THE SCORE PROJECT: STOVE FOR COOKING, REFRIGERATION AND ELECTRICITY

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ABSTRACT

This paper provides a description of the SCORE Project which is being funded by the Engineering and Physical Sciences Research Council, UK, and particularly the work at City University whilst acknowledging the contributions of all partners. The project, which is still underway, concerns the development of an electricity generating thermoacoustic engine which is driven by the heat of a cookstove for application in developing countries.

There is a significant level of innovation in the work in three respects: 1) research into the combination of the thermo-acoustic engine, linear alternator and cool box in a single device, powered by a biomass cooking stove, never attempted before, 2) design of a rugged and inexpensive linear alternator that could be easily produced at very low cost, 3) use of local manufacturing skills and simplicity of assembly, which are major research issues compared to the high-cost and high-tech therm-oacoustic systems produced so far. These challenges form the backbone of the scientific and technological work program. Within the overall 5-year duration, the first 3 years have been mainly focussed on conducting the necessary social and scientific research, while the last 2 years will broadly focus on technology handover, including representative field trials and a wide dissemination among target communities. By the end of the 3rd year a milestone was achieved, the world's first demonstration of a working thermo-acoustic engine operating in a wood fired cookstove.

INTRODUCTION

The SCORE consortium project has the aim of significantly improving health, quality of life, economic growth and social and educational opportunities in order to reduce poverty in Africa and Asia. The key to the project is the development of a low cost thermo-acoustic engine which is able to convert heat from a biomass cookstove to electrical power whilst providing heat for cooking. It includes understanding the energy needs of rural communities and working with them to develop the capability to manufacture an affordable versatile domestic appliance. The partnership brings together four UK universities, a leading US research centre (Los Alamos National Laboratory), a multi-national electrical goods manufacturer, an international charitable organization, Practical Action and numerous universities in Africa and Asia [1]. The collaboration is to ensure that the devices are acceptable at a technological, economic and social level and that there is sufficient scope for the communities to develop numerous businesses from the manufacture, repair and innovative applications of SCORE.

Electricity generation is based on a novel application of thermo-acoustic processes. Basically, these rely on the interaction between an acoustic field and solid boundaries, leading to a range of fluid- and thermo-dynamic processes, which do not require harmful working fluids or moving parts in the traditional sense; the electrical power extraction is accomplished by a linear alternator. The concept of the device is based on the proven thermo-acoustic Stirling engines and refrigerators developed by Los Alamos and the US military for applications including: cooling of satellite systems and radar arrays, gas liquefaction and cryogenics, use of waste heat for air conditioning, separation of binary gas mixtures and many others.

ROLES OF THE SCORE TEAM

This section briefly outlines the roles of the groups comprising the SCORE consortium:

The Electrical and Electronic Engineering Group at University of Nottingham has an international reputation for improving electrical motor drive efficiency and developing instrumentation methods and magnetic circuit modelling. It is responsible for overall leadership of the project and also in using its expertise to develop the electricity generation system.

City University, London with its Energy and Transport Research Centre and its links with Developing Technologies, a charity involved in providing technical support to alleviate poverty in developing countries, is responsible for stove design and in the development of the final output of the project, a SCORE prototype that is appropriate to the needs and resources of families in developing countries.

Queen Mary, University of London, has particular expertise in combustion and heat transfer and is responsible for heat exchanger design and also for overall prototype development. The School of Mechanical, Aerospace and Civil Engineering of the University of Manchester is a department known for its numerical and experimental thermo-fluids and aero- and thermo-acoustics research. It is providing the lead on thermo-acoustic research and development for the project. Practical Action is a non-governmental organisation, with a vision of a world free of poverty and injustice in which technology is used to the benefit of all. It is renowned for its international development work through the regional and country offices in Peru, Kenya, Zimbabwe, Sri Lanka, Sudan, Bangladesh and Nepal. It helps to eradicate poverty in developing countries by achieving socio-economic, financial and environmental sustainability, developing and using appropriate technology, demonstrating results, sharing knowledge and influencing others, including dissemination of research results of small-scale energy generation systems for developing countries. It provides guidance on the appropriateness of SCORE to target users in developing countries and will take a lead role in the field-testing of prototypes and dissemination of the technology.

PROPOSED RESEARCH AND ITS CONTEXT

Socio-economic issues

Over 3.3 billion people in the developing world live in rural areas, 2.4 billion use biomass for cooking and about 2 billion are without access to electricity, the great majority of them being rural people. The picture in Figure 1 shows a typical way of cooking on an open fire in Central Africa.

Figure 1 - Typical way of cooking in central Africa

The majority of these stoves are highly inefficient, forcing local people to spend a significant proportion of the day foraging for fuel, thus reducing the time available for education and other activities that could increase their wealth and well-being. Even when time is available, education in these regions is poor because they lack electric power for lighting to allow children to perform their homework in the evenings, or for schools to use the computers that aid organisations are willing to donate. Health care is often many days walk away, and care within the local community is hampered by not having refrigeration to store vital medicines [2]. Current contenders to meet the electrical needs are photo-voltaics, thermopiles, and hand or foot cranked mechanisms, but lighting is commonly provided by wax candles and kerosene lamps. The first two contenders do not currently meet the cost target, leading to a small penetration depth, while the remaining ones generate small amounts of power and/or lighting. Practical Action has been promoting small-scale renewable energy systems in Asia, Africa and Latin America for more than two decades and is convinced that affordability and sustainability are big barriers to the access of people to improved energy services. Their research indicates the current cost of a device, capable of producing 25W peak electrical power for a family dwelling, is around $500 (£275), while an acceptable economical level would be an order of magnitude lower (around £25), and proportionally more for a larger installation such as a school or health centre. A REFERENCE IS NEEDED HERE – PAMELA PLEASE REFERENCE SOURCE

Earlier investigation has shown that there are many social challenges to introducing new stoves in the developing countries. Acceptability depends on a wide variety of parameters and these differ from country to country. For instance, smoke inhalation from wood burning stoves is a major health risk and yet in some communities smoke-free stoves would not be easily accepted due to smoke being used as a means of keeping insects outside the dwelling. However, by far the biggest factor is cost.

It is apparent from the above that there is a strong case for designing, developing and disseminating an integrated device comprising a biomass fuelled cooking stove with an electricity generator and a refrigeration function, with appropriate levels of stove efficiency, smoke exposure and above all cost. This is particularly so if there is an incentive of increasing wealth and education of the communities and providing employment and business opportunities through the use of local skills and labour in the manufacture process.

Thermo-acoustic technology

Meeting the needs of the rural communities and working with them to find appropriate technology solutions is paramount in projects like this. The preliminary studies leading up to this proposal, and discussions with Practical Action, suggest that by far the most promising are thermo-acoustic technologies, which have a potential for a step change in domestic and communal appliances in terms of practicality, maintainability and cost.

By way of introduction, thermo-acoustic is briefly reviewed below. The first documented experiments in thermo-acoustic are those of Byron Higgins in 1777 **Reference needed**, who demonstrated a spontaneous generation of sound waves in a pipe by the appropriate placement of a hydrogen flame inside it. A century later Lord Rayleigh **Reference** explained the phenomenon qualitatively, on the basis of a phase difference between the periodic wall-gas heat transfer and gas displacement coupled with gas compression. In the 1970s' Ceperley **Reference** postulated that an acoustic wave travelling in a resonator equipped with a regenerative heat exchanger could cause the gas to undergo a thermodynamic cycle similar to that in a Stirling engine making the thermo-acoustic effect applicable in novel types of refrigerators or prime movers. Such systems are attractive for two main reasons: (i) they are inherently reliable due to the lack of moving parts, except electro-dynamic transducers (alternators) to convert between acoustic and electrical energy and (ii) the working fluids are typically inert gases, which eliminates the need for toxic, flammable and ozone depleting CFC or HFC substances, and pressurised air can be considered for low cost systems. Figure 2 shows a schematic of a quarter-wavelength, standing wave device working as a refrigerator thanks to the acoustic power input [3].

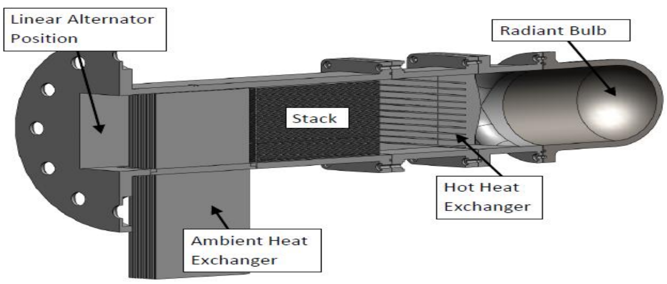

Figure 2 - Design concept for a standing-wave engine.

Central to the device's operation is a thermo-acoustic "stack". This can be imagined as a series of plates forming a set of parallel channels. The gas pressure in the resonator oscillates acoustically at a frequency set by the resonance between the gas in the duct and the moving mass of the transducer. The oscillating gas communicates heat with the stack and heat exchangers, and the acoustics of the system ensure that the timing between the pressure and gas displacement is such that heat is pumped out of the cold heat exchanger towards the hot heat exchanger, using a hydrodynamic energy transfer "cascade" enabled by compressing and expanding gas parcels. It is also possible to reverse the operation of such systems to form an engine: a high temperature gradient along the stack leads to a spontaneous generation of acoustic power which can be converted to electricity by a linear alternator. More complex systems can be built utilising the concept of "travelling wave" devices which are not discussed here for simplicity [2].

The detailed physics and state-of-the-art in thermo-acoustic are covered in a substantial review and recent monograph **Reference.** By the undisputed leader in this technology, Los Alamos National Laboratory, which has developed a number of practical systems including electricity generators and combustion-powered liquefaction of natural gas. However there is a growing interest in this technology in China, Japan, France, the Netherlands, and the UK.

Project definition and philosophy

The overarching theme of the proposed SCORE programme is to devise an affordable domestic appliance that, through its functionality, versatility and ruggedness, would address an array of social, economic and educational needs in rural communities in the context of energy supply. Viewed from this perspective, the programme has two strands of activities.

The first strand will comprise of socio-economic, cultural and technological research to explore the needs and opportunities existing in the communities, the manufacturing skills, technologies and indigenous materials available to the local people, as well as the acceptability criteria for new technologies. The implementation stage, on the other hand, must focus on dissemination of the technology developed under the scientific part of the programme, educational activities and field trials in the model target communities. The success of these activities will rely on the direct involvement of Practical Action (micro finance, "on the ground" experience etc), local academic and/or government institutions and target communities. The objectives of this strand are as follows:

1. Contribute to increasing wealth and education and improving health in developing countries by investigating appropriate and affordable novel technology to meet the energy needs of isolated rural communities in developing countries. This technology is designated, SCORE, the Stove for Cooking, Refrigeration and Electricity supply.
2. Develop a Project Network, comprising academics from both the research team and local universities acting as knowledge hubs in the target countries, charities and non-government organisations, government representative and the local communities themselves. Exchange and focus the scientific, technological and social knowledge required by SCORE. Promote SCORE worldwide and provide a database of end-user requirements and product applications
3. Plan and create the mechanisms for implementation of SCORE by identifying barriers to implementation and proposing solutions, forming collaborations within the developing countries, developing training strategy and suitable training materials, encouraging the acquisition of matching funding, promoting the building of local manufacturing capacity, and highlighting the wider business opportunities of SCORE in developing countries.

The second strand of activities will comprise the fundamental scientific research, technology development and engineering design and implementation. It is proposed to take as a starting point the existing concepts of thermo-acoustic systems, for which cost was not a significant issue, and devise a low-cost integrated system whereby a high efficiency, smoke-free (or low-smoke) cooking stove, fuelled by biomass, would provide necessary thermal energy to drive a thermo-acoustic engine, producing electricity via a linear alternator and enabling thermo-acoustic refrigeration. The objectives of this strand are:

1. Capture and evaluate the underpinning scientific knowledge of thermo-acoustic technologies and devise a new engineering concept combining the thermo-acoustic engine, electrical generation and refrigeration. Integrate these in a technology demonstrator.
2. Study heat transfer processes in combustion and thermo-acoustic systems and devise a high-efficiency, integrated combustor/heat exchanger/stove unit, capable of fulfilling its cooking function and providing the energy to the thermo-acoustic element. Evaluate its performance by experimentation and integrate it into a technology demonstrator.
3. Devise through interdisciplinary research an inexpensive method to convert acoustic energy into electricity that could be easily mass produced and evaluate its performance.
4. Study the manufacturability, cost and the potential of using indigenous materials and local skills and based on the technology demonstrator, to design feasible SCORE prototypes, which could be field tested at selected locations. Build and demonstrate the prototypes in selected rural communities.
5. Benchmark the design against other technologies and recommend future development paths, research and applications.

The scientific and technological programme is innovative in the following: (i) the level of system integration is not trivial, both from the viewpoint of a multi-functional thermo-acoustic device and the combustor/heat exchanger/stove design and this has not been performed before; (ii) the low-cost alternators of reasonable acoustic-to-electrical efficiency (upwards of 50%) are not readily available: the target price of £5-10 is not a trivial requirement (iii) substantial gains over open-hearth practices can be made in the thermal efficiency of the combustor and stove; one comparative study has shown that very simple stoves can be twice as efficient as open-hearths, while still only having an efficiency of 25%; (iv) the imposed low cost of the system (around £25 for 25 W of electrical power) poses a tough engineering and technological challenge in finding appropriate implementation technologies for SCORE.

The diagram in Figure 3 outlines one possible functional implementation of the proposed device.

These sections should have a reference to the SCORE literature from which the information is taken, including acknowledgement of the source of Figure 3

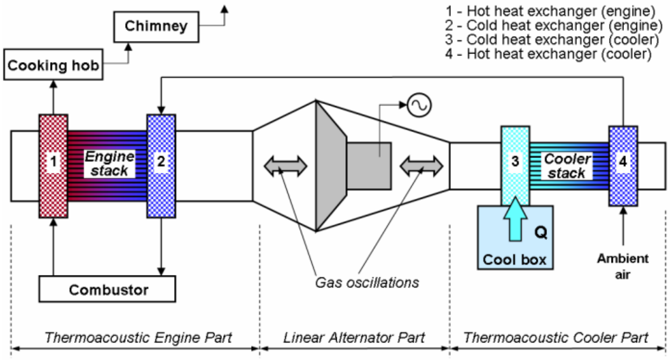

Figure 3 - Possible functional implementation of the proposed device.

It is based on a half-wavelength standing wave resonator, which combines a quarter-wavelength engine part, a linear alternator (to extract part of the acoustic energy as electricity) and a quarter-wavelength refrigerator (cooler) part. The only moving mechanical part is the linear alternator. In practice this standing-wave arrangement is likely to be replaced by a travelling-wave system (a thermo-acoustic equivalent of a Stirling cycle) resulting in a higher efficiency device but with higher geometrical complexity. Helium is clearly not an option in a developing country, and it is preferred to operate the thermo-acoustic system using non pressurised air such that small leaks do not cause a problem.

The external ambient air stream handles all of the external heat transfer functions. After removing the heat from the refrigerator's ambient side, the airflow passes into the ambient side of the engine stack absorbing more heat and into the combustion chamber where it oxidises the fuel. The hot flue gases flow through the engine's heat exchanger and cooking element, providing the necessary heat to both, and out into a chimney. The buoyancy of the hot gases in the chimney induces the circulation of air through the path just described. In order to achieve the necessary heat transfer from the flue gas, the heat transfer to the acoustically oscillating air in the duct must be understood. It may be possible to simplify and even enhance the external heat transfer function by utilising recently developed self-circulating thermo-acoustic heat exchangers. **Reference needed**

Electricity could be used directly or stored using battery systems in any of the implementations mentioned here. The latter may be desirable when there are time differences in the demand for cooking and electricity. This discussion simply illustrates that there is a significant spin out potential for the work proposed under the current call; that there is a considerable inherent flexibility to augment the "baseline concept" to meet more specific needs of rural communities following their specific feedback; and that there could be a significant amount of the follow-up research, preferably to be conducted in the academic institutions of developing countries under any matched funding that SCORE will be able to attract in the future.

The research team believe that, because of its improved stove efficiency and added functionality of electricity co-generation and refrigeration, a successful SCORE device will be an attractive purchase for many households. This will lead to improving health (e.g. reduced smoke inhalation, storage of medicines), education (e.g. use of radios and computers, light for reading) and comfort of living (e.g. reduced fuel foraging time, refrigeration of food products). It will also have desired effects on the rural communities in creating employment opportunities in local businesses which would manufacture and service the SCORE systems, but also by creating spin out specialised businesses such as battery charging or producing ice. Availability of electricity and refrigeration would also reduce the migration of skilled and educated individuals (technicians, doctors, nurses) outside the communities which they could serve.

STOVE TESTING

The initial concept for supplying heat to the thermo-acoustic engine is by radiation from a 300mm diameter stainless steel disc placed at the top of a combustion chamber in which wood is burnt. To achieve the heat transfer required of 2kW it is therefore imperative to maximise the temperatures of the flame and combustion walls. This has been a main focus of the initial research programme at City University. A secondary aim has been to achieve efficient cooking with a target of boiling 3l of water in 15 minutes. The stove specification aims to achieve these targets using 30% less wood than used by an average family in traditional cooking, a target of around 1.2kg per hour. The following section outlines the test programme to date.

Test stove

The stove used for tests has been designed for construction in developing countries and efforts have been made to ensure that all the materials used are freely available. It is based upon the rocket-stove principal [4]. with an L-shaped combustion chamber and is similar in design to the improved Lorena stove that is widely found in Central America..

The Lorena adobe stove was designed as a simple-to-build cook stove for use in Central America, one that could be manufactured locally using local materials. The name of Lorena stove comes from the combination of the two Spanish words lodo and arena (meaning mud and sand) as the stoves are basically a mix of the two. It is an enclosed stove of rammed earth construction, with two cooking pot positions and a chimney that takes smoke out of the kitchen. It has become very popular in Central America, with evidence suggesting that it is the most popular improved cooking stove in the region.

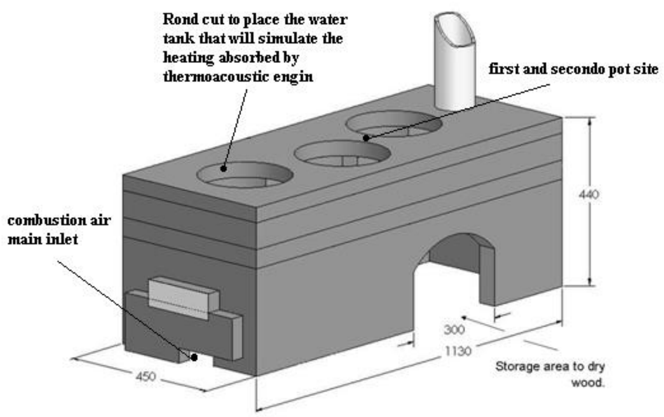

Figure 4 – Test stove.

The SCORE test stove is shown in Figure 4. The main difference from the Lorena stove is that there is an opening directly above the combustion chamber where the thermo-acoustic engine is located. As mentioned above the top of the combustion chamber is sealed with a radiating stainless steel disc and the combustion gases are exhausted horizontally through a channel from the top side of the chamber to flow around the two recessed cooking pots and then up the chimney. Although the direct contact between the gases and the cooking pots gives efficient heat transfer it means a fixed pot size has to be used and this is an issue that needs to be further investigated.

An essential aim of the stove design is to reach the threshold temperature at which the thermo-acoustic effect initiates in the shortest possible time. Using high mass materials such as mud for the stove is therefore not appropriate and research has been carried out into low thermal mass materials that might be used for construction. The test stove is constructed largely from a mixture of vermiculite (80%) and cement (20%) which produces a lightweight composite of 0.7 specific gravity with good compressive strength. However, it has a temperature limitation of around 600^{o}C and therefore the combustion chamber was made of tiles of 50% fireclay and 50% vermiculite. These showed crumbling of the surface in contact with the flames after a few tests and a 5mm thick coating of fireclay was applied which has proved quite durable. Not all of these materials may be available in all target countries and further research is going on to find alternatives.

In order to achieve the consistent high accuracy of construction needed for the SCORE stove, it has been cast in 4 sections (Figure 5). This has and will require the construction of simple moulds from plywood and other available materials. As indicated above the stove body needs to be made of lightweight material to minimize thermal mass and the amount of heat that goes into heating the stove body. It also needs to be robust so that it has a life of several years without cracking or crumbling.

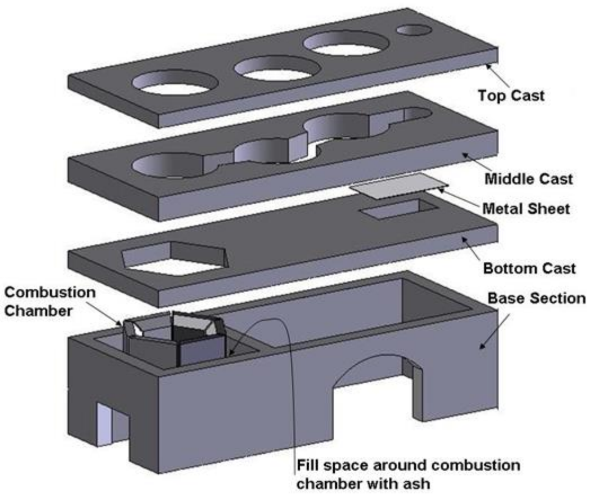

Figure 5 – Test stove layers.

Test Procedure

During the tests the thermal load of the thermo-acoustic engine was simulated by a steel tank containing 20l of water. The tank was well insulated to minimize heat loss and the rise in temperature of the water used to measure the heat flow from the radiating disc. As mentioned above the target rate was 2kW. The cooking performance of the stove was measured from the temperature rise of 2l of water in each of the cooking pots.

Tests were run over a 1 hour cooking cycle with a controlled rate of wood combustion of 1.5kg/hour. A door fitted over the wood inlet to the stove included an opening that could be varied to control the air inlet to the stove. The air passed under a steel plate heated by conduction from the stove to provide some preheating of the air before passing up through the grate to the combustion space. The effect of air-flow rate on temperatures reached in the combustion chamber and on subsequently on heat transfer rates to the thermo-acoustic engine and cooking pots is one of the main factors being investigated in the tests.

Measuring devices

The indirect combustion analyse is done by detecting various parameters during a normal combustion cycle. The excess air has been measured by measuring the inlet air during various phases of combustion. It has been done by a normal anemometer with a resolution of 0,01m/s, adapting to the main door by a 3 cm nozzle. The anemometer is inserted in the middle of the anemometer and a parabolic distribution of velocity has been supposed.

To measure temperatures reached inside the stove 20 thermocouples has been used disposed around the combustion chamber and on the upper part of the disk inside the gap between the water tank simulating the thermoacoustic engine. Four more thermocouples have been use to measure the flame temperature on the bottom and the top of flame. Also has been measured gases temperature inside the channel, at the exit from the combustion chamber, before the first pot, between the two pots and chimney. Thermocouples used are K- Type; the metal component are chrome and aluminium. It is the most common general purpose kind thermocouple with a sensitivity of approximately 41 µV/°C and range it's from −200 °C to +1350 °C . It was not possible to read the electric signal from the thermocouples but directly digital signal coming from the digital converter sent by USB plug to the computer, that reads and displays temperatures. Converter is programmed with calibration curve for K type thermocouples.

One of the major problems in designing improved stoves concern the combustion quality. In testing woodburning cook stoves this problem has almost been neglected entirely although Smith (1986) clearly showed the seriousness of the problem. The products of incomplete combustion are carbon monoxide, hydrocarbons and soot. Carbon monoxide especially deserves full attention when considering the stove performance. Absolute measurements of the carbon monoxide concentration in flue gases are only possible in closed stoves with a chimney. This is why for all practical purposes, the carbon monoxide to carbon dioxide ratio is used as an indicator of the toxicity of the combustion gases. All the combustion gases parameter have been measured inside the chimney after the second pot. The parameters measured are CO_2 (ppm), CO (%) , O_2 (%), excess air and temperature of exhausts. For gases measurement it's used *Telegan Sprint V2* gas analyser with the specifications shown in Table 2:

Table 2 – Gas analyser specifications.

	Range	Accuracy	Response time
Oxygen	0 ÷ 25%	± 0.2%	50 sec
Carbon monoxide	0 ÷ 10.000 ppm	±3ppm	90 sec
Carbon dioxide (calculated)	0 ÷ 25%	±0.2% v/v	50 sec
CO/CO_2 ratio	0 ÷ 1,00		

Temperature	-50º ÷ 1100ºC	±1 °C	
Efficiency	0 ÷ 100%		
XS_{Air}	0 ÷ 100%		

The gas analyser’s probe is insert inside the lower part of the chimney in a drilled hall made in the body of the stove.

In Figure 6 is shown a photos of the testing stove ready down the fan for exhaust rested on the trolley.

Figure 6 – Testing stove ready.

CONCLUSION

The “Stove for Cooking, Refrigeration and Electricity” Project has the ambitious objective of making a 150 W electricity generator based on thermoacoustic principles that is driven by the heat of a wood-burning stove. With a linear alternator involving the only moving part, it is intended that the device should eventually be produced at very low cost for widespread deployment in under-developed countries.

Up to now have been run over 40 tests to improve the model of the stove. For example, in Figure 7 and 8 are shown two graphs about the test we ran last summer. As shown in Figure 8 at that time in the first pot the water boiled in 25 minutes and in the second pot the water reached a temperature of about 65 °C, so the aim of the recent tests is to improve the efficiency of the stove in the cooking.

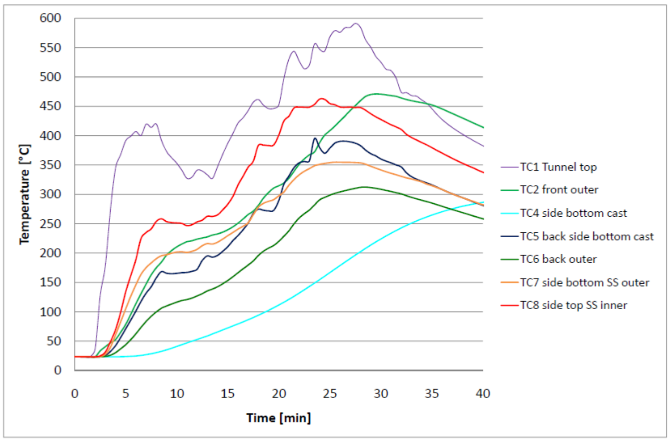

Figure 7 – Combustion chamber temperatures.

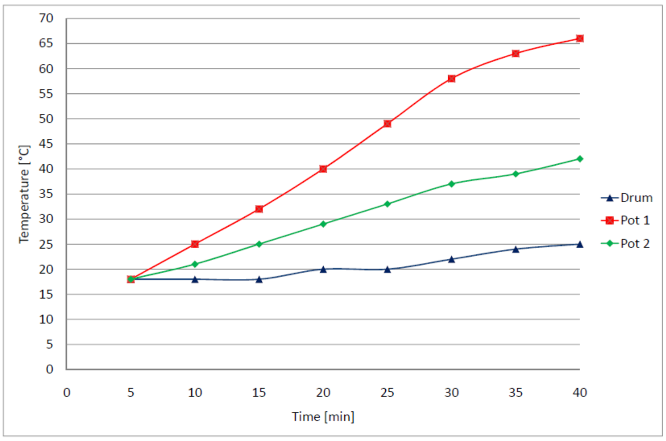

Figure 8 – Water temperatures.

About electrical production, on 23 November 2010 a wood burning thermoacoustic engine (Score Stove) produced 22.7 W of electrical power. Demo2 of the Score stove also averaged 8 W of power over a 60 minute period whilst charging a 12 V lead acid battery. This shows the concept of the design is sound, it’s necessary to build on this record and produce more electricity with lower wood consumption, as Paul Riley, SCORE Project Director, wrote [5].

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