Improvement of the chimney stove before dissemination among Cherara Cooperative members in Kericho County, Kenya

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Final report

January 2022

Summary

Figures

Acronyms

Cs	Cold start
Eff.	Thermal efficiency
GACC	Clean Cooking Alliance
HH	Household
Hs	Hot start
ICRAF	World Agroforestry
ICS	Improved Cookstoves
NGO	Non-Governmental Organisation
SFC	Specific Fuel Consumption
TTB	Time to Boil
WBT	Water Boiling Test

1. Introduction

1.1. Context of the study

In Kenya, PUR Projet is currently supporting coffee producers, part of Cherara Cooperative members in Kericho County, mostly promoting agroforestry implementation, the adoption of arabica coffee good agricultural practices, and the promotion of income-generating activities. It also aims to disseminate Improved Cookstoves (ICSs) among the coffee farmers' households (HHs), to generate positive impacts from production to consumption of fuelwood.

SalvaTerra and its Kenyan partner, Dr. James Kinyua Gitau (bioenergy researcher currently consulting with World Agroforestry - ICRAF), had been hired in 2020 to conduct a feasibility study for the dissemination of ICSs among these coffee producers' HHs (Salvaterra, 2020)[1] (SalvaTerra, 2021)[2].

After selecting and testing three promising ICS on the field, one ICS model appeared to be very promising: the "chimney stove", made from clay and bricks, has a chimney and two cooking spots (one using flames from the burning wood and the second using heat escaping with the smoke from the first cooking spot into the chimney). Meeting users' needs for firepower, adaptability to local cooking practices and utensils and safety, the chimney stove was preferred over the other technologies tested. The chimney, which allows most of the smoke to be exhausted outside the kitchen, was also an advantage for the users. However, the stove did not demonstrate any ability to reduce wood consumption compared to the traditional stove, called "Koitama".

The conclusions of the feasibility study therefore pointed towards a two-speed dissemination: a first wave of dissemination of the Kuni Okoa model that is efficient and adapted to small families particularly, with a parallel improvement of the chimney stove to increase its energy performance. Once this objective has been achieved, the improved chimney stove model will be ready to be disseminated to the members of the cooperative on a larger scale.

In this context, the objective of this assignment is therefore to find marginal improvements in stove design in order to achieve fuelwood savings while maintaining a high level of social acceptability.

A first field mission aimed at: i) analysing the process of development and subsequent improvement of the stove (since 2009) by consulting with key technicians from Friends of Londiani and Kipkelion (FOLK) and the non-governmental organisation (NGO) Brighter communities based in Ireland, ii) consulting with the manufacturers both those who introduced the stove and those who installed it, iii) carrying water boiling tests (WBT) in order to establish a baseline model without improvement. A complementary literature review has also been carried out in order to refine the working hypotheses.

The interviews with users identified weaknesses in the chimney stove. For example, the proportions between the height of the combustion chamber and the size of the inlet are not optimal, sometimes resulting in flames that are too high with regard to the position of the pots. The stove cannot allow users to roast maize while still cooking, which, although not among the most important cooking operations, can easily be improved. On the other hand, it was possible to see that the chimney draught was not problematic: the smoke is efficiently exhausted outside the kitchen. It was also confirmed that the stove can be used for almost all cooking operations, easy to maintained and even to customize.

The meeting with the original stove manufacturers made it possible to compare the dimensions of the models installed in Kericho with other models that have been improved over the years. In particular, improvements were suggested for the pot rests.

Finally, the analysis of the bibliography made it possible to quantify the potential for improvement of each of the parameters and to prioritise the parameters that seemed most promising in terms of performance. Parameters tested are detailed in the methodology section (see 1.4. below).

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[1] SalvaTerra, 2020. Overview of ICS market in the national and local levels in Kenya. 21p.

[2] SalvaTerra, 2021. Feasibility study for the dissemination of improved cookstoves among Cherara Cooperative members in Kericho County, Kenya - Testing and recommendations. Final report. 21p.

1.2. Stove technology tested

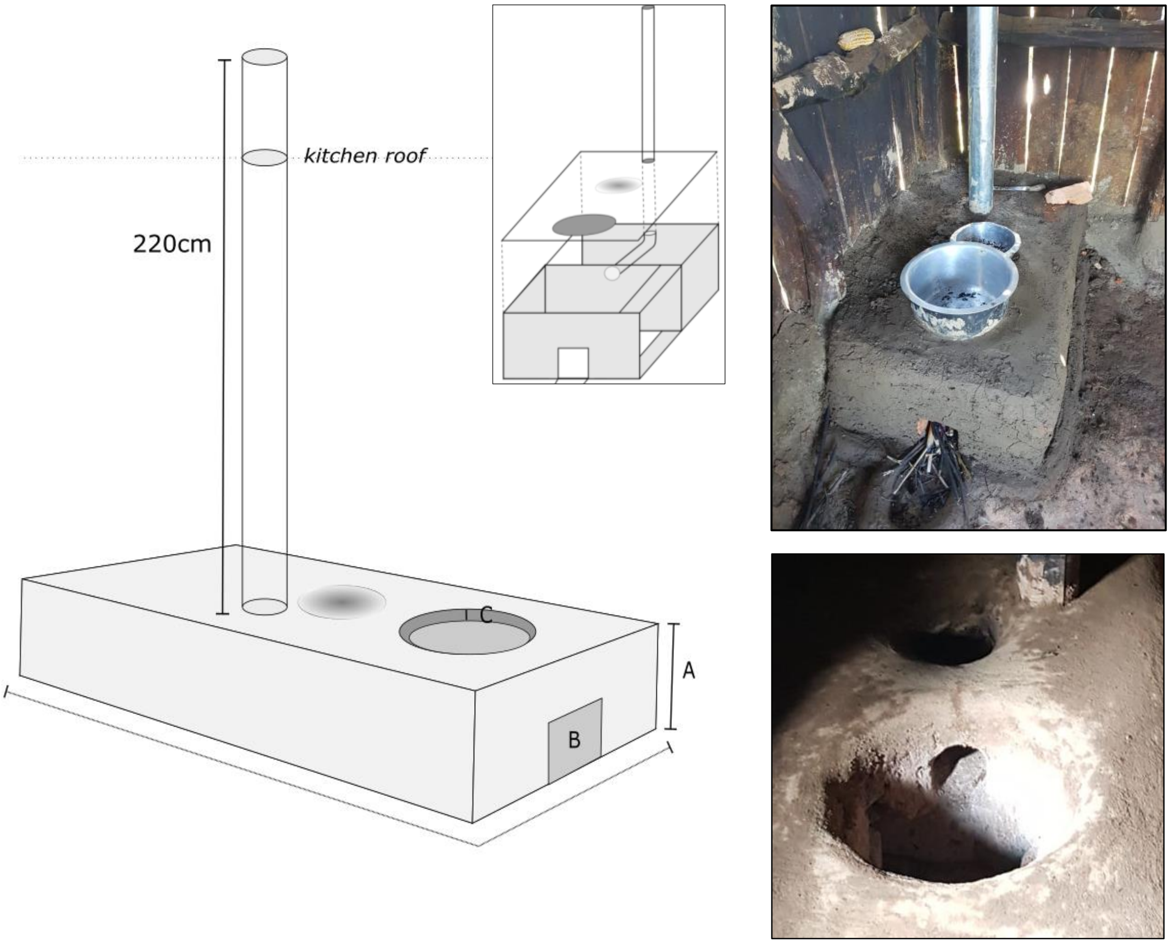


Figure 1: Chimney stove plans and details (Authors, 2021)

In order to harmonise the prototypes, the total height of the chimney was increased to 220 cm, allowing the stoves to be installed in all types of houses, avoiding the backflow of smoke during windy periods and keeping the hot tube part out of reach of the users living in the house (see figure 2 below). The diameter of the chimney and connecting pipe between the two pots remains unchanged at 10cm.

Figure 2: Left - Views of the chimney outside/inside the house / Right - Construction guide for the connecting duct between the two pots (Authors, 2021)

1.3. Methodology

Experimental design

In accordance with the experimental design methodology, high and low levels have been defined for each of the parameters, as detailed in the table below:

Letter associated with parameter	Selected parameter	Values	Level
A	Combustion chamber height	38 cm	+
		30 cm	-
B	Inlet size	225 cm^2 (15cmx15cm)	+
		144 cm^2 (12cmx12cm)	-
C	Pot rests depth	9 cm	+
		6 cm	-
D	Stone bed	Yes	+
		No	-

Figure 3: Parameters to be tested (Authors, 2021)

The test matrix for Experimental Design 2^4 is as follows:

N° of test	Parameters tested	A	B	C	D
1	Height comb. chamber 30cm/ Inlet size 144 cm^2/ pot rests depth 6 cm/ No stones	-	-	-	-
2	Height comb. chamber 38 cm/ Inlet size 144 cm^2/ pot rests depth 6 cm/ No stones	+	-	-	-
3	Height comb. chamber 30cm/ Inlet size 225 cm^2/ pot rests depth 6 cm/ No stones	-	+	-	-
4	Height comb. chamber 38 cm/ Inlet size 225 cm^2/ pot rests depth 6 cm/ No stones	+	+	-	-
5	Height comb. chamber 30 cm/ Inlet size 144 cm^2/ pot rests depth 6 cm/ No stones	-	-	+	-
6	Height comb. chamber 38 cm/ Inlet size 144 cm^2/ pot rests depth 9 cm/ No stones	+	-	+	-
7	Height comb. chamber 30 cm/ Inlet size 225 cm^2/ pot rests depth 9 cm/ No stones	-	+	+	-
8	Height comb. chamber 38 cm/ Inlet size 225 cm^2/ pot rests depth 9 cm/ No stones	+	+	+	-

9	Height comb. chamber 30cm/ Inlet size 144 cm^2/ pot rests depth 6 cm/ Stones	-	-	-	+
10	Height comb. chamber 38 cm/ Inlet size 144 cm^2/ pot rests depth 6 cm/ Stones	+	-	-	+
11	Height comb. chamber 30cm/ Inlet size 225 cm^2/ pot rests depth 6 cm/ Stones	-	+	-	+
12	Height comb. chamber 38 cm/ Inlet size 225 cm^2/ pot rests depth 6 cm/ Stones	+	+	-	+
13	Height comb. chamber 30 cm/ Inlet size 144 cm^2/ pot rests depth 9 cm/ Stones	-	-	+	+
14	Height comb. chamber 38 cm/ Inlet size 144 cm^2/ pot rests depth 9 cm/ Stones	+	-	+	+
15	Height comb. chamber 30 cm/ Inlet size 225 cm^2/ pot rests depth 9 cm/ Stones	-	+	+	+
16	Height comb. chamber 38 cm/ Inlet size 225 cm^2/ pot rests depth 9 cm/ Stones	+	+	+	+

Figure 4: Experimental design (Authors, 2021)

All parameters are tested in a precise combination, and compared with a "medium" stove to calculate the standard deviation (Height of the combustion chamber – 34cm; Inlet size -182 cm^2, pot rests depth – 7,5cm.

The 9 stoves were installed in the volunteer HHs during second field mission (see pictures in **Annex 1**). The prototypes installation plan is available in **Annex 2**.

WBT following the Clean Cooking Alliance (GACC, 2014)[3] methodology guidelines (see **Annex 3**) were carried out after a minimum of three weeks after installation in the HHs. Pots used were the same for all tests, containing 5l of water.

The WBT consists of three phases, that immediately follow each other (illustrated in figure 5 below):

1) **Cold-start (Cs) high-power phase:** the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot;
2) **Hot-start (Hs) high-power phase:** it is conducted right after the cold phase, while stove is still hot. The tester replaces the boiled water from Cs with a fresh pot of ambient-temperature water, using another pre-weighed bundle of fuel to boil the same amount of water in a standard pot;
   - ➔ "Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot". In our case, it is particularly important phase because the stove possesses a high thermal mass, and it might be keot warm between cooking sessions.
3) **Simmer phase:** this phase is meant to simulates the stove behaviour for long cooking of legumes for example. Water is kept simmering for 45minutes, just below boiling point.

[3] GACC, "The Water Boiling Test Version 4.1.2; Cookstove Emissions and Efficiency in a Controlled Laboratory Setting. Global Alliances for Clean Cookstoves, 2(January 2013), 52," 2014. Available: http://www.cleancookstoves.org/ourwork/standards-and-testing/learn.

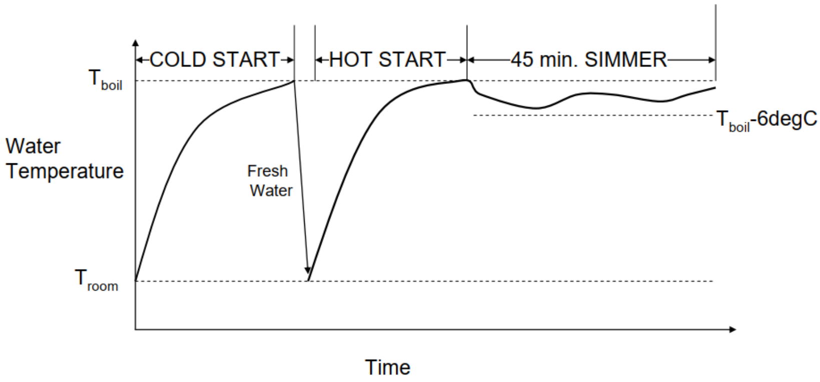


Figure 5: Temperature during the three phases of the water boiling test. (Nordica MacCarty *in* GACC, 2014)

Considering that the second cooking location is heated by smoke and not by direct flame, it was decided to perform the WBTs only on the main fire. This is the location most used by users, and gives a better idea of the stove's power, the second location being less powerful and used mainly to keep food/water hot.

The total field mission lasted 9 days, including tests and interviews with prototype users. The objective of these interviews was to make sure technical improvements were not made to the detriment of user satisfaction, and to be able to take into account the suggestions of practitioners. Mission agenda is available in **Annex 4**. WBT templates and interview guidelines are presented in **Annex 5** and **Annex 6** respectively.

Analysis

Efficiency and performance analysis of the prototypes is based on two main measures: Time to Boil (TTB) and thermal efficiency (Eff.). It can also be completed by Specific Fuel Consumption (SFC).

TTB corresponds to the time it took for the pot to reach boiling temperature from the starting temperature (GACC, 2014), i.e. in the case of this study, the time to boil 5l of water.

GACC (2014) defines **thermal efficiency** as "*a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot.*"

Thermal efficiency (hc) is calculated according to the following formula:

$$h_c = \frac{\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}}{E_{released,c}} = \frac{4.186(T1_{cf} - T1_{ci})(P1_{ci} - P1) + 2260 \cdot w_{cv}}{f_{cd} \cdot LHV}$$

With

Hc	Thermal efficiency (%)
P1	Dry mass of empty pot (grams)
$P1_{ci}$	Mass of pot of water before test (grams)
$P1_{cf}$	Mass of pot of water after test (grams)
$T1_{ci}$	Water temperature at start of test (ºC)
w_{cv}	The mass of water vaporized
$T1_{cf}$	Water temperature at end of test (ºC)
f_{cd}	Equivalent dry wood consumed (grams)
w_{cv}	Water vaporized (grams)
LHV	Net calorific value (dry wood) (17 000 kJ/kg)

SFC is a measure of the amount of fuel required to boil (or simmer) 1 liter of water. *"It is calculated by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at the end of the test"* (GACC, 2014) calculated as follows depending of the phase of the test):

$$SFC_{Cs} = \frac{fcd}{wcr} \quad \textbf{or} \quad SFC_{Hs} = \frac{fhd}{whr} \quad \textbf{or} \quad SFC_{S} = \frac{fsd}{wsr}$$

With

SFC_{Cs}, SFC_{Hs}, SFC_{S}	Specific Fuel Consumption (grams wood/liter water)
f_{cd}, f_{hd}, f_{sd},	Equivalent dry wood consumed in cold, hot and simmering phase respectively (grams)
W_{cr}, W_{hr}, W_{sr}	Effective mass of water boiled ("Boiled" water remaining at end of test) in cold, hot and simmering phase respectively (grams)

1.4. Parameters tested

From the synthesis of interviews and literature review, we proposed a set of four parameters that seem to be the most promising to improve the performance of the stove (See SalvaTerra, 2021)[4].

In addition to the selection of parameters to be tested, the field visits highlighted the importance of using a standardised method for the construction of cookstoves. Indeed, ICS is a technology that is sensitive to even minor changes in its manufacturing process and dimensions. It is important to use gauges or guides that will allow similar dimensions for the core parts of the stoves, such as the combustion chamber and the size of the side opening.

Parameter A - Height of the combustion chamber

Literature on design principles of cookstoves states that the combustion chamber height should be about three times taller than its width or diameter. Placing a short combustion chamber above the fire increases draft and helps the fire burn hot and fierce. Smoke will contact flame in the chamber and combust, reducing emissions. A taller combustion chamber will probably enable to evacuate more smoke but can lead to a too strong much draft bringing in too much cold air that will decrease heat transfer toward the pots (Approvecho Reasearch Center, 2005)[5].

Also, the height of the combustion chamber should be proportional to the flame height, to avoid creating flame quenching, incomplete combustion of fuel, deposition of soot at the bottom of the pot. The height of the flame is linked with the amount of fuel that is fed in the stove.

[4] SalvaTerra, 2021. Improvement of the chimney stove before dissemination among Cherara Cooperative members in Kericho County, Kenya. Methodological note: Parameters to be tested.

[5] Approvecho Reasearch Center, 2005. Design principles for Wood Burning Cook stoves. 40p. Available at: http://aprovecho.org/publications-3/

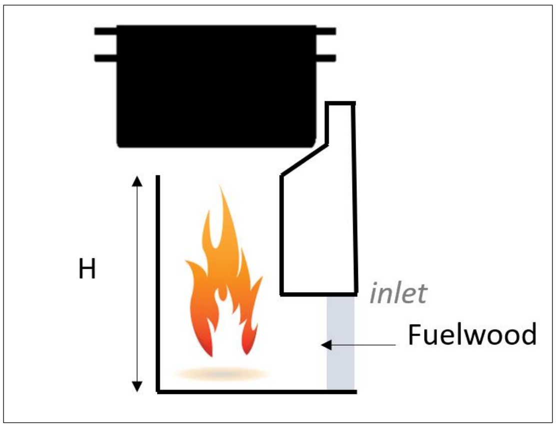


Figure 6: side section of the combustion chamber (Authors, 2021)

We propose to vary H between 30 cm and 38 cm. The average size of the combustion chamber today is 36 cm high, with an inlet surface of 369 cm^2 (19 cmx19cm).

According to Kabuleta et al., (2004)[6], the combustion chamber height is linked with the width and depth of the combustion chamber and inlet size. By reducing the inlet size and combustion chamber length & width, the combustion chamber should enable a better combustion and air flow.

From Darlami et al. (2019)[7] experimental design, varying the height of the combustion chamber could enable to improve the thermal efficiency by more than 10%. It is considered to be one of the most important parameters to ensure thermal efficiency.

Parameter B - Size of the stove inlet and Surface of the Combustion chamber

The side opening in the stove has the purpose of air and fuel inlet. Fuel burning rate, temperature of combustion chamber and air supply is controlled by side opening. There is also loss of heat through the opening. Therefore, the size of the inlet is of profound influence on the stove performance.

The chimney stove initially built has a very large combustion chamber, that is combined with a very large inlet, between 272 cm2 (17 cm x 16 cm) to 546 cm2 (21 cm x 26 cm). According to Winiarski's method (Approvecho Reasearch Center, 2005), a 12 cm by 12 cm opening (i.e. 148 cm^2) is usually sufficient for a family sized cooking stove. Darlami et al. (2019) tested different size of inlet, and also found an optimum at 148 cm^2. With smaller openings, low thermal efficiency was reported due to lack of space for incoming air as much of the space was occupied by fuelwood, which resulted in insufficient air for complete combustion. At larger opening, supply of excess air caused quenching of flame and at the same time more convection and radiation heat losses through openings.

Reducing the size of the opening will also help controlling the fuel feeding rate, which is often cited as one of the reasons for high fuel consumption.

The aim here is to find the subtle balance between a small opening that allows sufficient air to enter to maximise combustion, and ease of use by cooks. Indeed, among other issues, to small opening was considered a reason for household to get back to their traditional stoves, more suitable for local habits (e.g. carbon zero – CS - improved cookstove) (Dr. M. Njenga – 05-10-20).

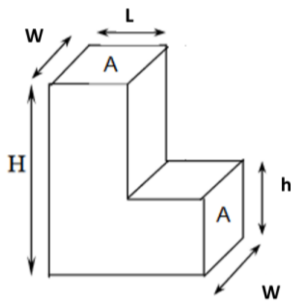


Figure 7: view of the combustion chamber, adapted from Kabuleta et al. 2004 (Authors, 2021)

Kabuleta et al. show that, for optimal combustion, the size of the inlet and the surface of the combustion chamber must be equivalent. Following this principle, we will have:

W x L = W x h = A

We therefore propose to test a square opening, varying h and W (see figure beside), between 12 cm x 12 cm (148 cm^2) and 15 cm x 15 cm (225 cm^2).

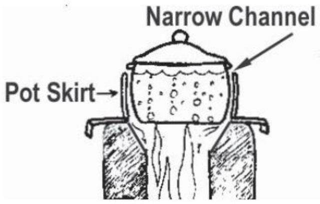
[6] Kabuleta RK, Mugerwa L, Lubwama H. 2005. How to build improved households stoves. 36p.

[7] Darlami et al. 2019.

Parameter C - pots rests depth

The initial pot rests of the stove were slightly funnel shaped, but the contact surface between the flames and the pots are not optimal. In some cases, the pot rest is too large, causing, when the pot is in place, a partial obstruction of the flue pipe, thus producing: 1) smoke convection in the chamber, 2) a layer of soot on the pots, and 3) a lower heat input to the second cooking place.

Pot rests are to be modified to increase the contact of the pot and the flame and avoid flame quenching, while allowing good air circulation.



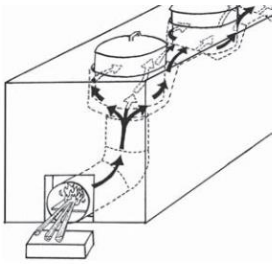


Figure 8: Heat transfer principles with pot skirt and on fixed mud ICS (Approvecho Reasearch Center, 2005)

Following Winiarski's principle, the objective is to maximise heat transfer, without weakening the stove.

"In general, there are three ways to increase convective heat transfer:

i) *The flue gases scraping the surface to be heated, should be as hot as possible,*

ii) *The surface area of the heat exchanger should be as large as possible,*

iii) *The velocity of the hot flue gases should be increased as much as possible, since a faster flow over the exterior of the pot disturbs the stagnant boundary layer of air that slows effective heating."*

(Approvecho Reasearch Center, 2005).

With mud stoves, the deeper is the funnel shape of the pot rest, the more fragile it might be.

We therefore propose to test a pot rest between 6 cm – 9cm depth, adapting the form to narrow down the channels as much as possible without compromising the stove lifespan.

Figure 9: Pot rests funnel shaped installed on the prototypes tested (Authors, 2021) →

Parameter D - Raise the fireplace above the ground

Figure 10: River rock bed installed in the prototypes, 2cm apart (Authors, 2021)

Use of grate or a shelf increases the thermal efficiency of the cookstove (Approvecho Reasearch Center, 2005)

(Kshirsagar et al 2014)[8]. It lifts the stick so the air can pass underneath them. Thermal efficiency of cookstove can be improved by 3% to 5% by enabling air to enter underneath the fire (Gusain et al, 1990 cited in Darlami 2019). In our case, a metal grate might be difficult to find locally and would increase the stove cost.

Sun24 have been carrying out some tests using small rocks to raise the fireplace above the ground. The training video recommends to use small rock below firewood and river rocks are easily available in the project area, stones are to be placed under the wood, 2 cm apart.

2. Results

2.1. Standard deviation calculation

To define whether the effect associated with a parameter is significant, the precision of the measurements must be known. To do this, we will use statistical methods by repeating the test 4 times at the centre of the experimental domain, and therefore calculate the reference standard deviation.

In our case, it is the prototype with the following characteristics:

- Combustion chamber's height of 34cm;
- Inlet size (13.5cmx13.5cm) of 182 cm^2;
- Pot rests depth of 7.5cm;
- Rock bed.

The results of the WBT carried out on this medium stove are presented in the table below:

N° trial	TTB in minutes (Cs)	Eff. in % (Cs)	TTB in minutes (Hs)	Eff. in % (Hs)
1	40	12	26	13
2	32	14	29	10
3	49	10	32	12
4	53	9	28	15
Mean	**43**	**11**	**28**	**13**

Figure 11: WBT results – standard deviation (Authors, 2022)

[8] Kshirsagar MP., Kalamkar VR. 2014. A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. Renewable and Sustainable Energy Reviews, 30, 580–603., Available: https://doi.org/10.1016/j.rser.2013.10.039.

The estimated standard deviation over the experimental domain for the response TTB and efficiency will be obtained by the formula:

Standard deviation = = $\sqrt{\frac{\sum(x-mean)^2}{3}}$

For TTB (Cs), the standard deviation is $\sqrt{\frac{(40-43)^2+(32-43)^2+(49-43)^2+(53-43)^2}{3}} = 9{,}42$ min and for Efficiency (Cs) $\sqrt{\frac{(12-11)^2+(14-11)^2+(10-11)^2+(9-11)^2}{3}} = 2{,}23\%$

For TTB (Hs), the standard deviation is $\sqrt{\frac{(26-28)^2+(29-28)^2+(32-28)^2+(28-28)^2}{3}} = 2{,}65$ min and for Efficiency (Hs) $\sqrt{\frac{(13-13)^2+(10-13)^2+(12-13)^2+(15-13)^2}{3}} = 2{,}16\%$

2.2. Significant parameters

The table presenting exhaustive results of the WBT is presented in **Annex 7** and the complete matrix of results is available on **Annex 8**.

Below are two matrices synthetising the main results, first highlighting most influent parameters over the TTB and Eff. calculations and second, presenting test results:

Parameters	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	BCD	ABD	ACD	ABCD
Effect on TTB (Cs)	-0,25	-6,50	4,25	1,00	3,63	1,88	0,38	0,38	-0,38	0,63	-7,50	-1,50	-1,00	-0,50	-1,625
Effect on eff. (Cs)	1%	-4%	3%	1%	2%	1%	0%	-1%	-1%	1%	-7%	-1%	0%	0%	-2%
Effect on TTB (Hs)	2,75	-13,94	11,63	3,69	0,28	3,97	-3,16	0,59	-0,72	-1,22	-18,81	-0,69	-0,31	2,31	-6,156
Effect on eff. (Hs)	1,04%	-0,58%	-2,21%	0,92%	-1,67%	0,46%	0,33%	0,58%	0,46%	-0,17%	-1,58%	0,29%	0,29%	-0,08%	0,46%

Figure 12: WBT results – significant parameters (Authors, 2022)

The results show a significance level for TTB and Eff. of 9.42 minutes and 2.23 % respectively for cold start and 2.65 min and 2.16 % respectively for hot start. The parameters that are significant are highlighted in yellow in the table below. The effects of parameters below these thresholds are not significant (in grey), meaning we cannot say with certitude that these parameters have influenced the performance of the stoves tested.

This is reflected, for example, in the TTB (Cs) effect line, where none of the results exceed the significance threshold, making it impossible to identify an influential parameter on the TTB in Cs phase. The important standard deviation between the tests is partly responsible for this result, however, if we consider the most important results of this line (in absolute values), it is mainly the B and C parameters that stand out on Eff. in Cs phase, and those parameters also stand out with significance in Hs phase. There is therefore no loss of information at this stage.

On the other hand, in the Hs phase, all parameters are important: a high and narrow combustion chamber, deep pot rests and a stone bed favoured a shorter boiling time.

For thermal efficiency, parameters B (Size of the combustion chamber) and C (depth of the pot rests) are particularly significant. In this case, interactions between parameters are not particularly significant.

A smaller combustion chamber size and deeper pot rests allow for better thermal efficiency. This is in line with the conclusions of the various studies found in the literature.

N° of test	TTB Cs (min)	Eff. (Cs)	TTB Hs (min)	Eff. (Hs)
1	51	15%	39	13%
2	32	15%	19	18%
3	22	0,16	18	15%
4	29	10%	27	11%
5	46	9%	46	8%
6	44	9%	28	14%
7	32	11%	27	10%
8	41	9%	36	9%
9	49	11%	28	14%
10	31	0,13	28	21%
11	22	0,14	18	17%
12	35	12%	20	14%
13	48	12%	44	9%
14	56	9%	36	13%
15	37	11%	25	11%
16	35	13%	28	14%

Figure 13: WBT results (Authors, 2022)

If we consider only the **thermal efficiency results**, the prototype with a **combustion chamber height of 38cm, inlet size of 12cm×12cm, pot rests depth of 6cm and a rock bed** (test 10) is the most interesting, with efficiency results of up to 21% once the stove is hot (in blue). Over the whole experiment, efficiency is 17%. On the other hand, TTB on this prototype is quite long which can be an issue for users (see also section 2.3 below). In the following section, this prototype will be called "blue" prototype.

As a comparison, the thermal efficiency of the initial model of chimney stove is 9% on average (8% for Cs, 9% for Hs), TTB of 27 minutes on average (31 minutes for Cs, 22 minutes for Hs).

TTB, all four parameters are significant, and the interactions between the height of the combustion chamber and the depth of the pot rests as well as the height of the combustion chamber and the stone bed are particularly significant, especially when the stove is hot.

Along with the stove efficiency, TTB is also very important for users considering the time spent cooking by women per day.

In that regard, test number 3 and 11 (in green), corresponding to the prototype with a **combustion chamber height of 30cm, inlet size of 15cm×15cm, and pot rests depth of 6cm** seems to be the most interesting. Results are the same with and without using a rock bed.

It shows a better thermal efficiency than the initial model, although it is not as efficient as the blue prototype. Mean thermal efficiency is 16%, which is still better than the initial model.

2.3. User's satisfaction

The full results of the satisfaction surveys are available in <u>**Annex 7**</u>.

Five users found it difficult to use maize crop residues as fuel with their respective prototypes. Some pointed to the size of the inlet, which does not allow enough residue/small branches to accumulate to produce a large enough fire to cook food.

Although user perception is a very important factor to take into account when choosing an ICS model, it is common for users who are not used to being restricted in the wood loading area to complain when the inlet size is reduced. It should be noted, however, that in addition to influencing combustion, the reduction in wood consumption is strongly related in most studies to the ability to load less wood at a time. Users are more sparing when cooking, and this behaviour also saves fuel.

For some others, the cooking time seemed too long, which is consistent with the test results (see Section 2.2).

However, this is not the case with the green prototype, which, according to the user, has none of the shortcomings reported by other users.

Below is a more detailed analysis on the users' appreciation of the two most interesting prototypes.

➔ The **blue prototype** is considered to be powerful and is the only stove used in the household for all cooking operations. All smoke is exhausted outside, which is appreciated by users.

No maintenance problems have been reported, and ignition is very easy.

However, the stove is slower than the traditional stove, which is a problem for users. In addition, the power of the second fire does not allow for cooking food.

➔ The **green prototype** is considered powerful on both fires and is the only stove used in the fireplace for all cooking operations. The first fire is used for cooking Ugali, beans, maize, meat, tea, vegetables, while the second is used for cooking vegetables and frying of the already boiled cereals.

The user considers it as fast as the traditional stove, and allows the use of the usual fuelwood.

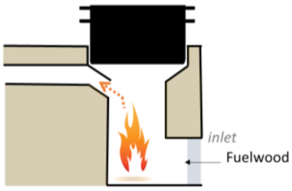
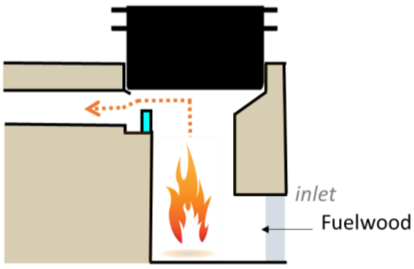
As for the blue prototype, all smoke is exhausted outside and maintenance and ignition remain easy.

2.4. Other improvements and good practices

The surveys revealed several points that could be improved but which are more related to the ease of use, or the optimisation of the chimney stove lifetime. Among these parameters, some were directly implemented on the prototypes, other will be included with the validation of the final model.

These improvements are:

Improvement	**Description**	**Implementation**
Users want to be able to grill corn when it is in season, so it is possible to add a space for grilling in front of the stove inlet, while keeping a distance from the inlet so as not to disturb the air circulation. ➔ *A space has been carved out at the front of the stove so that the ember bed can be spread out and a grate added if required, without obstructing the airflow.*	 *Before (right) / After (Left)* *(Also see Annex 1e)*	**Implemented**
The joining technique between the roof and the chimney can be improved in order to extend the life of the stove. ➔ *A mud mortar was been applied on the roof in the older model but was replaces with a mould of sand and cement during the installation of the prototypes.*		**Implemented**

Use of a better-quality mortar for the combustion chamber. After discussions, the different manufacturers exchanged on the quality of the clay and proposed a change of supplier for a more durable mortar. ➔ *A different type of clay have been used for the prototypes installation. It will have to be regularly checked and noted in the construction specifications.*		**Implemented**
Sometimes the draught is too great and the flame is drawn through the pipe to the second cooking location, causing some heat loss. ➔ *A 2 cm high baffle should allow the flame to be directed to the #1 pot first before the heat is directed to the second pot location. To do this, it is necessary to move the bricks a few centimetres when setting up the combustion chamber, so that the baffle (in the same material as the bricks) can be installed (see scheme on the right). Results expected can improve thermal efficiency and TTB.*	Actual air flow without baffle:   Baffle installation (in blue):  	**To be implemented**

2.1. Cost analysis - initial model vs. improved model

Materials	Unit	Quantity previous	Approx. price/unit (KES)	Final Costs (KES)
Bricks	brick	70	15	1050
Clay	bag	1	200	200
Chimney	tube	1	1,000	1,000
Labour	installation	1	2,000	2,000
Transport	Bricks+clay		750 (used motorbikes to transport from the factory to each household	750
Total				**5000**

Figure 14: Costs associated to the initial model installation (Salvaterra, 2021) [9]

Compared to the feasibility study, new opportunities for sourcing materials and new manufacturers to be mobilised for construction of the stoves have been identified.

Sourcing of material

Bricks - If bricks are sourced from the people producing them, the price can go as low as 10 KES per piece. Henry and Mercy can be able to reach out to the people making the bricks and get the actual prices. For the prototype chosen, slightly less bricks can be used (60 rather than 70 pieces).

Clay- The new installers were able to get the clay for free from an old quarry during the recent installation. There should be enough materials for building of hundreds of stoves. The remain costs would be for loading, transport and off-loading. The materials were dropped at central point and the HH members were requested to assist with carrying the materials to their houses.

Chimney- Estimates from one local person who does fabrication was 600 KES per piece. Thomas, from Friends of Londiani, whom the expert had a meeting with together with the installers, offered to connect Pur Projet's team with their chimney suppliers. He mentioned one chimney to cost about 500 KES.

Labour- Labour costs remain the same, although manufacturers were asked to re-evaluate their charges according to the time spent building the stoves. They stated 2000 KES as the lowest price which they can charge per stove installed.

Materials	Unit	Quantity previous	Approx. price/unit (KES)	Final Costs (KES)
Bricks	Brick	60	12	720
Chimney	Tube	1	600	600
Labour	Installation	1	2,000	2,000
Transport	Bricks + Clay		522*	522
Total				**3842**

Figure 15: Costs associated to the improved model installation (Authors, 2022)

** For the construction of the 9 stoves for this study, 4700 KES were paid for transport of materials. This amounts to 522 KES per stove. However, the tractor has capacity to carry materials for at least 30 stoves or more. This would therefore amount to 160 KES per stove.*

→ The construction of a stove would therefore cost 3842 KES (i.e. approximately 30 EUR), a saving of 20% on the final cost.

[9] SalvaTerra, 2021. Feasibility study for the dissemination of improved cookstoves among Cherara Cooperative members in Kericho County, Kenya. Testing and recommendations. 21p.

3. Conclusion and recommandations

Prototyping processes often require a large number of iterations to improve stoves models. Each modification has a series of consequences on the functioning of the stove and the way it is used. It usually takes several years to achieve the best compromise between technical efficiency, smoke emission and practicality.

In the case of this study, the objective of the approach was to improve the thermal efficiency of the stove without deteriorating the user experience. The research process resulted in the identification of two prototypes that allow an improvement in the thermal efficiency of the chimney stove. However, **only one of the prototypes allows both an efficiency gain, while keeping the cooking time low and allowing full use of the stove.**

The stove that is currently most suitable for local use has the following characteristics:

- **Combustion chamber height of 30cm,**
- **Inlet size of 15cm×15cm,**
- **Pot rests depth of 6cm.**

Compared to the initial model, the prototype shows improved performance:

Stove model	TTB in min (average)	Thermal Efficiency in % (average)
Initial model	27	9
Prototype	20	16

Thermal efficiency of modified cookstove increased from 9% to 16%, i.e. an increment of 7%.

The construction costs of the improved model were also refined during the study. Thanks to better sourcing of raw materials and economies of scale for transport in particular, the construction of a stove would therefore cost 3842 KES per unit, i.e. a **gain of 20% on the final cost**.

It is possible to continue investigations on the most efficient model with the field officers trained during the different missions, in partnership with the manufacturers.

In particular, it is very likely that adding a baffle (see section 2.4 above) to the model with a combustion chamber height of 38cm, inlet size of 12cm×12cm, pot rests depth of 6cm will allow the excess draught to be adjusted and at the same time allow the power between the two cooking spots to be rebalanced, as well as reducing the TTB.

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Annexe 1. Installation of the prototypes

a. Sizing of the combustion chamber
b. View of the inlet before mortar is laid
c. Top view of the combustion chamber before the mortar is laid

d. Laying of the internal bricks and mortar

e. Stove during drying

Annexe 2. Prototype installation plan

Name of the household head **Parameters tested**	Erick Mutai	Nelson Kemei	Jackson Kurgat	B. Kurgat	J. Kemei	H. Kipkemoi	R. Chepkwony	P. Rob	N. Kirui
Nb of prototype	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**
Height	30cm	38cm	30cm	38cm	30cm	38cm	30cm	38cm	34cm
Inlet/com. Chamber	12×12 cm	12×12cm	15×15cm	15×15cm	12×12cm	12×12cm	15×15cm	15×15cm	13.5×13.5cm
Pot rest	6cm	6cm	6cm	6cm	9cm	9cm	9cm	9cm	7.5cm

Annexe 3. WBT methodology – (from GACC, 2014)

INTRODUCTION AND BACKGROUND

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 and the quantity of emissions produced while cooking.

Benefits and limitation of the WBT

Primary benefits:

- Provide initial or laboratory assessments of stove performance in a controlled setting
- Compare the effectiveness of different designs at performing similar tasks
- Evaluate stove changes during development
- Select the most promising products for field trials
- Ensure that manufactured stoves meet intended performance based on designs

Limitation: It is an approximation of the cooking process and is conducted in controlled conditions by trained technicians.

WATER BOILING TEST (WBT) OVERVIEW

The WBT consists of three phases that immediately follow each other. The entire WBT should be conducted at least three times for each stove, which constitutes a WBT test set. The test workbook for WBT 4.2.3 can accommodate results for up to 10 tests.

1) For the cold-start high-power phase, the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of ambient-temperature water to perform the second phase.

2) The hot-start high-power phase is conducted after the first phase while stove is still hot. Again, the tester uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot. This is particularly important for stoves with high thermal mass, since these stoves may be kept warm in practice.

3) The simmer phase provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world

A full stove test should always include all three test phases. A quick test for a laboratory's internal use may include only the cold-start and simmer phases if the stove has low mass (no ceramic) and previous WBTs have shown that the cold-start and hot-start phases produce the same results

REQUIRED EQUIPMENT

- Scale with a capacity of at least 6 kg and accuracy of ±1 gram
- Heat resistant material to protect scale
- Digital Thermometer, accurate to 0.5 degree C, with thermocouple probe suitable for immersion in liquids
- Wood moisture meter OR oven for drying wood and scale for weighing (moisture meter is less accurate, especially for very wet wood)
- Timer
- Tape measure for measuring wood and stove (cm)
- Standard pots: pots that are used in your region and have a volume of about 7 liters (for 5-L tests) or 3.5 liters (for 2.5-L tests). For each size, you should choose a standard shape (height and circumference) that is used in your area.
- Wood or metal fixture for holding thermocouple in water (see Appendix 1.1)
- Small shovel/spatula to remove charcoal from stove
- Tongs for handling charcoal
- Dust pan for transferring charcoal
- Metal tray to hold charcoal for weighing

- Heat resistant gloves

TESTING A NEW STOVE

Perform at least one practice test on each type of stove. The tester should perform enough tests to become familiar with the testing procedure and with the characteristics and operation of the stove. This will provide an indication of how much fuel is required to boil the required amount of water.

New stoves should also be seasoned (used a few times) prior to testing as stove performance can vary based on how often the stove has been used. New stoves often have ceramic components which contain unknown amounts of moisture. It is helpful to run the stove first to drive off any moisture before conducting any tests. If a scale is available to weigh the stove, the stove should be run until the weight of the stove stabilized. This should be done with a small fire because large ceramic components can easily be damaged if fired quickly.

SELECTING FUEL AND POT(S) FOR TESTING

1) Determine the type and characteristics of fuel you will use. The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. For that reason, all tests of a single stove, or all tests to compare designs or stoves, must be done with fuel of the same type and moisture content, and similar size. Obtain all of the fuel from the same source if possible. There isn't a prescribed standard dimension or level of moisture for all tests. Testers may use fuel (type, size, moisture content) that is readily available in their area. Solid fuel should be well dried and uniform in size.

Document the fuel type, moisture content, and size. Fuel between 1.5 cm x 1.5 cm to 3 cm x 3 cm is suggested. If comparability between labs is a goal for your tests, use wood with cross-sectional dimensions of 1.5 cm x 1.5 cm.

2) Determine the type of pot you will use, and record its size and shape. The 7-liter pot should be used except for the following situations:

a) The stove is designed for a much smaller pot and cannot boil 5 liters of water (use the 3.5-liter pot), or b) It is extremely uncommon to boil as much as 5 liters of water in your region (use the 3.5-liter pot); or c) The stove is designed for a specific pot (use the pot for which it was designed).

If you use the 7-liter pot, use 5 liters of water for each phase of the WBT. If you use the 3.5-liter pot, use 2.5 liters of water for each phase

DAILY PREPARATION

Preparation for each day’s testing may be done the previous day.

1) **Find your space**. Make sure that there is adequate space and sufficient time to conduct the test without being disturbed. Testing should be done indoors in a room that is protected from wind, but with sufficient ventilation to vent harmful stove emissions. Wind or air draft changes heat transfer between the stove and the pot and will affect the results of the test, and should be avoided.

2) **Prepare fuel.** Prepare and weigh one bundle of fuel for each WBT that will be conducted. Each bundle should be at least 5 kg. More fuel may be needed for some stoves, including high mass stoves. If kindling will be used to start the fire, it should be prepared ahead of time and included in the preweighed bundles of fuel.

3) **Determine moisture content of the fuel to be used.**

4) **Prepare water**. At least **10 liters of water** (or 5 liters for small pots) for each pot being used are required for the three phases of the WBT. If water is scarce in your area, water used one day may be cooled and reused in the next day’s testing. Water should be at ambient temperature prior to the test. Do not start any tests with water that is hotter than room temperature.

PREPARATION FOR EACH SET OF 3 WATER BOILING TESTS

1) Create a new Excel workbook for each set of three tests by making a copy of “WBT_datacalculation_sheet_4.2.3.xls”. Excel files should always have a unique name or code number. You, the tester, should fill out all gray cells and cells with listboxes (choices). Other cells are calculations.
2) Fill out the [General Information] sheet. A copy of this sheet is given in Appendix 7 if you wish to fill it out by hand. This sheet asks you to record:

a) **Test and Stove Description**

- Name of Tester(s)
- Test Number or Code
- Test Dates
- Test Year
- Test Location
- Replicate Test Number (if you are performing more than 3 sets of tests)
- Altitude
- Stove Type/Model
- Manufacturer
- Description and Notes about the stove*
- Description of Pot(s)

b) Ambient Conditions

- Air relative humidity (%)
- Local boiling point of water (determined using Appendix 1.2) (°C)

c) Notes or description about stove or operation not included elsewhere on this form, especially fuel addition, during the high-power and simmering tests (you should know this from your practice tests) weigh the dry pots without lid and the char container

d) Fuel description

- General description of fuel
- Fuel type (select from list)
- Fuel description (select from list)
- Average length (cm)
- Cross-sectional dimensions (cm x cm)
- Gross, Net and Char calorific values and char content (by your own measurement or filled in automatically based on selected fuel type)
- Description of fire starter, small wood, or kindling

e) Description of operation the high-power test

- How is fire started?
- When do you add new fuel to the fire?
- How much fuel do you add at one time?
- How often do you feed the fire without adding fuel (e.g. push sticks)?
- Do you control the air above or below the fire? If so, what do you do?

g) Description of operation during the simmering test

- How is fire started?
- When do you add new fuel to the fire?
- How much fuel do you add at one time?
- How often do you feed the fire without adding fuel (e.g. push sticks)?
- Do you control the air above or below the fire? If so, what do you do?

** Guidance for stove description: Photograph the stove, if possible. Use a tape measure to record the dimensions of the stove. A cross sectional drawing of the stove with dimensions may be useful. Identify the materials used for stove construction. Use an additional sheet if necessary*.

3) Fill out the [Fuel Moisture] sheet if you are using a handheld moisture meter. A copy of this sheet is given in Appendix 7 if you wish to fill it out by hand, but you will need to enter the values in the worksheet to obtain the calculated moisture content.

4) Determine whether your fuel is fed continuously or in a batch. Many wood and crop waste stoves are continuous feed, while most charcoal and liquid-fuel stoves are loaded with fuel before the test. The two types of fuel-feeding have some separate instructions.

5) Do not proceed if wind will affect your testing location.

PREPARATION FOR EACH WATER BOILING TEST

1) If you wish to record data by hand at first, print a [Test Entry] Sheet or from Appendix 7. If you wish to record the data directly in the workbook, you will be entering data into the [Test-1], [Test-2] or [Test-3] (up to 10 tests possible) sheets, for each replicate of the WBT.

Prepare one pot (or more if testing multi-pot stoves) for the cold start test. Record the dry weight of each pot (g). Fill each pot with 5 kg (5 liters) of clean room temperature water. If using the smaller standard pot, fill each pot with 2.5 kg or 2.5 liters of water. The amount of water should be determined by placing the pot on the scale and adding water until the total weight of pot and water together is 5 kg (or 2.5 kg) more than the weight of the pot alone.

If the stove cannot accommodate the standard pot and the pot that is used cannot accommodate 5 (or 2.5) kg of water, OR if a multi-pot stove is used with non-standard pots that cannot accommodate 5 (or 2.5) kg of water, fill each pot about 2/3 full and record the change in procedure in the comment space. Use the same amount of water for each phase and each test.

Record the weight of pot(s) with water (g), Cold Start High Power, Start.

2) If you have enough pots, prepare additional pots and water for the hot start test. If not enough pots are available, measure out the needed volumes of water in another container.

3) Measure and record the ambient conditions: air temperature (°C), wind conditions (select from list).

INSTRUCTIONS FOR WBT PHASES

Remaining data for the three phases of the test should be recorded on the Test Entry form. The stove should begin at room temperature.

Instruction		Data, Cold Start High Power section	Units
1	Prepare the timer (do not start it yet).		
2	Continuous: Weigh the bundle of fuel plus kindling.	**Weight of fuel, Start**	g
3	Place the pot on the stove. Using the wooden fixtures, place a thermometer in each pot so that water temperature may be measured in the center, 5 cm from the bottom. If there are additional pots, use the additional thermometers if possible. Measure the initial water temperature in each pot. Confirm that it does not vary substantially from the ambient temperature. ***There should NOT be a lid on the pot while conducting the WBT***	**Water temperature, Start**	°C
4	Start the fire in a reproducible manner according to local practices. (This procedure should be documented.)		
5	Once the fire has caught, start the timer and record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the pre-weighed bundle. Control the fire with the means commonly used locally. (This procedure should be documented.)	**Time, Start**	hr:min
6	When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 6.a – 6.f		

	a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also.	**Time, Finish Water temperature, Finish**	hr:min °C
	b. Continuous: Remove all wood from the stove and extinguish the flames. Flames can be extinguished by blowing on the ends of the sticks or placing them in a bucket of ash or sand; do not use water – it will affect the weight of the wood. Knock all loose charcoal from the ends of the wood into the container for weighing charcoal.		
	Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle.	Weight of fuel, Finish	g
	Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks	Weight of charcoal+container, Finish	g
	c. Weigh each pot, with its water.	Weights of Pot with water, Finish	g
	d. Discard the hot water.		

Continuous Measurement of Temperature: The water temperature may be continuously recorded if a device is available to do so.

Lids: While a lid helps to retain heat and is often used in actual cooking tasks, it does not affect the transfer of heat from the stove to the pot. Lids may increase the variability of the WBT results, making it harder to compare results from different tests.

This completes the high power cold-start phase. Next, begin the high power-hot start phase, immediately while the stove is still hot. **Be careful not to burn yourself!**

WBT PHASE 2: HIGH POWER (HOT START)

Instruction		Data, Hot Start High Power section	Units
1	Reset the timer (do not start it yet).		
2	If the pot for the hot start phase has not been prepared in advance, refill the pot with 5 (or 2.5) kg of fresh ambienttemperature water. Weigh the pot (with water) and measure the initial water temperature. For multi-pot stoves, fill the additional pots, weigh them and record their weights.	**Weight of pot(s) with water, Start**	g
3	Continuous: Record the weight of the second bundle of fuel plus kindling.	**Weight of fuel, Start**	g
4	Place the pot on the stove and replace the thermometer in the pot. Measure the initial water temperature in each	**Water temperature, Start**	

	pot. Confirm that it does not vary substantially from the ambient temperature.		
5	Start the fire using fuel from the second pre-weighed bundle designated for this phase of the test. Follow the ignition procedure used in Phase 1.	**Time, Start**	hr:min
6	Once the fire has caught, start the timer. Record the starting time. Bring the first pot rapidly to a boil without being excessively wasteful of fuel using wood from the second pre-weighed bundle. Control the fire using the procedure used in Phase 1.		
7	When the water in the first pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps 7.a – 7.c a. Record the time at which the water in the primary pot (Pot # 1) first reaches the local boiling temperature. Record this temperature also. b. **Continuous:** Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the combustion area (you will not weigh the charcoal at this stage). Weigh the unburned wood removed from the stove together with the remaining wood from the second preweighed bundle. c. Weigh each pot, with its water.	 Time, Finish Water temperature, Finish Weight of fuel, Finish Weights of Pot with water, Finish	 hr:min °C g g
8	Return the unburned wood to the stove. Proceed immediately with the low power test		

Speed and Safety: Speed and safety are important during Step 8 because the water temperature should stay as close as possible to boiling in order to proceed directly to the simmer phase. The pot of hot water may be temporarily covered with a lid and placed on a hot plate (if available).

WBT PHASE 3: LOW POWER (SIMMERING)

This portion of the test is designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel. For multi-pot stoves, only the primary pot will be assessed for simmering performance.

Instruction		**Data, Simmer Test section**	**Units**
1	Reset the timer (do not start it yet).		
2	Record the weight of the pot with water.	**Weight of pot with water, Start**	g
3	Continuous: Record the weight of fuel remaining from the hot start high power phase plus the third bundle of fuel plus kindling.	**Weight of fuel, Start**	g

4	Relight the hot wood that was replaced. Follow the ignition procedure used in Phase 1		
5	Once the fire has caught, reset and start the timer. Record the starting time.	**Time, Start**	hr:min
6	Place the pot on the stove and replace the thermometer in the pot.		
7	For 45 minutes maintain the fire at a level that keeps the water temperature as close as possible to 3 degrees below the boiling point. The test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.		
8	After 45 minutes rapidly do steps 8.a – 8.c:		
	a. Record the time. Record the final water temperature – it should still be about 3 °C below the established boiling point.	**Time, Finish Water temperature, Finish**	g °C
	b. **Continuous:** Remove all wood from the stove and extinguish the flames. Knock all loose charcoal from the ends of the wood into the charcoal container.		
	Weigh the unburned wood removed from the stove together with the remaining wood from the second preweighed bundle	**Weight of fuel, Finish**	g
	Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks.	**Weight of charcoal+containe r, Finish**	g
	c. Weigh the pot with the remaining water.	**Weight of pot with water, Finish**	g

Maintaining Temperature: *Many stoves lack adequate turndown ability, which makes it difficult to maintain the desired temperature withou the fire going out (especially after the initial fuel load has been consumed). In this case, use the minimum amount of wood necessary to keep the fire from dying completely. Water temperatures in this case will be higher than 3° below boiling, but the test is still valid. The tester should not attempt to reduce power by splitting the wood into smaller pieces.*

Changes to Testing Conditions to Improve Repeatability

The WBT is designed to test many stoves in many places, but comparisons become less reliable as testing conditions vary. You should identify the reasons for testing when deciding on the form of the test. If you are using the WBT as a preliminary measure of stove performance during the design phase, then adapt the protocol to local conditions. Some laboratories may be using tests to compare the performance of their stoves with other available stove models. In these situations, some changes may be made to the test to improve repeatability. However, we caution that these changes may make the stove perform differently than it would in practice. If laboratory tests are very different from real operation, then comparisons done in the laboratory may lead to incorrect conclusions about stoves in real operation. Any specific changes to the WBT should be noted in the documentation for each test.

1. Fuel

a. Type: Wood with high heat content (between 20-21 MJ/kg), and without excessive pitch content, should be used for all tests. Choose one wood which is used widely in the region.

b. Dimensions: Different sizes of solid fuels have different burning characteristics. Some laboratories have used wood with cross-sectional dimensions of 1.5 cm x 1.5 cm.

c. Moisture content: All testing should be carried out with wood of low moisture content (values used have been 6.5% or 10% on a wet basis). This reduces variability but may make combustion unlike field conditions.

2. Initial Water Temperature: A fixed initial temperature can be chosen for the water rather than relying on ambient temperature (15 °C has been used).

3. Cooking Pot: The tests should be conducted with either a large standard pot (with a 7 liter capacity) or a small standard pot (with a 3 liter capacity), depending on the size of the stove.

INTERPRETING RESULTS OF THE WATER BOILING TEST

COMMONLY USED MEASURES

The measures that most stove programs use are summarized here.

Stove characteristics: burning rate, firepower, turn-down ratio

Efficiency and performance measures: time to boil, specific fuel consumption, thermal efficiency
Emission measures: emissions per fuel burned, emissions per MJ, emissions per task

CAUTIONS

Results for high-power and low-power tests may vary greatly. Stoves often perform well on the high-power test and poorly on the low-power test or vice versa. Testers should examine the results of both types of tests rather than relying on the totals.

Although some of the metrics are normalized to the amount of water boiled, comparisons for stoves of different sizes should be done with caution.

Reports from the individual phases (cold-start high-power, hot-start high-power, and simmer) may be less accurate than the overall total. This is especially true because the tester doesn't weigh the charcoal after the hot-start test, so estimates of the fuel used during the hot-start and simmer tests are not exact.

STOVE CHARACTERISTICS

Burning Rate – A measure of the average grams of wood burned per minute during the test. When compared between tests, this compares how consistently the user was operating the stove. When compared between stoves, this measure indicates how rapidly the stove consumes fuel.

Firepower – Firepower is a measure of how quickly fuel was burning, reported in Watts (Joules per second). It is affected by both the stove (size of fuel entrance/combustion chamber) and user operation (rate of fuel feeding). Generally it is a useful measure of the stove's heat output, and an indicator of how consistently the operator ran the stove over multiple tests. A higher or lower value is not necessarily preferable, but rather is an indicator of the size of the stove.

Turn-Down Ratio – Turn-Down ratio indicates how much the user adjusted the heat between high power and low power phases. A higher value indicates a higher ratio of high power to low power, and could signal a greater range of power control in the stove. However, this value reflects only the amount of power control that was actually used

EFFICIENCY METRICS

Time to Boil – The time it took for pot #1 to reach boiling temperature from the starting temperature.

Temperature Corrected Time to Boil – The time it took for pot #1 to reach boiling temperature, corrected to reflect a temperature rise of 75 deg C from start to boil. This measure can be compared across tests and stoves to determine the "speed" of the stove at high power, often an important factor to cooks.

Thermal Efficiency (IWA Metric for High Power) – Thermal efficiency is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot. While thermal efficiency is a well-known measure of stove performance, a better indicator may be specific consumption, especially during the low power phase of the WBT. This is because a stove that is very slow to boil may have a very good looking TE because a great deal of water was evaporated. However the fuel used per water remaining may be too high since so much water was evaporated and so much time was taken while bringing the pot to a boil.

Specific Fuel Consumption – This is a measure of the amount of fuel required to boil (or simmer) 1 liter of water. It is calculated by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at the end of the test. In this way, the fuel used to produce a useful liter of "food" and essentially the time taken to do so is accounted for. Specific Fuel Consumption is listed as the IWA metric for Low Power, which is reported in MJ/(min·L).

Temp-Corrected Specific Fuel Consumption – This is the previous measure, also corrected as if the temperature rise from start to boil was 75 degrees C, in order to easily compare different tests that may have had different starting or boiling temperatures. It is best to always look at the temperature corrected value rather than the uncorrected value. A higher T-C SC indicates more fuel required to complete the same task of producing a liter of boiled (or simmered) water.

Temp-Corrected Specific Energy Consumption – This is the same measure as the previous, but reported as energy (kilojoules) rather than fuel (grams). This allows for a direct comparison between different fuels, such as various types of wood, charcoal, dung, etc.

Benchmark Values – The benchmark values combine the phases of cold start, hot start and simmer into one value for the overall test. It is the average of temp-corrected specific consumption (or emission) in cold and hot start, added to simmer. Having one overall value to look at can be helpful in comparing a large number of stove designs.

PREPARATION FOR THE WATER BOILING TEST

HOLDING THE THERMOCOUPLE IN THE POT

Its should be at the middle of the pot and 5cm above the bottom of the pot

DETERMINING LOCAL BOILING POINT

The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. The local boiling temperature is influenced by several factors including altitude, minor inaccuracies in the thermometer, and weather conditions. For these reasons, the local boiling temperature cannot be assumed to be 100° C.

It is better to determine the local boiling point empirically using the following procedure:

1) Choose whether you will use the large or small standard pot. Measure 5 liters of water for the large standard pot (or 2.5 liters for the small standard pot). Bring it to a rolling boil. Make sure that the stove's power output is high, and the water is fully boiling!

2) Using the same thermometer that will be used for testing, measure the boiling temperature when the thermometer is positioned in the center, 5 cm above the pot bottom. You may find that even at full boil, when the temperature no longer increases, it will still oscillate several tenths of a degree above and below the actual boiling point.

3) Record the temperature over a five minute period at full boil and note the maximum and minimum temperatures observed during this period. The maximum and minimum temperatures should then be averaged. This result will be recorded as the "local boiling temperature" on the [General Information] sheet in the Excel work book whenever you do a test.

DETERMINING FUEL MOISTURE CONTENT

Measuring wood moisture with a wood moisture meter. This device measures fuel moisture on a dry basis by measuring the conductivity between two sharp probes that are inserted in the wood. This is more convenient than oven-drying because the measurement can be rapidly done on site as the fuel is being prepared. The probes should be inserted parallel with the grain of the wood. The device may be adjusted for different species and calibrated for different ambient temperatures. The meter measures between 6% and 35-40% moisture (dry basis). If the sample of wood is wetter than the upper range of the meter, the meter will either show an error. Wood moisture can vary in a given piece of wood as well as among different pieces from a given bundle. When the meter is used, take three pieces of wood randomly from the bundle and measure each piece in three places. This yields nine measurements overall. The moisture of the bundle should be reported as the average of these nine measurements. Convert this average to a wet basis using the formula (this is done automatically in the computer spreadsheet). Record this average in the [Fuel Moisture] sheet.

Annexe 4. Mission #3 agenda

Date	Activity
1-2 Dec **&** **15-22 Dec 2021**	WBT
23 Dec 2021	Survey with the prototype users

Annexe 5. WBT Template

Water Boiling Test - Test Entry Form

Air Temperature/ambient		Date:	
Type of kitchen	sheltered + 1 wall / 2 walls / 3 walls / 4 walls	Stove Type:	Basic chimney stove
Fuel Dimensions		Test Number	
Fuel type (wood sp.)		Name HHs	
Moisture Content (wet basis)			

Dry Weight Pot	
Weight Container for Wood	
Local Boiling Point *	

* enter on General Information

	Cold Start		Hot Start		Simmer	
	Start	End	Start	End	Start	End
Time						
Weight of Fuel						
Water Temperature						
Weight of Pot with water						
Fire Starting Materials						
Notes : - Time when adding fuel / pushing sticks in the fire - weight of fuel added - air control ?						

Average temperature (Base of the chimney tube)	
Average temperature (End of the chimney tube)	

Annexe 6. Interviews guidelines

Introductory statement: Good morning/afternoon/evening. My name is --------------------------------

And I am conducting interview on the experiences with the chimney stove so far for the Improved Cook Stoves project on behalf of the PUR Project. We would be grateful for your assistance in our research. Information you provide will be treated in strict confidence.

General information

Variable/ Question		Response options
District, sub-county, location, sub-location		
Name of the household head		
Name of the respondent		
Contact number		
Interview date		

No	Question	Response options
1a	Have you been using the chimney stove installed in your household?	Yes = 1; No = 2
1b	If "yes", how often do you use it?	Yes = 1; No = 2
1c	If yes do you use it alongside other stove or alone?	Alone =1; Alongside other stoves=2
1d	What makes you use it alongside other stoves and not alone?	
2a	Does the stove meet all your cooking needs or there some foods which don't cook well on the stove?	1=It meet all the cooking needs, 2=It meets some of the cooking needs
2b	If it meets some of the cooking needs, list the ones the stove don't meet	
3a	Does the stove work well with biomass fuels available in this area?	Yes = 1; No = 2
3b	If No, name the biomass fuels which don't work well with the stove?	
4a	Do you face any challenges with use of the stove?	Yes = 1; No = 2
4b	If yes, name the challenges experienced	
5a	Do you propose any modification to the stove to make it better?	Yes = 1; No = 2
5b	What modifications do you think if done to the stove they would improve its performance?	

Annexe 7. Users' satisfaction survey - results

	a	b	c	d	e	f	g	h	i
1a. Have you been using the chimney stove?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b. If yes how often	Daily	Daily	Daily	Daily	3days per week	3days per week	3days per week	3days per week	Daily
1c. If yes do you use it alone or alongside other stoves?	Alongside other stoves	Alone	Alone	Alone	Alongside other stoves	Alongside other stoves	Alongside other stoves	Alongside other stoves	Alone
1d. If alongside other stoves, why?	Use chimney stove to cook only light foods and hard ones with koitama since they take very long to cook on chimney stove	N/A	N/A	N/A	Chimney stove is abit slow and only cook with it when I am not in a huryy; when using light firewoodand residues which more available to me, I use koitama since they don't work well with chimney stove	Getting blocks of firewood which work well with chimney stove is not easy, residues such as maize cobs, stalks and light firewood work well with koitama	Hard foods such a mixer of maize and beans takes long to cook on chimney stove, When having firewood in the form of blocks I use chimney stove but when having residiues and light firewood I use koitama since they don't work well on chimney stove	Chimney stove uses more firewood than kiotama, It takes longer to cook food on chimney stove than on koitama	N/A
1e. Which is the other most common stove do you use?	Koitama	N/A	N/A	N/A	Koitama	Koitama	N/A	Koitama	N/A
1f. Have you done any repairs?	No, only resmearing to make it look good	No, only resmearing to make the stove look good	No, only resmearing to keep the stove looking good	No, only resmearing to make it look nice	No, only resmearing to keep the stove looking good	No, only resmearing to look good	No, only resmearing to keep the stove looking good	No, only resmearing to look good	No, only resmearing to look beautiful
1i. If yes, how easy was it for you to do the repairs?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1j. Is any part of your kitchen blackened by smoke from the chimney stove?	No-All the smoke is exhausted to the outside	No	No-All the smoke is exhausted to the outside	No	No	No	No	No	No
1h. How do you find the lighting of the chimney stove?	Easy	Easy	Easy just like koitama	Easy	Its easy though not as easy as koitama	Easy	Easy	Easy	Easy
1i How is the firepower of the chimney stove?	Strong enough for light foods but not enough for foods which requires much heat	Its strong but need to be made stronger to make cooking faster	Its has a strong firepower	Good enough for our cooking	Its good though food takes longer to cook especially when uisng light firewood	Fairly strong	Strong but not good enough for cooking hard foods	Strong	Strong enough for our cookings
1j. While cooking with the chimney stove, do you use both fire places	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1k. If yes, which food types do you cook on the first fire place	rice, tea, vegetables	N/A	Ugali, beans, beans+maize, meat, tea, vegetables	Ugali, rice, githeri (mixer of maize and beans), stew, tea	Ugali, tea, vegatables, chapati, stew	Ugali, vegetables, tea, porridge, rice, stew	Ugali, tea, meat, frying githeri, stew, rice	Ugali, beans, tea, frying githeri	Ugali, rice,beans, githeri, tea
1l. If yes, which food types do you cook on the second fire place?	porridge, vegetables	N/A	Vegetables, frying of the already boiled cereals	vegetables	tea, vegetables	warming food mainly	tea, vegetables, meat	vegetables	vegetables, warming food
1m. If No, what makes you not to cook on both fire places?	N/A	Flame reaching the second fire place is not enough for any cooking	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2a. Does the stove meet all your cooking needs or some of the cooking needs?	No	Yes	Yes	Yes	No	No	No	No	Yes
2b. If it only meets some, list the ones the stove don't meet	Hard foods such as cereals take very long time to cook on chimney stove, Ugali also don't cook wekk on ugali	Ugali and hard foods takes very long to cook on chimney stove	N/A	N/A	Cooking hard foods-it takes much time with chmney stove hence I use koitama	Githeri, cereals take time to cook and need more heat power which is not possible to get with chimney stove with residues	Hard foods such as beans and beans+maize take very long to cook on a chimney stove	Githeri-take long to cook and requires loading much firewood which is not possible with chimney stove since it has a small inlet	N/A
3a. Does the stove work well with biomass fuels available in this area?	No	No	Yes	Yes	No	No	No	No	Yes
3b. If no, name the biomass fuels which don't work well with the stove	Residues and light firewood (small branches) don't work well on chimney stove since the combustion chamber is too small hence only little amount can be loaded and dont' give enough firepower.	Light firewood (small branches and twigs) and residues such as maize cobs don't work well with chimney stove due to the need for frequent reloadings	N/A	N/A	Residues such as maize cobs, light firewood branches-frequent loading and tending is required before the food gets ready	Residues such as maize cobs, stalsk and light firewood from small branches don't work well with chimney stove since it has a small combustion chamber hence only little can be loaded	Light firewood and residues such as maize cobs, don't do well with chimney stove hence when using them I use koitama	Light firewood and maize stalska and cobs don't work well with chimnev stove	N/A

4a. Do you face any challenges with use of the stove?	No	Yes	No	No	No	Yes	No	No	No
4b. If yes, name the challenges faced	N/A	The pot is not stable especially when cooking foods which requires vigorous stirring	N/A	N/A	N/A	Need for keeping tending fire especially when cooking foods which take long to cook hence I have to sit there until food is cooked	N/A	N/A	N/A
5a. Do you proposed any modifications to the stove to made it better?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
5b. If yes, what modifications do you propose?	Increase the inlet of firewood to accommodate more firewood and make cooking faster due higher firepower, Increase the size of the combustion chamber to make the flames more focused to the pot than much of it moving to the second fire place	Increase the depth of the pot rest to hold the pot on position better especially when cooking foods which need vigorous stiring, Increase the size of the combustion chamber and firewood inlet to increase firepower and making cooking faster and reduce additional workload of spilting firewood into small pieces	Fix a door on the stove to reduce the heat loss through the inlet hence saving on firewood	Increase the of the firewood inlet to be able to put bigger blocks of wood to reduce tending, reduce the height of the stove for the flame to reach the pot faster	Increase the size of the inlet to reduce the need to split firewood into smaller pieces and also to be able to put bigger blocks of wood which can burn for a longer period hence reduced tending	Increase the size of inlet and combustion chamber to allow more firewood to be loaded and hence get more firepower and cook faster, increase the depth of the pot rest to hold the pot in position properly especially when cooking foods which needs vigorous stirring, reduce the height of the stove to bring flames closure to the pot like it is with the koitama	N/A	Reduce the height of the stove to bring the pot closer to the flame, Increase size of the inlet and combustion chamber to make it possible to load more firewood without need for much splitting hence increased firepower and speed cooking	Increase the depth of the pot rest to hold pot properly in place especailly when cooking foods which requires vigorous stiring such as ugali

Annexe 8. Matrix of results

N° of test	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	BCD	ABD	ACD	ABCD	TTB (Cs)	Eff. (Cs)	TTB (Hs)	Eff. (Hs)
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1	**51**	**15%**	**39**	**13%**
2	1	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1	1	1	-1	**32**	**15%**	**19**	**18%**
3	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1	**22**	**16%**	**18**	**15%**
4	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	1	-1	1	1	**29**	**10%**	**27**	**11%**
5	-1	-1	1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1	**46**	**9%**	**46**	**8%**
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	1	-1	1	**44**	**9%**	**28**	**14%**
7	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	1	**32**	**11%**	**27**	**10%**
8	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1	**41**	**9%**	**36**	**9%**
9	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1	**49**	**11%**	**28**	**14%**
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	**31**	**13%**	**28**	**21%**
11	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	-1	1	1	**22**	**14%**	**18**	**17%**
12	1	1	-1	1	1	-1	1	-1	1	-1	-1	-1	1	-1	-1	**35**	**12%**	**20**	**14%**
13	-1	-1	1	1	1	-1	-1	-1	-1	1	1	-1	1	-1	1	**48**	**12%**	**44**	**9%**
14	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	-1	1	-1	**56**	**9%**	**36**	**13%**
15	-1	1	1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	**37**	**11%**	**25**	**11%**
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	**35**	**13%**	**28**	**14%**
Effect on TTB (Cs)	**-0,25**	**-6,5**	**4,25**	**1**	**3,625**	**1,875**	**0,375**	**0,375**	**-0,375**	**0,625**	**-7,5**	**-1,5**	**-1**	**-0,5**	**-1,625**				
Effect on eff. (Cs)	**1%**	**-4%**	**3%**	**1%**	**2%**	**1%**	**0%**	**-1%**	**-1%**	**1%**	**-7%**	**-1%**	**0%**	**0%**	**-2%**				
Effect on TTB (Hs)	**2,75**	**-13,9375**	**11,625**	**3,6875**	**0,28125**	**3,96875**	**-3,15625**	**0,59375**	**-0,71875**	**-1,21875**	**-18,8125**	**-0,6875**	**-0,3125**	**2,3125**	**-6,15625**				
Effect on eff. (Hs)	**1,04%**	**-0,58%**	**-2,21%**	**0,92%**	**-1,67%**	**0,46%**	**0,33%**	**0,58%**	**0,46%**	**-0,17%**	**-1,58%**	**0,29%**	**0,29%**	**-0,08%**	**0,46%**				

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