DEVELOPMENT OF A LOW SMOKE MONGOLIAN COAL STOVE USING A HETEROGENEOUS TESTING PROTOCOL

C Pemberton-Pigott
[1] SeTAR Centre, University of Johannesburg, P. O. Box 524, Auckland Park 2006, Johannesburg

ABSTRACT

This report is on the application in domestic stove development of heterogeneous test methods that can simultaneously quantify gaseous emissions, condensed particulates and the mass of fuel burned in real time. Such measurements can rapidly identify ideal combustion conditions by post-facto dividing the test into arbitrary segments for detailed analysis. Domestic coal stoves typically operate daily across a wide range of operating conditions. The analysis technique was applied repeatedly throughout the development of a lignite burning stove suitable for use in Ulaanbaatar, Mongolia, the coldest and most heavily air-polluted capital city in the world. The outcome is a natural draft chimney stove with a >99% reduction in PM 2.5 emissions and >90% reduction in CO, relative to the baseline product. Including the ignition phase, the fire emits less than 0.5 mg of PM2.5 per MegaJoule. This challenges the popular notion that high-volatiles 'low quality' coals are inherently smoky.

1. INTRODUCTION

The promotion of fuel efficient and lower emissions stoves for cooking and space heating is the mainstay of projects increasing peoples' access to modern energy' [1] – an expression which means providing one or more of: fuel saving, better indoor air quality, more controllability, better thermal performance or access to a broader range of fuels at a lower cost in money, time or effort. The unfortunate reality is that relative to the needs of the three billion people cooking over fires each day, relatively few improved stoves are in use after decades of donor-funded development and promotion. It is the author's view that the primary reasons for this are: a) that the products generally have poor quality and performance; and b) that, broadly stated, the methods used to evaluate stove performance in the laboratory do not readily reveal their advantages leading to poor product evaluation.

Growing interest in improving the combustion of domestic coal stoves has been prompted by health problems attributable to stove emissions of dry and condensed particulate matter. The Mongolian capital city of Ulaanbaatar is the coldest and, because of lignite stoves (Fig. 1), the most polluted capital in the world. The direct cause is the burning of wet lignite from the Nalaikh coal mine in simple stoves originally designed to burn wood. A decade of promoting 'improved stoves' brought no measureable relief because the stoves are not, for the most part, 'improved'.

Figure 1: Traditional Mongolian stove

The most common stove performance evaluations involve completing some task such as boiling a pot of water [2]. In such tests, the thermal performance, gaseous emissions and particles of incomplete combustion are summed for the test and evaluated in the light of benchmarks, alternative constructions or tasks. If, during a portion of the test, the emissions are greatly reduced and during another portion, they are very high, the details of this are hidden by summing the emissions for the whole or even just a portion of the test. Particulate matter has usually been collected on filter paper which is weighed before and after the test. The mass of CO emitted is usually the average concentration of the whole volume of the emissions collected in a hood, or a representative sample is drawn from a chimney and the mass calculated from the concentration, the chimney area and the gas velocity. It appears these methods were original developed for the evaluation of combustors which operated in continuous mode such as power stations and furnaces. The methods are not appropriate for testing domestic stoves and have misdirected many researchers seeking better performance.

2. THE HETEROGENEOUS TEST PROTOCOL FOR STOVES (HTP)*

The development of heterogeneous test methods [3] which can simultaneously quantify gaseous emissions, condensed particulates and the mass of fuel burned in real

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* Developed by the author and James Robinson at the SeTAR Centre, University of Johannesburg, South Africa.

time under multivariate conditions has given stove developers a powerful tool to rapidly improve product performance. Real time measurements can rapidly identify ideal combustion conditions by dividing the test into arbitrary segments post-facto. Domestic coal stoves typically operate in a range of operating conditions each time they are used. A heterogeneous testing protocol (HTP) allows the division of the experiment into what are effectively multiple, even overlapping, tests with different combustion conditions. An HTP analysis sheet is used to find optimal performance conditions without the tester knowing in advance when these might occur.

The performance of a thermal device should be provided in the form of one or more performance curves with the device operating at different firing and workloads. A multivariate test involves operating the stove at different power levels, different excess air ratios, different primary and secondary air supply ratios, different pot loads, test durations, fuel loadings and so on. Many of these variables are not at all constant in a domestic stove, particularly a coal stove which is re-fuelled periodically. An HPT-based analysis provides sets of performance curves capturing some of this heterogeneity, thereby enabling the more rapid diagnosis and improvement of the design and performance of domestic stoves.

3. RESULTS AND DISCUSSION

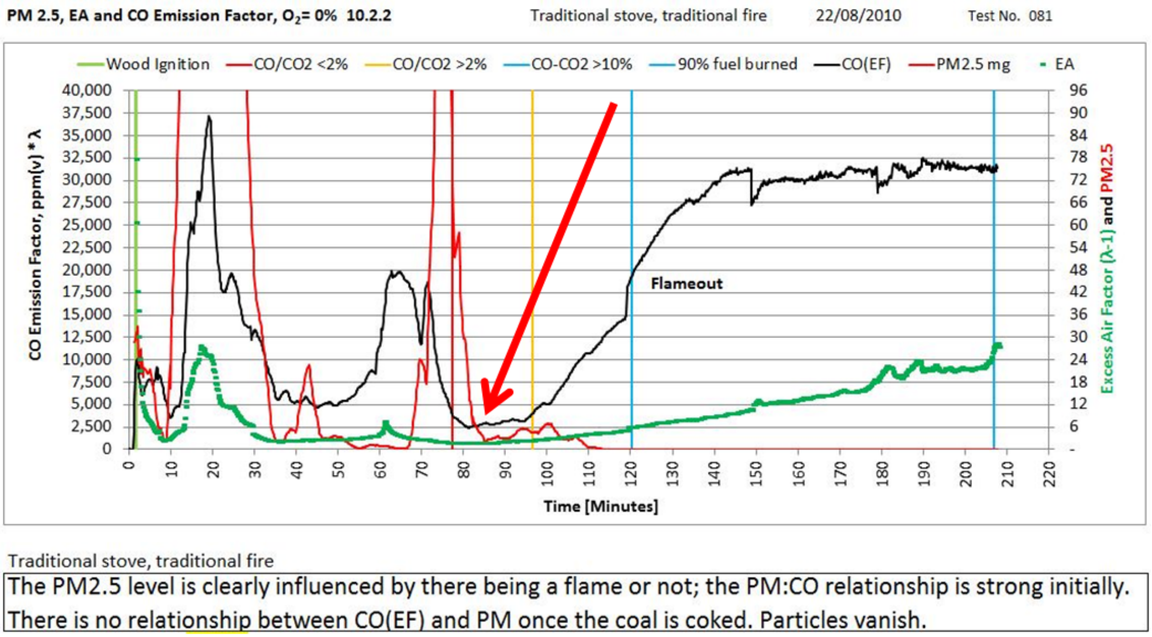
3.1 USE OF THE TEST TO IMPROVE A COAL BURNING STOVE IN MONGOLIA

It was soon observed that there is a general relationship between PM formation and carbon-monoxide (CO) formation, but only during the earlier stages of a coal fire when most PM is emitted. This initial correlation is good enough to guide a stove developer in the exploratory phase of design, provided the CO concentration is expressed as an emission factor: CO(EF).

> The emission factor CO(EF), expressed in ppm(v), is the measured CO concentration multiplied by the total air supply (λ). It gives the calculated CO concentration of a standard cubic metre of combustion gases containing 0% O_2 (i.e. zero excess air). For any given fuel there is a CO_2 Maximum potential stack concentration. For each CO_2 Max there is a CO(EF) that represents a CO/CO_2 ratio of 2%, a common legislated CO emission limit. The CO(EF) is a simple way to assess HTP outputs.

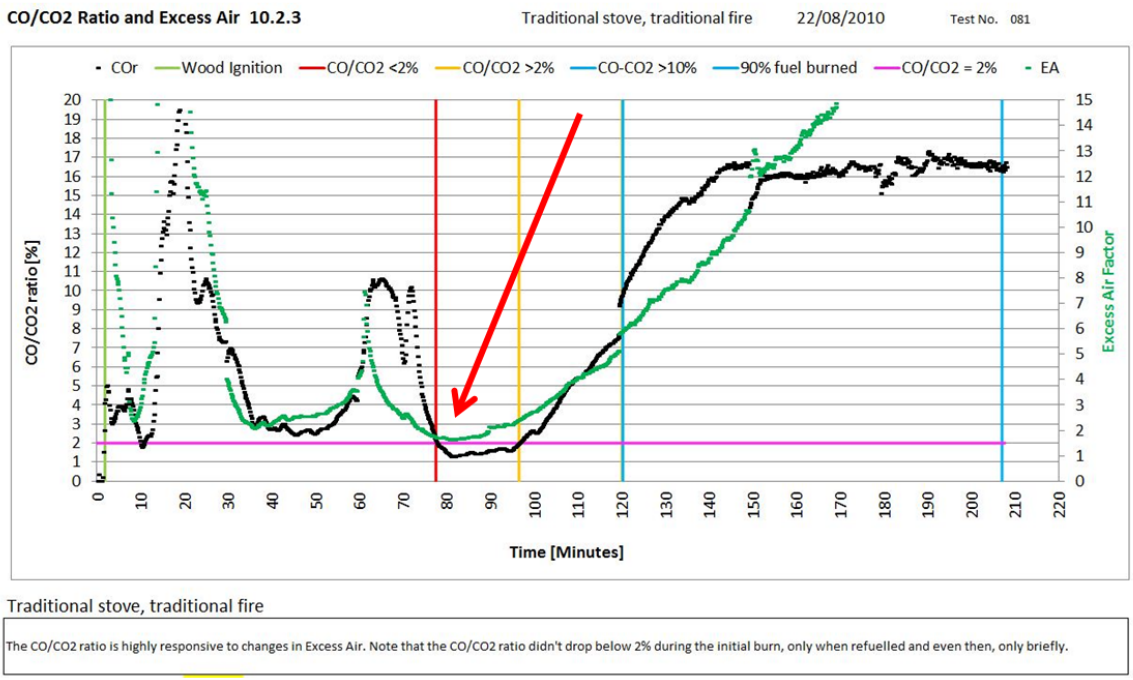
A typical set of graphs from a combustion test are shown in Fig. 2., in this case for the baseline (traditional) Mongolian wood stove fuelled with coal. The CO(EF) (black line) in Fig. 2 shows that combustion efficiency is poor for a great deal of the time, but that after refuelling at minute 60, the fire in a hot stove newly loaded with high volatiles coal does burn quite well for about 25 minutes. The conditions prevailing when the CO(EF) was low always featured an Excess Air (EA) level below a threshold value: 300% (section indicated by red arrow).

The vertical lines are used to indicate sections of interest. Between the Red and Orange lines in Fig. 2 the CO/CO_2 ratio is below 2%, meeting the SA National Standard on the maximum CO emissions for a flame domestic stove. Fig. 3 plots the CO/CO_2 ratio and Excess Air at the same point of the test showing that fuel-specific CO(EF) values can be used as a substitute for more expensive CO_2 measurements. The CO(EF) number is more accurate than CO_2 values commonly calculated from CO and O_2.



The PM2.5 level is clearly influenced by there being a flame or not; the PM:CO relationship is strong initially. There is no relationship between CO(EF) and PM once the coal is coked. Particles vanish.

Figure 2: Baseline stove CO(EF) and PM2.5 lines. Values below 3650 (red arrow) show CO/CO2 is below 2%.



The CO/CO2 ratio is highly responsive to changes in Excess Air. Note that the CO/CO2 ratio didn't drop below 2% during the initial burn, only when refuelled and even then, only briefly.

Figure 3: Good combustion occurred only when EA is less than 300% (λ < 4)

The first idea is to quickly increase the percentage of the time the EA is low. When the EA was low, the CO(EF) was usually low. Note that the correlation did not hold at all times. Only when there was a robust flame was this true. Refuelling in a way that covered the flame created very poor, low EA combustion with a consequent increase in black carbon (BC) and condensed particle emissions. In such rare cases low EA correlated with a high CO(EF).

It was decided to light the fire at the back of the stove next to the heat exchanger inlet. A 60 mm diameter throttling pipe in which to burn the smoke was added to bring all smoke, flames and CO together (Fig. 4). The idea was that if a fire could be established near the exit of the combustion chamber all CO and smoke would have to pass through the before leaving. Several lighting techniques were tried before settling on one that produces a fairly large initial fire immediately in front of the pipe entrance as shown in Fig. 5.

Figure 4: Pipe set into the back wall with clay

Figure 5: Fire and smoke are drawn into the pipe

The result is approximately the same as turning the South African *Basa njengo Magogo* TLUD (top-lit up-draft) lighting technique on its side. The *End-lit Cross-draft* (ELCD) configuration turned out to be the cheapest way to significantly reduce PM emissions from Mongolian coal stoves, costing only $1.00 for the pipe.

The real-time thermal efficiency curves for the two stoves show that the ELCD firing technique increased the thermal efficiency to 72% as shown in Fig. 6 and provided a more constant heat delivery. A comparison of the thermal efficiency of the two designs in real time and cumulative (mass-compensated)† is plotted in Fig. 7.

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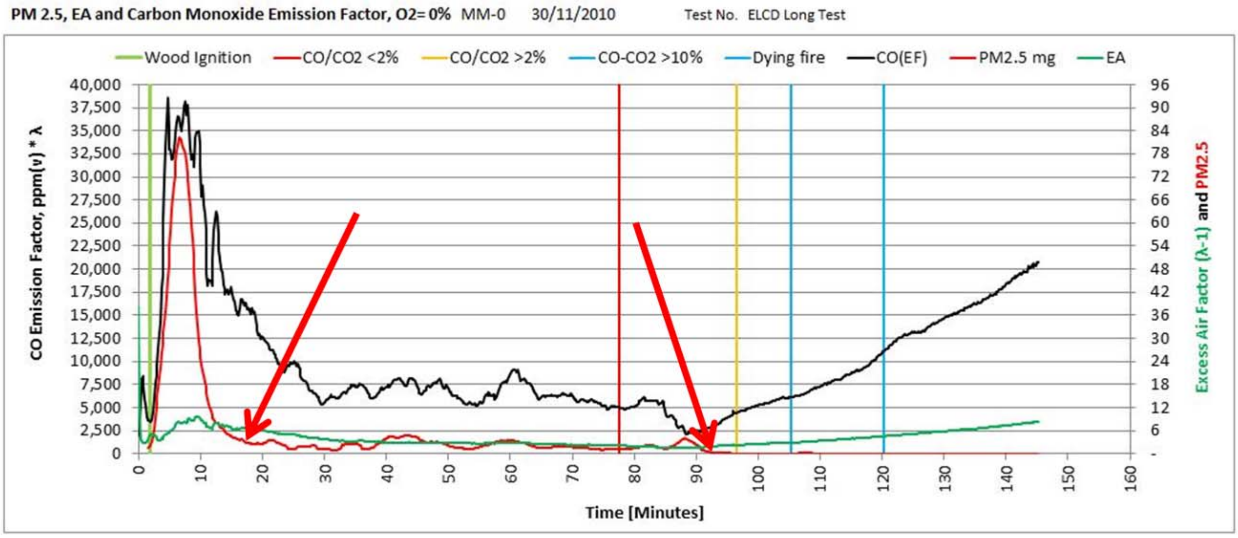
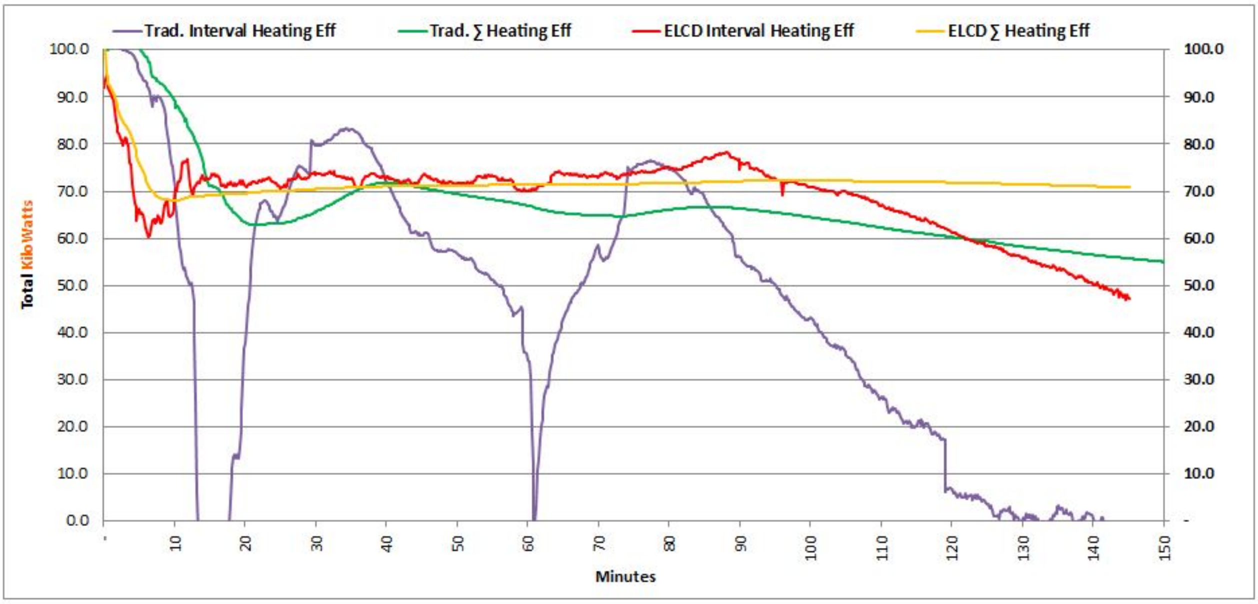
† The cumulative plotted values compensate each reading with the mass burned during the relevant interval, normally per 10 seconds. The result is a true reflection of the net heat delivered into the home at that point.



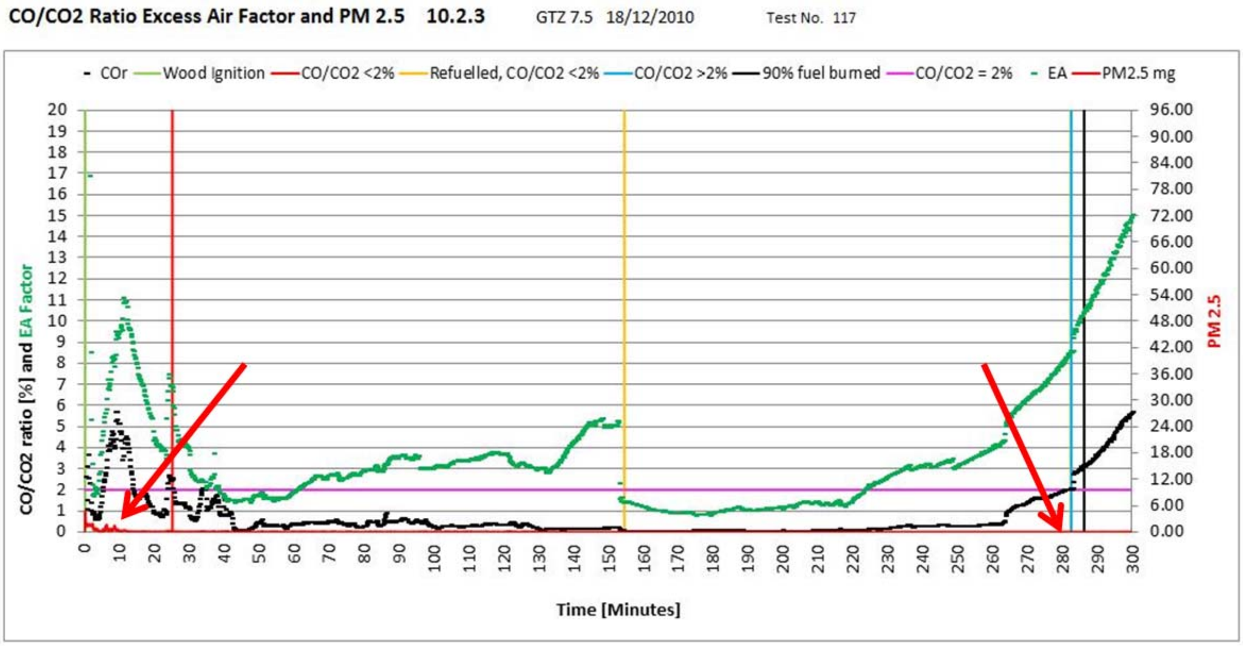
Low PM from about 15 minutes and continuously thereafter. Flame is sproviding for ignition of condensible particulates.

Figure 6: ELCD fire configuration has a lower peak of PM2.5. The level reduces rapidly 10 minutes after igniton and thereafter remains low and nearly constant from minute 15 to minute 90.



The ELCD fire has nearly constant effciency (Red) compared with the Traditional fire (Blue).

Figure 7: The two smoother lines are the cumulative, mass-burned-compensated thermal efficiencies for the traditional (green line) and the ELCD (yellow line) stoves.



With Excess air well controlled near or under 300%, with a constantly igniting fuel load providing new volatiles continuously, the PM2.5 drops 99% relative to the Traditional Stove.

Figure 8: With a controlled excess air ratio and a continuous supply of new coal falling from a hopper, the cross-draft fire burns evenly and cleanly over a prolonged period well after the coal is completely coked.

Table 1: Performance comparison between the Baseline, ELCD modified traditional and Improved stoves.

	Traditional Stove	End-lit Cross-draft	Improved Stove
CO, g MJ^{-1}	8.16	3.6	0.53
CO reduction, %	0.0%	56%	94%
Thermal efficiency, heating	63%	72%	72%
Average CO/CO$_2$ fuel 90% burned	9.6%	4.4%	0.6%
Net kW delivered into home	3.7	5.7	4.2
Fuel burn rate, kg hr^{-1}	1.6	2.1	1.8
PM 2.5, mg MJ^{-1}, whole test	388[‡]	67	0.4[§]
PM 2.5 reduction, %	0.0%	83%	99.9%

[‡] Others have reported double this figure in tests of wood stoves in other countries.[4]

[§] A portion of this measurement is undoubtedly contamination from the ambient air. For more than 50% of test time the flue gases are cleaner than the ambient air passing into the stove so it is net-negative for PM2.5 during this time.

It was clear that supplying coal constantly to the fire was key to burning the volatiles as they arose from the devolatilising coal. An entirely different new stove was constructed using a hopper to drop fuel constantly onto a grate, made in such a way that it maintained a cross draft fire. The gases are led to a small exit hole measuring 80 x 100 mm. The hopper was sealed to ensure that the fire did not develop upwards into the fuel load.

The fuel hopper, the combustion area and the heat exchanger are separated with this design, allowing them to be adjusted separately. The result was very encouraging. Fig. 8 shows the performance of the improved stove. The real time PM 2.5 line (Red) is barely visible on the X Axis. The kindling ignition was adapted to take full advantage of the benefits of TLUD fires.
A comparison of the three stoves is shown in Table 1. The parameters given are the most relevant of those calculated by the HTP analysis sheet.

4. CONCLUSION

It is possible to burn high volatiles (50%) lignite in a simple natural draft stove if the combustion parameters are carefully set. What the optimum parameters are can most readily be established by using a heterogeneous testing protocol with real time measurements displayed and calculated in sections of interest.
The use of simpler testing methods seems to have failed to deliver substantially improved products. Such methods include tracking the temperature of the chimney, measuring the CO concentration in the chimney and judging the smoke production.

The method adopted in this investigation, using the heterogeneous testing protocol, involves identifying periods of good combustion *post hoc*, and in subsequent tests attempting to extend such optimal combustion conditions from only a few minutes to several hours. A basic understanding combustion is applied and observations made. Many adjustments are made to the stove while it is running and the HTP analysis methods are applied to reveal meaningful relations and ratios.
The approach led successfully to the rapid development of a greatly improved stove product which is now being manufactured in the city of Ulaanbaatar, Mongolia.

5. ACKNOWLEDGEMENTS

This study was conducted at the Stove Emissions and Efficiency Testing laboratory (SEET) in Ulaanbaatar, Mongolia. The author acknowledges financial and administrative support for SEET from the Asian Development Bank, Mongolia and the Ministry of Mines, Minerals and Energy (MMRE). Financial support, workshop and design services for the improved stove were provided by GTZ Mongolia. Coordination between Donors and government was managed by the World Bank through UB-CAP. Essential insights were provided by Prof Lodoysamba from the Nuclear Research Laboratory at the National University of Mongolia. He and Prof Tseyen-Oidov from the Mongolian University of Science and Technology operated the stove for the baseline tests and are members of the SEET testing team. Finally, thanks to the SeTAR Centre at the University of Johannesburg for their continued collaboration on the development of the Heterogeneous Testing Protocol and data processing methods.

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Author: Crispin Pemberton-Pigott has worked with dozens of Appropriate Technologies for 30+ years, designing stoves and labour-enhancing equipment. He won 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 engineering student 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