CENTRE FOR RESEARCH IN ENERGY AND ENERGY CONSERVATION

Energy for generations

STOVE PERFORMANCE TEST REPORT

Cookstove Samples: 2018/B026, 2018/B027, 2018/B028

Test Report No: B/TR/2018/006

Prepared for:

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Acronyms and abbreviations

Acronym	Term or definition
CI	confidence interval
CO	carbon monoxide
CO2	carbon dioxide
g	gram
kg	kilogram
kW	kilowatt
m	meter
mg	milligram
min	minute
MJ	megajoule
MJd	megajoule useful energy delivered
PM2.5	particulate matter with an aerodynamic diameter ≤ 2.5 microns
SD	standard deviation
CEDAT	College of Engineering Design Art and Technology
COV	Coefficient of Variation
CREEC	Centre for Research in Energy and Energy Conservation
ISO	International Standards Organisation
RTKC	Regional Testing and Knowledge Centre
WBT	Water Boiling Test

1. Description of cookstove system tested

A cookstove system consists of the stove, cooking vessel, fuel, and operating procedure. The operating procedure used for testing the cookstoves was as per client instructions. The cookstoves were delivered to the testing laboratory by the client, Potential Energy.

1.1 Type of cookstove

The cookstoves are metallic and use wood as fuel. The cookstove is known as the Berkeley Darfur Stove. A total of three (3) cookstove samples were delivered to the laboratory for testing.

1.2 Construction materials

The cookstoves are metallic

1.3 Stove description

Figure 1: Berkeley Darfur Stoves

The cookstoves shown in the figure above are three samples of Berkeley Darfur Stove. They were assigned lab codes 2018/B026, 2018/B027 and 2018/B028 for easy laboratory identification. The stove samples are white in silver in colour, use wood as fuel and they are dodecagon (12 sided) in shape. The combustion chamber is metallic and the stove stands are metallic and attached at the very bottom of the stove (i.e. they do not raise the stove to any height- they just stabilize it). The stove skirt in which the pot is placed is metallic, and handles are wooden in nature. The stoves have a squared wood inlet and a metallic grate with 24 holes.

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Table 1: Measurable physical parameters the Berkeley Darfur Stove

Parameters	Unit	Stove 1	Stove 2	Stove 3	Average	Std. Dev	CoV
Lab code		2018/B026	2018/B027	2018/B028			
Stove weight	kg	4.3	4.3	4.2	4.3	0.058	1%
Top diameter of the stove	cm	30.2	30.5	30.5	30.4	0.173	1%
Bottom diameter of the stove	cm	26.5	26.5	26.4	26.5	0.058	0.2%
Combustion chamber top diameter	cm	8.1	8	7.9	8.0	0.100	1%
Combustion chamber height	cm	9	8.8	9	8.9	0.115	1%
Length of the secondary air inlet	cm	3.9	4	4.3	4.1	0.208	5%
Length of the primary air holes	cm	10	10	10	10.0	0.000	0%
Height of the primary air inlet	cm	9	9	9	9.0	0.000	0%
Height of the secondary air inlet	cm	16.3	16.4	16.5	16.4	0.100	1%
Pot rest height	cm	1	1	1.1	1.0	0.058	6%
Pot rest length	cm	3.5	3.5	3.5	3.5	0.000	0%
Stove height above the ground	cm	30.1	30.1	30.2	30.1	0.058	0.2%
Length of wood inlet	cm	10	10	10	10.0	0.000	0%
Height of wood inlet	cm	9	9	9	9.0	0.000	0%
Length of wood rest	cm	7.8	7.8	7.8	7.8	0.000	0%
Width of handles	cm	7.5	7.5	7.6	7.5	0.058	1%
Length of handles	cm	12.1	12	12.1	12.1	0.058	0.5%
Bottom skirt diameter (cooking surface)	cm	26.2	26.3	26.3	26.3	0.058	0.2%
Diameter of wood grate	cm	17.5	17.4	17.4	17.4	0.058	0.3%
Top skirt diameter	cm	30.1	30.4	30.4	30.3	0.173	1%
Skirt height	cm	5.1	5.3	5	5.1	0.153	3%

There is minimal variation across stove samples

1.4 Cooking vessel

A flat-bottomed aluminium pot of 7 litres capacity was used to boil 5 litres of water. The pot had a diameter of 26.0 cm and a height of 12 cm. The pot was cylindrical in shape.

The 7 litre pot size with larger diameter was selected as per the *WBT version 4.2.3 protocol*

Figure 2: A 7 litre flat bottom aluminium pot

1.5 Accessories

None

1.6 Fuel description/biomass species

Air dried *Eucalyptus grandis* wood with average dimensions of 3 cm x 3 cm x 30 cm was used. All the fuel was sourced from one supplier, Green Resources Company in Jinja, Uganda. The wood fuel had a gross calorific value of 17,272.45KJ/Kg and moisture content of 12% and the char had a net calorific value of 25,884 KJ/Kg.

Figure 3: Fuel used when testing

1.7 Operational conditions

The operating conditions at the laboratory were as follows:

- Ambient temperature (°C): 18.4 – 24.7 deg C
- Altitude (m): 1240m above sea level
- Local boiling point (°C): 96 ±1 deg C

1.8 Tests done

The following tests were conducted:

- Efficiency and emissions test (three tests on each cookstove sample thus a total of 9 tests on the 3 samples)
- Safety test (one test one sample)

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2. Test protocols

2.1 Water Boiling Test

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot. The Water Boiling Test was developed to assess stove performance in a controlled manner, and thus it is probably less like local cooking. The test reveals the technical performance of a stove, not necessarily what it can achieve in real households. Some of the parameters measured during a WBT include thermal efficiency, specific fuel consumption, time to boil, burning rate, turn-down ratio and fire power.

The cookstoves were tested using the *Water Boiling Test (WBT) protocol version 4.2.3* (GACC, 2014)[1].

Three test replicates were done for the stove. All three WBT phases were conducted i.e.:

- High-power (cold-start): Five litres of water were brought to a boil in a 7 litre pot using a stove at ambient temperature
- High-power (hot-start): Five litres of water were brought to a boil in a 7 litre pot using a pre-heated stove.
- Low-power (simmering): The water temperature is kept at about 3°C below boiling point for 45 minutes.

For each test phase, the measured parameters included time taken, mass of fuel used, mass of water in pot. *Refer to Appendix 2 for explanations on the analysis of test results.*

2.2 Safety Test

The safety test evaluates harmful factors that may result from cookstove use like burns, scalds, cuts and loss of property. A safety test encourages stove designers and manufacturers to consider safety concerns when designing a stove. *The Biomass Stove Safety Protocol version 1* was used[2].

Refer to Appendix 3 for explanations on the analysis of safety results.

[1] WBT 4.2.3 was released on 19th March, 2014, and is available at: http://www.cleancookstoves.org/our-work/standards-and-testing/learn-about-testing-protocols/protocols/downloads/wbt-protocol.pdf

[2] Safety test protocol available at: http://cleancookstoves.org/technology-and-fuels/testing/protocols.html

3. Measurement methods

The Water Boiling Test (WBT) was conducted on the cookstove samples using a 30kg capacity digital weighing scale, thermocouple thermometer, container for char and a timer.

For the safety test, an infrared thermometer was used to measure surface temperatures.

Figure 4: Auxiliary equipment used: Digital weighing scale and infrared thermometer

The emissions test was done simultaneously with the Water Boiling Test (WBT) using the LEMS (Laboratory Emissions Measurement System). The LEMS has a sensor box that measures emissions for carbon monoxide (CO) and carbon dioxide (CO_2) as well as a gravimetric system for measuring PM 2.5.

Figure 5: LEMS set up with the gravimetric system for emissions measurement PM2.5

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4. Thermal performance test results

Table 2: Test results for the Berkeley Darfur Stove

****Test results based on 9 tests from 3 stove samples (2018/B026, 2018/B027, and 2018/B028)*

		Metric	Value	Unit	Sub-Tier
Efficiency/Fuel Use					
Tier	**2**	High power Thermal Efficiency	39.5%	%	3
		Low power specific Consumption rate	0.036	MJ/min/l	2
Emissions					
Tier	**0**	High power CO	5.811	g/MJd	4
		Low Power CO	0.187	g/min/L	1
		High power PM 2.5	525.87	mg/MJd	1
		Low power PM 2.5	8.314	mg/min/L	0
Indoor emissions					
Tier	**0**	Indoor emissions CO	0.691	g/min	1
		Indoor emissions PM 2.5	49.779	mg/min	0

Tier 0 → Improving Performance → Tier 4

The stove had an average high power thermal efficiency of 39.5% and a low power specific fuel consumption of 0.036 MJ/min/l. This places the stove in tier 2 which is a substantial improvement over the baseline.

The stove performance in terms of emissions was mostly affected by the high PM2.5 at low power phase; this placed the stove in tier 0 as per IWA performance tier levels. Refer to Appendix 2on analysis of test results.

The average time to boil 5 litres of water was 21.4 minutes.

Refer to appendix 1 for more detailed test results

5. Safety test results

Table 3: Safety test results for the Berkeley Darfur Stove

Safety evaluation parameters		Rating	Value	Weight	Total	Remarks
1	Sharp edges and points	Poor	1	1.5	1.5	The stove has up to 8 sharp edges and points that could cause cuts to the user, or get entangled to a cloth.
2	Cookstove tipping	Best	4	3	12	The stove is stable on the ground with a tipping ratio of 0.61. The stove is not likely to tip over if it is slightly tipped.
3	Containment of fuel	Good	3	2.5	7.5	Burning fuel is relatively well contained when the stove is in operation.
4	Obstructions near cooking surface	Best	4	2	8	There are no obstructions near the cooking surface
5	Surface temperature	Poor	1	2	2	The surface temperature rose up to 158.7^{0}C during the test. This temperature is not safe to the user
6	Heat transfer to the environment	Poor	1	2.5	2.5	Heat transmission to the surrounding was high at 117.3^{0}C. Combustibles around the stove may be ignited.
7	Handle temperature	Best	4	2	8	Handle temperatures rose up to 48.6^{0}C; this temperature cannot burn the user when handling the stove
8	Chimney shielding	Best	4	2.5	10	The stove has no chimney
9	Flames surrounding cookpot	Best	4	3	12	There were no flames around the cookpot
10	Flames Exiting Fuel Chamber, Canister, or Pipes	Best	4	4	16	No flames exit from the fuel magazine
				Total score	**79.5**	The stove has a high risk of causing minor injuries but a moderate risk of causing major injuries
				Fair	**Good**	
				Tier	**2**	Substantial improvement over the baseline

The key identified risk areas were sharp edges, surface temperatures, and heat transfer to the floor. The sharp edges need to be smoothened, the stove need to be insulated to reduce surface temperatures and heat loss. There is also need to add a permanent ash dumper/stove base.

6. Interpretation of data and limitations

The Water Boiling Test was developed to assess stove performance in a controlled manner, and thus it is probably less like local cooking. It is an approximation of the cooking process and is conducted in controlled conditions by trained technicians. The test results will generally provide an indication of which cookstoves are likely to perform better or worse when the cookstoves are operated under conditions reasonably similar to those in the laboratory. Laboratory test results might differ from results obtained when cooking real foods with local fuels, even if efficiency and emissions were measured in exactly the same way for both tests. This is due to variation in fuels, cooking vessels, foods prepared, user behavior, and environmental conditions. In order to confirm desired impacts (whether it is fuel conservation, smoke reduction, or other impacts), stoves must be measured under real conditions of use.

7. Quality Assurance/Quality Control

All weigh scales and thermometers used in the laboratory are calibrated by the Uganda National Bureau of Standards.

8. Acknowledgements

CREEC is grateful to Potential Energy for the provided opportunity to work together, and we look forward to a continued collaboration and longer partnership.

9. Appendices

Appendix 1: Detailed stove performance results

Stove type/model		2018/B026			2018/B027			2018/B028					
IWA Performance Metrics	**units**	**test 1**	**test 2**	**test 3**	**test 1**	**test 2**	**test 3**	**test 1**	**test 2**	**test 3**	**Average**	**St.Dev**	**CoV**
High Power Thermal Efficiency	%	38.8%	40.2%	37.9%	41.2%	41.4%	39.2%	38.6%	40.6%	37.9%	39.5%	0.01	3%
Low Power Specific Consumption Rate	MJ/min/L	0.035	0.034	0.038	0.038	0.035	0.037	0.036	0.034	0.037	0.036	0.00	4%
High Power CO	g/MJd	3.96	5.15	7.14	6.47	5.32	6.67	5.92	5.49	6.18	5.811	0.95	16%
Low Power CO	g/min/L	0.14	0.18	0.18	0.23	0.17	0.20	0.23	0.17	0.18	0.187	0.03	15%
High Power PM	mg/MJd	534.5	416.9	584.2	604.4	481.9	582.1	602.5	449.6	476.9	525.870	71.32	14%
Low Power PM	mg/min/L	9.33	7.41	6.99	10.26	7.58	5.72	10.68	7.60	9.26	8.314	1.65	20%
Indoor Emissions CO	g/min	0.53	0.65	0.66	0.84	0.63	0.73	0.84	0.65	0.68	0.691	0.10	14%
Indoor Emissions PM	mg/min	54.9	37.8	49.2	59.5	51.3	58.8	56.7	38.4	41.4	49.779	8.63	17%
Safety	Index												

	Tier	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Tier**	**Sub Tier**	**Tier**
High Power Thermal Efficiency	3	3	3	3	3	3	3	3	3	3	2
Low Power Specific Consumption Rate	2	2	2	2	2	2	2	2	2	2	
High Power CO	4	4	4	4	4	4	4	4	4	4	0
Low Power CO	1	1	1	0	1	1	0	1	1	1	
High Power PM	1	1	1	1	1	1	1	1	1	1	
Low Power PM	0	1	1	0	1	1	0	1	0	0	
Indoor Emissions CO	2	1	1	1	1	1	1	1	1	1	0
Indoor Emissions PM	0	1	0	0	0	0	0	1	0	0	

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Stove type/model		2018/B026			2018/B027			2018/B028					
Standard Performance Measures		**test 1**	**test 2**	**test 3**	**test 1**	**test 2**	**test 3**	**test 1**	**test 2**	**test 3**	**Average**	**St.Dev**	**CoV**
Fuel to Cook 5L (850/1500)	g	825.5	820.6	906.9	845.9	813.8	859.7	860.6	811.9	896.8	849.1	35.1	4%
CO to Cook 5L (20)	g	40.6	50.6	56.7	64.7	49.1	58.4	63.4	50.0	54.7	54.2	7.6	14%
PM to Cook 5L (1500)	mg	3199.8	2556.5	2816.7	3521.4	2669.0	2505.0	3653.6	2625.2	3119.3	2,962.9	428.1	14%
Energy to Cook 5L (15,000/25,000)	kJ	13,169	13,091	14,468	13,494	12,982	13,715	13,729	12,951	14,307	13,545.0	560.6	4%
Time to Boil	min	20.1	23.1	25.1	20.5	18.7	20.4	21.8	24.3	24.7	22.1	2.3	10%
CO2 to Cook 5L	g	1191.0	1525.9	1651.3	1566.1	1538.5	1641.5	1503.1	1406.0	1613.5	1,515.2	143.4	9%
Basic Operation	units												
COLD START													
Time to boil Pot # 1	min	22	23	24	22	17	21	23	21	24	22.1	2.1	9%
Burning rate	g/min	14.15	13.26	13.22	12.46	17.30	15.78	14.47	14.70	14.32	14.4	1.5	10%
Thermal efficiency	--	39%	40%	39%	44%	40%	37%	38%	40%	39%	0.4	0.0	5%
Specific fuel consumption	g/liter	65.74	64.50	66.73	57.20	61.83	70.74	68.88	65.50	72.11	65.9	4.6	7%
Temp-corrected specific consumption	g/liter	66.9	65.9	69.6	58.2	64.0	72.5	70.8	69.3	74.3	67.9	4.9	7%
Firepower	watts	3,762	3,525	3,514	3,313	4,600	4,194	3,848	3,909	3,808	3,830.2	386.8	10%
Equivalent Dry Fuel Consumed	g	316.2	309.6	319.4	276.0	298.1	338.7	329.7	312.6	342.1	315.8	20.5	6%
HOT START													
Time to boil Pot # 1	min	17	22	24	18	19	18	20	25	24	20.7	2.9	14%
Burning rate	g/min	18.86	15.00	14.72	17.69	15.12	16.59	16.18	11.83	14.30	15.6	2.0	13%
Thermal efficiency	--	38%	40%	37%	38%	42%	41%	39%	41%	37%	0.4	0.0	5%
Specific fuel consumption	g/liter	67.25	68.41	74.52	65.66	59.22	63.25	66.00	60.53	71.13	66.2	4.9	7%
Temp-corrected specific consumption	g/liter	68.5	70.5	77.7	67.4	61.4	64.8	68.3	64.0	74.0	68.5	5.1	7%
Firepower	watts	5,014	3,989	3,914	4,704	4,019	4,411	4,301	3,145	3,801	4,144.3	544.9	13%
Equivalent Dry Fuel Consumed	g	323.1	325.1	353.8	317.3	285.2	303.4	316.8	291.1	339.5	317.3	21.9	7%
SIMMER													
Burning rate	g/min	8.04	7.86	8.61	8.62	8.23	8.53	8.47	8.03	8.59	8.3	0.3	4%
Thermal efficiency	--	42%	42%	42%	43%	42%	39%	39%	40%	40%	0.4	0.0	3%
Specific fuel consumption 45 min	g/liter	97.4	95.9	107.7	106.4	100.1	103.3	102.6	95.7	105.2	101.6	4.5	4%
Firepower	watts	2,136	2,090	2,289	2,293	2,189	2,269	2,251	2,135	2,284	2,215.0	78.5	4%
Turn down ratio	--	2.05	1.80	1.62	1.75	1.97	1.90	1.81	1.65	1.67	1.8	0.1	8%
Equivalent Dry Fuel Consumed	g	361.6	353.7	387.3	388.0	370.6	384.0	381.0	361.3	386.6	374.9	13.3	4%

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Appendix 2: Analysis of test results

The measured data was checked, verified and the Coefficient of Variation (CoV) done across the three tests for each stove to make sure the results were consistent and were true results obtained from the stove performance tests. The recommended limit for CoV on Fuel use/Efficiency and bench mark values is 25%. The test results were summarized using the tiers of performance. The tiers of performance were developed by the International Standards Organization (ISO)/International Workshop Agreement (IWA) (*IWA 11:2012*)[3]

Table 4: Performance indicators and respective metrics

Performance indicator	Metrics	Units
Efficiency/Fuel Use	High power Thermal Efficiency	%
	Low power Specific Consumption	MJ/min/L
Emissions	High power CO	g/MJ_d
	Low power CO	g/min/L
	High power PM	mg/MJ_d
	Low power PM	mg/min/L
Indoor emissions	Indoor emissions CO	g/min
	Indoor emissions PM	mg/min
Safety	Points from 10 weighted safety parameters	Points

Basing on the results, the stoves were categorised under different tiers of performance according to ISO/IWA guidelines, as follows:

Table 5: Tier levels and their explanations

Tier	Explanation
Tier 0	No improvement over open fire / baseline
Tier 1	Measurable improvement over baseline
Tier 2	Substantial improvement over baseline
Tier 3	Currently achievable technology for biomass stoves
Tier 4	Stretch goals for targeting ambitious health and environmental outcomes

(Source: PCIA/GACC, 2012)

Table 6: Tier levels Values of IWA performance metrics used to categorize stoves

Performance indicator	IWA VITA WBT Tiers	Units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
Efficiency/Fuel Use	High Power Thermal Efficiency	%	<0.15	≥0.15	≥0.25	≥0.35	≥0.45
	Low Power Specific Consumption	MJ/min/L	>0.05	≤0.05	≤0.039	≤0.028	≤0.017
Emissions	High Power CO	g/MJd	>16	≤16	≤11	≤9	≤8
	Low Power CO	g/min/L	>0.2	≤0.2	≤0.13	≤0.1	≤0.09
	High Power PM	mg/MJd	>979	≤979	≤386	≤168	≤41
	Low Power PM	mg/min/L	>8	≤8	≤4	≤2	≤1
Indoor emissions	Indoor Emissions CO	g/min	>0.97	≤0.97	≤0.62	≤0.49	≤0.42
	Indoor Emissions P	mg/min	>40	≤40	≤17	≤8	≤2

[3] Guidelines for Evaluating Cookstove Performance available at http://www.iso.org/iso/catalogue_detail?csnumber=61975

Appendix 3: Analysis of safety results

The safety stove performance indicator developed by the International Standards Organization (ISO)/International Workshop Agreement (IWA), as well as additional performance measures were used to summarize the results. The safety performance indicator is derived from points scored by a set of 10 weighted safety parameters.

Each safety parameter receives a rating of either poor, fair, good or best. The ratings correspond to a value of 1 to 4 (see table below), which is then weighted to obtain a score for each parameter. A performance tier according to ISO/IWA guidelines is then calculated from the sum of scores in the 10 safety parameters. The results of the safety test are analyzed and presented according to the defined safety levels as described below:

Table 7: Safety ratings

		Risk of injury	
Degree	**Description**	**Minor**	**Major**
1	Poor	Very high	Moderate to high
2	Fair	High	Moderate
3	Good	Moderate	Low
4	Best	Low to unlikely	Unlikely

Individual Rating	Value
Best	4
Good	3
Fair	2
Poor	1

Overall Rating	Total Point Score
Best	93 ≤ SUM ≤ 100
Good	84 ≤ SUM ≤ 92
Fair	76 ≤ SUM ≤ 83
Poor	25 ≤ SUM ≤ 75

Stove Safety Tier	Total Point Score
Tier 0	SUM < 45
Tier 1	45 ≤ SUM < 75
Tier 2	75 ≤ SUM < 88
Tier 3	88 ≤ SUM < 95
Tier 4	SUM ≥ 95

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