Final Technical Report

Project Title: Technology Innovations to Improve Biomass Cookstoves to Meet Tier 4 Standards

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Recipient: Aprovecho Research Center

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Executive Summary:

Protecting public health has become a major motivation for investigating how improved cook stoves might function as a viable intervention. Currently, the great majority of cookstoves for sale in the developing world were not designed for this purpose but instead success was based on criteria such as reduced fuel use, affordability, and ease of use.
With DOE funding Aprovecho Research Center spent three years creating stoves using an iterative development and modeling approach resulting in four stoves that in lab tests met the World Health Organization (2014) intermediate rate vented targets for PM2.5 and for CO. The following summary of technical effectiveness is taken from *Clean Burning Biomass Cookstoves* (Still et al., 2015):

- A large range of stoves achieved over 40% thermal efficiency when tested at medium power with a 6mm pot skirt.
- Stoves with a sufficient turn down ratio scored in the ISO/IWA Tier 4 low power categories that are based on Specific Consumption.
- Cleaner burning wood stoves easily achieve Tier 4 on measures of Carbon Monoxide.
- Unfortunately, even the best unvented stoves (in lab tests) emitted more PM 2.5 than required by the new WHO indoor air standards and the similar IWA Indoor Air Tier 4 metric.
- ARC added chimneys to the DOE project stoves in an effort to comply with the WHO PM2.5 Intermediate guideline.
- Three of the DOE project wood burning stoves emitted less than 7.1 (mg/min) at high power which meets the WHO vented stove Intermediate Emission rate PM 2.5 target.
- The stoves now move into field testing to determine if the PM 2.5 levels in real use can be attained.
- A charcoal burning stove scored in the Tier 4 range on all nine ISO/IWA metrics. When charcoal is well made (the wood is completely burnt out) the charcoal does not make appreciable amounts of smoke. However, making charcoal can waste about 5/8ths the energy in the wood.

Hopefully, a new generation of clean burning biomass stoves will provide the Global Alliance for Clean Cookstoves and other organizations with a greater range of improved technologies to attempt to meet health oriented goals. The clean burning biomass cookstoves with chimneys were constructed at Shengzhou Stove Manufacturer (SSM) in China. The projected cost of the new stoves ranges from $17 to $30. SSM has a production capacity of approximately 5 million stoves per year. Adding clean burning biomass stoves to gas and liquid fueled approaches widens the possibility that health protecting interventions for all users may become more likely.

Comparison of actual accomplishments with the goals and objectives of the project:

There were 8 tasks set out in this project. In summary tasks were:

Task A Year One: Conduct review of ARC- and Chinese-manufactured stoves to select the best candidate stoves for laboratory analysis.

Task B Year One: Establish baseline data on selected stoves.

Subtask B.1: Assemble the selected clean-burning stoves designed by ARC and selected Chinese manufacturers that are expected to approach the Tier 4 standard within each of the four stove categories.
Subtask B.2: Complete a statistically valid Water Boiling Test (WBT) (version 4.0) analysis under the emissions hood (measuring weighted amounts of CO, CO_2, PM and fuel use).
Subtask B.3: ARC analyze the data from the WBTs and identify the top candidate stoves for further research.
Subtask B.4: Prepare a report of research findings.

Task C.0 Year One: Select stoves for in-field testing in year two.

Task D.0 Year One: Select stoves for market testing.

Task E0 Year One: Verify lab testing results through third party.

Task F.0 Year Two: Optimize stoves through rigorous field testing.

Task G.0 Year Two: Verify lab and field results through third party.

Task H.0: Year Two: Select top-performing stoves to move into Phase Three.

Task I.0 Year Two: Research and development documentation.

Below is a detailed description of the planned activities for each task, the actual accomplishements and an explanation of any variation.

Task number: A

1. **Planned Activities**:
    a. Conduct review of non-Chinese and Chinese manufactured stoves to select the best candidate stoves for laboratory testing with WB T 4.2.2. Assemble stoves at ARC laboratory
    b. 13 non-Chinese Stoves identified and shipped to ARC
    c. Ten Chinese Stoves are shipped to ARC Lab

2. **Actual Accomplishments**:

Based on results from an initial survey, ARC together with Sub-Recipients identified and selected the stoves that were most likely to meet or exceed the Tier 4 standards. Stoves from the following categories were to be evaluated: 1) Batch-Loaded Fan and Top-Lit Updraft (TLUD) Stoves; 2) Side-Feed Fan Stoves; 3) Clean Natural Draft Stoves and 4) Gasifier stoves. 14 stoves were actually brought to the ARC lab. Selected stoves were prepared for intensive laboratory research for performance evaluation.

3. **Explanation of Variance**: A fourteenth non-Chinese stove was brought to the lab.

Task number: B

1. **Planned Activities**:

    a. ARC with assistance from BUCT performs tests on the thirteen stoves.
    b. A minimum of 13 stoves will be selected and brought to the ARC lab. Of these selected a minimum of 10 stoves will be evaluated for IWA/ISO standing.(Milestone)
    c. Report on WBT/ISO test results from ARC completed

2. **Actual Accomplishments**:

    A survey of fourteen non-Chinese 'clean burning' cooking stoves has been completed. The survey with gravimetric measurement of PM includes testing of manufactured non-Chinese clean burning cooking stoves and ARC prototype stoves that were developed in the STTR project.
    The stoves were tested using the WBT 4.2.2 under the LEMS emissions hood. The LEMS measures the total emissions produced during stove combustion. The stove is placed under a hood which collects the emissions and air from the laboratory. The tester then processes the recorded data using provided software to report the performance of the stove based on the mass of emissions measured and fuel consumed.
    Stove performance was evaluated using the Tier system as proposed in the ISO International Working Agreement. The Tier system separates the reporting metrics into nine categories: eight performance related Tier ratings and one safety rating.

3. **Explanation of Variance:** None

Task number: C

1. **Planned Activities**:

    a. Selection of candidate stoves for optimization from six stove categories will be completed
    b. Iterative design changes will be incorporated for each stove type with

testing results reported

c. Complete CAD drawings will be drafted for the improved designs
d. Perform IWA/ISO on final designs
e. Prepare report on WBT/ISO results of iterative design changes and performance improvements
f. Optimized prototypes are taken to Shengzhou Stove Manufacturer (partner factory in China). Initial investigation of manufacturing is accomplished.
g. Explore options with SSM staff to manufacture Tier 4 stoves that are least costly, attractive and have two years durability
h. Initiate manufacture at SSM adequate number of prototype stoves for field testing

2. Actual Accomplishments:

ARC and BUCT will select stoves to be optimized in the laboratory based on best WBT/ISO performance. The Iterative design process on the Natural Draft Rocket stove, TLUD Natural Draft stove, Natural Draft Chimney Stove, Side Feed Fan stove, Top Loaded Fan stove and the VITA stove will result in six types of Tier 4 prototype stoves to enter field testing. Each prototype design will have complete CAD drawings for manufacture . ISO/IWA test results of the final designs will be reported in a summary of the new designs and readied for manufacture in sufficient quantities for field testing.

Using the results from the survey of 10 Chinese and 15 non-Chinese 'clean burning' cooking stoves, select stoves were modified using an iterative design process to develop 8 prototype tier 4 stoves.

By making numerous design changes and continual testing with the WBT, final designs that meet tier 4 criteria were found for each design type. Final designs were put through full IWA/ISO testing. The stoves were tested using the WBT 4.2.2 under the LEMS emissions hood. The LEMS measures the total emissions produced during stove combustion. The stove is placed under a hood which collects the emissions and air from the laboratory. The tester then processes the recorded data using provided software to report the performance of the stove based on the mass of emissions measured and fuel consumed. Stove performance was evaluated using the Tier system as proposed in the ISO International Working Agreement. The Tier system separates the reporting metrics into nine categories: eight performance related Tier ratings and one safety rating.
The research and development phase of cooking stoves in the ARC lab resulted in eight stove options that met the 'Tier 4' criteria. In September, 2014 the ARC team brought these stoves to Shengzhou Stove Manufacturer (SSM) in Shengzhou, China and worked with their engineers to create most affordable stoves that feature various clean burning. In the end there were 4 of these 8 of stoves that ARC asked

SSM to produce. These were the Side feed Fan stove, Tom Reed style fan driven gasifier, the improved charcoal stove, and a sunken pot rocket stove with chimney. Each stove was redesigned at SSM in an effort to optimize the stoves for lowest cost manufacturing. An upper limit of $15 FOB wholesale stove cost helped to define the process. The next year will be spent working with SSM to create stoves specifically fitted to the most promising markets.

In addition to these 4 prototypes produced at SSM, a 5th design of a Natural Draft Top Lit Up Draft Stove (TLUD) was made at ARC and a 6th design of a improved high power fan stove for the Chinese market was produced at BUCT.

3. **Explanation of Variance:** None

Task number: D

1. **Planned Activities**:

    a. Start process of networking with Chinese manufacturers so that adequate prototypes will be ready for Task F.
    b. BUCT will work closely with Chinese manufacturers to prepare those stoves for production and advancement into existing distribution channels established by Global Alliance partners in target regions worldwide
    c. Sufficient prototypes will be produced to enable samples for field testing to be sent to 6 priority countries.

2. **Actual Accomplishments**:

    ARC and BUCT contacted Chinese manufacturers to prepare those stoves for production and advancement into existing distribution channels established by Global Alliance partners in target regions worldwide. Scheduling of trips to China for early September were planned.

    BUCT is preparing for Controlled Cooking Tests to compare unimproved Xunda stove to improved Xunda stove. A design committee of cooks other stakeholders will be had to get feedback on the design. Once these results are accumulated the will be presented to the Chinese manufacturer.

    All 6 of the prototype stoves are assembled (5 at ARC, 1 at BUCT) and made ready for field testing. The initial logistics for testing with regional partners in Mumbai India, Phnom Penh Cambodia, Beijing China, Nairobi Kenya, Kumasi Ghana and Lima Peru are being set up.

3. **Explanation of Variance:** None

Task number: E

1. Planned Activities:

Stoves delivered to third party for independent testing and evaluation

2. Actual Accomplishments:

The original plan was to have Jim Jetter of the US EPA test the stoves as ARC has collaborated extensively with him in the past. Upon further discussion with DOE it has been suggested that LLB will also test the stoves. In addition to this we are having the stoves independently tested in the field by CRT Nepal. Results of this are included in the field testing reported in Task F.

3. Explanation of Variance: None

Task number: F

1. **Planned Activities**:

a. 2nd generation prototype stoves are shipped to up to 6 key partners for field testing. ARC, Stove Tec, BUCT and in country partners conduct field testing in the steps described below
b. Work with Regional Testing and Knowledge Center staff to assemble Design Committees in rural towns and conduct Controlled Cooking Tests using emissions hood to assess emissions, fuel use and feedback from end users
c. Market testing of stove is performed to acquire data on sales potential
d. Identify needed changes in stove
e. Second generation stove design and CAD drawing made
f. ARC, Stovetec, and BUCT analyze CCT and market testing and prepare report on 6 country field testing results

2. **Actual Accomplishments**:

Integrating consumer feedback from the first round of testing resulted in 5 improved stove designs. 1) The charcoal stove remained unchanged and will be tested in new locations. 2) Both the side feed and the top feed fan stoves were well liked by consumers. A common complaint was that the stoves would smoke at times. A chimney was added to each of these stoves. The efficiency in these designs is tier 2, making them an improvement over the baseline stove. 2 additional designs with sunken pots were also produced as the fuel efficiency results in tier 4 with this addition, though the user is limited to using just one size of pot. These designs were taken to 2 locations for field testing to date. They were brought to the indigenous community of the Bri Bri people of Costa Rica and were also brought to the newly developed testing center of Earth University. At Earth University they were tested for

fuel use and emissions reductions as well as consumer feedback was gotten from the diverse community of consumers from over a dozen countries.

3. **Explanation of Variance: None**

Task number: G

1. **Planned Activities**:

   Stove are to be sent for third party evaluation.

2. **Actual Accomplishments**:

Stoves were already sent to CRT/N in Nepal for independent third party testing and reported in prior quarterly reports. A testing plan was made also to also have the stoves tested at Dr. Ashoks lab in Berkely California. Delays in scheduling have postponed this. Though this is still planned to take place it will take place outside of the bounds of this award.

3. Explanation of Variance: None

Task number: H

1. Planned Activities:
   ARC and BUCT will determine based on laboratory and field/consumer testing the tier 4 stoves that have the best chance of being successfully marketed.

2. Actual Accomplishments:

The purpose of this work was to design tier 4 stoves and then take these designs into the field to refine them in two stages toward the goal of producing stoves that will have the highest probability of penetrating the stove market. To this this end the stoves were taken to 10 different focus group locations and were refined into 5 significant designs, (1) a charcoal stove, (2) a fan driven top loaded stove, (3) a fan driven top loaded stove with a sunken pot, (4) a fan driven side feed stove and (5) a fan driven side feed stove with a sunken pot. A comprehensive report in the form of the book Clean Burning Biomass Cookstoves was produced where detailed drawing and explanations of these final designs can be found. Extensive surveys were performed in each focus group and a summary of the findings were as follows:

(1) Charcoal stove - The Charcoal stove was generally liked where charcoal was of

common use. A small number of users commented that the stove was lower power then they were accustomed to. This comes from the fact that the combustion chamber is sized down. The smaller size chamber is key to the fuel efficiency and clean burning of the stove so this aspect cannot be changed. Willingness to pay for the stove ranged from around $10 to $35. Production cost of the stove will be key to acceptance.

(2) Fan driven top loaded stove - The fan driven top load stove was tested with a chimney option (flat top) and without a chimney (using a skirt). Users generally liked the stove without the chimney as it was more fuel efficient. In this configuration the stove would not be tier 4 and would have to be used in a more ventilated environment. Willingness to pay for the stove ranged from around $5 to $40. Production cost of the stove will be key to acceptance.

(3) Fan driven top loaded stove with a sunken pot - This configuration is similar to design (2) except that it has an attachment that requires the use of a 7 liter pot which leads to a chimney. The stove was generally like by cooks. One request was to have the chimney adapter changeable so that it could be used for different sized pots. Willingness to pay for the stove similarly ranged from around $10 to $35. Production cost of the stove will be key to acceptance as the sunken pot adapter will increase the cost.

(4) Fan driven side feed stove - The Fan driven side feed stove was tested with a chimney option (flat top) and without a chimney (using a skirt). Users generally liked the stove without the chimney as it was more fuel efficient. In this configuration the stove would not be tier 4 and would have to be used in a more ventilated environment. Willingness to pay for the stove ranged from around $5 to $40. Production cost of the stove will be key to acceptance.

(5) Fan driven side feed stove with a sunken pot. - This configuration is similar to design (4) except that it has an attachment that requires the use of a 7 liter pot which leads to a chimney. The stove was generally like by cooks. One request was to have the chimney adapter changeable so that it could be used for different sized pots. Willingness to pay for the stove similarly ranged from around $10 to $35. Production cost of the stove will be key to acceptance as the sunken pot adapter will increase the cost.

In summary the stove market is a newly developing place. While charcoal stoves in an urban setting is well developed the market for wood burning stoves is much more nascent. While it was found that there is a growing awareness of the importance of improved wood burning stoves and a corresponding increased willingness to pay, it will be important to increase these two interrelated variables to make a successfully distributed improved cookstove design. But the initial finding of these surveys were promising toward this goal.

3. Explanation of Variance: None

Task number: I

1. Planned Activities:
   Comprehensive report o f work accomplished will be developed of tasks accomplished

2. Actual Accomplishments:

A comprehensive report in the form of the book Clean Burning Biomass Cookstoves was produced. This book details the work performed under this award and includes detailed design specifications for the prototype stoves developed under this work.

3. Explanation of Variance: None

5. Summarize project activities for the entire period of funding, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results. Include, if applicable, facts, figures, analyses, and assumptions used during the life of the project to support the conclusions.

The project began with comprehensive Water Boiling Test 4.2.3 fuel use, CO, PM2.5, and CO2 surveys of best practice cooking stoves from China and from the rest of the world. The stove designs were in the following categories: 1) Batch-Loaded Fan and Top-Lit Updraft (TLUD) Stoves; 2) Side-Feed Fan Stoves; 3) Chinese Fan-Assisted Stoves; and 4) Clean Natural Draft Stoves and 5) Gasifier stoves. The purpose of this testing was to determine: 1) baseline performance data for emissions, thermal efficiency, and safety metrics; 2) technical and operational functionality; 3) modifications needed to achieve Tier 4 benchmarks; and 4) additional adaptations required for the specific needs of end users.

The survey of best performing stoves identified three technical areas that required improvement to meet ISO/IWA Tier 4 guidelines: increased turn down ratios, reduction of PM2.5, changing the designs to include chimneys. The results of the survey were published in a peer reviewed NIH journal. See: (EcoHealth, Still, et al, 2015). The entire project was summarized in a 174 page book titled “Clean Burning Biomass Cookstoves” (2015).

Summary of the Clean Stove Survey Results

- The Three Stone Fire was dramatically outperformed on all measures by the cleaner burning stoves.
- A large range of stoves achieved over 40% thermal efficiency when tested at medium power with a 6mm pot skirt.

- Stoves with a large turn down ratio could score in the Tier 4 low power categories. While batch loaded stoves could be clean burning at high power if they were unable to adequately reduce power, they did not do well on the fuel use and emissions metrics based on Specific Consumption.
- Cleaner burning wood stoves easily achieve Tier 4 on measures of Carbon monoxide.
- Unfortunately, even the best stoves emitted more PM 2.5 than required by the new WHO unvented indoor air standards and the similar IWA Indoor Emissions Tier 4 metric. Until cleaner burning biomass stoves are proven to emit acceptable amounts of PM 2.5 in real use even the best stoves seem to require chimneys in the effort to protect health.
- A charcoal burning stove did well and scored in the Tier 4 range on all metrics. When the charcoal is well made (wood is completely burnt out) the charcoal did not make smoke. The auto-ignition temperature of CO is 609C which was quickly reached in the new ARC/DOE very well insulated charcoal stove.

Based on results from the initial survey, ARC identified and selected five stoves that were further developed to meet the ISO/IWA Tier 4 standards utilizing the iterative development and modeling methodology. These stoves were: 1.) Natural Draft Sunken Pot 2.)Rocket Stove, 3.)Natural Draft TLUD, 4.)Top Loaded Forced Air Stove, 5.) Charcoal Stove. Approximately one hundred iterations and tests were made on each stove model to improve performance. The ISO/IWA Tier results on most of the 8 metrics were Tier 4.

Stove type/model		**Sunken Pot**		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	49.7%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.020	19%	3.7
High Power CO	g/MJ_d	2.22	38%	4.7
Low Power CO	g/min/L	0.05	42%	4.3
High Power PM	mg/MJ_d	152.2	53%	3.1
Low Power PM	mg/min/L	1.73	58%	3.2
Indoor Emissions CO	g/min	0.00		4.0
Indoor Emissions PM	mg/min	0.0		4.0

Stove type/model		Natural Draft TLUD		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	43.8%	5%	3.8
Low Power Specific Consumption	MJ/min/L	0.018	12%	3.9
High Power CO	g/MJd	0.15	34%	4.9
Low Power CO	g/min/L	0.01	37%	4.9
High Power PM	mg/MJd	26.4	16%	4.3
Low Power PM	mg/min/L	0.28	57%	4.7
Indoor Emissions CO	g/min	0.05	37%	4.8
Indoor Emissions PM	mg/min	3.6	5%	3.7

Stove type/model		Side Feed Fan Stove		
Location		Average	COV	Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.1%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.010	8%	4.3
High Power CO	g/MJd	1.76	30%	4.7
Low Power CO	g/min/L	0.01	24%	4.8
High Power PM	mg/MJd	47.2	53%	3.9
Low Power PM	mg/min/L	0.47	48%	4.5
Indoor Emissions CO	g/min	0.16	22%	4.6
Indoor Emissions PM	mg/min	4.5	57%	3.5

Stove type/model		Top Load		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	37.8%	3%	3.2
Low Power Specific Consumption	MJ/min/L	0.106	8%	0.4
High Power CO	g/MJd	0.90	14%	4.8
Low Power CO	g/min/L	0.05	10%	4.4
High Power PM	mg/MJd	24.7	26%	4.3
Low Power PM	mg/min/L	1.54	24%	3.4
Indoor Emissions CO	g/min	0.15	8%	4.6
Indoor Emissions PM	mg/min	5.0	26%	3.4

CHARCOAL Stove

Stove type/model		Charcoal		
Location		Average	COV	Average Tier
IWA Performance Metrics	**units**			
High Power Thermal Efficiency	%	47.0%	4%	4.0
Low Power Specific Consumption	MJ/min/L	0.002	10%	4.8
High Power CO	g/MJd	6.35	19%	4.2
Low Power CO	g/min/L	0.01	11%	4.9
High Power PM	mg/MJd	33.2	31%	4.1
Low Power PM	mg/min/L	0.01	6%	4.9
Indoor Emissions CO	g/min	0.41	25%	4.0
Indoor Emissions PM	mg/min	2.0	39%	4.0

In order to evolve market-ready, clean cooking stoves that meet Tier 4 benchmarks, research teams from ARC and StoveTec took the same five stoves selected in Phase One into the field using the facilities at partnered Regional Testing and Knowledge Centers (RTKC) In Nepal, Senegal, India, Peru. The BUCT team also completed field tests in China. The ARC and BUCT teams assembled Design Committees in locales where biomass is the preferred fuel. These committees followed the testing procedures outlined in Dr. Sam Baldwin's book "Biomass Stoves: Engineering Design, Development, and Dissemination." The ARC and BUCT researchers performed a series of Controlled Cooking Tests using the emission hood at the RTKCs and developed sufficient data to identify which stoves meet interim and Tier 4 standards and to advance to the production phase.
After field testing and market testing results were analyzed the Side Feed Forced Draft Stove with Chimney was shown to be most likely to be commercially viable. The stove can be operated with or without forced air and it can be fitted with either a sunken pot or a flat top feature that allows multiple pot use. An Auto-Damper was developed that automatically diverts all emissions up the chimney when the pot is removed. The currents StoveTec plan is to begin manufacturing the stove in 2017.

For further detail See book Clean Burning Biomass Cookstoves.

6. Identify products developed under the award and technology transfer activities, such as:

a. Publications (list journal name, volume, issue), conference papers, or other public releases of results. If not provided previously, attach or send copies of any public releases to the DOE Project Officer identified in Block 11 of the Notice of Financial Assistance Award;

Clean Burning Biomass Cookstoves.

b. Web site or other Internet sites that reflect the results of this project;

n/a

c. Networks or collaborations fostered;

n/a

d. Technologies/Techniques;

5 prototype stove designs as described in section 4 above.

e. Inventions/Patent Applications, licensing agreements; and

n/a

f. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.

n/a