal and wood combustion and vehicles. Low temperature coal combustion produces 87% of finer particles in residential districts. Wind-blown fugitive dust contributes 91% PM<sub>10</sub> in the same areas.

The extraordinary air pollution in Ulaanbaatar (up to 4 200 µg m<sup>-3</sup>) was monitored using Nucleopore® filters and particle counters. Particle analysis confirmed low temperature coal combustion as the major air quality problem in poor districts. High time-resolution PM 2.5 data showed particles are emitted during the ignition of lignite fires. Over 50% of all PM comes from the ignition phase of stoves lighted in the morning and in the late afternoon after people arrive home from work.

A laboratory (modelled on the SeTAR Centre Laboratory, University of Johannesburg) was established to quantify domestic stove emissions. Measured particulate matter was as much as 12 g m<sup>-3</sup> of flue gases. Data analysis uses the SeTAR Centre Heterogeneous Testing Protocols and analytical methods. A combustor testing programme led rapidly to the development of an extremely clean-burning cooking and space heating stove that has been developed and brought to market within a single year. An acceptable 9 kW low-emission (up to 99% reduction of PM 2.5) and high efficiency (50% fuel savings) cross-draft cooking and space heating stove was developed and is being piloted for large scale production in Ulaanbaatar at this time.

## 1. INTRODUCTION

Mongolia's continental position in east central Asia and its high altitude (1 400 m) produces an extreme continental climate, which is characterized by long, cold winters lasting 7 to 8 months. It is this unrelenting cold that labels Ulaanbaatar (UB<sup>1</sup>) the coldest capital city in the world. Staying alive means generating heat – lots of it. For the poor majority, that means burning anything available, but principally lignite from the nearby Nalaikh coal mine.

With a monthly average winter temperature of -20° C, the heating of a traditional '*ger*' (yurt), or a similar sized small one or two room house, requires burning about 25 kg of lignite per day. A large portion – more than half – of Ulaanbaatar's 1.1 million inhabitants are relatively recent arrivals and are in the process of constructing a permanent home on their *hashaa*<sup>2</sup>. Between them, these homes burn about 660 000 tons of coal per year, averaging 4.5 tons per homestead.

The rapid expansion of the *ger* districts in the late 1990's brought a major problem into the city: coal smoke produced by traditional stoves that were originally designed to burn wood. In order to reduce the corrosion of the thin sheet metal used to construct these artisanal stoves, people took to lining them with clay bricks. This increased stove life but reduced the thermal efficiency by insulating the fire and sending hotter flue gases up the chimney, resulting in increased fuel consumption. The concentration of particulate matter in the ambient air varies widely across the city but is at best several times the national standard limit of 25 µg m<sup>-3</sup> for PM<sub>2.5</sub>. One area of the city has an annual average PM level of 600 µg m<sup>-3</sup>.

The main sources of PM emissions in UB are related to the demand for heating and cooking. In addition, road traffic and industrial activities contribute their share. The dry ground conditions and nearby power station ash ponds are sources of particles that become airborne with wind action and vehicular movement over unpaved roads.

More than 200 apartment blocks are located in the central city areas with their own coal-fired boilers. The *ger* areas are more scattered, mainly up-slope and away from the

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<sup>1</sup> Also called Ulan Bator

<sup>2</sup> Free land allocation, whether rural or urban

river. There are some 160 000 domestic heating systems in UB and their emissions are the dominating portion of ground level air pollution. The PM concentrations vary but the influence is felt throughout the city. The low elevation of the emissions points (3 to 4 m above ground) contributes to the problem. There are three power plants within the city burning about 6 million tons of coal per year; however the height of their stacks – 100 to 200 m – allows for effective dispersion and little PM from these stacks is found at ground level within the city boundaries.

## 2. PARTICULATE MATTER MEASUREMENT SITES AND APPORTIONMENT TO SOURCES

Eight sites were selected for measurement of PM concentrations based upon knowledge of the spatial air pollution distribution in UB derived from data collected from stationary monitoring efforts [1-3]. The geography and topography of UB, population density representations and the locations of family hospitals participating in the project were considered. Three sites (numbers 1, 2 and 5) represented the centre of the city and other sites are referred to as 'ger areas'.

Pollution source apportionment was done based on air sample collection at three sites. Filter samples were collected twice a week on Wednesdays and Sundays from 1 June 2008 - 31 May 2009. From October 2008 samples were collected daily during the last week of every month.

More than 15 species in three size categories were selected for Positive Matrix Factorisation (PMF) modelling. The sizes are PM<sub>2.5</sub>, PM<sub>2.5-10</sub> and PM<sub>10</sub>. The species monitored included: Black Carbon, Na, Mg, Al, Si, S, Cl, K, Ca, Ti, V, Mn, Fe, Zn and Pb. Multi-element analysis was performed using the ion beam method [6] and the results fed into a source apportionment model [7]. Sulphur nucleus detection was used to differentiate between high and low temperature coal combustion, separating power station particles (high) from those created by domestic stoves (low).

A total of 545 particulate matter samples were included in the receptor modelling analyses covering the period June 2008 to May 2009. The relative source contributions to the PM<sub>2.5</sub> pollution, the result of PMF analysis, at the 3 sites, are shown in Figure 1. From the PMF data analysis, the main pollution sources are shown to be soil, coal combustion, road dust, and biomass burning. Results for the three sites broadly represent the main PM sources in UB, also giving a degree of understanding of spatial contributions to the PM.

Combustion sources were found to be significant contributors to airborne particulate matter, primarily PM<sub>2.5</sub>. Cold temperatures and inversion conditions during the winter season severely limit the dispersion of air pollution in Ulaanbaatar and therefore high concentrations of combustion-derived PM<sub>2.5</sub> are found throughout the Ulaanbaatar airshed.

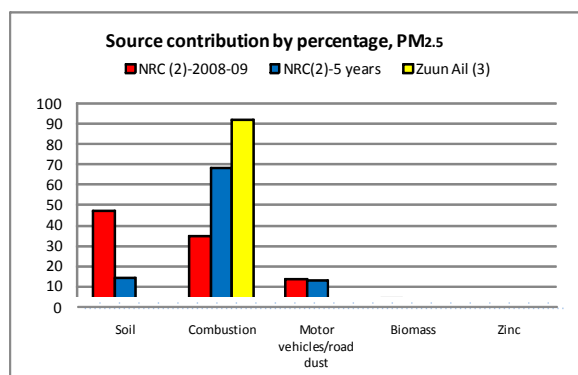


Figure 1: Typical source attribution results

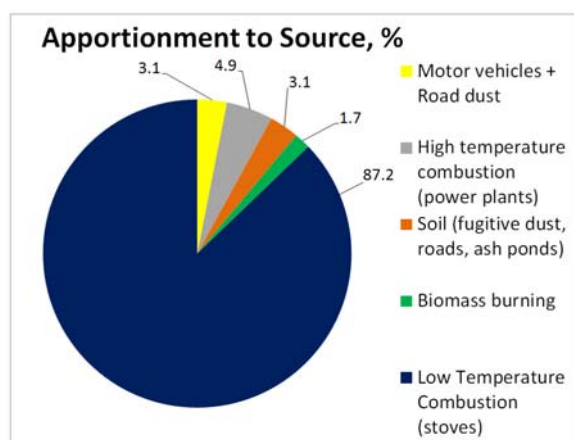


Figure 2: PM source apportionment to for site Zuun Ail

The biomass portion originates from domestic cooking activities, especially from the use of wood in the ignition of coal fires.

## 3. PARTICULATE MATTER CONCENTRATIONS

Monthly average PM<sub>10</sub> concentrations at the sites used for apportionment are listed in Table 1. Domestic combustion in natural draft devices produces nearly no larger particles, thus the PM<sub>2.5</sub> fraction is of particular interest. These results and other investigations [3,4] show that Ulaanbaatar is not only the coldest, but also the most highly polluted capital city in the World.

Inversions are common in winter, almost a daily occurrence. In areas affected by all emitter sources, the PM<sub>2.5</sub> concentrations can be extremely high as a result of these inversions. The January average measured at the site No 7 was 1 536 µg m<sup>-3</sup>. However the concentration of stove emissions does not correlate well with the tonnage of coal burned in domestic stoves. This attracted our attention.

Table 1 Monthly average PM2.5 concentrations at selected sites ( $\mu\text{g m}^{-3}$ )

Months	NRC (site 2)	100 Ail (site 3)	Buudal (site 4)	Bayan Hoshuu (site 7)	Airport (site 8)
Jun-08	29	26	85		169
Jul-08	22	13			
Aug-08	65	49			
Sep-08	19	38	37	47	38
Oct-08	46	39	281	498	185
Nov-08	122	331	527	568	406
Dec-08	107	576	1205	1421	893
Jan-09	121	1291	859	1536	515
Feb-09	141	358	342	971	413
Mar-09	80	346	179	321	207
Apr-09	129	120	94	1373	92
May-09	279	371	42	59	53
<b>Avg</b>	<b>97</b>	<b>296</b>	<b>365</b>	<b>618</b>	<b>297</b>

The Airport (site 8) is a peri-urban *ger* area relatively isolated from other particulate sources and it provided a key understanding of the nature of the air pollution produced from stoves. The PM 2.5 level in December (Table 1) is significantly higher than it is in February even though about twice as much coal is consumed per day in February. The reason is that stoves are lit much more frequently in November/December than in February is because *it is not as cold* in November. The record level of  $>4\,200\,\mu\text{g m}^{-3}$  was on a day in early November, not on some cold, high consumption mid-winter's day. In January 2009, the coldest day of the winter was also the cleanest. Some who deal with air pollution have had difficulty accepting this counter-intuitive scenario. Contrary to widely held views, the PM emissions are not inherent in the fuel, they are mostly the product of poor combustion **during ignition**. When it is colder the stoves are more likely to be kept running, emitting less total PM per ton burned than when being lit.

The hourly distribution of PM concentration is shown in the Figure 3. The chart is typical for the beginning of winter. One can clearly see several peaks in the time series of PM near all *ger* district sites.

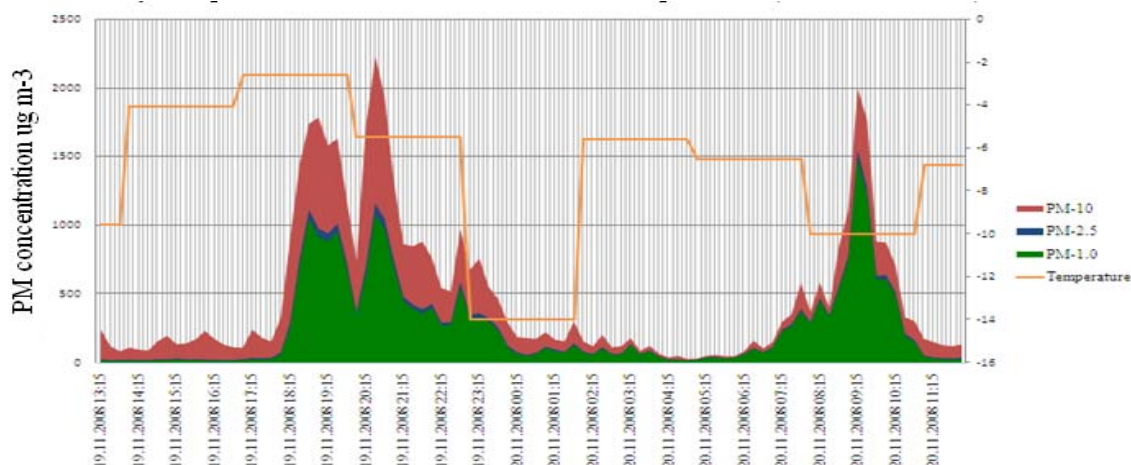


Figure 3: Example of PM1, PM2.5 and PM10 time series for 24 hours during an early winter's day (19-20 November 2008) starting at 13:00.

The twin peaks (left) at 18:15 to 20:15 show the evening fire ignition and reloading as workers return home in two waves followed by a refuelling at bedtime. The peak (right) from 07:15-10:15 is almost exclusively PM1.0 from domestic stove ignitions.

#### 4. DEVELOPMENT OF AN ULTRA LOW EMISSION COAL STOVE

Having demonstrated that domestic stove ignitions are the major air pollution problem and that it is these emissions which dominate the whole profile, a laboratory capable of measuring condensed particulates in real time was established by the Asian Development Bank in 2010. It is modelled on the SeTAR Centre's facility at the Industrial Design workshop, Bunting Road Campus of the University of Johannesburg[8].

The lab equipment includes an Emerson X-Stream dual channel gas analyser ( $\text{CO}$ ,  $\text{O}_2$ ,  $2\times\text{CO}_2$ ), Dusttrak DRX particle counter, 150 kg x 2 g Adam scale with novel desktop software and an Agilent 34972A thermocouple multiplexer. A particle condensing tunnel is supplied with air from a Nafion dryer. The dilution level is monitored by comparing the  $\text{CO}_2$  in the stack with the  $\text{CO}_2$  in the diluter and can be varied as often as required to keep the PM level in range.

A typical burn cycle was identified and reproduced in the laboratory. It consists of the ignition of about 1 kg of dry pine, the later addition of 4 kg of coal, and refuelling the fire after about 2 hours with another 4 kg of coal. The stove tested is shown in Figure 4.



Fig 4: Inexpensive traditional Mongolian stove

The data sets from four instruments were analysed using the SeTAR Centre's Heterogeneous Test Protocol Excel® spreadsheet[9]. A typical two-section test result is for a traditional stove burning of 5.6 kg is shown in Figure 5.

The black line is the real time PM2.5 and shows three significant spikes. The first and smallest (left) is from the ignition of the wood and a small amount of coal. The second and largest spike is the coal being added to the existing fire in a cold stove. The third is from the refuelling after 75 minutes when the stove was hot. The PM produced averaged  $388.4 \text{ mg MJ}^{-1}$ .

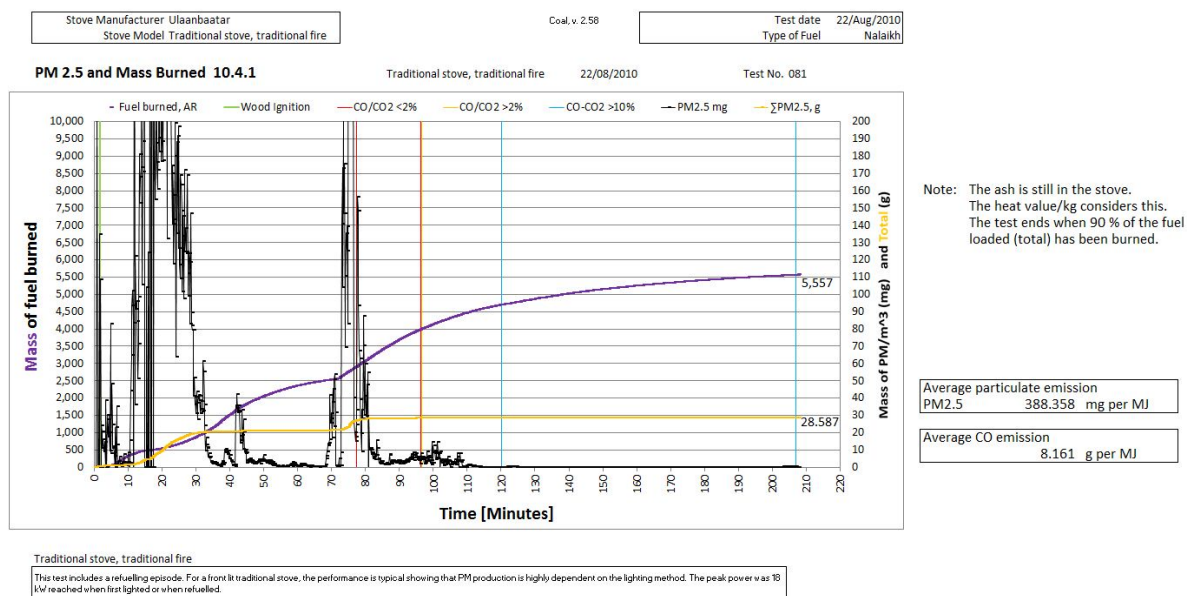


Fig 5: PM 2.5 emissions from a traditional stove, real time and cumulative, with cumulative mass burned.

The combustion conditions in a stove, unlike a power station, vary a great deal during a burn cycle. It was immediately clear that during at least part of the cycle, the combustion efficiency was very good and the PM emissions unexpectedly low. It is often assumed that coal is inherently smoky, yet these tests showed this was not the case, even for Nalaikh lignite with 50% volatile content. When combustion conditions were right, it burned quite cleanly. Closer examination of the fire showed that when a flame was present across the coal's upper surface the PM level remained low. The absence of flames when volatiles were still present always resulted in high PM.

An attempt was made to channel all emissions and flames into a pipe placed at the back of the combustion chamber. The fire was ignited next to this outlet so that all smoke

produced by igniting coal would be mixed with flames and burn inside the pipe. This was quite successful, resulting in a drop on PM emissions of about 80%.

This approach results in a fire that burns from the end of the combustion chamber towards the front igniting the coal as it proceeds – about 100 mm per hour. It requires a different ignition sequence. The result is a cross-draft fire that burns at a steady rate, sustains the ideal low PM conditions for much longer. Because of higher combustion efficiency, the CO level is reduced as well as yielding more heat and a higher thermal efficiency as a space heater. The profile (Figure 6) is very different, producing only a fraction of the start-up emissions. The CO MJ<sup>-1</sup> total is also down by 50%.



An existing GTZ stove with a hopper was modified to create ideal combustion conditions almost from the start. It is able to maintain nearly ideal combustion conditions for several hours at a time.

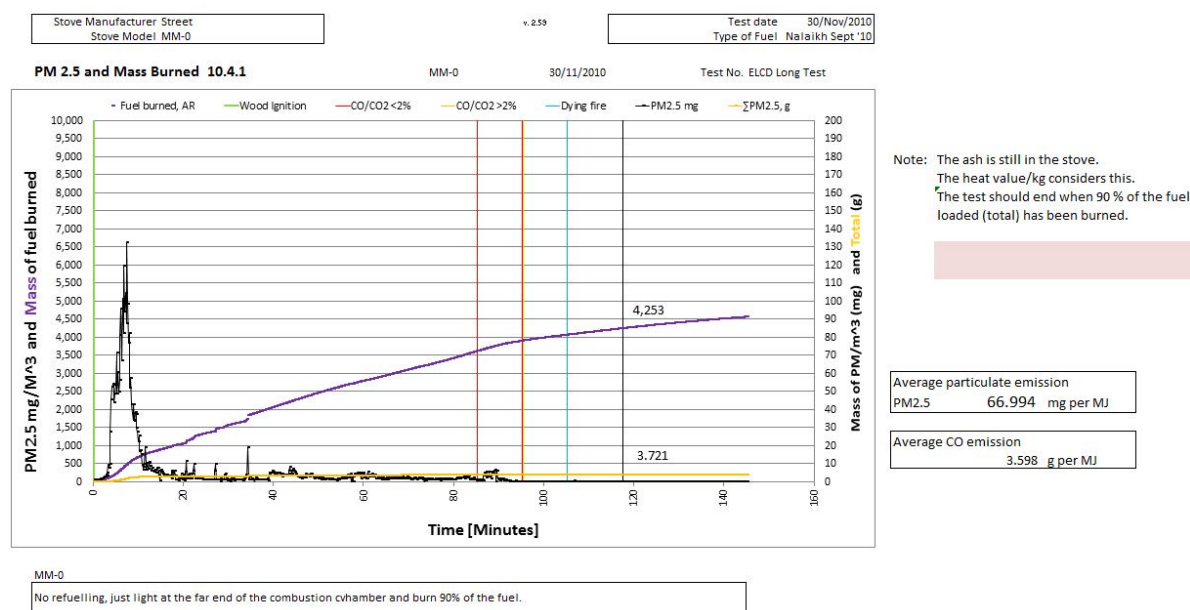


Figure 6: Traditional stove with an end-lit cross-draft fire without refuelling.

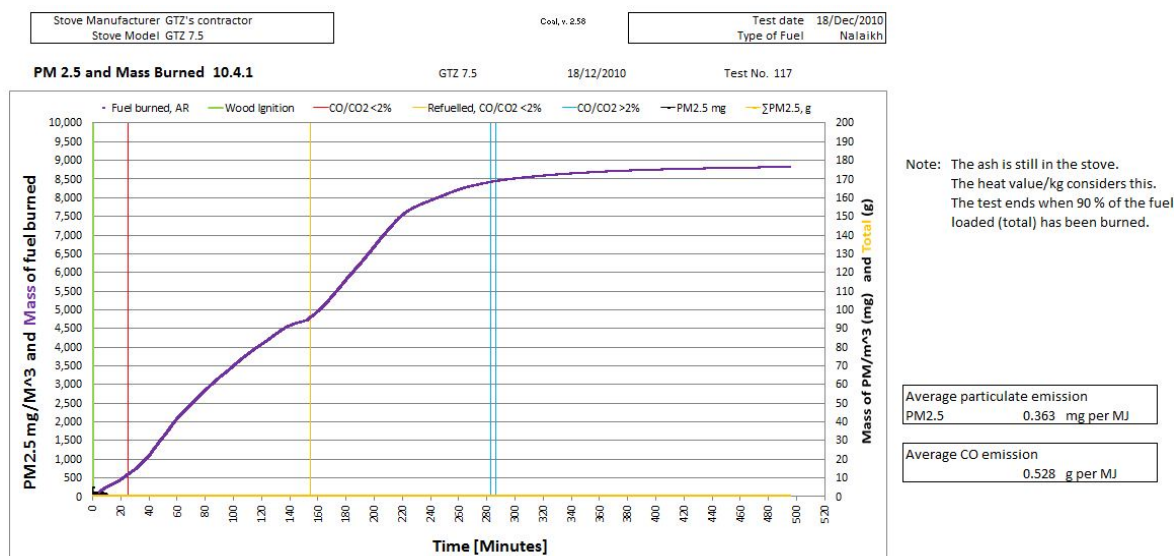


Figure 7: GTZ 7.5 cross-draft stove with a hopper.

The black PM emission line is barely visible on the bottom left and lies flat on the X-axis after the first 5 minutes. This test includes refuelling after 150 minutes. The PM reduction is 99% and the CO is down 93%. The steady rise in the mass burned shows a steady power level. This stove is now in production in Ulaanbaatar. Early reports indicate the stove saves 50% of the fuel normally used because it has a higher thermal efficiency.

## 5. CONCLUSION

In conclusion please note the following summary:

- Ulaanbaatar city air is grossly contaminated with PM emissions from stoves making it the most polluted capital city in the world;
- The main smoke pollution source is from high volatile coal being burned in unsuitable wood stoves;

- In poor residential ‘ger’ areas these stoves contribute 87% of fine PM pollution;
- Lignite/brown coal is not an inherently smoky fuel. Conditions can be successfully created for burning wood and high moisture, high volatiles lignite with very low PM emissions in a practical device.
- The SeTAR Centre Heterogeneous Testing Protocol and data analysis method led to rapid development of an optimized stove solution.
- Emission benchmarks for domestic coal combustion can and should be lowered with consequent improvement in health and welfare.
- The PM emissions are so low that for much of the time the improved stove substantially cleans the ambient air that passes through it. The chimney gases are usually cleaner than the outdoor air. It is not quite PM negative *in toto* but work continues toward this target.

Next-Generation Cookstove Workshop, 16-20 Nov 2009, Bangkok, Thailand.

- [9] Makonese, T., Robinson, J., Pemberton-Pigott, C., Molapo, V. & Annegarn, H. “A heterogeneous testing protocol for certifying stove thermal and emissions performance for GHG and air quality management accounting purposes”. Paper presented at A&WMA Conference, 10-14 May 2010, Xian, China, In press JAWMA, 2011.

## 6. REFERENCES

- [1] Lodoysamba S., Shagijamba D., “Soil Apportionment in Ulaanbaatar City Air Pollution Sources, Proceedings of International Conference on Contemporary Physics-IV, Ulaanbaatar, Mongolia, 2007, pp. 160-164.
- [2] Lodoysamba S., Shagijamba D., Gerelmaa G., “Characterization of PM<sub>2.5</sub> and PM<sub>10-2.5</sub> Air Pollution of Ulaanbaatar City”, *МУИС ЭШБичиг, Физик*, No. 309,15, x-1-4, 2009.
- [3] World Bank, Discussion Papers, “Air pollution in Ulaanbaatar, Initial Assessment of Current Situation and Effects of Abatement Measures”, Dec.2009. [www.worldbank.org.mn](http://www.worldbank.org.mn).
- [4] Lodoysamba S., Larssen S., Gerelmaa G., Li Liu, Shagijamba D. & Nygaard J. “Results of PM Air Pollution Baseline and Source Apportionment Study of Ulaanbaatar City of Mongolia”, Proceedings of A&WMA International Specialty Conference Leapfrogging Opportunities for Air Quality Improvement, May 10-14, 2010, Xi’An Shaanxi Province, China, pp. 187-193.
- [5] Lodoysamba S., Shagijamba D., Gerelmaa G., “Study Air Pollution Sources of Ulaanbaatar City”, BAQ2010 Conference, Singapore, 9-11 November, 2010. [www.cleanairinitiative.org](http://www.cleanairinitiative.org).
- [6] Trompetter W.J., Markwitz A. and Davy P., "Air Particulate Research Capability at the New Zealand Ion Beam Analysis Facility using PIXE and IBA Techniques", *International Journal of PIXE*, Vol. 15, Nos. 3-4, 2005, 249 – 255.
- [7] Paatero, P. "Least squares formulation of robust non-negative factor analysis." *Chemom. Intell. Lab. Syst.*, Vol. 18, 1997, 183-194.
- [8] Pemberton-Pigott, C., Robinson, J., & Annegarn, H. “Stove Testing in South Africa: Heterogeneous Testing Protocols for Emissions and Thermal Performance”. Paper presented at the ASEAN-US

**Principal Author:** Sereeter Lodoysamba, physicist, whose main field is nuclear instrumentation, nucleonic gauging and electronics. He earned a Ph.D. in physics at



the Moscow State University. He worked in the Joint Institute for Nuclear Research, Dubna, Russia, with the team that discovered Dubnium, Element 105. Now a professor and Department Head at the National University of Mongolia he has been working for years on air pollution, analysing particle composition, pollution source identification and apportionment. Now active in stove testing and emission measurement, Lodoysamba is working on the establishment of the SEET Laboratory as a national consultant to the Asian Development Bank.

<lodoysamba@num.edu.mn>

**Co-author:** Crispin Pemberton-Pigott has worked with



dozens of Appropriate Technologies for 30+ years, designing stoves and labour-enhancing equipment. He is a recipient of the DISA Chairman's Award (2004) for the Vesto Stove made by his company, New Dawn Engineering. A co-founder of the Eastern Cape Appropriate Technology Unit, the Renewable Energy Association of Swaziland and the Industrial Designers Association of South Africa, he

presently he advises two Mongolian clean air projects and the SEET Laboratory. He is the senior technical advisor at the *Sustainable Energy Technology And Research* (SeTAR) Centre at the University of Johannesburg. He volunteers at ETHOS and SABS co-writing stove standards and test protocols and has advised student engineering projects at the Universities of Alberta (Edmonton) and Waterloo in Canada and Dartmouth College, USA. For more information visit:

www.newdawnengineering.com [crispin@newdawn.sz](mailto:crispin@newdawn.sz)

**Presenter:** The paper is presented by Lodoysamba.