SBIR/STTR
FINAL SCIENTIFIC/TECHNICAL REPORT

COVER PAGE

DOE AWARD NUMBER:
DE-SC0008233

RECIPIENT:
ASAT, Incorporated.

PROJECT TITLE:
Improved Biomass Cooking Stoves and Improved Stove Emission Equipment

PRINCIPAL INVESTIGATOR:
Dean K. Still

EXECUTIVE SUMMARY

In developing countries, there is an urgent need for access to safe, efficient, and more affordable cooking technologies. Nearly 2.5 billion people currently use an open fire or traditional cookstove to prepare their meals,[1] and recent models predict that use of biomass for cooking will continue to be the dominant energy use in rural, resource-poor households through 2030.[2] For these families, cooking poses serious risks to health, safety, and income. An alarming 4 million people, primarily women and children, die prematurely each year from indoor and outdoor exposure to the harmful emissions released by solid fuel combustion.[3] Use of traditional stoves can also have a significant impact on deforestation and climate change. This dire situation creates a critical need for cookstoves that significantly and verifiably reduce fuel use and emissions in order to reach protective levels for human health and the environment.

Additionally, advances in the scientific equipment needed to measure and monitor stove fuel use and emissions have not kept pace with the significant need within the industry. While several testing centers in the developed world may have hundred thousand-dollar emissions testing systems, organizations in the field have had little more than a thermometer, a scale, and subjective observations to quantify the performance of stove designs. There is an urgent need for easy-to-use, inexpensive, accurate, and robust stove testing equipment for use by laboratory and field researchers around the world.

ASAT and their research partner, Aprovecho Research Center (ARC), have over thirty years of experience addressing these two needs, improved cookstoves and emissions monitoring equipment, with expertise spanning the full spectrum of development from conceptual design to product manufacturing and dissemination. This includes: 1) research, design, and verification of clean biomass cookstove technology and emissions monitoring equipment; 2) mass production of quality-controlled stove and emissions equipment at levels scalable to meet global demand; and 3) global distribution through a variety of channels and partners. ARC has been instrumental in designing and improving more than 100 stove designs over the past thirty years. In the last four years, ASAT and ARC have played a key role in the production and sales of over 200,000 improved stoves in the developed and developing world. The ARC-designed emissions equipment is currently used by researchers in laboratories and field studies on five continents.

During Phase I of the DOE STTR grant, ASAT and ARC worked together to apply their wealth of product development experience towards creating the next generation of improved cookstoves and emissions monitoring equipment. Highlights of Phase I for the biomass cookstove project include 1) the development of several new stove technologies that reached the DOE 50/90 benchmark; 2) fabrication of new stove prototypes by ASAT's manufacturing partner, Shengzhou Stove Manufacturing (SSM); 3) field testing of prototype stoves with consumers in Puerto Rico and the US; and 4) the selection of three stove prototypes for further development and commercialization during Phase II. Highlights of Phase I for the emissions monitoring equipment project include: 1) creation of a new emissions monitoring equipment product, the Laboratory Emissions Monitoring System (LEMS 2) the addition of gravimetric PM measurements to the stove testing systems to meet International Standards Organization criteria[4]; 3) the addition of a CO_2 sensor and wireless 3G capability to the IAP Meter; and 4) and the improvement of sensors and signal quality on all systems. Twelve Regional Testing and Knowledge Centers purchased this equipment during the Phase I project period.

[1] Rehfuess, E., et al, 2006. Assessing household solid fuel use: multiple implications for the Millennium Development Goals. Environ Health Perspect 114, 373–378.

[2] Daioglou V, van Ruijven BJ, van Vuuren DP. Model projections for household energy use in developing countries. Energy 2012;38(1)601-15.

[3] Lancet, 380: 2224-60, 2012. S Lim, et al. A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 regions, 1990-2010: A Systematic Analysis for the Global Burden of Disease Study.

[4] In 2011, an interim set of cookstove emission and fuel-us performance standards were adopted by the International Standards Organization. http://www.pciaonline.org/files/ISO-IWA-Cookstoves.pdf

COMPARISION OF ACCOMPLISHMENTS TO PROJECT GOALS: DOE 50/90COOKSTOVES

Background

Less than ten years ago, a stove was defined as "improved" if it reduced fuel use by 24% and reduced emissions of carbon dioxide (CO) and particulate matter (PM) by 64% and 36%, respectively, compared to an open fire.[5] Today, these reductions are known to be insufficient to protect health or address climate change. According to the US DOE, in order to protect fuel supply, health, and environment, a cookstove should reduce fuel use by 50% and reduce both CO and PM emissions by 90% compared to the three-stone fire.[6] In addition, the stove must be affordable, reliable, meet user preferences, and be commercially successful in order to be consistently used in homes.

In Phase I, the most efficient and clean burning stoves available on the market were collected and tested at the ARC laboratory for comparison and compilation within the library of testing results of over 100 cookstoves. Pairing performance of these stoves with iterative design changes under the emissions hoods resulted in the development of prototype stoves that met or had the potential to reach the DOE 50/90 benchmark. In partnership with Shengzhou Stove Manufacturing (SSM), the first run of prototypes was produced for consumer field testing in Puerto Rico and in the US.

The major improvements to the stoves during Phase I included: 1) a new approach to the fan stove to force low volume, high velocity jets of air to enter the combustion zone from under the fire which created almost complete combustion; 2) the natural draft Rocket Stove was shown to burn quite cleanly when operated at medium power in tests conducted by ARC and Dr. Jim Jetter at the USEPA after a 'governor' was invented that forces the cook to operate the stove at medium power. The Rocket Stove, after adding this feature and in combination with optimal heat transfer to the pot, was found to meet the DOE 50/90 standard; 3) the Top Lit Up Draft type of stove was modified to include a powerful lantern that lights up the kitchen area while food is being prepared. The TLUD lantern is exceptionally clean burning and the field testing resulted in high approval ratings from cooks; and 4) in partnership with SSM, experiments with new stove materials resulted in the discovery of improved refractory ceramics that are durable and have the potential for reducing stove costs by fifty percent.

Objectives and Accomplishments

OBJECTIVE 1: Complete a benchmark study on the performance of existing state-of-the-art biomass-fueled cook stoves, including user preferences and needs, and to determine the best candidate stoves to develop into prototypes meeting the DOE 50/90 standard.

OUTCOMES:

- ARC surveyed globally-available state-of-the-art clean burning stoves and selected the best stoves for fuel use and emissions testing with the Water Boiling Test 4.2.1; (Figure 1-3 below)
- Results were added to ARC's extensive library of 100+ stove tests[7]. (See Figure 4 below).

[5] MacCarty NA, Still DK, Ogle DM. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy for Sustainable Development. 2010;14:161-171

[6] US Department of Energy, 2011

[7] MacCarty, N., et al. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy for Sustainable Development, 14, 161–171, 2010. http://www.sciencedirect.com/science/article/pii/S0973082610000311

Figure 1: Carbon Monoxide Levels of Phase I Prototypes in comparison to Three Stone Fire

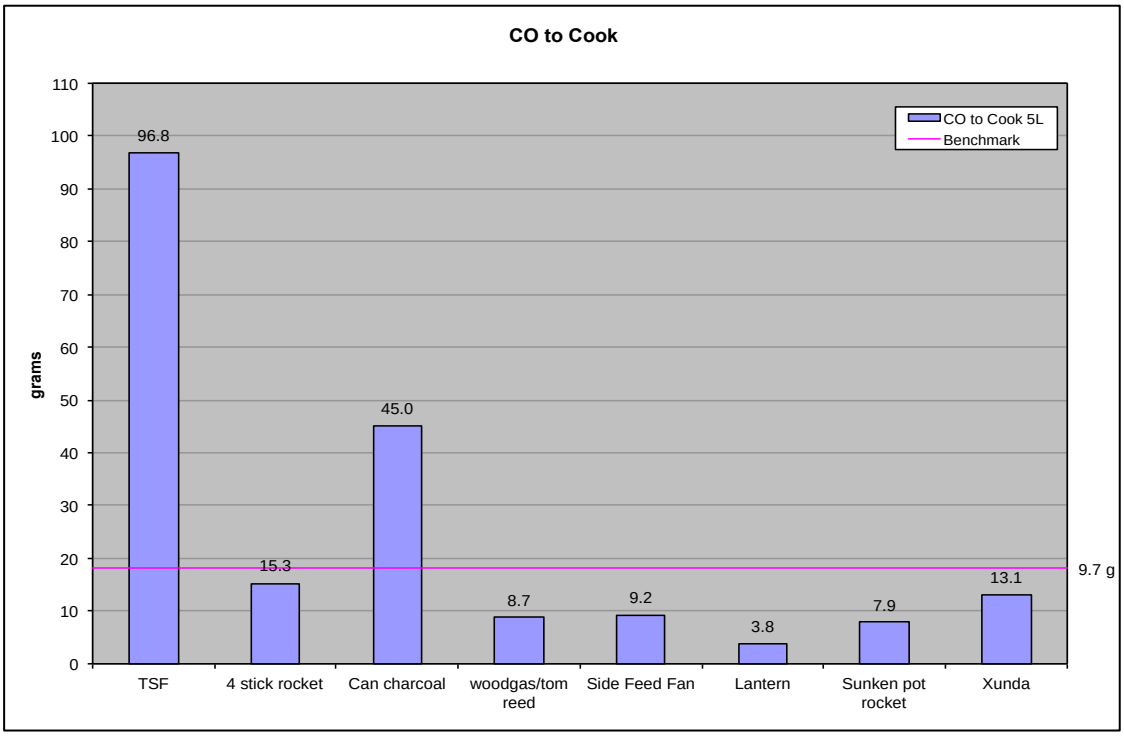


Figure 2: Particulate Matter Levels of Phase I Prototypes in comparison to Three Stone Fire

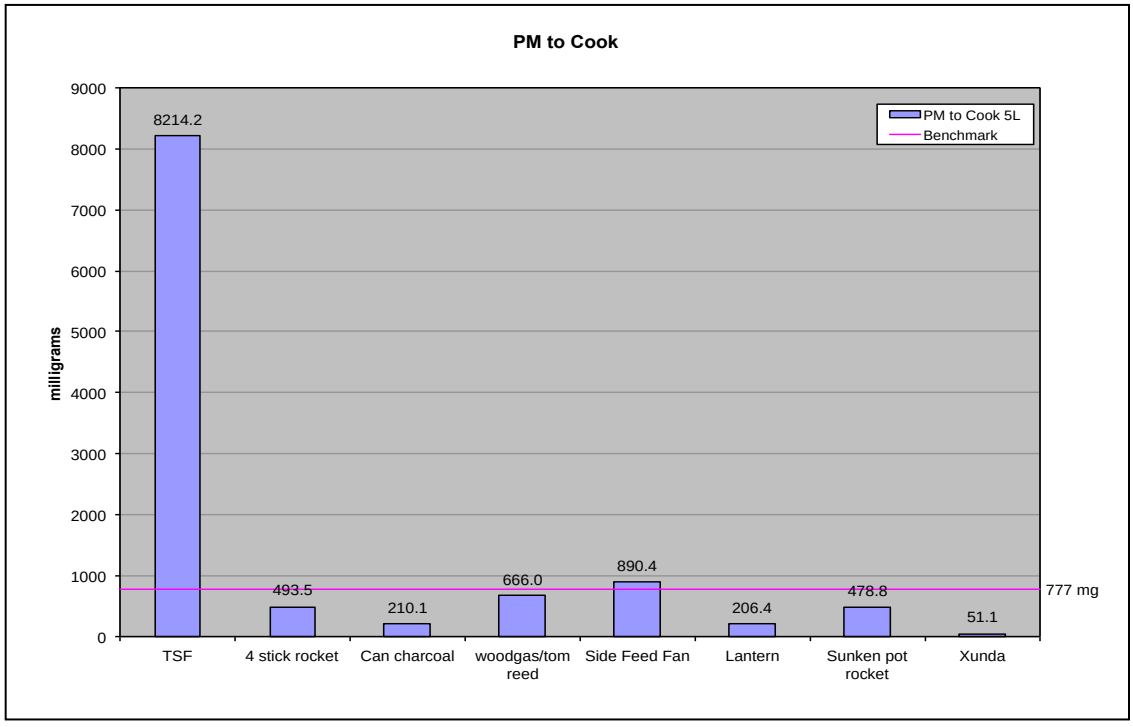


Figure 3: Energy to Cook Levels of Phase I Prototypes in comparison to Three Stone Fire

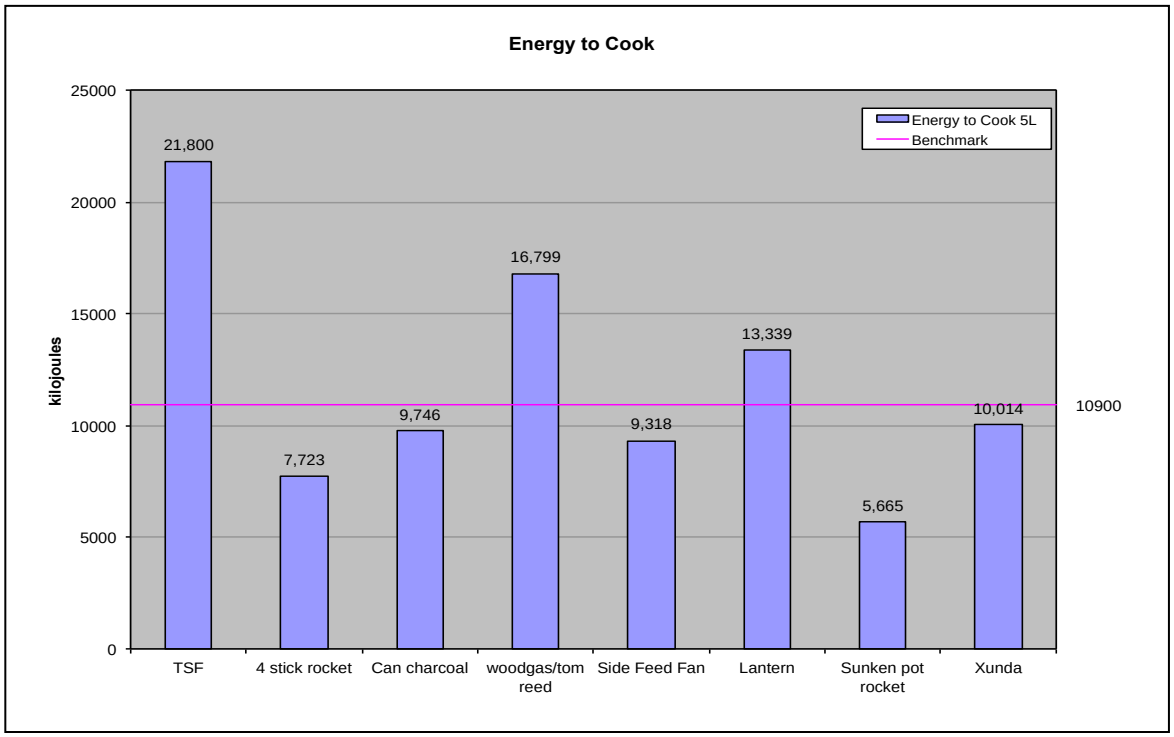
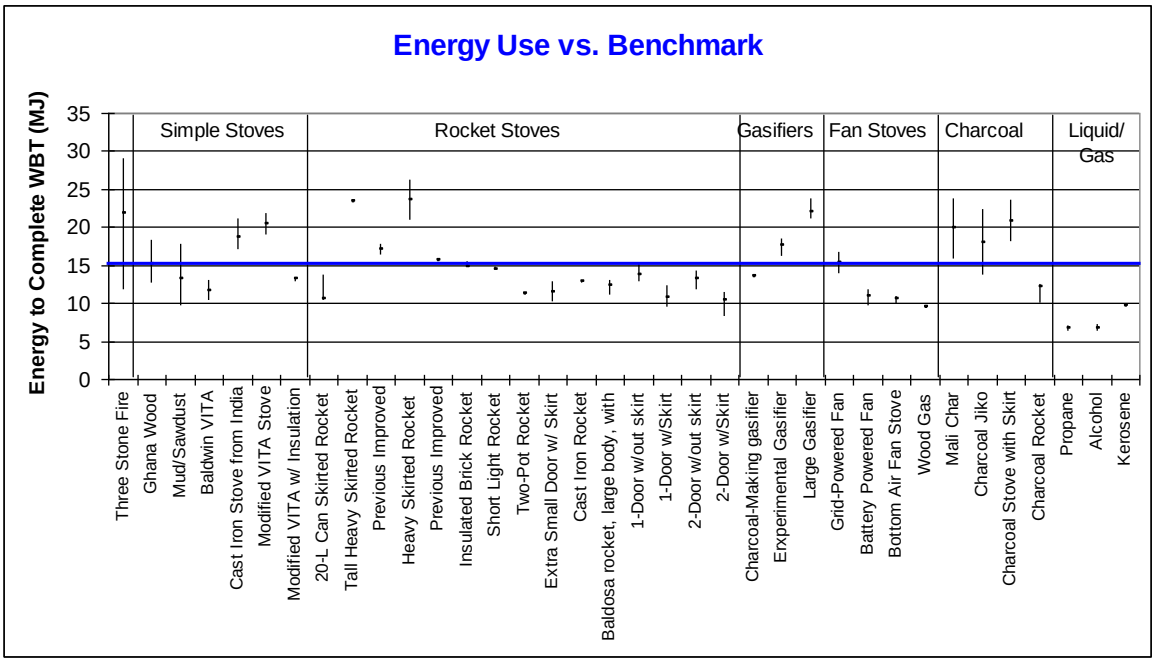


Figure 4: Sample from ARC's Stove Test Library



OBJECTIVE 2: Complete the preliminary design of one or more prototype stoves that meet the DOE 50/90 standard.

OUTCOMES:

- ARC developed six prototype biomass-fueled cook stoves that either met or are close to meeting the DOE 50/90 benchmark. The six stove prototypes, close to manufacturing specifications, were fabricated at SSM, ARC's partner factory in China. (See Figure 5 below).

These prototype designs are the:

1. Top-Loaded Fan Stove (Tom Reed)
2. Side-Feed Fan Stove
3. TLUD Lantern Stove
4. Sunken Pot Chimney Stove
5. Four Stick Rocket Stove
6. Can Charcoal Stove[8]

Figure 5: Six ASAT Prototype Stoves

[8] Please note: during Phase I, ARC developed a charcoal stove that was very low for PM and fuel use but did not reduce CO by 90%, therefore it did not meet the DOE 50/90 standard and move forward into Phase II. However, market studies have shown that a low cost, cleaner and more fuel efficient charcoal stove is the product most desired by urban consumers in many developing countries around the world. A very low PM charcoal stove might be used by ASAT as a loss leader to open market entry and encourage DOE 50/90 stove purchases.

- Stove technology breakthroughs included: 1) changes to the fan stove design that force low volume, high velocity jets of air to enter the combustion zone from under the fire resulting in close to 100% combustion efficiency; 2) a 'governor' was invented for the natural draft Rocket stove that results in cleaner combustion by metering the fuel more successfully; 3) the Top Lit Up Draft stove design was modified to include a lantern that lights up the kitchen while food is being prepared; 4) New refractory ceramics were tested by ARC and manufacturing partner, SSM, and found to be a durable and affordable alternative stove material that reduces overall stove costs by 50%; and 5) The concept for a diverter valve to direct smoke up the stove's chimney before the pot is removed.

OBJECTIVE 3: Demonstrate that the prototype design meets the DOE 50/90 standard in laboratory and in-field studies including analysis of commercial viability.

OUTCOMES:

- Consumer testing was conducted in Puerto Rico and at the StoveTec store in Eugene, Oregon.
- Three DOE 50/90 stoves were identified as market viable in consumer tests. These three stoves include the Sunken Pot Rocket Stove with Chimney, the Side Feed Fan Stove, and the TLUD Lantern Cookstove. (Figures 6-8 below)
- In March 2013, ASAT initiated the first phase of the manufacturing process for the first DOE 50/90 prototype stove, the Sunken Pot Rocket Stove with Chimney that will be developed for commercialization during Phase II.

Figure 6: TLUD Lantern Test Results

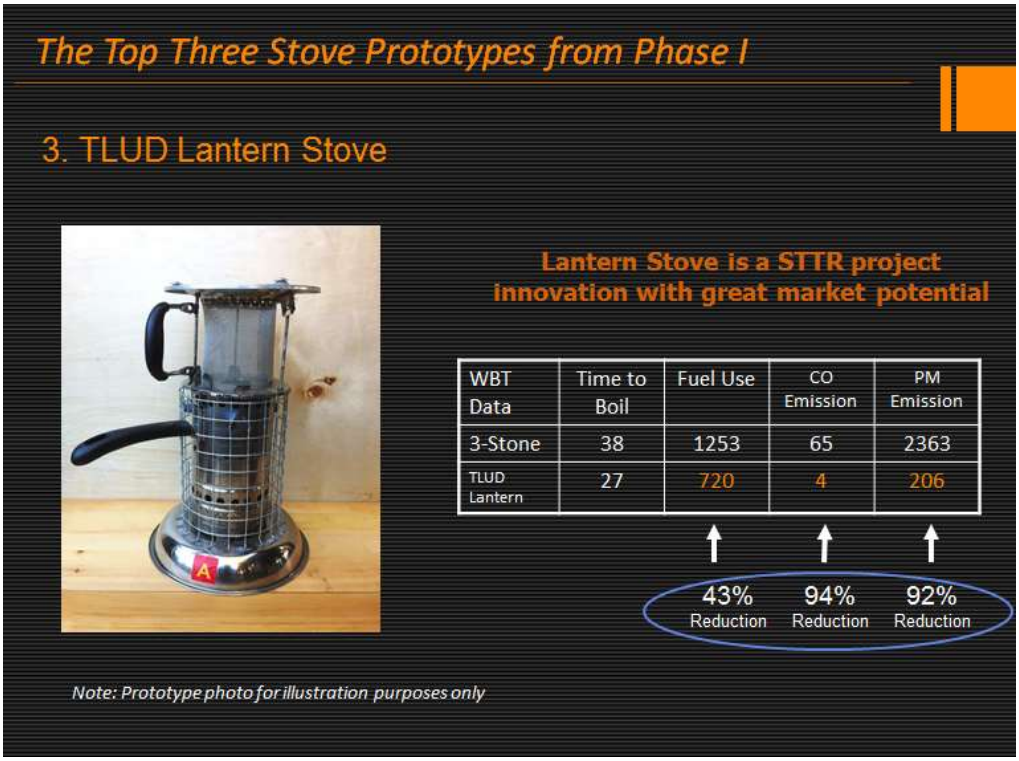


Figure 7: Sunken Pot Rocket Prototype

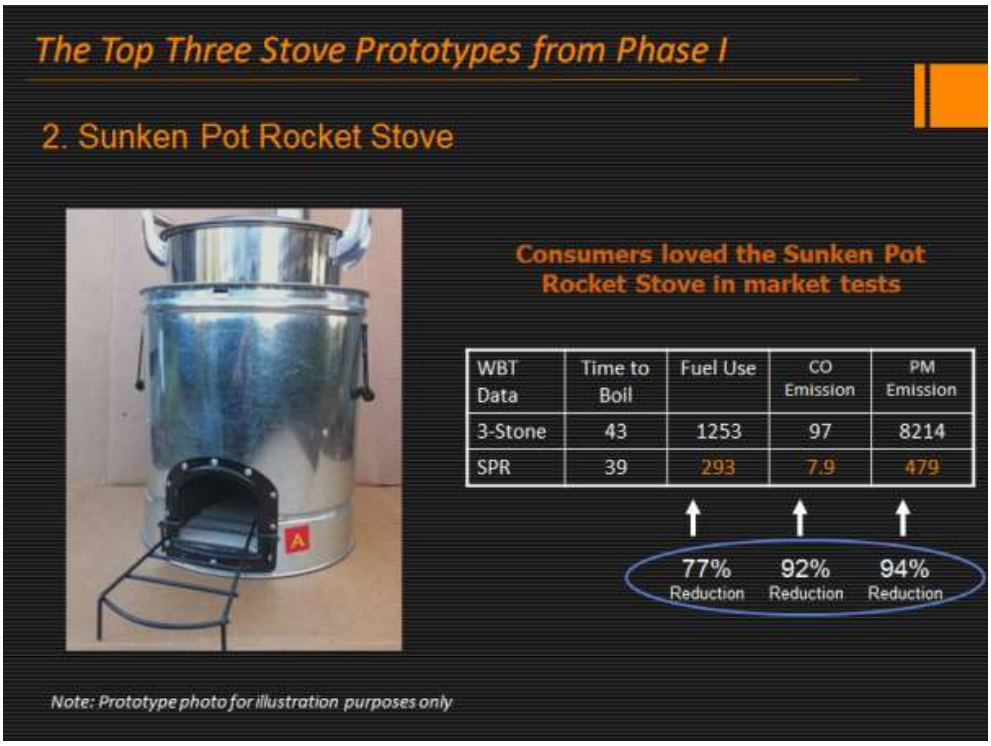
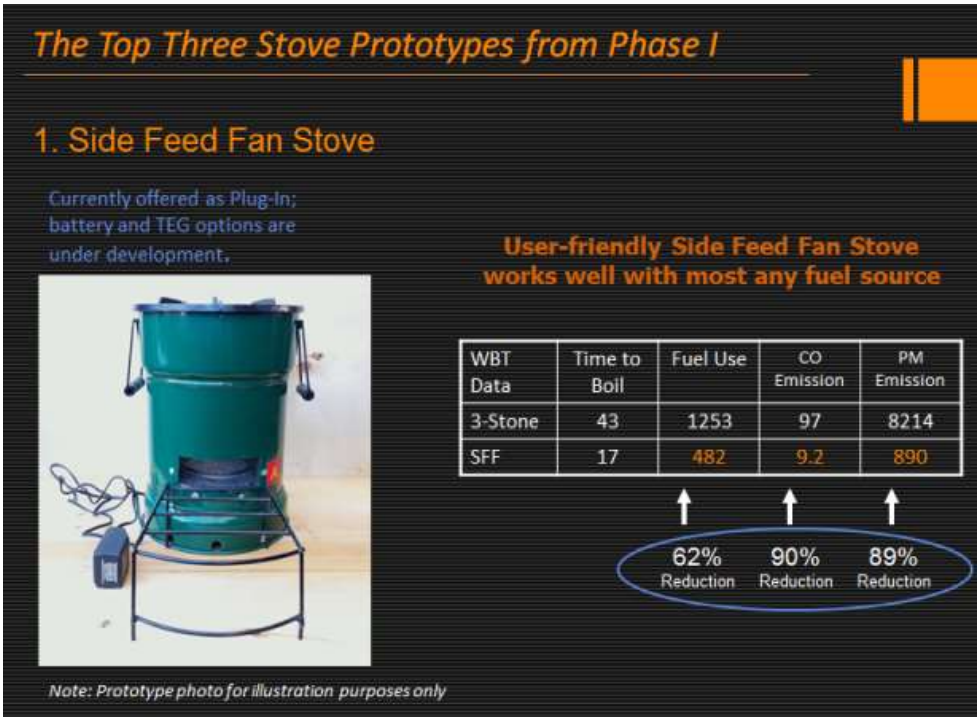


Figure 8: Side Feed Fan Stove



OBJECTIVE 4: Document the measurement and evaluation protocols and methodology used in developing the prototype stove(s).

OUTCOMES:

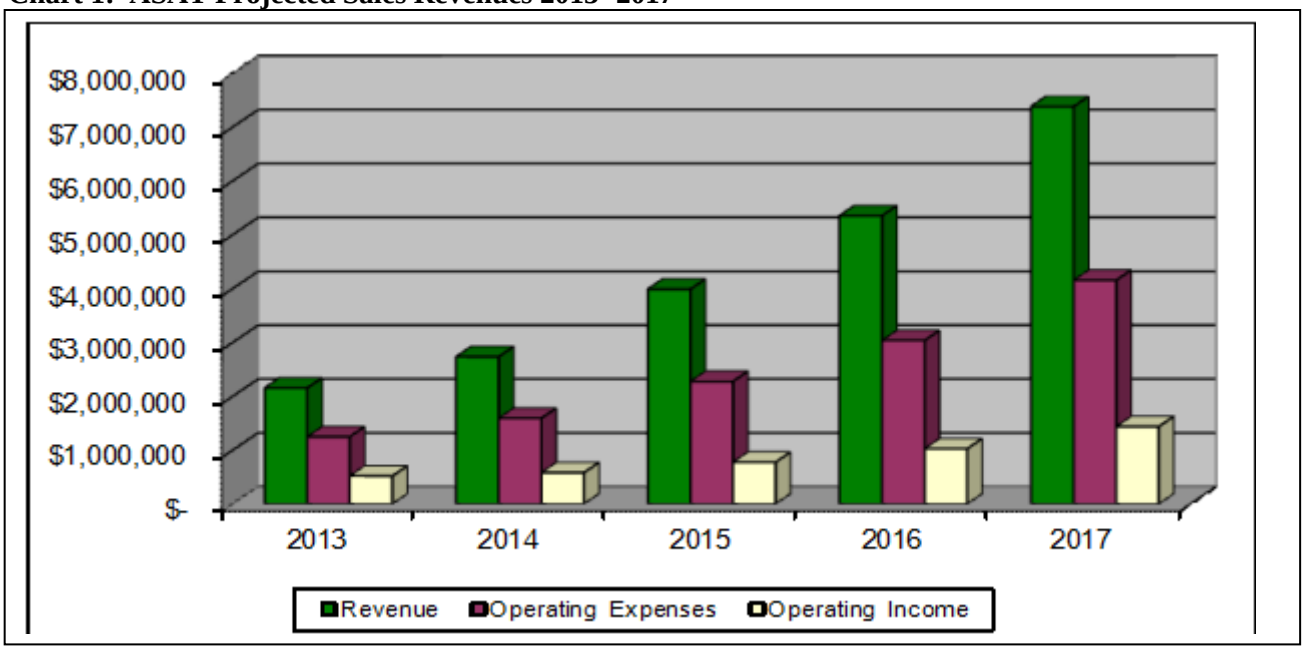
- ARC engineers kept extensive records of all test results, evaluation protocols, and methodology used during the prototype development process.

OBJECTIVE 5: Complete an initial commercialization plan that describes major milestones that will lead to production in Phase II of the prototype stove designs developed in Phase I.

OUTCOMES:

- ASAT conducted extensive research and identified seven primary markets for cookstoves: the U.S., China, Thailand, Mexico, Peru, Ghana, and Kenya.
- A five year commercialization plan was prepared (Please see Commercialization Plan section of grant application). Table 1 below shows expected increase in annual sales revenue for stove and emissions equipment products over the next five years.

Chart 1: ASAT Projected Sales Revenues 2013 -2017



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COMPARISION OF ACCOMPLISHMENTS TO PROJECT GOALS: IMPROVED EMISSIONS MONITORING EQUIPMENT

Background

Equipment that accurately quantifies pollutant emissions in both the laboratory and the kitchen is required for development of the new generation of cookstoves, as precise measurement of emission rates for new designs in the laboratory and ultimately during real-world use is necessary to verify achievement of the DOE 50/90 benchmark. With hundreds of cookstove projects in operation globally, there is a critical need for inexpensive and accurate equipment capable of easy use by in-field investigators in a variety of conditions around the world.

Demand exists for portable equipment to measure real-time cookstove emissions in the field. This equipment is crucial for measuring indoor air pollution (IAP) and personal exposure concentrations. It is also needed to measure total stove emissions such as CO, CO2, and PM. To solve this problem, ASAT's research partner ARC has designed and now manufactures with ASAT two products on the market that are designed specifically for biomass cookstoves, that can measure all three major emissions components (CO_2, CO, and PM), and that can provide the measurement data in one compact file for quick and easy analysis. These products are the Indoor Air Pollution Meter (IAP Meter), which is designed specifically to measure IAP and personal exposure concentrations, and the Portable (or Laboratory) Emissions Monitoring System (PEMS and LEMS), which are designed to measure total stove emissions.

In Phase I, ongoing improvement of the accuracy and usability of the ASAT testing systems already in use by projects worldwide was completed: the Portable Emissions Measurement System (PEMS) for in-field pollutant capture and measurement, and the Indoor Air Pollution (IAP) Meter for personal exposure or in-home air quality monitoring. A new type of equipment was developed: the Laboratory Emissions Measurement System (LEMS) for detailed research at testing centers and laboratories. Additional major improvements to the equipment included the addition of gravimetric PM measurements to the LEMS and PEMS, a CO_2 sensor and wireless 3G data transmission capability added to the IAP Meter, and improved sensors and signal quality on all systems. Documentation and training materials were refined, and a commercialization plan was drafted. Like the stoves, the emission equipment is commercially viable, robust, and a proven technology enabling the evaluation of emissions performance of any kind of cooking stove.

Objectives and Accomplishments

OBJECTIVE 1: Complete a study on the performance of existing emissions monitoring and testing technologies, and user needs and preferences.

OUTCOMES:

- ASAT and ARC engineers conducted a comprehensive study of available emissions equipment suited to cookstove testing. They found that while there are several high-accuracy monitoring options available, most are highly sophisticated, costing over USD $100,000 and involving several levels of operational complexity. Most of these products are not designed specifically for evaluating improved cookstoves and therefore require significant expertise and alterations for operation with the concentrations seen in cookstove emissions.
- Research further indicated that while there are several products available that are capable of measuring cookstove emissions in the field these products have varying degrees of portability, affordability, and usability. It is possible to combine these products into a complete system that

can measure and log CO_2, CO, and PM. However, a technician must possess significant knowledge and expertise to not only assemble an appropriate system, but to also process and combine the distinct sets of data from each sensor for analysis.

- It was determined that the ASAT emissions equipment is unique within the market place in that it is specifically designed for:
    - Easy operation with little experience;
    - Measurement of three major air pollutants at levels appropriate to cookstove emissions;
    - Output of a single file of data with specialized processing software to directly report measures of interest to cookstove researchers.

OBJECTIVE 2: Improve the Portable Emissions Monitoring System (PEMS), Laboratory Emissions Monitoring System (LEMS) and Indoor Air Pollution (IAP) Meter equipment to achieve the goals of greater affordability, accuracy, durability, wireless capability, and ease of use.

OUTCOMES:

PEMS/LEMS Improvements

- The Laboratory Emissions Monitoring System (LEMS) was developed, which is a stationary system that includes a longer exhaust sampling duct, external blower, large metal hood, and gravimetric PM system to meet all IWA/ISO testing specifications. (See Figure 1 below).

Figure 1: New LEMS in Use for Stove Testing

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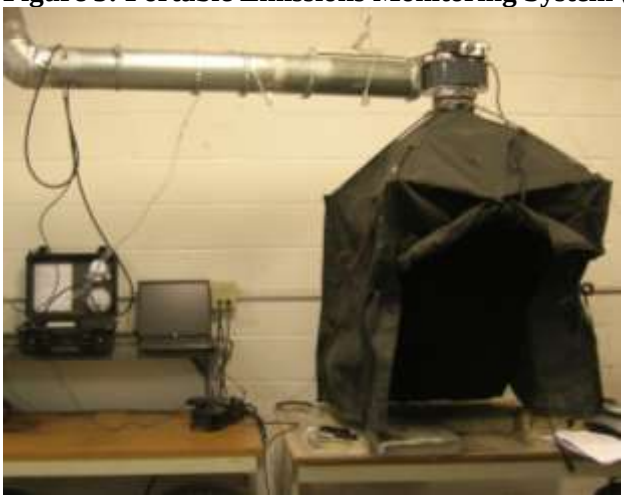
- A high-flow gravimetric pump and filter collection system was designed and installed to complement the laser light scattering PM measurement system. (Aprovecho is currently writing a paper for publication later this year about the correlation between the LEMS gravimetric and light-scattering PM sensors.) This system is now available to customers and allows pre-and post-weighing of the filter to be done on site with an affordable micro-scale. This accomplishment enabled the Regional Testing and Knowledge Centers (RTKC) established by the Global Alliance for Clean Cookstoves to use equipment that meets the IWA/ISO testing requirements. As a result, almost all of the twelve new RTKCs have purchased the new LEMS, making accurate and consistent stove testing possible in these labs for the first time. (See Figure 2 below).

Figure 2: New Gravimetric Pump and Filter System

- The maximum allowable stove size and maximum emissions output was increased.
- The sampling accuracy in the duct/fan system was increased via a study of flow profiles in the ductwork with optimized length and location of straight sections to increase accuracy of flow and sampling measurements.
- Electrical interference was mitigated in the PEMS/LEMS. A kit was assembled to address electrical noise problems in the field. (See Figure 3 below).

Figure 3: Portable Emissions Monitoring System (PEMS)



IAP Meter Improvements (See Figure 4 below)

- An LED-based low power CO_2 sensor was integrated, allowing for potential indication of in-field CO/CO_2 ratio, combustion efficiency, and stove operational firepower.
- A survey of relative humidity and temperature sensors was completed, and a high quality single chip unit was chosen and integrated into the IAP Meter.
- A cellphone network-based data uploading system was designed and tested, including a web-based interface for remotely viewing data to allow for reduced legwork and invasiveness in field studies.
- A survey of micro-fans was done, and an ultra-quiet version was chosen and integrated for quieter operation in homes.
- The power management system was redesigned so the microprocessor could actively control power to all subsystems. This increased the battery life from 7 days to 39 days.
- A battery level indicator was added to the meter.

Figure 4: Improved IAP Meter with Wireless Capability

OBJECTIVE 3: Complete an initial commercialization plan that describes major milestones that will lead to production in Phase II of the emissions equipment developed in Phase I.

OUTCOMES:

- Through networks such as the GACC and existing university partners, ASAT identified hundreds of NGO's, government and university entities that could benefit from emissions testing equipment.
- An aggressive marketing and outreach program is planned to reach those who would most benefit from the equipment.
- Strategic partnerships with some of the largest promoters of improved stoves, such as GIZ, Global Alliance, and The Chinese Alliance for Clean Cookstoves has led to a well-developed roadmap to market the emission monitoring products.

Summary

There is a significant need and market for improved cook stoves that meet the DOE 50/90 criteria, and the emission measurement equipment necessary to develop and confirm that they do so. ASAT is in a unique position, due to strategic partnerships with ARC and SSM, to develop and manufacture and sell improved stove designs and emissions measurement equipment to meet this need. To do so, ASAT surveyed presently available products and applied R&D and the iterative design process to develop high-performance, user-friendly, affordable products. As a result, the new 50/90 stoves are in pre-production and the ISO compliant emission equipment is now being manufactured by ASAT. Eleven LEMS have been purchased by the new Regional Testing and Knowledge Centers funded by the Global Alliance that are required to use gravimetric measurement of PM. Without the work completed in Phase I the vital purchase of needed emission equipment by the worldwide network of Centers could not have occurred. Laboratory and market testing have resulted in three new DOE 50/90 stoves that will be sold in North America at a substantial profit capitalizing the market entry into the most promising developing world countries: China, Thailand, Mexico, Peru, Ghana, and Kenya without the need for further subsidy.

PRODUCTS DEVELOPED AND TECHNOLOGY TRANSFER ACTIVITIES UNDER THE AWARD

Publications, Conference Papers, or Other Public Releases of Results

1. "Charcoal Stove Comparison" *Energy for Sustainable Development,* Volume 12, Issue 2. With the improvements made to the emissions equipment under this grant, ARC was able to accurately quantify the emissions of 16 charcoal stoves, documented in this article.

Networks or Collaborations Fostered

Networks and collaborations include but are not limited to:

- Global - The Global Alliance for Clean Cook Stoves, GIZ, Burn Design, EcoZoom, Mercy Corps, SNV, GERES, and WFP
- Central/South America
    - HELPS International
    - Trees, Water, People
    - StoveTeam International
    - Proyecto Mirador
    - Ambiental PV (Brazil) – Experts in Carbon Credit. Distributing Justa Stove project now and looking to expand into single pot stoves
    - Estufas Delgado Hermanos (Mexico) – Provides Mexican homes with high quality inexpensive stoves to improve the quality of life.
    - Zamorano University (Honduras)
    - Chemonics (Haiti)

- Asia
    - Mercy Corps and Dili Institute of Technology (DIT) (Timor-Leste)
    - Prakti Design Labs (India)
    - GERES (Cambodia)
    - SNV (Vietnam and Lao)
    - Centre for Rural Technology (CRT) (Nepal)

  - Shengzhou Stove Manufacturer (SSM) and Beijing University of Chemical Technology (BUCT) (China)
  - Asia Regional Cookstove Program (ARECOP) (Indonesia)

- Africa
  - Ecozoom
  - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
  - CSIR - Institute of Industrial Research (Ghana)
  - KIRDI - Kenya Industrial Research and Development Institute
  - CREEC (Uganda)
  - CERER - UCAD University Dakar Senegal
  - SUN Energy (Ethiopia)
  - ICEED (Nigeria)
  - Sea Quest - large scale carbon market stove distribution (Malawi)

Technologies/Techniques

1. A Combination Lantern and TLUD Cook stove
2. A Top Loaded Fan Stove
3. A Side Fed Fan Stove
4. A Sunken Pot Rocket Chimney Stove
5. A Side Fed TLUD Fan Stove and
6. A New Generation Charcoal Stove
7. Improved Portable Emissions Measurement System (PEMS)
8. Laboratory Emissions Measurement System (LEMS)
9. Improved IAP Meter with CO_2 and Wireless options

Inventions/Patent Applications, Licensing agreements and Other Products

- Improved Software processing software for PEMS, LEMS and IAP meter
- Improved Manuals for PEMS, LEMS and IAP meter
- 4 week training curriculum and certification program for stove testing, stove design, and equipment use.