STOVE TEST SUMMARY – APRIL 2011

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1. Background

1.1. A pause to reflect: In March 2011 a series of tests of coal stoves, both traditional and improved, was completed. While one can say testing never ends, at some point decisions must be made and this is a good time to pause and assess what products we should develop further, how, which to drop, and what we can expect from a stove rollout programme in the coming two years.

1.2. Number of tests: A significant number of tests were conducted starting in July when the laboratory first started providing real-time data and detailed analyses of emissions were possible. Since then we conducted about 100 tests, of which about 80 were either 'full blown assessments' or of substantial duration. Some were tests of the instruments and some were of the protocol itself. Twenty stove tests have been selected to give a reasonable cross-section of the designs available for consideration by promoters of improved stoves. All were cooking and heating stoves intended for use in gers.

1.3. Accuracy: There are several caveats one must place upon the assessments. The first is that our equipment and the protocol used have limitations. These limitations include the accuracy of the readings, the sum or the multiplying effect of those inaccuracies which compound each other. Another issue is the natural variations in the fuel content (a brown coal) and in the methods used to procure, store, weigh and add the fuel. It is difficult (though not pointless) to put a definite number on accuracy on the final values. No doubt this will be done, but the thing to consider when looking at test results is that in the hands of a competent operator, stoves perform much better than they do when in the hands of a novice or a child with little experience or on days when it is wet and rainy instead of cold and dry. We do the best we can to show how stoves are likely to perform. In the case of the Modified Mongolian stove (the 'MM' series) we ran it really well, badly, casually and looked at the differences. Three of the tests presented are MM tests and what is obvious is that there is a big improvement available no matter how it is run. That is the main lesson. The best of the best stoves are so profoundly clean that misplacing a single piece of wood at the beginning 'increases emissions significantly', meaning it results in a 'much bigger number' in terms of a % change. Well, we have to be practical. If the reduction in emissions compared with the baseline stove is 99.4% or 99.92% it does not really matter one whit.

1.4. Performance range: Fortunately for us, the difference between a high emissions stove and a low emissions one is huge. Thus determining whether the answer is accurate plus or minus 10.8 per cent or 21.5% is not all that relevant if the reduction is 100 or 500-fold. We used to get excited about 30%! The extremes measured (we are fortunate to be able to cover this range) for milligrammes of particulate matter (PM) emitted per normalized cubic metre are 2350 (for a downdraft stove that failed to light for several hours) and 0.8 (for a modern crossdraft stove). That assessment is made on the bases of emissions of smoke per Net MegaJoule of heat delivered to the home (mg/Net MJ). The range for the products tested is about 3000:1. The PM measurements ranged from 17,600 milligrammes per normalized m^3 to less than 0.001. Less than 0.001 means that some coal burning stoves are actually cleaning the air that passed into them!

We are fortunate to have a facility operating in Ulaanbaatar that can even attempt to make these assessments and thankful to the Asian Development Bank and the Ministry of Minerals Resources and Energy for making it possible.

1.5. Cooking: Another caveat is that the cooking ability of these stoves was not a focus of the testing. To do so would involve approximately doubling the number of tests performed and there simply was not enough time. A few key tests were performed. We rely on community feedback on cooking. We concentrated instead in two things: testing every stove we could find that was in some way novel and showed promise, and testing some stoves repeatedly in support of the evolution of the designs. The stove with the greatest number of tests are traditional (baseline) stove operated in different ways, the Modified Mongolian (MM-) series which is a low-cost and mostly conventional stove, and the GTZ 7 series of stoves that were the focus of several months research during calendar 2010. Three 'artisanal' stoves were turned away at the door with design advice given (and accepted). All were subsequently tested after changes had been made. Two of these, the Round ELCD and the NDH TLUD were found to be very successful from every point of view save durability which they must now address.

1.6. The baseline stove: It is important to note that when speaking of the baseline stove, we did not use a worn and leaky, broken old stove such as one might finds in the impoverished ger – those exist but are not the main target. We also did no use a specially made traditional stove with great care taken to close all joints, seal all openings and optimize all brickwork. That, we did have made and tested and it appears in the summary as the '125 Good Trad Stove', but it is not the baseline either. For the baseline we bought a tested a new low cost stove made by a well-known producer who makes several thousand a year. It is listed as '081 Avg Traditional'. It was operated by an experienced Prof Tseyen-Oidov who was raised with and beside this type of stove. The fuel used was Nalaikh coal purchased on the street and the method of operation can be said to be 'traditional'. In all cases the wood we use is probably better dried than in the average home. The emissions from damp wood can be very misleading if the stove turns out to be extremely clean so we have standardized on air dried wood, not fresh-cut damp wood which is highly variable. In all cases we tried to minimize the amount of wood needed to light the stove because wood is significant a source <PM1.0 particles, especially when smouldering. Happily, the emissions from the baseline stove over several months were consistently within the range of 700-800 mg/Net MJ. We have thus used a test from earlier in the year as the baseline. The PM2.5/Net MJ was in the high 700's.

1.7. Selection Criteria: The output from the Stove Comparisons spreadsheet is not a recommendation for funding because the criteria for each donor may be different, just as the criteria of consumers differs. There is on the TABLE tab a short list of three criteria that can be entered as 'your benchmarks' for deciding what stoves meet your definition of 'improved'. In the section below on the right, not protected from editing, is a block of questions with 'Yes' and 'No' answers. You can edit these entries using feedback from the community or your own opinion. The 'Yes' entries will generate a pink background so you can easily see which give continuous horizontal lines of happy, compliant pink. If you turn off the protection (Review tab, Unprotect Sheet) and copy the right-most column (ai45:ai65) to the right, you can create many more questions which should be answered 'Yes' to get a 'Pass'. We are interested in what you think are realistic and relevant questions.

1.8. Operating method: This cannot be overstressed: the stoves which performed best have been run using the best methods we know. In most (not just 'many') cases this is *not* the method suggested by the manufacturer. In the individual test reports there is a section detailing how the stove was operated, particularly how it was ignited. If you are thinking of promoting one of the stoves because the test results are attractive, be sure to read the relevant section in the complete stove test. There are two things that may be different from the product as delivered to the SEET Laboratory: physical changes may have been made to the stove, or the method of operation may be significantly different.

1.9. Physical changes: in most cases the physical change involved opening or closing something that is normally left alone. Two examples are important here. The first is the GIZ[1] 5 round coal stove was operated in a top-lit updraft (TLUD) mode, a mode that was definitely not envisaged by the producers. This required sealing the main side door in order to limit air entry (because it is not needed for TLUD operation) and also the closing of all 12 of the primary air holes under the grate, which was accomplished by pushing come clay into them. The stove was otherwise unchanged. In terms of 'normal mode' (BLUD)[2] emissions the stove is about the same as a traditional stove though it has a higher thermal efficiency and should save perhaps 25% of the fuel. Operated as a TLUD, the PM emissions dropped by more than 95% while increasing the thermal efficiency. So it would not be correct to say, "The GIZ 5 stove is very low on PM emissions," without also adding, "when operated in a TLUD mode". The second example is the Silver Model 126 (the second smallest one). This stove was not designed to burn high volatiles coal and in order to do so properly, it was operated with a simply but significant change to the air supply: the hole in the cast iron top was left open about 80%[3] during the entire burn and it solved the earlier problems encountered caused by thermal runaway. See the two Silver 126 test reports on the problem and its resolution. The superb performance which was obtained in this manner cannot be reproduced when cooking either flat bottomed or round bottomed pots. That is a very large caveat. It will require a physical change to the stove, which need was communicated in detail to the producers. Again, when considering a stove based on the emissions performance alone, the exact conditions under which these were obtained are most relevant. Basically, stoves do not operate themselves. There is always a user method, and sometimes the user method matters a great deal.

1.10. Method changes: The operating method of the MM series of stoves is a large part of the fuel and emission saving potential. The end-lit crossdraft fire (ELCD) also known as 'back-lighting' is a way of turning the humble traditional stove into a much longer burning and more thermally efficient product at very low cost (approximately $1). The fire is lit at or near the back of the combustion chamber (depending on whether or not one wants to cook right away). It burns towards the fuel

[1] GTZ has recently changed its corporate identity and is now known by the acronym GIZ
[2] Bottom-lit updraft (BLUD)
[3] This provided the equivalent of a 40mm diameter hole through which air flowed freely into the upper section of the combustion chamber.

loading door[4]. This ’across-the-grate-burning’ fire proceeds at roughly 120-150 mm per hour so the longer the stove, end to end, the longer it will operate without attention. The fire is significantly reduced in maximum power (preventing overheating of the ger) and the top of the stove is hot for a much longer period of time. These effects combine to give a higher average cooking efficiency, a longer cooking time and a higher heating efficiency which is quite a portfolio of benefits for such a small change in hardware and user method. The effect is enhanced by the placement of a flame tube into the back of the stove which burns 2/3 of the CO normally emitted. The technology change is thus in two parts: a slightly modified stove, and a different operating method. On its own the stove+flame tube will save fuel, PM and CO, but not nearly as much as when combined with the ELCD operating method.

2. Stove list: products tested and the method of operation

Test Number	Stove Name/Condition/Method
081	081 Good condition Mongolian coal stove owned by the average home
091	091 Same traditional stove burning coal that is well air-dried
106	106 End-lit crossdraft (ELCD) traditional stove with flame tube, well run
111	111 Anard ASE-7 downdraft stove lit using a hand-held propane gas cylinder
112	112 Anard ASE-7 downdraft stove lit using a jar lid of diesel
114	114 GTZ 7.4 crossdraft stove with a hopper
115	115 Silver 126 top-lit updraft, batch loaded stove (TLUD)
116	116 Silver 126 TLUD with added secondary air
117	117 GTZ 7.5 crossdraft stove with a hopper
122	122 Long body Modified Mongolian stove (MM-1) with flame tube operated badly
124	124 The same MM-1 ELCD with flame tube, operated casually
125	125 Good quality traditional stove, welded all round and well bricked, well run
130	130 GTZ5-TLUD with closed primary air holes and door bricked shut, no refuel
131	131 NDH TLUD with truncated conical combustion chamber, with small refuel
135	135 Royal 1 TLUD with separately controlled primary and secondary air
136	136 Silver 181 with added secondary air, including test of a refuelling method
137	137 Light-weight Round ELCD with flame tube and preheated secondary air
138	138 Gold downdraft stove with large ash drawer and rear heat exchanger
139	139 ANARD ASE-7 with cooking over the hopper and operable sidedraft bypass
141	141 TZ1 front-lit downdraft stove with transverse, mid-section coal hopper

[4] The more one wants to cook early, the more the fire is started towards the centre of the fuel load. In all cases it is lit in a way that develops a flame atop the coal and drafting straight into the flame tube at the rear.

3. Comparison of performance – Choose your goals

CRITERIA	Reduction Target
PM2.5 reduction	80%
CO reduction	50%
Fuel saving	30%
Kilowatts, Net to home	2.68
Kilowatts, Total generated	3.83

Based on the above targets, the compliant stove metrics are marked in pink. The colours appear automatically (not here, in the spreadsheet!)

Test Number	Avg KW, Total	Avg kW, Net to room	Est. fuel saving	Est. PM2.5 reduction	Est. CO reduction
081 Avg Traditional	5.38	2.68	0.0%	0.0%	0.0%
091 Trad Dry Coal	8.49	4.30	1.6%	74.7%	8.6%
106 ELCD MM-0	6.18	4.41	30.1%	86.5%	64.3%
111 Anard+Gas	3.69	2.63	30.2%	92.9%	69.1%
112 Anard+diesel	3.23	2.30	30.0%	98.4%	69.1%
114 GTZ 7.4	6.72	5.30	36.9%	99.9%	95.1%
115 Silver T-0126	11.19	8.85	37.0%	99.6%	78.3%
116 Silver T-0126+Air	6.90	6.15	44.1%	99.7%	96.9%
117 GTZ 7.5	6.34	4.52	30.1%	99.9%	96.4%
122 MM1 Misuse	5.04	3.96	36.6%	47.0%	55.7%
124 MM-1	5.58	4.47	37.8%	55.3%	61.1%
125 Good Trad	7.65	5.53	31.1%	20.3%	66.3%
130 GTZ5-TLUD	5.61	4.43	36.8%	96.5%	75.0%
131 NDH TLUD	6.62	4.77	30.9%	81.7%	75.4%
135 Royal 1 TLUD	6.52	4.59	29.2%	84.9%	86.1%
136 Silver 181	6.37	4.55	30.2%	94.0%	85.6%
137 Round ELCD	4.66	3.59	35.3%	91.8%	76.1%
138 Gold DD	8.39	6.10	31.4%	74.1%	61.9%
139 ANARD ASE-7	3.43	1.95	12.6%	97.2%	-3.0%
141 TZ1 FLDD	2.30	1.25	8.4%	-195.8%	-66.2%

4. Additional Considerations

Stove	Heats well	Hot refuelling	5 year life	Locally made	Self-maintain	Good looks	Control heat	Fast to cook	Under $130
081 Avg Traditional	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
091 Trad Dry Coal	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
106 ELCD MM-0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
111 Anard+Gas	No	Yes	No	Yes	Yes	No	Yes	No	No
112 Anard+diesel	No	Yes	No	Yes	Yes	No	Yes	No	No
114 GTZ 7.4	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No
115 Silver T-0126	Yes	No	Yes	No	No	Yes	Yes	Yes	No
116 Silver T-0126+Air	Yes	No	Yes	No	No	Yes	Yes	Yes	No
117 GTZ 7.5	Yes	Yes	No	Yes	No	Yes	Yes	No	No
122 MM1 Misuse	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
124 MM-1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
125 Good Trad	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
130 GTZ5-TLUD	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No
131 NDH TLUD	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
135 Royal 1 TLUD	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No
136 Silver 181	Yes	No	Yes	No	No	Yes	Yes	Yes	No
137 Round ELCD	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
138 Gold DD	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
139 ANARD ASE-7	No	Yes	No	Yes	Yes	No	Yes	No	No
141 TZ1 FLDD	No	Yes	Yes	Yes	No	No	Yes	No	No

5. Main conclusions
   5.1. All the stoves that operate in a top-lit updraft (TLUD) mode, all the end-lit crossdraft stoves (ELCD) and all the bottom-lit downdraft stoves (BLDD) are much cleaner burning than all the traditional stoves. The reason for this is that the fuel is deliberately not all heated at once. The common element is that some of the fuel is ignited in a way that the heat produced does not set fire to the remaining fuel. Over time, the fire burns into the rest of the coal, either by burning downwards into the pile (TLUD), across the pile (ELCD) or upwards into the pile (BLDD). In all these cases the smoke produce by the initial heating, which is the main source of particulates from the traditional stove, are channeled through the fire and are burned before leaving the combustion area.
   5.2. In the case of the stove with flame tubes, the tube (usually 60 to 65mm inside diameter pipe) serves as an afterburner with a hot flame consuming the CO and PM that made it as far as the end of the combustion chamber. It is a simple and inexpensive insert of weld-in modification to any stove.
   5.3. It is possible to refuel a TLUD stove under certain circumstances. This was confirmed with the successful refueling of a hot Silver 181 stove using Nalaikh coal. The method is restricted to coals which have a high moisture content, which is the case for lignite (young ‘brown’ coal). Nalaikh has about 25% moisture by mass and Baganuur has about 33%. The principle invoked is that at some point in the cooling-off stage near the end of the burn, the thermal mass and

temperature of the stove are low enough to be cooled by the moisture content of the in-coming fuel. When the stove has cooled a bit, but is still giving off enough heat to maintain a warm ger, the ash and remaining coke is dumped into the ash drawer using a lever on the side of the stove. A fresh load of coal (typically 9-12 kg) is thrown into the hot stove and lit on top as if it was starting for the first time. Timing is important. If the stove was to be refueled when it had, say, 20% of the fuel still left in it and was very hot, adding coal on top would produce an enormous cloud of thick smoke, high CO and a very high temperature. It may not always suit people to wait until the stove is ready to be refueled so the actual PM reduction per day may be different from the theoretical or 'perfect test' reduction.

This end-of-fire (EOF) refueling technique can be used with any of the TLUD stoves as long as provision is made for the ash and coke to be removed. It was successful in that the stove was able to give nearly continuous heat and can be judged to be able to operate 24 hours a day. Correctly sized and run, a stove should be able to heat continuously with two refuelings per day.

6. What to expect from this stove development work
   - 6.1. The target anticipated a few years ago was a 30% reduction in emissions from domestic stoves. This has now been so greatly exceeded that no one is considering funding anything that does not reduce smoke by 80% or more. It is likely that a target reduction for financed or subsidised, new improved stoves may one day be 98%. There are several stoves that if operated well, are more than 99% cleaner than a traditional stove operated in a traditional manner. We celebrate this achievement.
   - 6.2. CO: The reduction in Carbon-monoxide is on the performance list, however there is no sign of a CO problem in the air of Ulaanbaatar. The risk from CO is an in-house risk. If something goes wrong with the stove either because of misuse or deterioration, CO might escape into the home and poison the occupants. The use of CO monitors is recommended and as time passes, testing of old stoves may show where the risk is and how better stove designs can limit it. Insulating and sealing a home increases the CO risk. CO in a chimney represents a heat loss (a so-called 'chemical loss') and the better stoves produce very small amounts of it, well below the permitted Mongolian threshold of 2% of all CO_2 emitted. CO measurements are mostly of interest to designers. The stoves have to be made in a way that, late in the fire, CO does not seep out of holes and vents in the body.
   - 6.3. Fuel saving: There is an absolute need to heat homes because they lose continuously to the environment. The saving in fuel for the average ger-dweller comes from burning the fuel completely, and doing so as continuously as possible, eliminating huge flaming fires followed by a rapid collapse an hour later into a smouldering pile of coke. That high-low, high-low burn cycle of the traditional stove is a major source of heat loss up the chimney. All the better stoves produce heat more or less continuously and as a result people feel warmer, burning less fuel in total. By increasing the surface area of the traditional stove's heat exchanger at the back, it has been show (using the MM-1 and MM-2) that a 30% fuel saving can be obtained without stepping up to the more complex modern designs. This simple design change could save about 1.5 tons of coal per family per year, or $150.
   - 6.4. Local production of high efficiency stove products: There is a great deal of interest being expressed by local manufacturer of metal products in the idea of them producing domestic heating products of many types. The casting quality of cast iron needs to be improved. This is not seen to present major technical problems. Many local producers have the necessary sheet

metal equipment and could easily become stove or component manufacturers if given the right drawings and on occasion, technical advice.

7. Confirming news from elsewhere about the flame tube, which is a core component of several of the clean stoves tested: An advanced design of a downdraft stove with very low emissions has been produced at the University of Johannesburg which may be of interest. It consists almost entirely of a flame tube with a hopper attached and could create a new class of wall stoves and low pressure boilers. One was built locally in March 2010. The success of the flame tubes in the Mongolian stoves is a hint that this approach should continue to be investigated.

8. Accessing individual test results: Single test results are available in PDF format (typically 2.5 MB) by request. They will be posted at a soon-to-be created website (fiscal year 2011-12) where test data will be shared.

9. Access to the test facility: Visitors are welcome to visit the Stove Emissions and Efficiency Testing (SEET) Laboratory whenever it is open. It is located about block east and one block south of the Korean Embassy, facing the river. It has a red roof with two chimneys sticking up through two square metal boxes and has a door onto the street. Access is through the main side gate. There are many stoves on display. Visits can be arranged with Prof Lodoysamba (SMS 99-18-35-46).

10. Support for producers: There is a major opportunity to assist stove producers with testing and analysis. This is largely in two forms.

10.1. Testing while a new product is being developed: This provides the manufacturer or more accurately, the inventor, with feedback on how the stove is performing at each stage of the burn. During these tests the stove controls can be manipulated to show how emissions and efficiency are affected. This has already proven to be very helpful to GIZ during the development of the 7-series stoves which have a new type of crossdraft combustor that works very well with Nalaikh coal. Most stove developers have never had any testing done on their products before. In particular, the ignition methods usually need to be improved and as this portion of the burn is the main source of PM emitted, it always gets attention. The feedback is often accompanied by fairly detailed suggestions for dimensional changes. Not all producers are interested in receiving advice so sometimes none is given on those cases. Nearly all stoves tested so far fall into the category of 'new product being developed'. [5]

10.2. Testing of stove using a variety operating methods to try to quantify their emissions and establish what the performance is likely to be when in use by the public. This testing includes 'foreseeable misuse', casual and improper use, improper fueling, extreme testing, basically. The goals are two-fold: establishing what the baseline really is and establishing what the improved stove baseline is likely to be. This testing is done at the request of the stove projects, not the manufacturers. The knowledge it really the property of the stove projects for internal use. It might be made available to the public, it might not. If a particular project has chosen one or two stoves to promote, they might like a comprehensive series of tests to establish what the risks and benefits are, and make a

[5] Only two, the traditional stove and the G2-2000 have been on the market for a long time. The G2-2000 test did not show any significant savings of PM or CO so it was not included in this summary report.

decision internally to choose one or the other based on their own criteria, not those favoured by the other players, manufacturers or users. For example, a project may decide to go with the product that has the highest safety rating, rather than the one with the lowest emissions. At this early stage there is so little information available on each product it is pretty much only the PM and CO and thermal efficiency that are the 'numbers-based' assessments one can go on. As time passes we will expect to have other evaluations. The set of questions contained in the test result comparison spreadsheet which related to non-numerical aspects. For example, is the stove easy to make, or easy to light? Does it cook a particular type of meal well? Can it boil 20 litres in milk in a reasonable time? Can it cook the leg of a camel? Things like that. A very important one is whether or not the operating method needed to get good performance is easy to learn. Many of these answers cannot be obtained in a laboratory. The best the lab and its staff can offer is an assessment of what the stove is likely to do and how to do it.

11. The SEET Laboratory is completely reliant on a complex array of supporting organisations and government Departments for its existence, for the meaningful application of its findings and for a continuous flow of ideas on what services to offer the City of Ulaanbaatar. It is with some happiness that we can report that two scientific papers coming from SEET Lab will be presented at the 18th annual Domestic Use of Energy conference in Cape Town in the second week of April. One will be on the subject of how it was determined that the ignition of stoves was the major air pollution problem in the ger districts, and the other is on how the SEET testing protocol used to create in rapid succession, a number of stoves that are dramatically better than the baseline stove. The success has already attracted attention in the blogosphere of stoves (there is one!) because of the advances made. We all look forward to the continued success of this worthy endeavour.

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