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DEVELOPMENT OF A SELF-POWERED FOOD SANITATION CENTER

by
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14. ABSTRACT
The present Food Sanitation Center (FSC) relies upon either the non-powered M2 gasoline burner or the electrically powered MBU logistics-fuel burner. Because of the open burners, it is inefficient and uncomfortable to operate. Various approaches to heating the sanitizing sink and rinse water of a Self-Powered FSC (SP-FSC) were investigated including direct heating of the sanitizing sink by a burner, indirect heating of the sink by an external fuel-fired hydronic heater, and heating the sink by steam injection. Various diesel-fired steam/water heaters and burners were evaluated. The final approach consisted of a lightweight logistics-fueled boiler capable of generating 44 lb/hr of low-pressure steam at 80% combustion efficiency with an integral thermoelectric generator that supplies sufficient electricity (40 W) for operating its burner and the electric water pump. The burner-base used is the bottom portion of an Army H-45 logistics-fueled space heater. The SP-FSC employs a shallow wash sink that provides a work surface and 110°F water spray for manual cleaning of cookware. Items are rinsed with a 140°F hot water spray and sanitized by immersion in a tank that is maintained at a minimum temperature of 170°F by direct steam injection.

15. SUBJECT TERMS

SELF POWERED	SANITIZATION	HEATING	COST SAVINGS	TRANSPORTABILITY
FOOD SANITATION	KITCHENS	PROTOTYPE	FUEL SAVINGS	COMPACTNESS
FIELD KITCHENS	FIELD EQUIPMENT	EFFICIENCY	WATER USAGE	FLEXIBILITY
FOOD SERVICE	EVALUATION	SAFETY	COMFORT	LIGHTWEIGHT

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Preface

As the Army moves to a lighter, more mobile Objective Force structure, it becomes more important for equipment and materials to be lighter and easier to move. The Field Sanitation Center (FSC) has historically been a cumbersome piece of equipment, consisting of several oddly shaped and heavy components. The objective of this project was to find ways to decrease the overall weight and number of components while at the same time designing a system that is inherently more water and fuel efficient than any of its predecessors.

The present FSC relies upon either the non-powered M2 gasoline burner or the electrically powered MBU logistics-fuel burner. Because of the open burners, it is inefficient and uncomfortable to operate. Various approaches to heating the sanitizing sink and rinse water of a Self-Powered FSC (SP-FSC) were investigated including direct heating of the sanitizing sink by a burner, indirect heating of the sink by an external fuel-fired hydronic heater, and heating the sink by steam injection. Various diesel-fired steam/water heaters and burners were evaluated. The final approach consisted of a lightweight logistics-fueled boiler capable of generating 44 lb/hr of low-pressure steam at 80% combustion efficiency with an integral thermoelectric generator that supplies sufficient electricity (40 W) for operating its burner and the electric water pump. The burner-base used is the bottom portion of an Army H-45 logistics-fueled space heater. The SP-FSC employs a shallow wash sink that provides a work surface and 110°F water spray for manual cleaning of cookware. Items are rinsed with a 140°F hot water spray and sanitized by immersion in a tank that is maintained at a minimum temperature of 170°F by direct steam injection.

This project was conducted at Advanced Mechanical Technology Inc. in Waltham, MA from November 1999 to May 2002 under contract number DAAD16-99-C-1044. This work was for the Combat Feeding Program under Project Number AH99, Program Element Number 622786, Task Number 110, and Work Unit Number CAD.

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DEVELOPMENT OF A SELF-POWERED FOOD SANITATION CENTER

1. Introduction and Summary

The report describes work carried out during the period October 1999 through December 2001 under contract number DAAD16-99-C-1044 for the design and development of a self-powered food sanitation center (SP-FSC) for washing of pots, pans, and utensils in the field.

The present Food Sanitation Center (FSC), relies upon either the non-powered M2 gasoline burner or the new electrically powered MBU logistics-fueled burner. It is comprised of three sinks heated from below by three separate burners, and is relatively heavy, bulky, and cumbersome. As a result of the open burners, it is inefficient and uncomfortable to operate. The new MBU burner is safer and more convenient to operate than the M2, but requires a source of electric power. Since the FSC is frequently in operation after feeding, its three MBU burners would often be the only significant electrical load. This results in additional operating hours on the engine-generator, usually at a low load, which causes "wet stacking" of the diesel engine, resulting in increased maintenance.

Various approaches to heating the sanitizing sink and rinse water of an SP-FSC were investigated. These included direct heating of the sanitizing sink by a burner, indirect heating of the sink by an external fuel-fired hydronic heater, and heating the sink by steam injection. Various diesel-fired steam/water heaters and burners were evaluated. The approach that was finally selected consisted of the low-pressure boiler with integral TEG heated by the burner-base of the Army's H-45 logistics-fueled space heater.

The SP-FSC employs a shallow wash sink that provides a work surface and supply of detergent water for manual scrubbing and cleaning of cookware. Following manual cleaning, items are rinsed with a spray nozzle using 140^{o}F hot water, and are then sanitized by immersion in a final rinse tank that is automatically maintained at a minimum temperature of 170^{o}F. The sanitizing rinse water is heated by steam injected directly into the sanitizing sink water. The steam is supplied from a low-pressure (½ psi) boiler heated by a logistics-fueled burner. A coil built into the boiler provides hot water that is pumped by an electric pump to a hot-water accumulator for use as the rinse spray. The boiler contains an integral thermoelectric generator (TEG) that supplies sufficient electricity for operating its burner and the electric water pump.

The major accomplishments of the project were:

- Development of a prototype self-powered food sanitation center (SP-FSC)
- Development of a lightweight logistics-fueled boiler capable of generating 44 lb/hr of low-pressure steam at 80% combustion efficiency

- Development of a thermoelectric power source co-generating 40 Watts of power for the SP-FSC

- Development of a fully automatic hot rinse system for the SP-FSC operating on co-generated power

- Development of a control that automatically modulates the burner between high and low fire to maintain uniform steam pressure while minimizing consumption of fuel and water.

The SP-FSC is independent of outside sources of electricity, requires less water and fuel than current systems, will be less costly, and should provide greater productivity and user comfort, better compactness and transportability, more flexibility, and higher safety than present field food-sanitation equipment.

This report describes the design and development of the prototype SP-FSC and its performance results. A discussion of the relevant food sanitation codes is included in this report. Appendix A contains the preliminary operating instructions. Appendices B and C describe the evaluation and development of some of the alternate heat sources and burners. Appendix D describes the design and development of the initial MK-1 boiler.

2. Design Requirements

The SP-FSC employs a shallow wash sink that provides a work surface and supply of 110°F - 120°F detergent water for manual scrubbing and cleaning of cookware. Following manual cleaning, items are rinsed with a spray gun using fresh hot water at 120°F - 140°F, and are then sanitized by immersion in a final rinse tank that is automatically maintained at a minimum temperature of 170°F. The heat source for the SP-FSC is a steam boiler fired by logistics fuel. A thermoelectric generator contained within the SP-FSC boiler generates sufficient electrical power to operate the burner and to power a 2 GPM intermittent-duty rinse water pump.

2.1 Mission Requirements

The mission requirements of the SP-FSC are:

Purpose

The purpose of the SP-FSC is ware washing. It is intended to wash two (2) complete *Field Range Outfits* (excluding M2 burner unit). The weight of the utensils and cookware in 2 Field Range Outfits is estimated to be 800 lb. For purposes of estimation of heat load, the material is assumed to be aluminum (specific heat = 0.214 Btu/lb-°F).

Duty Cycle
The duty cycle consists of a three (3) hour period entailing heating of water prior to washing, standby, and ware washing. This 3-hour period does not include unpacking, setup, filling, draining, cleaning, and packing of the SP-FSC. During ware washing, manually operated equipment, such as rinse spray, is assumed to operate at a 33-1/3% duty cycle; i.e., 30 seconds on, 60 seconds off.

Sanitation Requirements
The SP-FSC shall meet the standards of the *FDA Food Code (1997)*. At a minimum, the SP-FSC must provide for accomplishment of:

(1) Application of cleaners and the removal of soil;
(2) Removal of any abrasive and removal or dilution of cleaning chemicals; and
(3) Sanitation.

The preferred cleaning and sanitation method will be:

(1) Food debris on equipment and utensils shall be scrapped over a waste disposal unit, scupper, or garbage receptacle (4-603.12(A)).
(2) Utensils shall be effectively washed over a wash tray to remove or completely loosen soils by using manual means necessary such as the application of detergents containing wetting agents and emulsifiers; abrasive cleaners; hot water; brushes; or scouring pads (4-603.14(A)). The temperature of the wash solution in manual warewashing equipment shall be maintained at not less than 43^{o}C (110^{o}F) or the temperature specified on the cleaning agent manufacturer's label instructions (4-501.19). The use of hot rinse water admixed to detergent or abrasive cleaner shall be deemed to meet this requirement.
(3) Use of a distinct, separate water rinse at a temperature of not less that 49^{o}C (120^{o}F) after washing and before sanitizing. The rinse shall be applied by a manual sprayer or by immersion in a separate sink.
(4) Sanitation by immersion in hot water at a temperature not less than 77^{o}C (171^{o}F)[1] for at least 30 seconds as specified under 4-501.111.

Energy Requirements
The SP-FSC shall use a logistics fuel burner to supply all of the energy for washing, rinsing, and sanitizing. In addition, the heat from the burner will be used to generate sufficient electric power to allow the SP-FSC to operate independently of outside electric power. A storage battery may be used for starting and operation, but any electricity supplied by the battery will be replenished by the internal generator.

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[1] The Food Code prescribes a minimum sanitation temperature of 171^{o}F, which is greater than the current Army specification of 170^{o}F. For purposes of this design, the lower temperature is assumed.

2.2 System Design Specification

Duty Cycle
The duty cycle of the SP-FSC is assumed to be 3 hours long, consisting of:

(a) a half-hour period for heating the sanitizing sink to 170^{o}F;
(b) a 1 hour idle period during which the sanitizing sink is maintained at minimum temperature of 170^{o}F;
(c) and a 1.5 hour active period during which the rinse spray operates at 2 GPM for 1/3 of the time.

Utensil Heat Load
In addition to the energy for hot water supply, the burner must heat the utensil load of the sanitizing sink. The rinse spray heats the utensils to an intermediate temperature (assumed to be 90^{o}F) by the rinse spray. The utensils are heated to 170^{o}F by immersion in the sanitizing sink. The utensil heat load on the sanitizing sink is assumed to be 7000 Btu/h; e.g., 400 lb/h of aluminum utensils heated from 90^{o}F to 170^{o}F

Gross Heat Output
The gross heat output is the heat required to be transferred to the sink by the burner. This equals the heat to the rinse water (26,667 Btu/h), plus the utensil load (7,000 Btu/h), plus the uncovered heat loss from the sink (9,415 Btu/h), or a gross output requirement of 43,082 Btu/h.

Electric Power
The overall requirement for the thermoelectric generator (TEG) is that it must generate sufficient electricity to supply the power consumed by the SP-FSC during its operating cycle

A preliminary estimate of the electric power requirement for the water pump is assumed to be 30 watts. This is based upon an average flow rate of 2/3 GPM at 35 psig over a 1.5 hour duty cycle, or a total of 60 gallons of water. This would permit the pump efficiency to be as low as 34%. The total power consumption over the assumed 1.5 hour duty cycle is 45 watt-hours.

An additional allowance of 10 watts is provided for controls and parasitic losses. The total 40 watt net output is in addition to any power required to operate the burner.

The TEG is also required to supply power for operation of the burner during warm-up and standby. Since the pump is not operating during these periods, the net power output during standby need only be enough to provide for controls and parasitic losses, or about 10 watts.

2.3 Safety
The main categories of safety hazard associated with the SP-FSC are fire, explosion, asphyxiation, and scalding. There is a remote probability of a catastrophic mishap resulting in fire or explosion of the burner or its fueling system. There is a remote possibility of asphyxiation

resulting from improper venting of the burner. There is a probable or occasional probability of a critical scalding injury resulting from unintentional contact with hot water.

The probabilities of fire, explosion or asphyxiation will be minimized by the use of burner components and designs that conform to recognized safety standards for portable liquid-fuel burning heaters and stoves. Guidelines for construction and operation promulgated by the National Kerosene Heater Association (NKHA) and the Consumer Product Safety Commission (CPSC) will be followed.

Scalding hazard will be minimized by appropriate labeling and by provision of devices to facilitate immersion while reducing proximity to hot water, such as handles or baskets.

3. Description of the SP-FSC

The system is intended to clean and sanitize food service equipment in the field where limited or no electric power is available. To conserve water and to reduce volume, the conventional 3-sink wash/rinse/sanitizing system is replaced by a wash/rinse station and a sanitizing sink. The wash/rinse station consists of a shallow 24" x 36" tray on which items are scrubbed clean and then rinsed with 140ºF water from a commercial-type washdown sprayer. Once cleaned and rinsed of detergent, the item is then immersed into the sanitizing sink and placed on a drying rack. A single heat source operating on logistics fuel provides heat for the rinse spray, the sanitizing sink, and generates sufficient electric power to operate the rinse pump, controls, and to recharge a small battery.

The assembled system is depicted in Figure 1 and consists of three main sections: the boiler, the sanitizing sink, and the wash/rinse station. The sanitizing sink is 24" x 24" x12" deep and holds 20 gallons of water at a minimum temperature of 170ºF. The rinse/wash station is a shallow tray with a rinse-spray nozzle that provides 140ºF water at a flow rate of 2 gpm. This sprayer is intended to be used in 30-second intervals at a duty cycle of 1/3; i.e., at an average flow rate of 2/3 gpm. The boiler weighs under 50 pounds (dry) and raises steam in 10 minutes. Its output is sufficient to heat the sanitizing sink in about 30 minutes, to supply 1 gpm of water to 140^{o}F continuously, or to produce 2/3 gpm of 140ºF water continuously for processing 400 lb/hr of cookware, while maintaining the sanitizing sink a 170^{o}F. The self-powered boiler has a combustion efficiency of 80%, operates on logistics fuels with a Bacharach Smoke Number less than 4, and can operate at fuel inputs between 33,000 to 65,000 Btu/hr. It switches automatically between high fire and low fire to maintain steam pressure at about ½ psig.

Figure 1. Assembled SP-FSC System.

3.1 Burner

The burner used to heat the boiler is the unmodified burner-base of an H-45 space heater. The burner-base of the heater is about 12" high and 18" in diameter. Fuel is supplied to the burner by gravity feed from an external fuel reservoir via a fuel control valve. The fuel control valve is a float chamber combined with a flow control orifice. The float chamber maintains a fuel level in a fuel vaporizer located inside the burner. The vaporizer is an inverted U-tube. Fuel is supplied to one leg of the U-tube and is vaporized by the heat of the flame. The fuel vapor rises into the other leg of the U-tube and is discharged out the bottom of the tube into the base of the combustion chamber beneath two mixing baffles. The combustion chamber is formed by a concentric inner “basket-wall”. Primary air enters the sides of the cylindrical basket walls and mixes with the fuel. Air ports located around the rim at the top of the basket chamber allow secondary air to mix with the primary products to complete combustion. Fuel flow-rate is controlled by an adjustable restriction between the float chamber and the fuel vaporizer. Combustion air is induced into the burner by the natural draft provided by the exhaust stack.

3.2 Boiler

The MK-2 boiler is an 18" diameter x 15" high water-jacket heat-exchanger designed to sit on top of the burner-base of the H-45 space heater. The heat transfer surfaces are optimized to take full advantage of the radiant heat transfer of the luminous flame, as well as the convection of the hot combustion products. Power producing thermoelectric generators (TEG's) are installed onto the lower portion of the six heat exchanger.

The prime heat transfer surface of the boiler is built from sections of flat aluminum panels with internal rectangular flow passages, assembled in the shape of a hexagon. Because the time and cost to make custom extrusions would have been prohibitive for the prototype, the panels were assembled from aluminum sheets and joined by a dip-brazing process. Each panel of the hexagon has multiple vertical flow passages that are about 1" square in cross section, separated by thin walls. Figure 2 shows both the aluminum extrusion and the assembled heat exchanger panel.

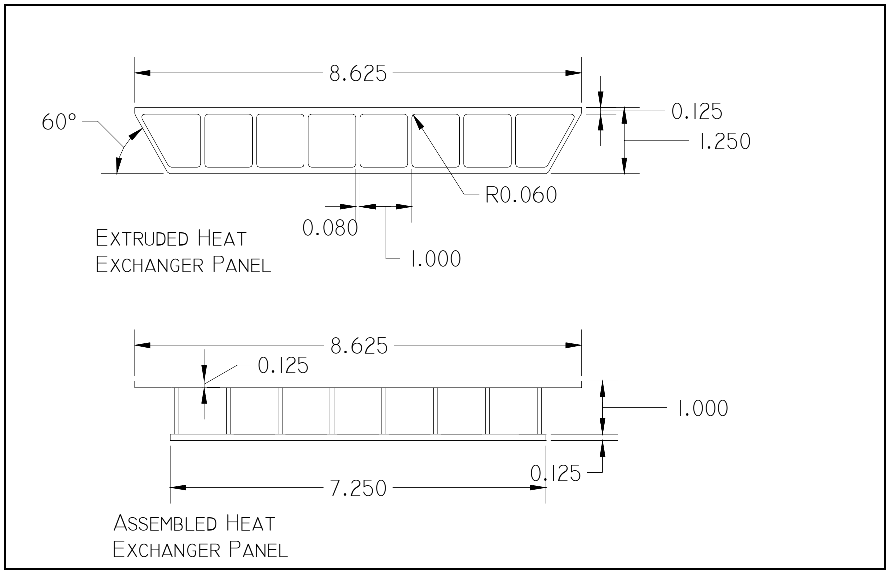

Figure 2. Heat Exchanger Panels.

Figure 3 shows a photograph and a sketch of the boiler and the flow path of combustion products through the heat exchanger. The heat exchanger encloses an upper combustion chamber in which the combustion products from the lower burner base complete their reaction. The combustion products are partially cooled by heat transfer to the panel walls facing the chamber. The products flow down the surfaces of the panels and enter each of the passages at the lower end and travel upward to an exhaust plenum. One side of the panel is water backed, and the other side faces the combustion chamber and has a direct view of the radiant flame. The webs of the panel link the water-backed surface to the surface facing the combustion chamber and add additional convective heat transfer area within the passage. This allows the radiation heat transfer from the flame to be directly absorbed by the water via conduction through the fins. This aluminum fin configuration creates a very light and compact boiler, which are two major design goals. The three photographs in Figure 4 show the boiler at various stages of construction.

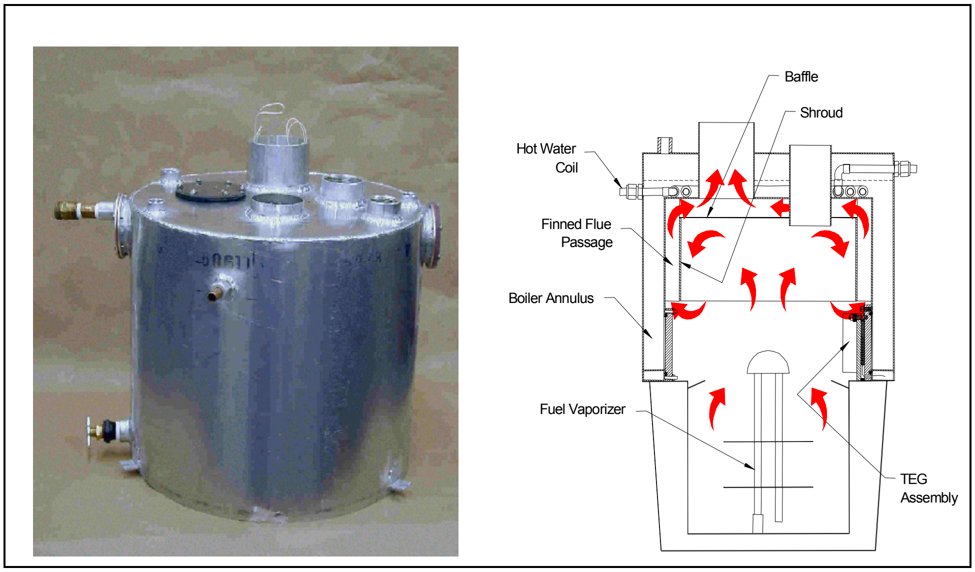

Figure 3. Photograph and Sketch of MK-2 Boiler and Combustion Products Path.

Figure 5 shows a profile section of the boiler. The water jacket is formed by wrapping the hexagon with a 18" high, 18" diameter, 0.0625" thick aluminum cylinder. Above the 15" high hexagon shaped section is a 3" high, 18" diameter plenum. A boiler water level is maintained so that this plenum is filled about 1.5" deep, leaving a 1.5" steam plenum. Penetrations in the shell allow for the boiler water feed through a float valve, a steam outlet connection, a pressure relief valve, a vacuum breaker, a low water cutoff, an entrance and exit of an internal hot water coil, and a plastic-covered sight port

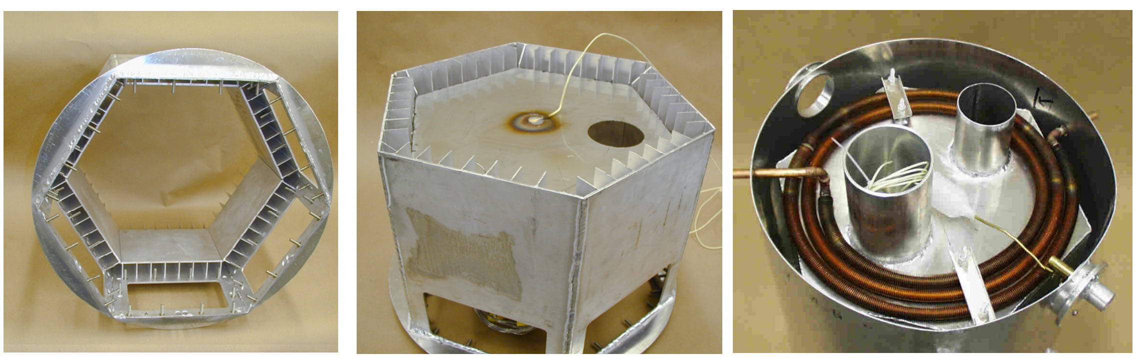

Figure 4. MK-2 Boiler at Various Stages of Construction.

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Prior to development of the MK-2 aluminum boiler, a MK-1 boiler which was a larger, heavier stainless-steel proof-of-concept boiler was fabricated and tested. Details of its design and test results can be found in Appendix D.

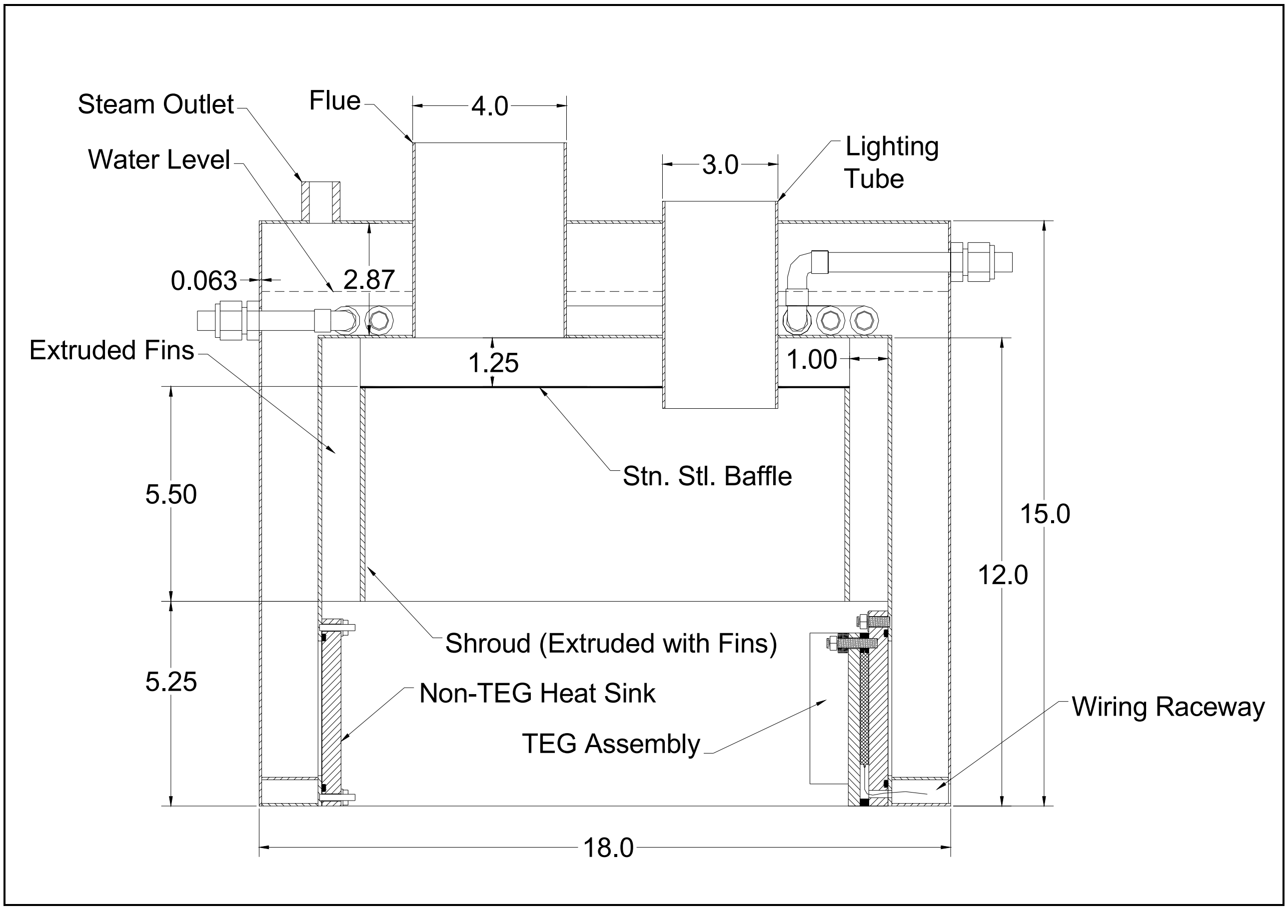

Figure 5. MK-2 Boiler Section.

3.3 Hot Water Coil

A finned coil is installed into the boiler so that it is completely submerged in boiling water to generate hot water for the spray system. It is intended for this coil to be aluminum to prevent galvanic corrosion, but due to the unavailability of such a coil, a copper coil was used in its place.

The coil material will not have an effect on coil performance. The copper fin-tube is wrapped in a flat spiral shape and is located in the top plenum above the main heat transfer surfaces. Figure 6 shows the coil in the boiler. It is a 0.440" ID copper tube with an OD of 0.625", fin pitch of 11 fins per inch, and an average wall thickness of .025". The total length of the coil is 8.6 feet. The required length calculated in the design model was 5.76 feet, but to allow for some amount of fouling, the length was increased by 50%. The inlet and outlet connections were sealed with aluminum Swagelok fittings welded to the side of the boiler.

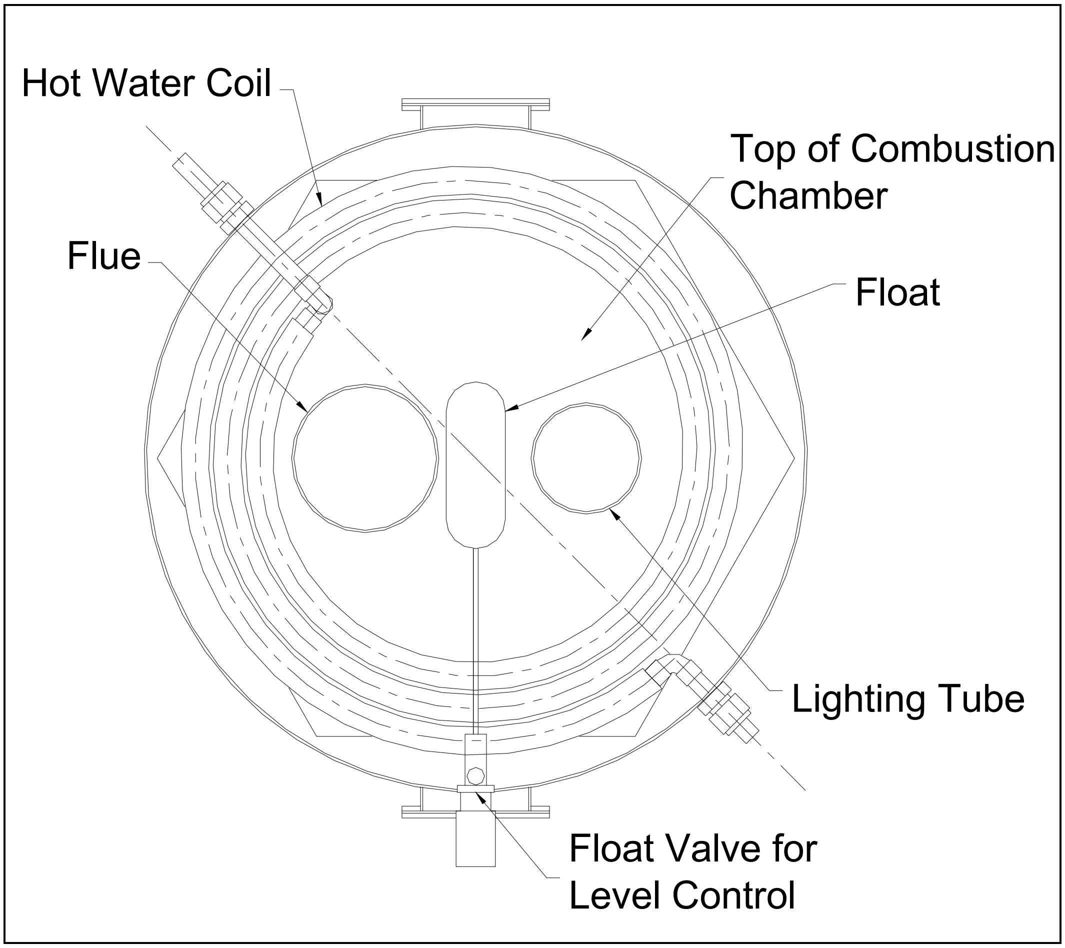

Figure 6. Hot Water Coil in Boiler.

3.4 Sanitizing Sink

The sanitizing sink is a 24" by 24" by 12" deep molded polypropylene tub with 3/16" thick walls. The molded construction results in a single unit with no seams or weld joints. Also the corners are smooth and rounded to allow for easy cleaning. A polypropylene cover is included to be placed over the tub to reduce the evaporation heat losses during initial heat-up and during stand-by periods. A 3.5" commercial sink-drain is installed in the bottom of the tub. A bulkhead fitting on the side of the tub allows attachment of a steam supply line and steam sparger. The tub is placed on a plastic molded polyethylene tray of a utility cart. The tray is reinforced with a network of webs under the tray. A 4" hole for the waste drain is made in the tray between the tray webs so the tray integrity is not compromised. The legs of the cart have notches on 1" intervals so the trays can be placed at any level. The height of the tray on the cart was adjusted so that the lip of the sink is at 36" elevation.

3.5 Wash/ Rinse Tray

The wash/rinse tray is a modified Metro Deep Ledge Utility Cart. It is about 38" long, 27" wide, and 36" high. The cart has upper and lower trays, each being about 3.5" deep, made of high density polyethylene. The cart has a total weight capacity of 400 pounds and each tray can carry 150 pounds. The upper tray serves as the wash/rinse tray, and the rinse components are controls are mounted on the lower tray. Four 1" diameter poles connect the two trays. The poles have notches at 1" intervals so that the trays can be positioned at a variety of heights. For this application, the rinse tray is placed at the highest location, and the component tray is placed at its lowest setting. A 3.5" diameter commercial sink drain (waste outlet) is installed about 10" from the end and about 11" from the front of the upper tray. This is done in order to place the drain in between the reinforcement ribs located on the underside of the tray, and to allow for the drain stopper handle to be accessible to the user. The height of the spray nozzle can adjusted to suit the operator's preference by adjusting two mounting clamps on one of the rear cart posts.

3.6 Spray System

The spray system plumbing is shown in Figure 7. The pump draws water from an external water supply (water buffalo) and the flow is split into two streams. One stream goes to the inlet of the hot water coil and boiler float valve, and the other goes to the cold side of the mixing valve. The outlet of the hot water coil is connected to the hot side of the mixing valve. The mixed water (140ºF) then flows to and is stored in the accumulator. The pump fills this accumulator with about 0.75 gallons of 140ºF water. The final pressure of the accumulator is about 45 psi. A pressure regulator between the spray nozzle and the accumulator is set to about 20 psi. This regulator ensures a constant, even water flow rate through the nozzle. The spray nozzle is actuated by a valve on the spray-head body.

3.7 Pump

The pump is an Aquatec 5800 series 12 Volt (DC) diaphragm pump which has a maximum flowrate of about 1.2 gpm, and will pump about 0.7 gpm at 20 psi. This pump is capable of priming itself, up to 7 feet of water, and can operate dry without damage. The pump is actuated by a pressure-switch sensing the pressure of the accumulator. The pressure-switch is set to 45 psi and has a 5 psi differential.

3.8 Mixing Valve

The mixing valve blends the heated water and the supply water to produce a stream of 140ºF water. A thermally actuated element inside the valve throttles both the hot and cold steams to achieve the set temperature. The mixing valve has a temperature output range of 120ºF to 145ºF.

3.9 Accumulator

The accumulator is an Amtrol 2-gallon Therm-x-trol expansion tank. It is 8" in diameter, and about 11" high. A rubber diaphragm inside the accumulator expands with increasing water volume. The maximum working fluid temperature in the accumulator is 220ºF.

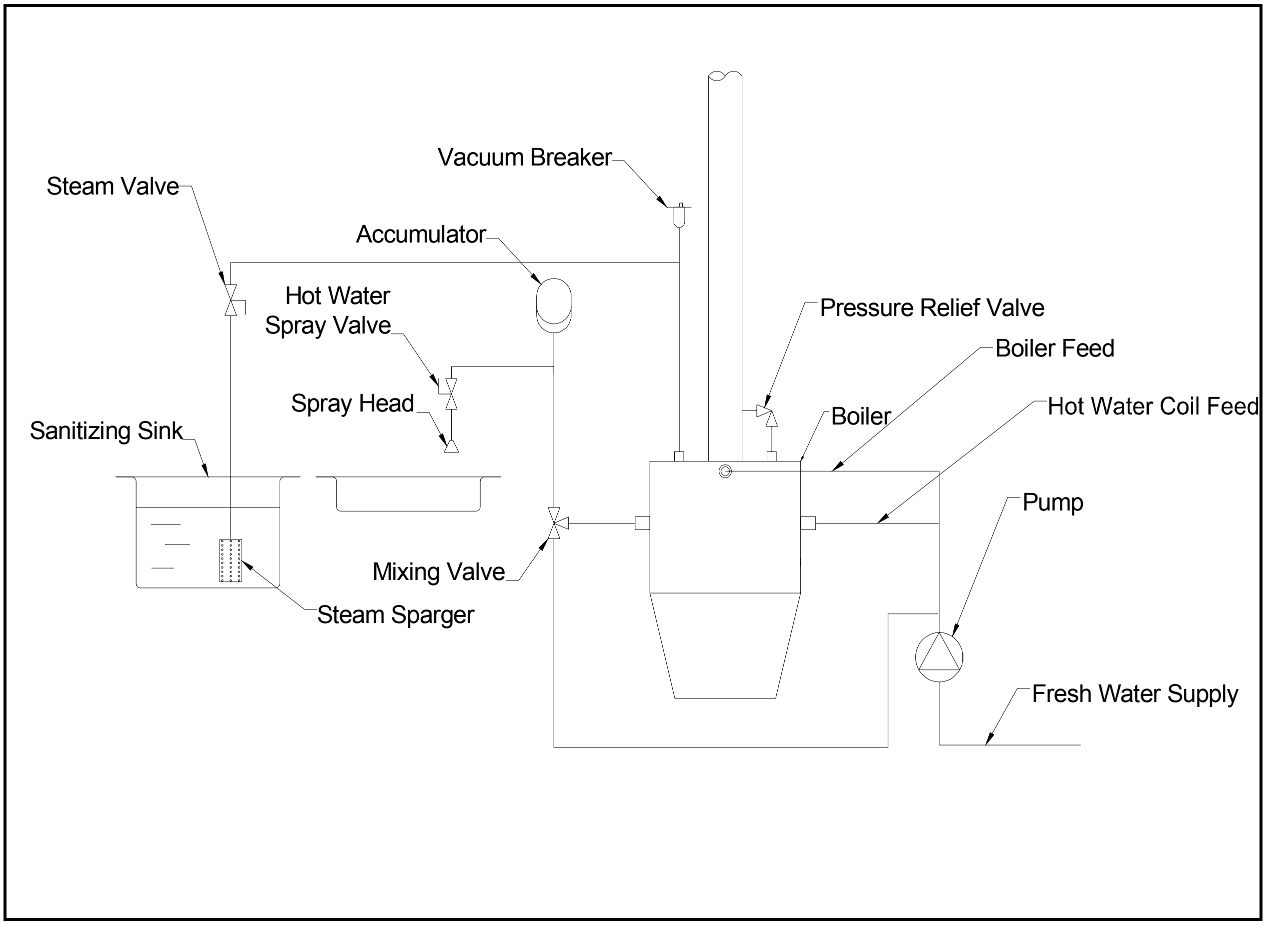

Figure 7. Plumbing Schematic.

3.10 Spray Nozzle

The spray nozzle is a commercially available washdown spray assembly. The assembly consists of a spray head, a 4 foot long flexible hose, and a spring hose sheath. The nozzle is modified to produce a 2 gpm flow of water at 20 psi by fabricating a CPVC nozzle disc with a 16-hole array of 0.070" diameter holes angled outward from the flow centerline by 5º to produce a diverging spray pattern. This spray pattern was found to produce the design flow-rate with minimal splashing.

3.11 Thermoelectric Generator

Three pairs of Hi-Z HZ-20 modules are installed in the boiler. Each module has a nominal rating of 20 Watts. The module power output is a function of both voltage and current output. The voltage output is directly related to the temperature across the module. The current output is a function of the resistance of the load connected to the module. The maximum current occurs when the load resistance matches the internal resistance of the module. The nominal rating of 20 Watts is for a 200ºC temperature differential and a matched load resistance condition.

Two modules share a common hot and cold block. The modules are captured between the two blocks, which have been hard-coat anodized to provide electrical resistance. A thermal paste was applied to each block to reduce the contact resistance and enhance thermal conductivity through the modules. Figure 8 shows a photograph of two TEG modules installed on the cold block and a completed generator assembly. The modules are installed in pairs, in 3 of the 6 heat exchanger panels. A section of the heat exchanger panel is removed to permit the TEG module cold block to be cooled directly by the boiler water and its hot block to be heated directly by the combustion products. The other three open panel sections were covered with a flat plate. The six modules are wired in series to produce the needed voltage for operating the pump and for recharging a small battery.

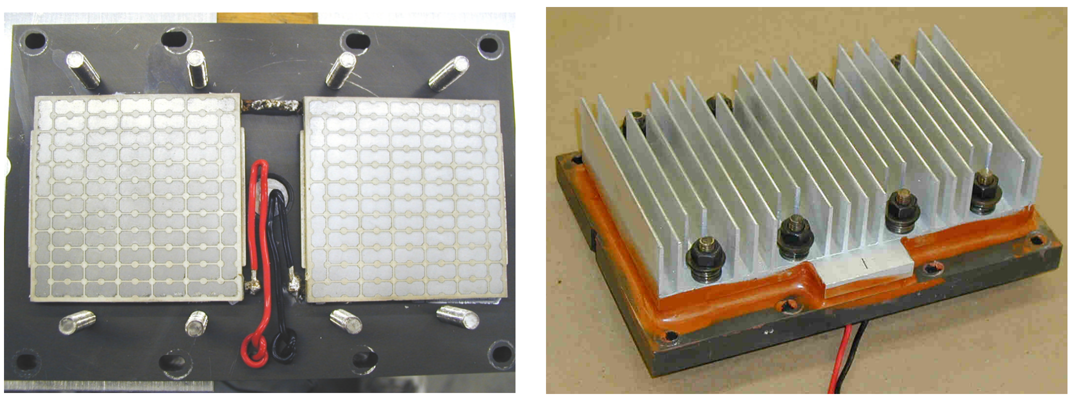

Figure 8. TEG Assembly.

3.12 Electrical System and Controls

3.12.1 Electrical Circuit

The electrical schematic of the system is shown in Figure 9. The power generated by the TEG is used to charge the 12V, 7A-h sealed lead-acid battery. Under normal operation, the pump is connected directly to the TEG output. This was done because the TEG is to provide maximum power at about 9 volts. Since the battery charger requires a source greater than 14.4 volts, the net generated power is greater when the load is connected directly to TEG rather than passing through the battery charger. Other devices, such as the fuel solenoid valves, controls, and panel lights, etc., are connected to the battery because they must be operated before the burner is lit.

3.12.2 Pump Circuit

This pump circuit is modified slightly at start-up to allow the boiler to be filled with water. The pump override button switches the pump to run off the battery so that the boiler can be filled prior to lighting the burner. This turns on the pump which causes the boiler will automatically fill and the accumulator will be charged. After the accumulator is fully charged, the pump will shut off automatically, and the override circuit will drop out and reconnect the pump directly to the TEG.

3.12.3 Steam Relief Valve

A steam relief valve is installed on the top of the boiler to relieve pressure when the sanitizing sink is at the required temperature and the steam valve is closed. The pressure relief valve will vent steam into the flue at a boiler pressure of about 0.8 psi. When the boiler reaches about 0.7 psi, a pressure-switch deactivates the high-fire fuel-control solenoid, bypassing the high-fire fuel-orifice and forcing the fuel to flow through a low-fire orifice.

3.12.4 Low-Water Cut-Off Safety Switch

The boiler is equipped with a low-water cut-off actuated by a float switch installed on the top section of the boiler. It is positioned so that the main fuel solenoid will shut when the water level reaches within about 0.25" from the top surface of the boiler. In order for this device to work properly, the boiler must be level. A mercury tilt-switch is installed inside the electrical box on the boiler to prevent the fuel valve from opening unless the boiler is within 10º from level in any direction. This also serves as a fuel safety shut-off in case the boiler tips over.

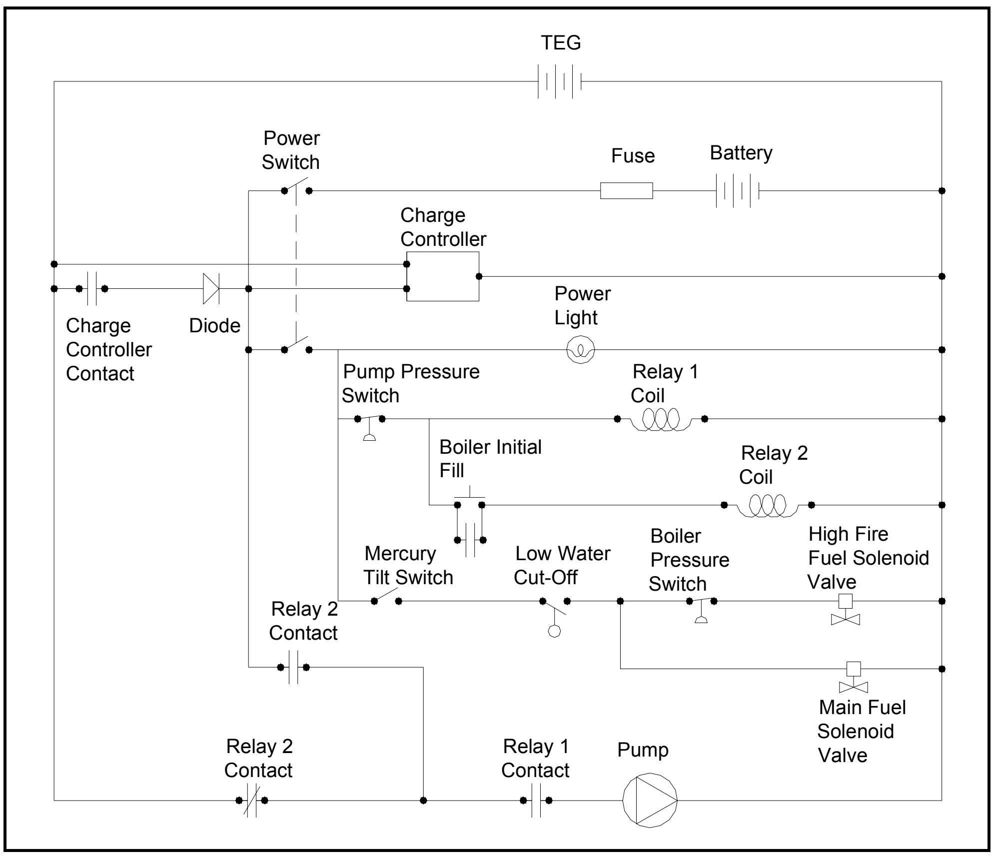

Figure 9. Electrical Diagram of Charging Circuit.

4. Performance Results

4.1 Boiler Heat Transfer Performance

An analytical heat transfer model was constructed to aid in sizing the heat transfer surface area and flow passage shapes and sizes. This model, along with experimental performance results obtained from an earlier prototype made it possible to design a lightweight, compact boiler that met the performance and emission goal set out at the beginning of the project. Figure 10 shows some of the key temperatures calculated by the model compared with the experimental results from the MK-2 prototype.

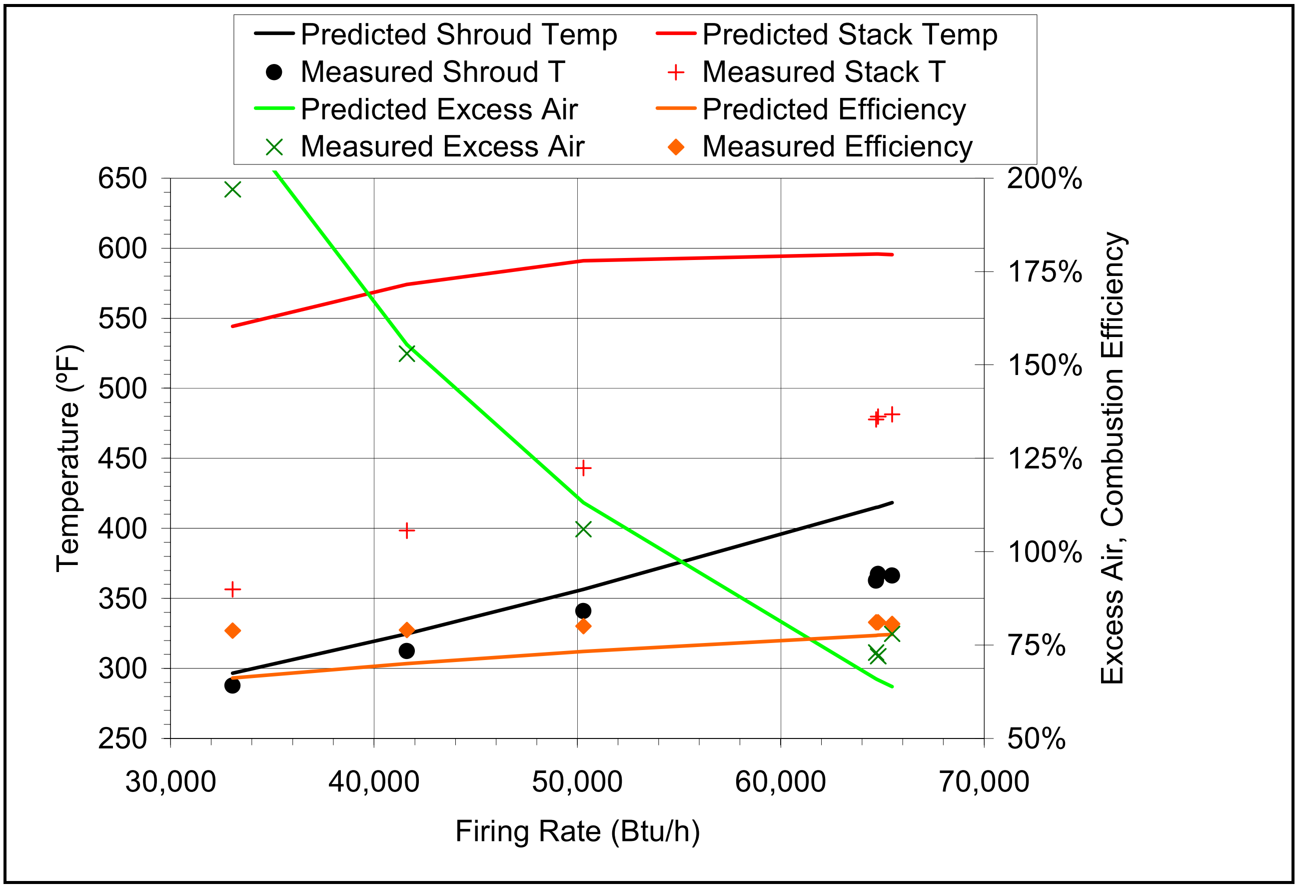

Figure 10. MK-2 Model Predictions and Experimental Results.

The MK-2 boiler was tested to compare its performance with the design model predictions. The boiler was instrumented with thermocouples in key locations to measure and verify the heat transfer predictions made in the design model. Thermocouples measured fin, shroud and baffle temperatures along with stack and water temperatures. Excess air, carbon monoxide (CO), oxides of nitrogen (NO_x), and smoke measurements were also made.

The boiler was operated over a range of firing rates from about 33,000 Btu/h to 65,000 Btu/h. These firing rates correspond to the fuel valve settings of 1 to 4 on the scale under the JP8 fuel setting. An uninsulated, 13.5 foot tall, 4 inch diameter flue pipe was installed on the boiler and was vented through the roof of the building. Efforts were made to make sure the building was at the same pressure as the outside so that a pressure differential would not influence the natural draft.

Table 1 shows the results of the boiler performance tests. The boiler was operated successfully from 33,000 to 65,000 Btu/h with a natural draft providing the airflow. Below 33,000 Btu/h, the carbon monoxide (CO) increased beyond measurement. For a target operating point between

60,000 and 65,000 Btu/h, the efficiency is about 80%, the NO_x, CO and smoke emissions are low, and the aluminum heat transfer surface temperatures are within design specifications.

Table 1. Boiler Performance Test Results

Fuel Valve Setting	1	2	3	4
Firing Rate-Btu/h	33,049	41,614	50,296	64,485
Excess Air	197 %	153%	106%	78%
CO - Air Free - ppm	389	167	39	18
NO_x @ 3% O_2 - ppm	28	35	57	57
Smoke	0	0	0	2.0
Stack Temperature - ºF	364	405	436	481
Average Shroud Temperature - ºF	297	320	343	366
Combustion Efficiency	79.9%	80.5%	81.2%	80.6%

4.2 Hot Water Coil

Tests were conducted to measure the performance of the rinse water heating coil with the burner firing at approximately 60,000 Btu/hr. The coil was fed with a flow-regulated water supply at a temperature of about 58ºF. Figure 11 shows the temperature rise of the water through the coil for the various flow rates. Above a flow rate of 0.9 gpm, the water stopped boiling in the vessel. At the 0.9 gpm flow rate, a temperature rise of 100 ºF was achieved.

The amount of heat transferred to the coil is determined by the amount of water passing through it. Since the pump flow-rate is nearly constant, the amount of water passing through the coil is determined by the mixing valve and the incoming water temperature. If the incoming water temperature is 35ºF, then at a total pump flowrate of 0.7 gpm, about 0.6 gpm is forced through the coil by the mixing valve. At 0.6 gpm, the coil temperature rise is 125ºF, which is sufficient to heat the mixed water to 140ºF.

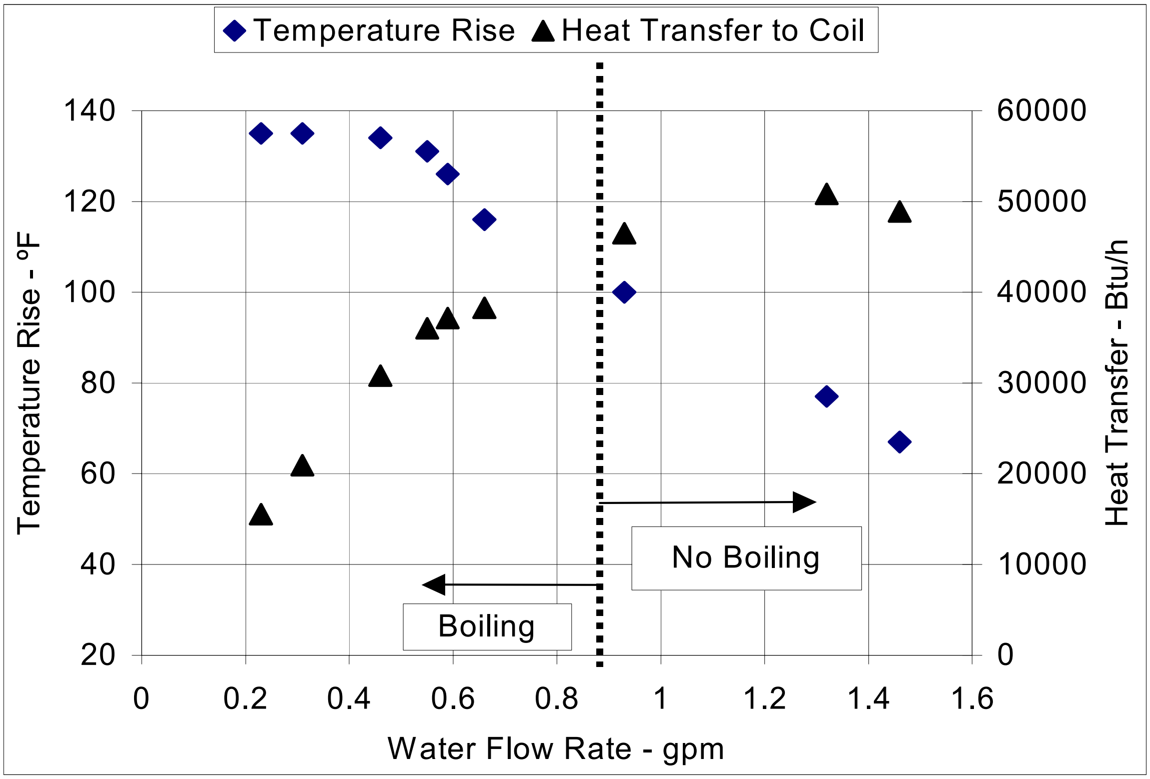

Figure 11. Hot Water Coil Performance.

4.3 TEG Performance

The original 4" by 6", flat-plate TEG hot blocks did not achieve the goal temperature of 500ºF. The measured hot block temperatures were below 400ºF at a burner firing rate of about 65,000 Btu/h. The cold block temperatures were about 225ºF. As a result of the low hot block temperature, the TEG power output was less than desired.

To increase power output the flat plates were replaced with hot blocks made from the Wakefield Engineering extruded aluminum heat sink material. It has a 0.3" thick base and 0.07" thick, 1" tall fins on a 4 fins per inch pitch. All the TEG modules were assembled using the thermal grease as their thermal interface. Because the Wakefield heat sink material was not anodized, alumina wafers were placed at the hot block interface to electrically isolate the TEG modules.

Figure 12 shows the power curves for the test with the finned hot blocks. The firing rate was about 65,000 Btu/h with about 76% excess air. The measured hot block temperature at these conditions ranged between 450º and 475ºF and the cold block temperatures were around 226ºF. The electrical peak power output of the modules improved to between 11 and 14 Watts for each pair. The combined peak power output was around 38 Watts.

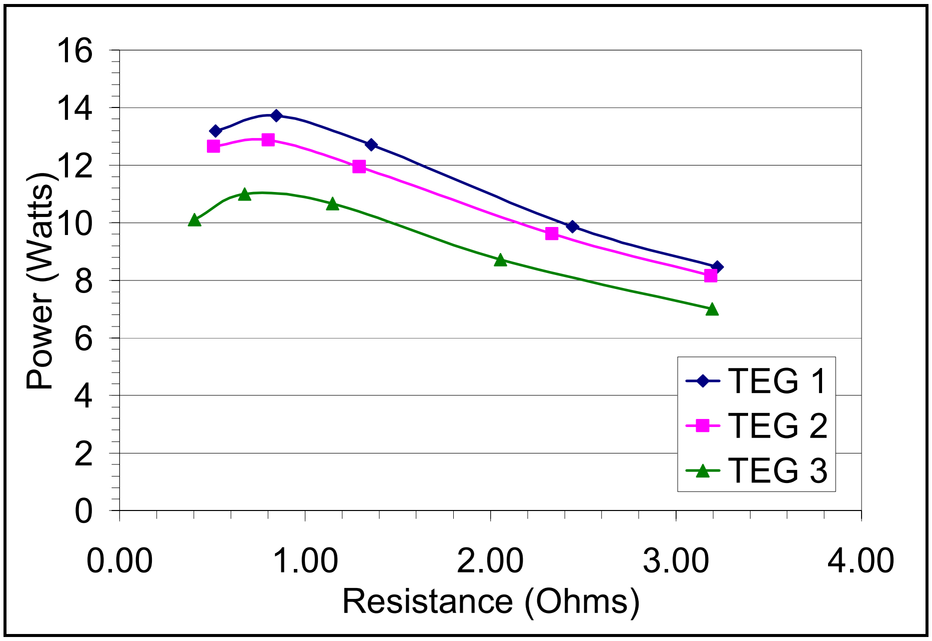

Figure 12. TEG Performance with Finned Hot Block.

Figure 13 characterizes TEG power as a function of burner input. Since TEG power is directly dependent on the temperature difference across the module, and the modules in this application are "cooled" by boiling water, TEG power in this application is effectively related to only the hot side temperature. Since the hot side temperature is linearly related to the burner input, TEG power is also linearly related to burner input. The temperatures illustrated are the temperatures of the hot side heat sink which are about 20°F higher than the TEG hot face temperature due to thermal contact resistance between the heat sink and the TEG module. Hi-Z recommends a continuous module hot face temperature limit of about 480°F, so the heat sink temperature should be limited to about 500°F. The average hot side heat sink temperature is only about 470°F at 65,000 Btu/hr (the design high-fire burner input), so there is potential to improve the power output of the TEG system. Figure 12 implies that a 30°F increase in the heat sink temperature would result in about 10W of additional TEG power.

Figure 13 also shows that TEG power is related to electrical characteristics of the system. The two power curves shown represent the two power applications of the system, pump operation at 12 VDC and battery charging at 14.4 VDC. Maximum power is obtained from a TEG when its internal impedance matches the load impedance. However, the maximum power point for this system only provides 9 VDC which is not characteristic of any electrical system power requirement, so the TEG system operates at less than its peak efficiency. This is not detrimental to overall system efficiency since the TEG is essentially a topping cycle with its "waste" heat being used to heat the boiler. An 8-module system would produce about 12 VDC at its peak power point, but the additional power is not needed and the additional modules would add about $250 to the cost of the system.

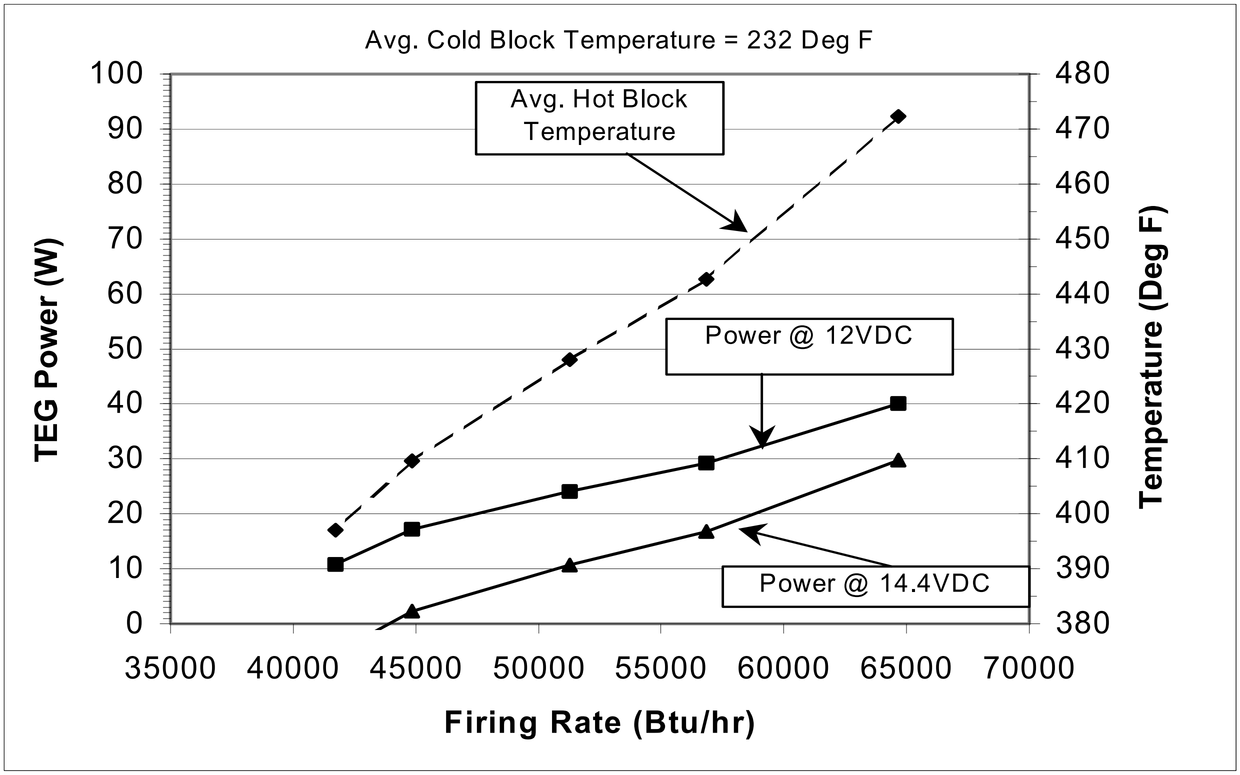

Figure 13. TEG Performance versus Firing Rate and Temperature.

5. Food Code

Various U.S. Army manuals and documents describe food service sanitation requirements and specify the typical 3-sink washing, rinsing, and hot water sanitization method for manual warewashing. The U.S. Food and Drug Administration has issued a comprehensive Food Code which is designed as a general guideline to assist local, state, and federal agencies in the development of their own specific food service sanitation requirements. Both the U.S. Air Force and the Navy refer to the Food Code as source of guidance. The proposed SP-FSC complies with the Food Code in that the design complies with the alternative methods for manual warewashing permitted by the Code and it accomplishes the functions of washing, rinsing, and sanitizing as required by the Code. The Food Code requires that alternative methods to the standard 3-sink system be approved before use. In this application, it is expected that the Army Preventive Medicine command is the agency which must approve the SP-FSC for Army field food service use.

5.1 Discussion

The operation of U.S. Army field kitchens is prescribed by Field Manual (FM) 10-23 Basic Doctrine for Army Field Feeding and Class I Operations Management. FM 10-23 states that field kitchen sanitation practices are to be in accordance with FM 10-23, TB MED 530 Food Service Sanitation, and FM 21-10 Field Hygiene and Sanitation. The Food Service Specialist

Soldiers Manual identifies FM 10-23 as the required reference for proper cleaning and sanitation services at a field kitchen, with TB MED 530 and FM 21-10 as related references. TB MED 530 also identifies Military Handbook (MIL-HDBK) 740 as a general guide for field kitchen sanitation. MIL-HDBK-740 is standardization handbook for dishwashing operations intended for use by all branches of the military.

The sanitation center described in FM 10-23 uses three sinks heated individually by M2 field burners located beneath the sinks. Both FM 10-23 and TB MED 530 define a manual washing procedure which includes scrapping, pre-washing, washing in the first sink with a detergent solution maintained at a temperature between 110°F and 120°F, rinsing in the second sink with clean water maintained at a temperature between 120°F and 140°F, and final rinsing (sanitizing) in the third sink with clean water maintained at a temperature of at least 170°F. FM 10-23 offers no flexibility in the physical arrangement of the sanitation center.

The three sink manual warewashing system specified in FM 10-23 is typical of manual warewashing procedures described for other branches of the military as well as in various civilian sanitation codes such as the Food Code. The U.S. Food and Drug Administration (FDA) publishes the Food Code to provided a model for local, state, and federal regulators to develop or update their own food safety rules in a way that is consistent with national food regulatory policy. To date, the Food Code has been adopted by the US Air Force and the US Army Veterans Service, and is close to adoption by the US Army Preventive Medicine agency. The Food Code is also referenced by NAVMED P-5010, Manual of Navy Preventive Medicine, as a source of additional guidance for food service sanitation.
In contrast to FM-10-23, the Food Code offers some flexibility in manual dishwashing provided that the essential functions of scrapping, washing, rinsing and sanitizing are accomplished. Section 4-301.12 of the Food Code establishes the sink compartment requirements for manual warewashing as follows:

(A) Except as specified in (C) below, a sink with at least 3 compartments shall be provided for manually washing, rinsing, and sanitizing equipment and utensils.

(B) Sink compartments shall be large enough to accommodate immersion of the largest equipment and utensils. If equipment or utensils are too large for the warewashing sink, alternative equipment as specified in (C) shall be used.

(C) Alternative manual warewashing equipment may be used when its use is approved. Alternative warewashing equipment may include:

(1) High-pressure detergent sprayers;
(2) Low- or line-pressure spray detergent foamers;
(3) Other task-specific cleaning equipment;
(4) Brushes or other implements;
(5) 2-compartment sinks as specified under (D) and (E); or
(6) Receptacles that substitute for the compartments of a multicompartment sink.

(D) Before a 2--compartment sink is used, the permit holder shall have its use approved, and the nature of warewashing shall be limited to batch operations for cleaning kitchenware such as between cutting one type of raw meat and another or cleanup at the end of a shift, and:

(a) A limited number of items shall be cleaned,
(b) The cleaning and sanitizing solutions shall be made up immediately before use and drained immediately after use, and
(c) A detergent-sanitizer shall be used to sanitize and shall be applied as specified under 4-501.115, or
(d) A hot water sanitation immersion step shall be used as specified under 4-603.16(C).

E) A 2-compartment sink may not be used for warewashing operations where cleaning and sanitizing solutions are used for a continuous or intermittent flow of kitchenware or tableware in an ongoing warewashing process. (4-301.12)

The proposed SP-FSC is essentially a 2-compartment sink, and its intended use is consistent with 4-301.12 (D) & (E). The required approval for use of such an arrangement must come from the responsible command within the Army. NAVMED P-5101 indicates that the Navy Environmental and Preventive Medicine Units provide specialized consultation, advice and recommendations related to Navy food service facilities. It is expected that the Army Preventive Medicine command would be the proper organization to review and approve use of the proposed SP-FSC. Approval of the SP-FSC will hinge on whether the proposed design effectively accomplishes the essential steps of kitchen sanitation as defined by the Food Code.

Section 4-603.15 of the Food Code requires that if an alternative manual warewashing procedure as specified in 4-301.12(C) is used, equipment and utensils shall be washed as specified under Section 4-603.14(A) which requires that utensils be effectively washed to remove or completely loosen soils by using the manual or mechanical means necessary such as the application of detergents containing wetting agents and emulsifiers; acid, alkaline, or abrasive cleaners; hot water; brushes; scouring pads; high-pressure sprays; or ultrasonic devices. The wash solution used in manual warewashing must be maintained at not less than 110°F (or the temperature specified on the cleaning agen manufacturer's label instructions) according to Section 4-501.19.

Section 4-603.16 states that washed utensils and equipment shall be rinsed so that abrasives are removed and cleaning chemicals are removed or diluted through the use of water or a detergent-sanitizer solution. The most fundamental method specified is a distinct, separate water rinse after washing and before sanitation which applies to 3-sink systems as well as to 3-sink alternatives. An alternative manual method of rinsing is the use of a sprayer with a non-distinct water rinse that is integrated in the application of the sanitizing solution and which is wasted immediately after each application.

Sanitation in manual warewashing is accomplished according to Section 4-703.11 by immersion for at least 30 seconds in hot water maintained at 170°F or above, or by manual chemical operations, including the application of sanitizing chemicals by immersion, manual swabbing, brushing, or pressure spraying methods, using a solution as specified under Section 4-501.114.

The proposed SP-FSC concept accomplishes the steps of washing, rinsing, and sanitation of kitchenware in accordance with the Food Code. Washing is performed in a shallow sink with a detergent solution maintained at 110°F or above. Sanitizing is by immersion in a deep sink containing hot water maintained at a temperature of at least 170°F. Rinsing is accomplished by spraying water at a temperature of at least 120°F to remove abrasives and to removed or diluted cleaning chemicals. Depending on the water heating method chosen, rinse water will either be a distinct stream heated to 120°F, or a non-distinct stream drawn from the sanitizing sink and tempered to 120°F with cold supply water. The SP-FSC is intended for use in a batch mode for cleaning and sanitizing the utensils and cookware of 2 Field Range Outfits after preparation meals for a single unit feeding in the field. It is not intended for a use in a more permanent ongoing kitchen operation. The cleaning methods and operating scenarios proposed for the SP-FSC are all within the scope of acceptable food sanitation practices as specified by the Food Code.

Standards of the National Sanitation Foundation (NSF) have also been reviewed, and it has been determined that NSF does not address the process of manual warewashing in any way. However, NSF 2 does specify certain design and fabrication details that should be followed to the greatest extent possible in the design of the SP-FSC.

6. Conclusions and Recommendations

The project achieved its goal of developing and demonstrating a prototype self-powered food sanitation center. Once the burner is ignited and the sanitation sink is filled, operation is completely automatic and hands-free except for manual control of steam flow to the sanitation sink. The burner is automatically modulated between high- and low-fire in response to steam pressure. Temperature, pressure, and flow rate of the rinse spray system and all automatically regulated. Electrical power is completely self-contained and self-regulated. The SP-FSC is independent of outside sources of electricity, requires less water and fuel than current systems, will be less costly, and should provide greater productivity and user comfort, better compactness and transportability, more flexibility, and higher safety than present field food-sanitation equipment.

<u>Food Code</u>
No regulatory barriers have been identified which would cause the proposed SP-FSC concept to be rejected for U.S. Army field food service sanitation use. The proposed SP-FSC does not violate or conflict with any established principles of proper food service sanitation. Approval of its use is not dependent on obtaining a waiver or exemption from established sanitation codes, such as the FDA Food Code. It does require that the responsible U.S. Army command, most likely Army Preventive Medicine, review the design and approve its deployment; and that manuals such as FM 10-23, TB MED 530, etc. be revised to reflect acceptance of the new design.

Boiler
The system could benefit from some alterations in design, construction, and material choice. The prime heat exchanger surfaces were complex brazed panels with internal flow passages. The panels were constructed from aluminum sheet and brazed to form the desired structure. Ideally, the panels would be formed out of custom extruded aluminum sections.

Corrosion
The hot water coil is a finned copper tube wrapped in a flat spiral that sits near the top of the heat exchanger. Since the tube is immersed in the boiling water and is in direct contact with the aluminum shell it subject to galvanic corrosion. To eliminate this galvanic corrosion, the tube should be made of the same material as the shell.

Aluminum is subject to pitting corrosion in fresh waters. In order to provide general corrosion protection, the internal surfaces should be hard-coat anodized, or other suitable protective coating. It has been documented that the overall corrosion of aluminum is lower when a coating has been applied.

Wash/Rinse and Sanitation Stations
The wash/rinse station and the sanitation station are mounted on commercially available utility carts that were adequate for the purposes of the prototype. The carts have a weight limit of 150 pounds per tray. The sanitizing sink with 20 gallons of water in it weighs about 166 pounds. The cart is reinforced with a support installed between the two trays. Also the cart is about 12" wider than the sink, leaving this as wasted space. An alternative to this cart would be to use wire shelving in place of plastic trays as the support for the sink. The wire shelving uses the same construction as the plastic carts, but has a much higher weight rating (600 pounds per shelf). The shelves are available in a variety of sizes that would be appropriate to this application.

The wash/rinse cart does not hold as much water as the sanitizing cart, so it does not suffer from the weight problem. However, the tray depth is only about 3.5". This is rather shallow, and does not prevent the operator from being splashed by the rinse spray while rinsing large items. Also the tray is not pitched so that the water in the tray completely drains. An alternative to this tray would be a custom molded tub with a gradual slope directing toward a recessed drain opening.

Burner Ignition
The heat source for the boiler is the non-powered H-45 tent heater burner. Ignition of this burner is accomplished by spilling about ½ cup of fuel into the combustion chamber and dropping a burning towel into the puddle. When fitted with the upper tent heater heat exchanger section, burner ignition was fairly easy due to a large access door located on the heater top. The lighting access port on the boiler is more confined due to the required placement of the float valve, low water cut-off and other plumbing components. This results in a small hole with a limited view of the burner internal components. To make ignition easier, a tube was installed in the access port that places the priming fuel in the appropriate location for ignition. Also, an ignition wand was used to hold the ignition paper and to place it directly into the priming fuel puddle.

Although these modifications improved the ignition success frequency, it is possible to have a flame failure. A failed attempt to ignite the burner forces the operator to wait until the burner has cooled down sufficiently before another ignition attempt. Attempting to reignite the burner while it is hot can cause a dangerous flare-up in the burner.

The lighting technique could be improved further if some modifications to the burner construction were made. What would be required is direct access to the burner base. This could be a door or a tube that allowed the placing of the fuel and towel directly at the burner base.

Burner Turndown

Although the burner has turndown capability as low as 33,000 Btu/hr, its present minimum firing rate is limited to 45,000 Btu/hr due to the requirement for the TEG output voltage to be a minimum of 14.4 volts in order to recharge the battery. Reconfiguration of the TEG modules to increase their open-circuit voltage would enable the low-fire limit to be reduced, thereby reducing fuel and water consumption. While some voltage improvement can be obtained by increasing the TEG hot-block temperature, it is likely that the number of thermocouple elements will need to be increased, either by adding modules or by increasing the number of thermocouple junctions per module.

The lower limit of 33,000 Btu/hr is set by smoke and CO considerations. A further reduction in firing rate would require burner modifications, such as variable air-flow control.

Wiring

Since this system will be operated outdoors and will occasionally be splashed with water, the electrical wiring connectors and enclosures should be splash-proof. All of the external wiring of the system is protected in splash-proof electrical boxes with sealed connectors. However, there is an electrical wiring raceway around the base of the boiler used to protect the TEG wires. The intention was to use water-proof automotive-type connectors inside the raceway. However, the water-proof connectors were too large to fit within the raceway. Push-on spade connectors were instead used in this prototype. Future revisions should allow sufficient space in the wiring raceway for waterproof connectors.

Piping

The tubes and hoses were arranged to provide a compact, organized package. When stored, the system could experience below freezing temperatures. The operator must be aware that any residual water in the pipes, pump or accumulator could freeze and cause damage. It is recommended that the hoses be drained before storing and drains be installed in the rigid piping in places where water accumulates.

Sanitation Temperature Control

Once the burner is lit and the sanitation sink is filled, operation is fully automatic except for manual control of the sanitation sink temperature. This requires the operator to monitor the sink temperature and control the flow of steam accordingly. It should be relatively straightforward to add a thermostatically controlled steam valve to fully automate the sanitation sink.

FSC System

The present sanitation system is a prototype intended to demonstrate the feasibility of the concept. Further work is required to improve packaging, transportability, maintainability, and robustness of the system. Attention should also be directed at the waste handling system, including grease and solids traps and greywater treatment.

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Appendix A

OPERATING AND ASSEMBLY INSTRUCTIONS

OPERATING AND ASSEMBLY INSTRUCTIONS

System Item List

- Rinse / Spray Cart - Includes Control Box, Accumulator and Spray Assembly.
- Sanitizing Sink Cart - Includes Sink and Steam Piping.
- Drain Hose Assembly
- Steam Hose
- 2 Water Hoses
- MKII Prototype Aluminum Boiler
- Lighting Tube Cover – With window
- Electrical Control Cable
- Fuel Solenoid / Cable Assembly
- H-45 Burner
- 14 Feet of Stack, 4" diameter – Seven 2 foot sections.
- Lighting Tool

System Assembly Instructions

1. Refer to the System Item List and be sure all the items are present.

2. Place the Rinse Tray Cart and the Sanitizing Sink Cart next to each other with the drain handles facing toward the operator. The Cart handles will be at the outside left and right locations.

3. Install the Spray Hose Assembly onto the vertical pipe on the back of the Rinse Tray Cart. Utilize the adjustable clamps on this pipe to set the spray head height. Make sure that the locking ring is not holding the spray valve open.

4. Place the H-45 burner to the right of the Sanitizing Sink, about 12 inches away, leaving the top half off. Place it so that the fuel control valve will be facing the operator in front of the Sanitizing Sink.

5. With the H-45's fuel control valve in place, install the Fuel Solenoid Assembly onto the outlet fitting of the valve using the quick-disconnect fitting. Now attach the fuel hose (that runs into the H-45) to the outlet fitting of the Solenoid Assembly.

6. Carefully place the MKII Prototype Boiler on the H-45 being sure to do the following:
    a. Make sure the slotted mounting ears line up with the wing nuts on the H-45.
    b. Orient the Boiler so that the steam outlet is directly above the fuel control valve.
    c. Swing the wing nuts into place and tighten.
    d. Connect the Solenoid Cable to the Amphenol connector on the right side of the Boiler Control Box. Be sure the cable doesn't contact the Surface of the H-45 because it will be hot.

7. Connect the Steam Hose between the Sanitizing Sink Cart and Boiler.
    a. The length of the hose determines the distance between the Cart and Boiler. If necessary, move the Boiler & burner closer to the Cart.
    b. Be sure that the fuel control valve remains accessible and the "Tilt / Level" and "High Fire" indicators on the Boiler are visible to the operator standing in front of the Sink.
    c. The hose must be installed with an upward pointing arc between the Sink and Boiler connections. No drooping areas are allowed, as they could trap condensate and create a dangerous condition. With the continuous arc, any condensed steam is free to drain back to either the Boiler or Sink.

8. Connect the Drain Hose Assembly to the carts.
    a. Pass the end of the assembly with the two couplings through the Sink support on the Sink Cart and attach them to the drains.
    b. Be sure to route the exit end away from the immediate area and/or connect to a drain system.

9. Install the water hoses. They are labeled.
    a. Connect the hose end labeled "To Cart Out" to the coupler labeled "OUT" on the rear of the Rinse Tray Cart.
    b. Connect the other end of that hose, labeled "To Boiler In" to the coupler labeled "IN" on the Boiler.
    c. Connect the hose end labeled "To Cart In" to the coupler labeled "IN" on the rear of the Rise Tray Cart.
    d. Connect the other end of that hose, labeled " To Boiler Out" to the coupler labeled "OUT" on the Boiler.
    e. Be sure that the hoses do not contact the burner anywhere, as these surfaces will be hot enough to cause damage.

10. Connect the Control Cable. It is run between the Amphenol connector on the back of the Rinse Tray Cart, and the Amphenol connector on the left side of the Boiler Control Box. Be sure that the cable does not touch the H45 burner. The cable is reversible, so the ends are not labeled.

11. Assemble the 4" diameter stack onto the Prototype Boiler. It consists of seven pieces measuring 24" each prior to assembly.

12. Connect your water source to the fitting labeled "Supply" on the rear of the Rinse Tray Cart.

13. Connect your fuel source to the inlet fitting on the fuel control valve.

14. Be sure the lighting tube cover is installed on the lighting tube.

Burner Ignition Instructions

1. Verify all assemblies are in place per the setup procedure.

2. Verify the steam valve is open and the sanitizing sink drain is closed.

3. Verify the proper fuel type and setting number is selected on the H-45 fuel control valve.

4. Open the water supply valve. Turn the H-45 fuel control valve on.

5. Turn the Control Box selector switch to the on ("I") position. The "PWR ON" light will illuminate.

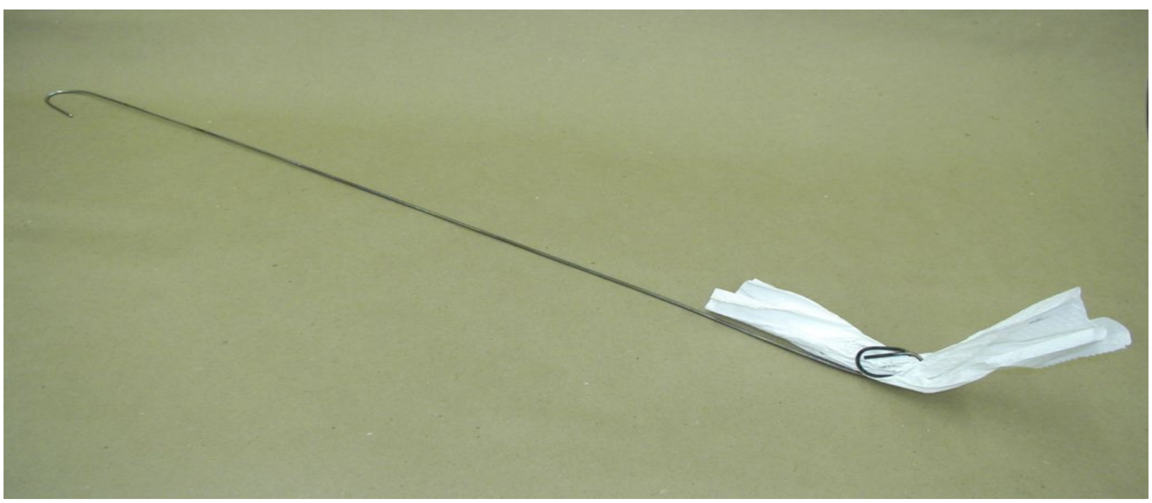
6. Push the pump button. The button should light and the pump will begin filling the boiler and accumulator with water.

7. When the " TILT / LEVEL OK " indicator on the boiler lights, the boiler can be fired.

8. Verify a water level exists in the boiler window before continuing.

9. Remove the cover from the lighting tube on the boiler. Verify that it is clean of soot and you can see through it clearly. Keep it nearby. Remove the lighting tool.

10. Prepare a paper towel (or equiv.) onto the lighting tool. Twist the towel and hook the lighting tool onto it at about the middle.

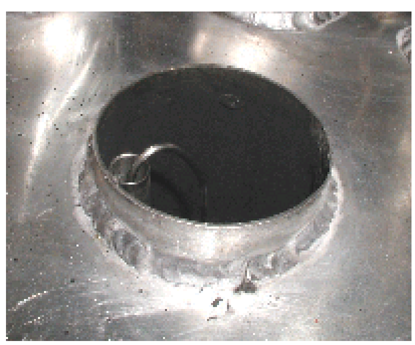


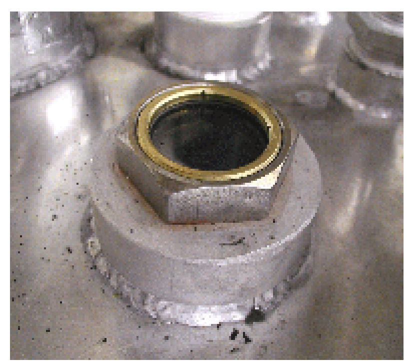
The next 3 steps (through #14) MUST be performed in immediate succession. Read all 3 first before attempting them.

11. Remove the lighting tube cover and place the small funnel into the priming tube. Pre-measure and pour 4 ounces (½ cup) of fuel into the funnel to create a puddle of fuel in the bottom of the H-45. Pour carefully to minimize spillage. Remove the funnel and put it aside when done.

DO NOT LOOK DOWN, OR HAVE YOUR FACE ABOVE THE LIGHTING TUBE DURING THE NEXT STEP. STAY OFF TO THE SIDE.

12. Light the paper towel on the lighting tool. Insert the tool into the lighting tube, past the baffles, forcing the flaming paper towel to the bottom of the burner and into the fuel puddle. Hook the top end of the tool onto the priming tube. Replace cover immediately.





13. Wait a few moments, and then look through the window to verify that the towel reached the fuel puddle and started a self-sustaining fire. If the paper towel did reach the fuel puddle, and did not ignite a sustaining fire, do not attempt a relight! This dangerous condition is considered a flame failure and you must follow the instructions regarding flame failure printed on the H-45 fuel control valve label.

14. The fuel puddle should ignite and begin vaporizing fuel in the system, creating a bright yellow well-established flame.

15. Swing the rinse sprayer over the sanitizing sink and be sure it stays there on its own.

16. Squeeze the handle and use the lock ring to hold the valve open and fill the sink. It takes roughly 20 minutes to fill the sink with 20 gallons of water. When the sink is full, remove the lock ring from the valve handle and place the sink cover on the sink.

17. When the water in the boiler begins to boil, you will hear popping noises from the steam sparger and see boiling action in the window.

18. Expect about a ½ hour warm-up time to bring the sink water to 170 degrees. The noise from the sparger will fade as the sink water warms.

19. The pump will cycle on and off as it supplies the boiler with fresh water.

20. The pump will also cycle as the sprayer is used.

System Drain & Breakdown Procedure

1. Before draining the system, verify the following:
    a. The switch on the Control Box is turned to the “O” (off) position.
    b. The burner has been out for a while, not hot, and all fuel valves are closed.
    c. The Boiler is NOT too hot to touch.
    d. The water supply is shut off.

2. Open the Rinse Tray and Sanitizing Sink drains.

3. Locate the Spray nozzle over the Sanitation Sink and install the lock ring to hold the valve open. This will drain water from the accumulator and relieve pressure from the system.

4. Remove the exhaust stack.

5. Place a container capable of holding 5 gallons of water under the boiler drain and open it. When the water flow nearly stops, tip the boiler to drain the remaining amount. Close the Boiler drain.

6. Remove the steam hose and place it into the Sink.

7. Remove the Rinse Spray assembly from its pipe and place it into the Sink. Using the adjustable clamps, raise the pipe to its highest available position to promote further draining.

8. From behind the Rinse Tray Cart, remove the three hoses and drain into a suitable container. Lower the Rinse Spray pipe to its lowest setting when the water stops dribbling out.

9. Remove the other end of the water hoses from the Boiler one at a time. For each hose, remove from the Boiler and raise that end up to drain the remaining water out. Remove the water supply hose in the same manner if applicable. Coil these hoses and place them into the Sink.

10. Make sure the exit end of the drain hose assembly is lower than the bottom trays and un-obstructed. Carefully remove the drain hose assembly from the two drain fittings. Use care while passing through the Sink support to avoid spillage. Hold up the end with the couplers to drain out all residual wastewater. Coil this assembly up and place it into the Sink.

11. Being sure that all valves are closed, disconnect the fuel supply. Use a small container for spillage.

12. Remove the control cable from the Boiler and the back of the Rinse Tray Cart. Coil the cable and place it into the Sink.

13. Disconnect the solenoid cable from the Boiler control box. Using the same small container for fuel spillage, remove the solenoid assembly from the H-45.

14. Loosen the three wing nuts securing the Boiler to the burner and swing down the bolts. The Boiler can now be removed from the H-45 burner.

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Appendix B

EVALUATION OF SABIE WATER HEATER AS A HEAT SOURCE FOR SP-FSC

EVALUATION OF SABIE WATER HEATER AS HEAT SOURCE FOR SP-FSC

1.0 Introduction and Summary

The Sabie water heater[2] has been proposed as a heat source for the self-powered food sanitation center (SP-FSC). The Sabie heater consists of a wick-type burner coupled to a water jacketed flue. The heat input rate with DF-2 is about 17,000 - 19,000 Btu/h. As received, the burner drew high amounts of excess air, resulting in an absorption efficiency of around 50%. After the air gap between the burner and the flue was minimized, the excess air was reduced to around 100%, with the result that the efficiency improved to about 62%. The addition of a flue baffle increased the absorption efficiency to as high as 77%, but with reduced draft and increased smoke. These preliminary tests indicate that the unmodified Sabie can supply up to about 10,000 Btu/h of hot water with DF-2, and if combustion is properly managed and with a modified heat exchanger, the output could be increased up to about 13,000 Btu/h.[3]

The energy requirements of the sanitation sink and the rinse spray are estimated to be about 17,000 and 23,000 Btu/h, respectively. At 75% efficiency, these would require firing rates of 23,000 and 31,000 Btu/h, respectively. Additionally, the sanitation sink would require a 3 GPM circulator drawing about 20 to 40 watts from a thermoelectric generator (TEG). The rinse pump is expected to draw an average of about 30 watts at 33% load factor.

It does not appear feasible to satisfy the needs of the SP-FSC with a single Sabie-type water heater. Instead, the preferred application would be a 30% larger (i.e., 23,000 Btu/h input) heater supplying the 170°F sanitation sink, and a 70% larger (i.e., 31,000 Btu/h input) unit supplying the 120°F - 140°F rinse water.

The rinse spray application appears quite straightforward. A small-capacity pump (e.g., 2/3 GPM) would supply cold water to the water heater whenever the burner fires. Water flow should be continuous in order to maintain TEG cooling. The heated water would be stored in a hot-water accumulator (e.g., 1 gallon) for use by the rinse spray. An automatic damper and/or pilot burner would need to be developed to cycle the burner between pilot mode and full-fire.

The sanitation sink application is less straightforward. One obstacle is the need to maintain sanitary conditions in the passages of the recirculating water system, including those of the water heater. Assuming that these can be satisfied, sufficient thermoelectric power must be generated (20 - 40 watts) using the 170°F sanitizing water. The high water temperature will require about 3 times the amount of TEGs as would be needed with cold-water cooling, raising the cost of the TEGs to about $1,200. The cost of the TEG and circulator can be avoided and the issue of maintaining sanitary conditions eliminated if the sink is direct fired instead.

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[2]U.S. Licensee: Action Link International LLC, P.O. Box 81055, Lafayette, LA 70598-1055.

[3]This compares with an advertised output of 16,600 Btu/h (2 l/min @ 63°F rise) with kerosene.

2.0 Sabie Water Heater

The Sabie heater consists of a wick-type burner coupled to a water-jacketed flue. The operational characteristics of the Sabie, based on tests conducted at AMTI, are shown in Table B1. As received, the burner drew high amounts of excess air, resulting in an efficiency of around 50%. After the air gap between the burner and the flue was minimized, the excess air was reduced to around 100%, with the result that the efficiency improved to about 62%. Smoke was acceptable at about #3 to #4 Bacharach smoke number. These preliminary tests indicate that the Sabie could supply up to about 12,000 Btu/h of hot water if combustion is properly managed.

Table B1. Sabie Water Heater Characteristics

	As Received	Reduced Air Flow
Burner Input - Btu/h	19,000	19,000
Stack Temperature - ^{o}F	500	900
Excess Air	400%	100%
Combustion Efficiency	52%	62%
Heat Output - Btu/h	9,900	11,800
Flue Height - in	57	
Stack Height - in	47	
Flue/Stack Diameter - in	2.38	

A thermal analysis of the Sabie indicates that in its present state its efficiency is unlikely to be improved much beyond 65%. However, a modified water heater with flue baffling to increase heat transfer could achieve an efficiency of about 75%. Additionally, the burner could be enlarged to increase burner input. The combination of these two modifications could increase the hot water output substantially.

To test the feasibility of increasing the absorption efficiency, a 2" x 57" straight flue baffle was inserted into the flue. This increased the heat transfer by radiating to the flue, without significantly increasing the flow resistance. The increase in heat transfer reduced the stack temperature from 900^{o}F to about 400^{o}F, increasing the absorption efficiency to about 77%. There was also a reduction in draft and a significant increase in smoke (to over #10 Bacharach smoke). Even after the excess air was increased by allowing additional air to enter at the base of the flue, smoke remained high. Next, the flue baffle was shortened to increase the exhaust temperature to about 600^{o}F, increasing the draft and dropping the absorption efficiency to about 72%. However smoke remained high. Subsequently, the baffle was removed, but the smoke still remained high. Consequently, it is unclear whether the flue baffle had any direct effect on smoke, or if the high smoke was simply a result of poor aeration/mixing of the flame. It is likely that better overall results could be achieved with some additional effort.

3.0 Energy Requirements

An estimate has been made of the energy requirements of the sanitation sink and the rinse spray. These results are shown in Tables B2 and B3. Table B2 shows that even if the efficiency of the water heater is increased to 75%, the burner input would have to increase to about 23,300 Btu/h in order to heat the 20 gallon sink by 100^{o}F (e.g., from 70^{o}F to 170^{o}F) in one hour. Input rates of 34,000 and 45,000 Btu/h are required to heat the sink in 45 or 30 minutes, respectively. On the other hand, it would take 90 minutes for the present Sabie with a net output of 11,800 Btu/h to heat the sanitizing sink.

Table B3 estimates the amount of energy required for sanitizing 400 lb/h of cookware, assuming that the cookware has been heated to 90^{o}F by the hot rinse. The cookware sensible heat load of about 8,000 Btu/h is in addition to the uncovered sink heat loss of about 9,000 Btu/h. Assuming a 75% water heating efficiency, the required burner input is about 22,000 Btu/h, or about the same as that required to heat the sink in one hour.

It is concluded that a modest increase in the net output of the Sabie water heater from the present 12,000 Btu/h to about 17,000 Btu/h should satisfy the needs of the sanitizing sink.

Table B2. Sanitizing Sink Warm-Up Heat Input

Warm-up Time	min	30	45	60
Initial Temperature	deg F	70		
Final Temperature	deg F	170		
Sink Capacity	Gal	20		
Boiler Efficiency		75%		
Net Energy Input Rate	Btu/h	33,320	22,213	16,660
Avg Covered Heat Loss	Btu/h	810		
Gross Heat Input Rate	Btu/h	34,130	23,023	17,470
Burner Input	Btu/h	45,506	30,697	23,293

Table B3. Sanitizing Heat Load

Ware Load	lb/hr	400
Ware Cp	Btu/lb-F	0.24
Ware Inlet Temp	deg F	90
Uncovered Heat Loss Rate	Btu/h	8,967
Ware Sensible Heat Load	Btu/h	7,680
Steady State Sink Input	Btu/h	16,647
Sanitizing Burner Input	Btu/h	22,196

The rinse energy requirements are shown in Table B4. In order to supply 2 GPM at a temperature rise of 70^{o}F at 33% duty cycle, a 75% efficient water heater requires a burner input of about 31,000 Btu/h. Using a 23,000 Btu/h input burner (i.e., the same input as used by the sanitizing sink), the duty cycle at 2 GPM and 70^{o}F rise drops to 25%.

Table B4. Rinse Energy Requirements

Water Inlet Temp.	deg F	70	
Water Outlet Temp	deg F	140	
Water Flow Rate	GPM	2	
Duty Cycle		24.6%	33.33%
Rinse Energy Input	Btu/h	17,250	23,333
Burner Efficiency		75%	75%
Rinse Burner Input	Btu/h	23,000	31,111

The conclusion from these energy estimates is that it is unlikely that a single Sabie-type water heater can supply the needs of both the sanitizing sink and the rinse spray during continuous operation. It may be feasible, on the other hand, to apply separate water heaters for the sanitizing sink and the rinse spray. The sanitizing sink water heater would require a modest increase in the firing rate of the Sabie water heater to 23,000 Btu/h. In order to meet the 33% duty cycle requirement, the firing rate of the rinse water heater would have to increase to about 31,000 Btu/h at 75% efficiency.

The present Sabie burner is 2.38" in diameter. Increasing its input to 23,000 Btu/h would require a 2.6" diameter; a 31,000 Btu/h input would require about 3". The flue diameter would have to increase similarly.

5.0 Power Requirements

Rinse Pump

The rinse pump is required to supply 2 GPM at about 20 psi at 33% duty cycle, or about 2/3 GPM on average. The theoretical power requirement is 5.8 Watts. Actual power should be about 30 watts.

Presumably the electric power for the pump would be supplied by a water cooled thermoelectric generator (TEG). To provide adequate cooling for the TEG, the water should flow continuously whenever the rinse burner is operating. Therefore, although the rinse spray could be supplied intermittently by a 2 GPM pump, it would be better to use a 2/3 GPM pump operating whenever the burner operated, and filling a 1 gallon accumulator.

Sink Circulator

Theoretically, it should be possible to operate the Sabie as a "side-arm" water heater, with the buoyancy of the heated water providing natural convection between the sink and the heat exchanger. However, the height of the Sabie relative to the elevation of the sink prevents effective natural circulation. Consequently a circulator pump is required.

The circulator should provide sufficient flow to prevent boiling. The supply temperature should not exceed 180^{o}F to 190^{o}F, or a temperature rise of 10^{o}F to 20^{o}F at a sink temperature of 170^{o}F. At a heat input to the water of about 17,000 Btu/h, this requires a water flow rate of about 1.7 to 3.4 GPM.

The power for the circulator would be supplied by a TEG. Therefore, the pump should provide sufficient head to overcome the pressure drop in the water heater and in the TEG, the TEG pressure drop being the larger of the two. A pump head of about 3-5 psi should be sufficient. This requires a theoretical pumping power of 3.7 to 7.4 Watts. An actual hot-water circulator meeting this requirement, the Grundfos UP 15-42 requires 86 Watts. A diaphragm pump, assuming one can meet the operating temperature, would require about 20 to 40 Watts.

6.0 Development Needs

The present Sabie water heater is deficient in several respects. Its substandard absorption efficiency is a result of poor management of aeration of the burner and of an inadequate heat transfer design. Burner aeration can be improved by elimination of air leakage, which results from poor fitting of the burner/flue interface. In addition, improved port design will result in better mixing and reduction in smoke. Heat transfer can be improved significantly by the addition of some rather simple flue baffling, as has been demonstrated.

Even with such improvements, the Sabie does not have sufficient capacity to meet the demands of the SP-FSC, and the size of the burner must be increased. If the burner diameter alone is increased, this will require deeper air-jet penetration in order to sustain air-fuel mixing. A possible approach may be to provide an inner air manifold to aerate the core of the flame, thus requiring lesser air-jet penetration.

Another required modification is an improved fueling system. The Sabie wick is surrounded by a fuel plenum containing about 1.0 lb of fuel. As the fuel level drops, the output is reduced. The fueling system should have a sufficient capacity for extended operation, should maintain proper combustion over a range of environments and fuel properties, should be fail-safe in the event of loss of flame, and should prevent flooding. The on-board fuel inventory also complicates shut-down of the burner, since the hot fuel must be safely disposed of. The burner is quite hot and smoky at shut-down, making it difficult to drain of fuel. For ease of transport, the burner should contain minimal fuel at shutdown and should be capable of being tightly sealed for transport.

The Sabie water jacket is quite adequate and does not require significant improvement. Reducing the width of the water annulus will shorten the warm-up time of the heater. The main modification to the coolant circuit will be the addition of a water-cooled TEG section at the base of the flue. Cold supply water will first cool the TEG before entering the upper water jacket.

There are two opportunities to eliminate the need for a powered circulator. One would be to modify the Sabie so that its heat exchanger would be largely below the level of the sink, so that the flow to the water heater could be provided by natural circulation. This would result in a water heater similar to a conventional hydronic boiler, and would require relatively large hoses between the sink and the water heater.

The second alternative is to heat the sink directly, eliminating the need for the second heat exchanger. This would also eliminate the issue of conveyance of food debris from the sink to the water heater. A Sabie type wick burner could be used to heat the sink.

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Appendix C

INITIAL BURNER DEVELOPMENT

INITIAL BURNER DEVELOPMENT

Introduction and Summary

This report describes development non-powered burners for the Self-Powered Food Sanitation Center during the first half of 2000. At the end of 1999, following an evaluation of the Sabie non-powered water heater, the project plan was modified to develop modified Sabie type water heaters suitable for heating of the sanitizing sink by steam injection and for once-through instantaneous heating of rinse water. Since the capacity of the Sabie wick-type burner was insufficient for these applications, a new, larger burner was required. The objective of the burner development was to produce a burner that was capable of operation with non-pressurized diesel-type fuels (such as the Sabie), but with greater heating capacity and with automatic turndown capability. Burner input needed to be increased from the Sabie's approximately 18,000 Btu/h to about 23,000 Btu/h and 31,000 Btu/h for the sanitation sink heater and the rinse water heater, respectively.

Tests of the Sabie burner had indicated that its smoking tendency was extremely sensitive to aeration. Moreover, the Sabie had no effective means of capacity modulation or regulation of air/fuel ratio, and its relatively large fuel inventory made shut-down slow and troublesome. This suggested that simply scaling up the Sabie would not be practical.

Several experimental prototype burners have been designed, fabricated, and tested with the objective of improving upon the Sabie by addressing its shortcomings. These have reduced on-board fuel inventory, controlled aeration, improved mixing, and provisions for capacity modulation. While these have met with varying degrees of success, to date none has operated with acceptable smoke levels. Currently, we have returned to testing of the Sabie burner under controlled conditions in order to determine the factors that most strongly influence smoke and soot formation.

Burner Development

The initial approach to improving the Sabie burner was to combine the simplicity of a wick burner with the low fuel inventory and modulation capability of a vaporizing burner. The size of the wick was reduced so that it could serve as a continuous pilot flame for the main vaporizing burner. The vaporizing burner was designed to evaporate a pool of fuel by conduction down the sizes of the burner and by radiation from the flame. Modulation of evaporation rate was to be accomplished by varying the size of the fuel pool, while air flow was to be controlled by shutters. Since the intention was to use the Sabie water heater as the flue for development testing, the size of the experimental burners was not increased.

Copper Swirl Burners

The first vaporizing burners tested were made from 2.5" copper tube and fittings. Combustion air ports were machined at an angle in the side of the tube so that the air entering the burner would enter tangentially, resulting in a swirling action. The tube was heated by the flame, and the heat was conducted down the sides of the tube to the fuel pool. These burners were very effective at conducting heat down to the fuel pool for vaporization.

Figure C1. Vaporizing Swirl Burner

The first copper swirl burner had a flat 2.5" pipe cap to hold the fuel. The fuel was introduced into this reservoir and the level was adjusted to control the firing rate. The firing rate was unstable because an increase in firing rate increased the heat transfer to the tube wall, which in turn increased fuel vaporization, thus increasing the firing rate. This burner emitted a plume of soot under all conditions.

This burner was then modified to include a 0.75" diameter wick at the center of a tapered fuel reservoir, as shown in Figure C2. Firing rate control was to be achieved by varying the fuel level in the tapered section. This burner was slightly more stable in operation, but still had a smoke number greater than 10.

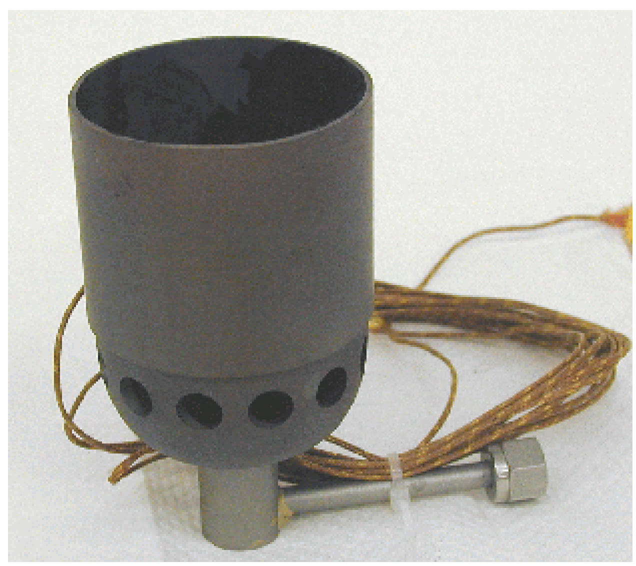

Figure C2. Stainless Steel Wick/Vaporizing Burner

It was observed that the strong swirl concentrated the flame at the center of the burner at low firing rates, thus minimizing heating of the tube wall. As firing rate increased, the flame expanded to the tube wall, resulting in a rapid increase in wall temperature. Consequently, it was concluded that the strong swirl might be responsible for the unstable operation. Furthermore, it was suspected that excessive heat conduction to the vaporizing chamber might be destabilizing.

Stainless Steel Wick/Vaporizing Burner
The next burner tested used a stainless steel pipe cap as the fuel reservoir, welded to a stainless steel, 2.5" OD, 2" long tube. Twelve 0.375" diameter holes were drilled into the pipe cap around its circumference. These holes were drilled 0.1875"offset from the center so that the air jets would not converge on each other at the burner center. This burner also had a small pilot wick installed at the apex of the tapered fuel cup. The rate of fuel flow to the burner could be controlled by a needle valve in the fuel line to the burner.

The burner had a firing rate of about 12,000 Btu/h and about 100% excess air from a natural draft of about 0.08" wc at the burner when connected to the Sabie water jacket. The firing rate appeared to be stable. The burner exhaust had a smoke number greater than 10 at all excess air conditions.

Stainless Steel, Wick, Vaporizing Staged Air Burner
Under the belief that the high smoke might be a result of introducing the air all at once at the base of the burner, the next burner had staged air injection. It was made with a 2.5" diameter stainless fuel cup welded to a 6" long 2.5" diameter cylinder. Three rows of twelve holes each were drilled into the fuel cup and the cylinder. The first row had 0.155" diameter holes drilled into the exit of the fuel cup, the second row had 0.214" diameter holes drilled 1.75" above the first, and the third row had 0.338" diameter holes 2" above the second row. All holes were tapped so that they could be plugged to vary the air staging ratios. This burner had a similar firing rate and excess air as the previous burner, and its exhaust had a smoke number greater than 10.

Figure C3. Stainless Steel, Wick, Vaporizing Staged Air Burner

Stainless Steel, Wick, Vaporizing, Staged, Preheated Primary Air Burner
It was thought that the high smoke might be due to cracking of the liquid fuel in the process of vaporizing it. Boiling of the fuel in the absence of air (oxygen) tends to 'crack' the fuel and forms soot. Once soot particles are formed, they are difficult to oxidize. Evidence of thermal cracking was seen in the previous burners, as coke and soot tended to accumulate on the burner walls, especially at the fuel liquid level.

Since the dew point of fuel is lower than its boiling point, it was believed that causing the fuel to evaporate into a heated air stream might reduce the smoke and soot. To accomplish this, the next burner had two rows of holes, about 5" apart. The primary air holes were angled down to direct the air flow directly onto the fuel pool. A cylindrical shroud channeled the primary air over the hot burner surface before entering the primary air holes. A thermal break was put between the fuel cup and the burner cylinder to reduce the heat conduction to the fuel cup.

This burner operated similarly to the previous burners. The firing rate was about 12,000 Btu/h, the excess air ranged from 35% to 100%. At an excess air of about 114%, the CO emission was 39 ppm. The smoke index however was still over 10.

To test the possibility the flame might be quenched before the soot had a chance to completely oxidize, a cylindrical combustion chamber with a volume of 400 in^3 was added between the burner and the Sabie water heater to increase the residence time of the flame before it was quenched by the cold water jacket wall. The effect of this additional combustion volume was to decrease the CO emission to 19 ppm at 35% excess air. However, the smoke index remained over 10.

Figure C4. Stainless Steel, Wick, Vaporizing, Staged, Preheated Primary Air Burner

Premixed Burner

Previous burners had operated smoke-free using premixed fuel and air. These burners required a high-pressure fuel supply, mainly to aspirate the combustion air. An attempt was made to achieve premixed combustion using low-pressure fuel. The burner consisted of concentric tubes that channeled the combustion air down the outside of the inner flame tube to the bottom of the burner, which preheated the air. The fuel was introduced at the top of a central tube covered with a sleeve wick. The heated air entered at the base of the wick and flowed counter to the falling fuel on central wick to evaporate and mix with the fuel. The top of the annular mixing chamber was capped with a perforated screen to act as a flameholder.

Testing of this burner revealed it had deficient fuel vaporization and fuel/air mixing. The air preheat section of the burner was unable to heat the air over 100 ºF. A heat gun and heating tape were used to elevate the incoming primary air to about 400 ºF. This resulted in an increase in fuel vaporization, but the air and fuel did not mix well prior to being burned on the flameholder. This resulted in a long, yellow and sooty flame residing mostly near the center of the flameholder.

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Appendix D

DESIGN, DEVELOPMENT AND TESTING OF THE MK-1 STAINLESS STEEL BOILER AND THERMOELECTRIC GENERATOR

DESIGN, DEVELOPMENT AND TESTING OF THE MK-1 STAINLESS STEEL BOILER AND THERMOELECTRIC GENERATOR

Summary

A boiler with integral hot water heating coil was designed to supply a hot water rinse stream and sanitizing water heating for the Army SP-FSC. The boiler was designed to use the burner of an H-45 tent heater as a heat source. In addition, a thermoelectric generating module was designed to cogenerate electricity to power the rinse water spray pump. The boiler has shown the potential to operate with a thermal efficiency of 70% to 73% with a burner input of about 60,000 Btu/hr, and the TEG has demonstrated the potential to generate about 40 Watts using (6) Hi-Z HZ-20 thermoelectric modules. Work remains to reduce the size and weight of the boiler in order to improve its transportability.

Boiler Development and Testing

An experimental pre-prototype of a boiler to produce hot water and steam for the Self-Powered Food Sanitation Center has been fabricated and tested. The purpose of building and testing a pre-prototype boiler was to investigate the feasibility of the design concept and to establish thermal and combustion design parameters to be used for the design of a practical system. Consequently, the design of the pre-production prototype emphasized ease of construction, facility for measurement and observation, and flexibility for modification, with lesser consideration for size, weight, and transportability.

The boiler, illustrated in Figure 1, was designed to use the burner of an H-45 tent heater as its source of heat. It is comprised of an 18" OD x 18" tall outer shell with a concentric 16" ID x 15" tall inner shell. The inner shell provides a combustion chamber and heat transfer surface. Twenty-four evenly spaced longitudinal fins are attached to the hot gas side of the inner shell. The fins are 15" long x 1" high. A 4" flue extends from the top of the inner cylinder through the top of the outer cylinder to exhaust combustion products to the stack. The boiler is fabricated of 16-gauge stainless steel and the fins of 16-gauge carbon steel.

The boiler is filled to a level about 1" above the top of the inner cylinder. Water fill and equalizing connections are provided in the outer cylinder for level control. Level control is by an external float chamber. A steam outlet is provided in the top of the outer cylinder and a drain is provided near the bottom of the outer cylinder. A coil is provided in the annulus formed between the inner and outer cylinders for indirect heating of rinse water. Coil inlet and outlet connections are provided in the outer cylinder.

The boiler was envisioned to rest on a series of thermoelectric generator (TEG) modules which in turn sit directly on the H-45 burner. The TEG modules are cooled by saturated or subcooled water from the bottom of the boiler annulus. A two-phase stream is returned to the boiler above the rinse water-heating coil. Designed in this way, the TEG co-generates both electricity and steam. The boiler was designed with a thermal efficiency target of 75%, including the contribution from TEG co-generation. The burner fuel valve is marked with settings of 2, 3, 4 and 5 which correspond to nominal burner inputs of 40, 50, 60 and 70 kBtu/hr respectively. At 75% efficiency, a fuel setting of 4 would result in heat absorption of about 45,000 Btu/hr which matches the maximum expected thermal demand of the SP-FSC.

Initial testing of the boiler was done without the TEG modules, and used fire bricks in place of the TEG modules to correctly position the boiler. Testing the As-Built boiler configuration showed it fell short of the target thermal efficiency. A series of modifications were made to the combustion chamber and heat transfer surface of the boiler with the aim of improving its efficiency without sacrificing combustion performance. The sequence of development is described below.

The burner/boiler performance of the As-Built configuration is described in Table D1. Analysis of the experimental data indicated that only a small portion of the heat transfer to the boiler was by convection, with thermal radiation as the primary heat transfer mode. Convective heat transfer coefficients (HTCconv) ranging from 0.5 to 0.65 Btu/hr-ft2-°F were calculated for burner inputs from 48,000 72,000 Btu/hr. This implied effective radiation coefficients (HTCrad) ranging from 3.5 to 5.0 Btu/hr-ft2-°F. While this configuration resulted in the maximum possible radiation heat transfer to the boiler, potential convective heat transfer was hardly being tapped.

Table D1. Performance of As-Built Burner/Boiler

Fuel Valve Setting 4
61,038 Btu/hr Burner Input

Excess Air	Stack Temperature	Thermal Efficiency	Smoke Number
80%	953°F	63%	6
98%	915°F	62%	4
119%	886°F	60%	2-3

To improve thermal efficiency, a 14" diameter circular baffle was added inside the combustion chamber at the mid-point of the fins[4]. See Figure 2a. This change was intended to force all of the hot gas flow to pass over the longitudinal fins, thereby increasing convective heat transfer. The baffle eliminated direct thermal radiation to the upper half of the inner cylinder. As a result, radiation heat transfer was expected to decrease. Addition of the baffle resulted in a significant improvement in thermal efficiency and a slight improvement in smoke number. The increase in convection more than compensated for the reduction in radiation.

Extending this concept, a 5" long cylindrical skirt was added to the top of the baffle, and the baffle/skirt assembly was positioned to shroud the middle third of the fins. See Figure 2b. This change was intended to further enhance convection. The overall thermal performance improved slightly. The 5" long shroud most likely resulted in significantly higher convective heat transfer, but the further reduction of heat transfer surface with a direct view of the burner had to reduce radiation. To improve the radiation view factor while retaining the convective enhancement, the baffle/skirt assembly was relocated upward so that the top of the skirt was about 1¼" from the top of the inner can. See Figure 2c. This resulted in a more significant improvement in both thermal efficiency and smoke number as shown in Table D2.

Table D2. Performance of Burner/Boiler w/ Baffle & 5" Skirt

Fuel Valve Setting 4
61,880 Btu/hr Burner Input

Excess Air	Stack Temperature	Thermal Efficiency	Smoke Number
84%	701°F	72%	4
100%	684°F	71%	1
116%	680°F	69%	0-1

Testing of the As-Built configuration and the various baffle and baffle/skirt configurations provided insight to the geometric factors that effect heat transfer to the boiler. Shrouding the fins clearly increases convection, and exposing more of the inner cylinder surface to a direct view of the burner increases radiation. A new configuration was tested with the intention of optimizing both heat transfer modes. The circular baffle was moved to a position about 1½" from the top of the inner cylinder, with a 12" cylindrical skirt extending from the baffle to 1½" from the bottom of the fins. This provided the greatest practical degree of shrouding for the fins. By locating the baffle

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4 A 4" diameter "trap-door" was installed in the center of the baffle to permit priming and lighting of the burner.

at the top of the skirt, the inner surface of the skirt would be directly exposed to radiation from the burner, be heated, and then re-radiate to the inner surface of the boiler. The performance of this configuration is shown in Table D3.

Table D3. Performance of Burner/Boiler w/ Baffle & 12" Skirt

Fuel Valve Setting 4
60,150 Btu/hr Burner Input

Excess Air	Stack Temperature	Thermal Efficiency	Smoke Number
73%	698°F	73%	2
102%	687°F	71%	1
118%	679°F	69%	0-1

Thermal performance for this configuration was similar to that of the baffle and 5" skirt in the upper position. However, there was a significant improvement in smoke number at low excess air levels. Smoke numbers no higher than 2 were obtained for excess air as low as about 73%. Thermal performance at that point was about 73%. Carbon monoxide emissions were also very low for this configuration leading to the conclusion that this configuration provides a large effective combustion volume and a long residence time that provides for very complete combustion. This configuration has the potential for higher efficiency without unacceptable smoke levels. More importantly, it also has the potential for a reduction in size while maintaining high efficiency and low smoke. Thermal performance and smoke numbers for the five configurations described above are shown in Tables 3 and 4.

To further characterize this configuration, thermocouples were attached to the skirt about 1" from its top and bottom edges. Thermocouples were also attached to adjacent longitudinal fins, about 3" from the bottom of one and about 3" from the top of the second. A second thermocouple was added at each fin thermocouple location to measure the local gas temperature. These local temperatures at two test points are shown in Table D4.

Based on this data, it is clear that the skirt is not overheated, but is heated to a temperature that would result in significant radiation to the inner boiler cylinder. In all of the testing done in this configuration, the gas temperature at the upper fin location is always more than 100°F cooler than the average exhaust temperature. Circumferential asymmetry in the hot gas mass flow was originally thought to have caused the low temperature measured by the gas thermocouple adjacent to the fin. To test this theory, the temperature entering each fin passage was measured, with the variation found to be too low to account for the low temperature at the top of the fin passage.

Table D4. Local Surface and Hot Gas Temperatures

Burner Input		62,163	62,287
Excess Air		99%	90%
Average Exhaust Temperature		690°F	691°F
Skirt Temperature	Top	926°F	943°F
	Bottom	989°F	1002°F
Fin Temperature	Top	341°F	373°F
Gas Temperature	Top	556°F	573°F
Calculated Base Temperature		305°F	316°F
Fin Temperature	Bottom	431°F	456°F
Gas Temperature	Bottom	784°F	787°F
Calculated Base Temperature		327°F	359°F

Another possible cause is hot gas leakage past the trap-door in the baffle. About 1 square inch of by-pass area exists. A relatively small amount of very hot gas leaking through the trap-door could account for the higher exhaust temperature. A mapping of the radial variation in combustion chamber temperature suggests an average core temperature of about 1350°F. At this temperature, a leakage rate of about 18% would account for the measured temperature differences. It is unlikely that the leakage rate is as high as 18%. The low gas temperature is most likely due to a combination of flow maldistribution, leakage past the trap-door, and thermocouple radiation error.

This issue highlights the need for a better means of lighting the burner to eliminate the need for the trap-door. This would eliminate any leakage and result in increased mass flow rate past the longitudinal fins, thereby increasing heat transfer to the boiler and improving thermal efficiency. However, this improvement would come at the expense of reducing the available stack draft.

The measurements of the fin and gas temperatures were used to determine the fin efficiency, which in turn was used to infer the degree to which the fins were bonded to the boiler wall. The fin thermocouples measured the fin temperature about ¼" from the tip of the fin. Using an average gas-side heat transfer coefficient of 5 Btu/hr-ft^2-°F calculated from the heat input, the fin efficiency was determined to be 83%-84%. Using this fin efficiency, the temperatures at the base of the fin were calculated to be 314°F and 344°F at the top and bottom locations, respectively, for the first test point, and 323°F and 375°F for the second set. Since the boiler wall temperature was estimated to be about 232°F, these calculated base temperatures implied imperfect contact between the spot-welded fins and the boiler wall. The combined effect of contact resistance and fin efficiency was estimated to reduce the heat transfer effectiveness by approximately 16%.

Hot Water Coil Development and Testing

A copper finned-tube water heating coil is installed in the boiler annulus to provide hot rinse water for the SP-FSC. The tubing is ¾" Wolverine type S/T Trufin with 19 fins per inch and a surface area ratio (outside to inside) of 3.62. A total coil length of about 20 feet is provided in 4½ coils. The coil was tested at flow rates from about 0.36 gpm to about 1.4 gpm, and with inlet temperatures from as low as 47°F to as high as 160°F. The coil proved to be nearly 100% effective with the outlet temperature reaching 210°-211°F in all cases while the boiler was still generating steam. The nominal design point for the hot water coil is a 70°F temperature rise at a minimum flow rate of b gpm.

Based on the test data, an overall heat transfer coefficient of about 450 Btu/hr-ft2-F can be expected at a flow rate of b gpm. With a normal inlet temperature of 70°F, only about 3.2 feet of tubing, or about ¾ of a coil, is needed to reach an outlet temperature of 140°F. For a low inlet temperature of 35°F, about 4.2 feet of tubing, or about 1 coil, is required. In practice, the coil inlet and exit fittings would be located 180° apart on the boiler so a 1½ coil tube will be used. This would result in a discharge temperature of about 180°F for an inlet of 70°F at b gpm, and about 169°F for a 35°F inlet temperature.

Thermoelectric Generator Development and Testing

A thermoelectric generator was designed to be incorporated into the SP-FSC to provide approximately 40 Watts of electrical power to operate the rinse water spray pump. The target power can theoretically be achieved by using (2) Hi-Z HZ-20 thermoelectric modules which are rated to produce 19 Watts with a hot face temperature of 235°C and a temperature difference of 200°C. In this application, the TEG hot face temperature can be readily achieved by exposing the TEG heat sink to hot gas in the combustion chamber. However, the temperature difference across the TEG is limited by the amount of cooling that can be done. Since rinse water will only run intermittently, cold water is not continuously available for cooling. The available options are air cooling or ebullient cooling by vaporizing subcooled or saturated water from the boiler.

Practical air cooling requires a blower and its associated parasitic electrical load. More significantly, since the thermal-to-electrical conversion efficiency of TEG's is less than 5%, air cooling wastes a significant amount of thermal energy. While ebullient cooling effectively limits the TEG cold face temperature to the boiling point of water, all of the waste heat from the TEG is used to generate steam which is returned to the boiler. A TEG designed in this way is nearly 100% efficient as a co-generation device. Hi-Z recommends a maximum module hot face temperature of 250°C. With boiling water as the ultimate heat sink and finite thermal conductances between the module and the cooling block, the expected module temperature difference is on the order of 130°C to 140°C. Hi-Z specification sheets predict a power output of 6 to 7 Watts for these temperatures, thereby requiring (6) HZ-20 modules to produce a nominal 40 Watts of electrical power .

The design of the TEG is illustrated in Figure 5. The TEG is basically a sandwich of an aluminum alloy extrusion, an HZ-20 module, and an aluminum cold block. The assembly shown in Figure 5 includes (2) HZ-20 modules, and is housed in a "picture frame" fabricated from steel angle. The size of the picture frame is about the same as the fire bricks used to support the pre-prototype boiler on the H-45 burner. For testing, a brick was removed and replaced by the TEG assembly. Water from the bottom of the boiler was ported to the cavity of the cold block, and risers were provided to return steam from the cold block to the boiler. HZ-20 modules are provided with exposed electrical junctions and therefore require a dielectric interface between the module and the heat sink and cold blocks. The heat sink and cold blocks were both hard-coat anodized to provide an interface with high electrical but low thermally resistance. The interface surfaces on both the heat sink and cold block were machined to a flatness of better than 0.001" to reduce contact resistance, and a thermally conductive grease was used at both interfaces to bridge any micro-gaps. The recommended 200 psi compressive load was maintained on the TEG assembly by a stack of Belville washers on each through-bolt.

The TEG module was installed in the burner/boiler and tested at burner fuel valve settings of 2, 3, 4 and 5. Thermocouples were installed in the heat sink and cold blocks to assess thermal performance, and the modules were connected to an external load circuit recommended in Hi-Z literature to measure electrical performance. TEG performance is shown in Table D5. Since each module produced about 6.5 Watts at a fuel valve setting of 4, the TEG design clearly has the potential to generate a nominal 40 Watts under the intended SP-FSC operating conditions.

Two significant assumptions were made in designing the heat sink fins for the TEG module, the average gas temperature and the HTC. The average gas temperature was measured to be on the order of 1200°F at a location about 1/4" in front of the fins. Using the measured heat sink and cold block temperatures, and the module temperature difference inferred from the open circuit voltage, a heat transfer coefficient of about 2.95 Btu/hr-ft2-°F can be back-calculated. This is much lower than the HTC's calculated for the boiler surfaces, even for the As-Built configuration. Since the TEG heat sink fins are un-shrouded, the convective contribution would be expected to be no greater than that of the As-Built boiler surface, and as a result the implied radiation contribution is less than that of the As-Built boiler.

Table D5. TEG Performance

Fuel Valve Setting	2	3	4	5
Open Circuit Voltage	2.46 V	2.77 V	3.03 V	3.22 V
Current	3.34 A	3.72 A	4.08 A	4.31 A
Electrical Power	4.38 W	5.44 W	6.53 W	7.29 W
Efficiency	2.1%	2.3%	2.6%	2.8%
Heat Sink Temperature	210°C	227°C	245°C	258°C
Cold Block Temperature	108°C	109°C	109°C	110°C
Module Delta T	96°C	109°C	119°C	126°C
Interface Delta T	3.0°C	4.7°C	8.5°C	10.6°C

However, the fin density of the TEG heat sink is about 6 times that of the boiler, while the fins are of equal height, resulting in high aspect ration channels between fins. Since the hot gas flow is not forced over the TEG fins, it very likely that the average local gas temperature between fins is much lower than the bulk gas temperature measured in front of the fins. If an average gas temperature of 1000°F were used in the calculation rather the 1200°F bulk gas temperature, an HTC of about 4 Btu/hr-ft2-°F would be back-calculated, which is closer to that of the As-Built boiler surface. It is also very likely that the high aspect ratio of the TEG fins reduces the radiation view factor sufficiently to result in lower radiation heat transfer to the TEG as compared to the As-Built boiler surface.

As illustrated in Figure 1, boiler water is supplied to the TEG and steam is returned to the boiler via external plumbing. Extending this concept to (2) additional TEG modules is not practical. The next prototype boiler/TEG must supply "cooling" water to the TEG in a manner that eliminates external plumbing.

Conclusions

The conclusions from the boiler efficiency and combustion tests are as follows:

- Thermal efficiency can be improved by increasing convective heat transfer, even though this reduces radiative heat transfer. The degree to which convective heat transfer could be increased in the pre-prototype boiler was limited by the dimensions and spacing of the fins. The thermal efficiency could be increased by the use of more closely spaced fins and longer fins. However, the practical degree to which thermal efficiency can be increased is limited by the effect of reducing stack draft, which would compromise combustion and smoke.

- The effectiveness of heat transfer was reduced by imperfect bonding of the fins to the boiler wall. This was a result of the spot welding process used to attach the sheet-metal fins to the boiler wall. The use of seam welded aluminum fins should avoid this problem. It may also be possible to use extruded aluminum heat sink material, with integral fins, for the inner boiler wall. The high raw material cost may outweigh the cost of attaching fins to the boiler wall, and the integral fins would eliminate contact resistance.

- The 18" diameter and 18" height of the boiler could be reduced by increasing the extended surface area ratio (ratio of fin to prime boiler surface area) and by correcting the imperfect fin-to-wall bond. Also, the weight of the stainless steel boiler and carbon steel fins can be reduced by an all-aluminum construction.

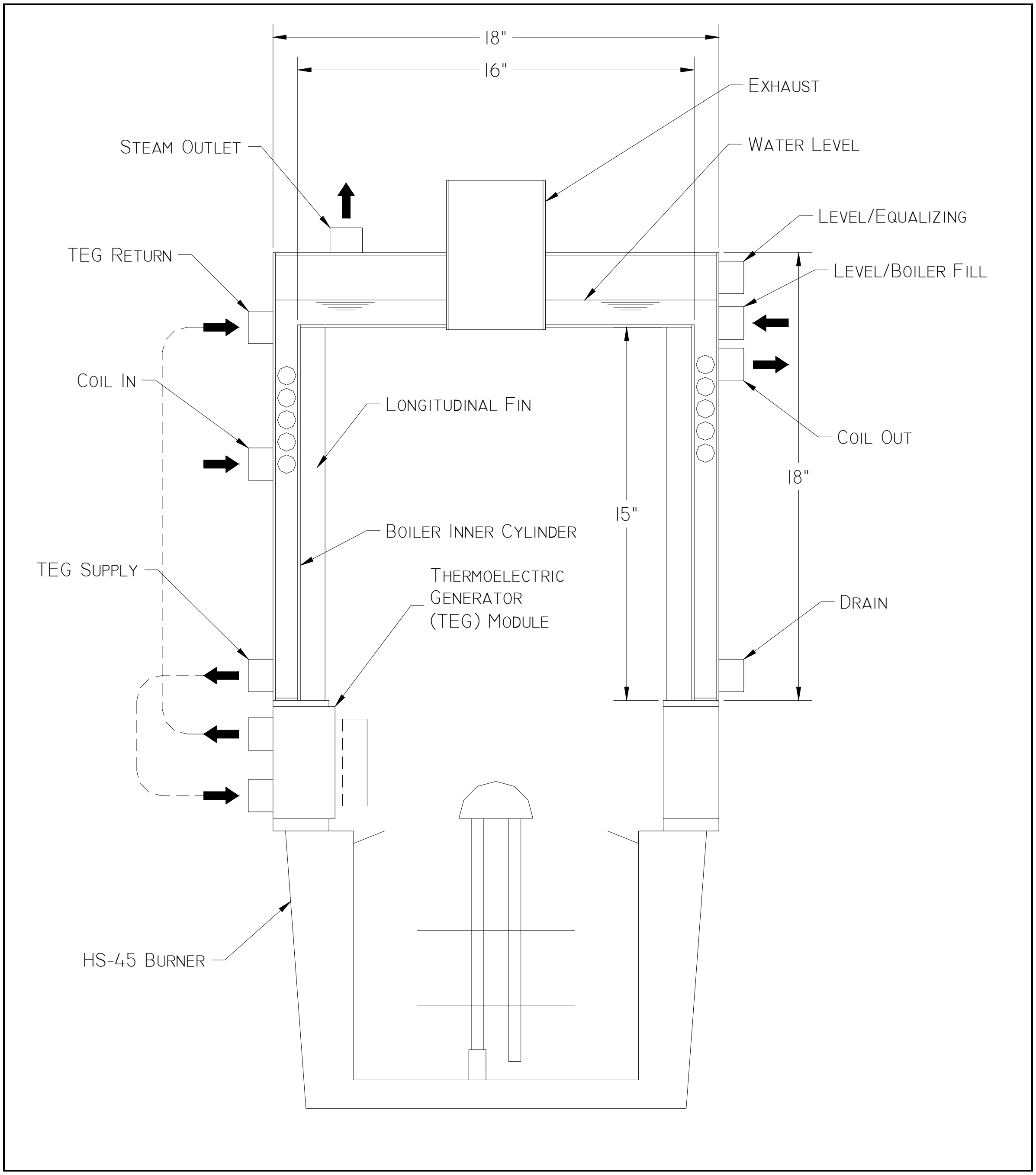

Figure D1: Prototype Boiler for Army AFSC

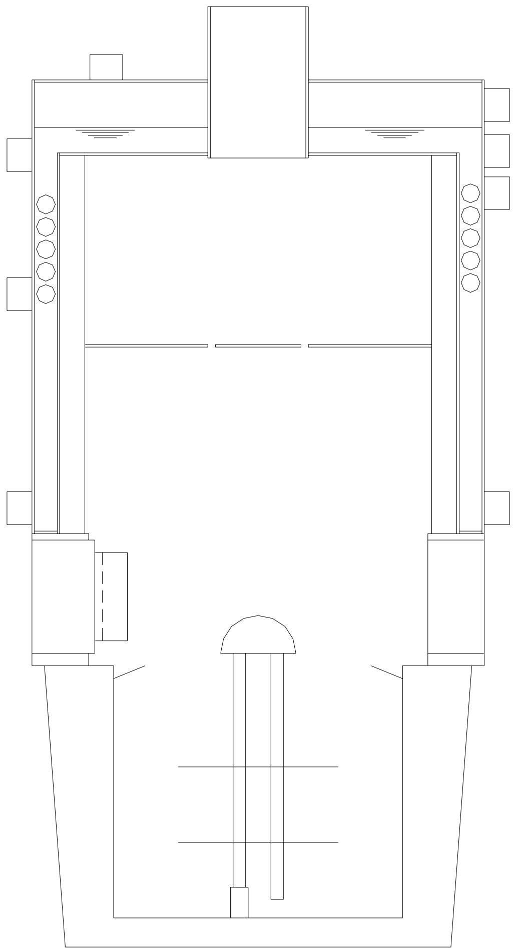

Figure D2: Baffle at Mid Height of Fin

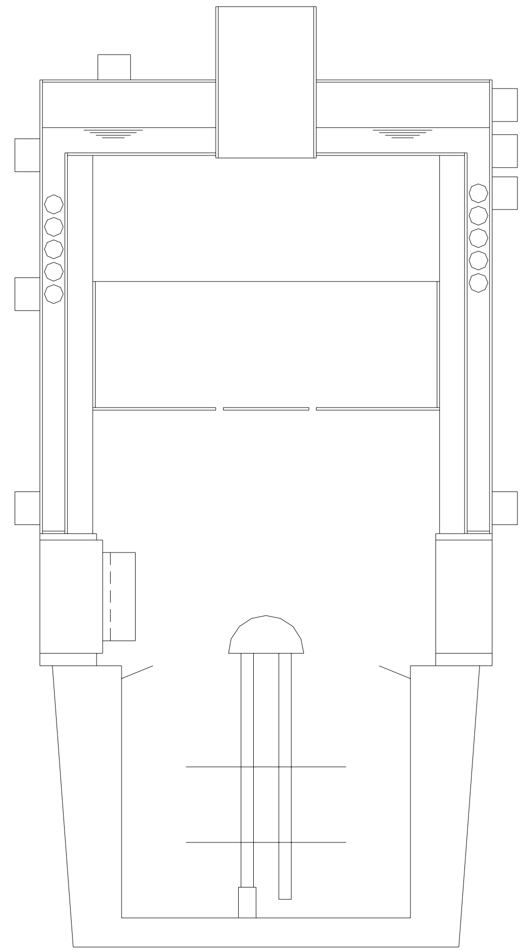

Figure D3: Baffle with 5" Skirt at Mid-Height of Fin

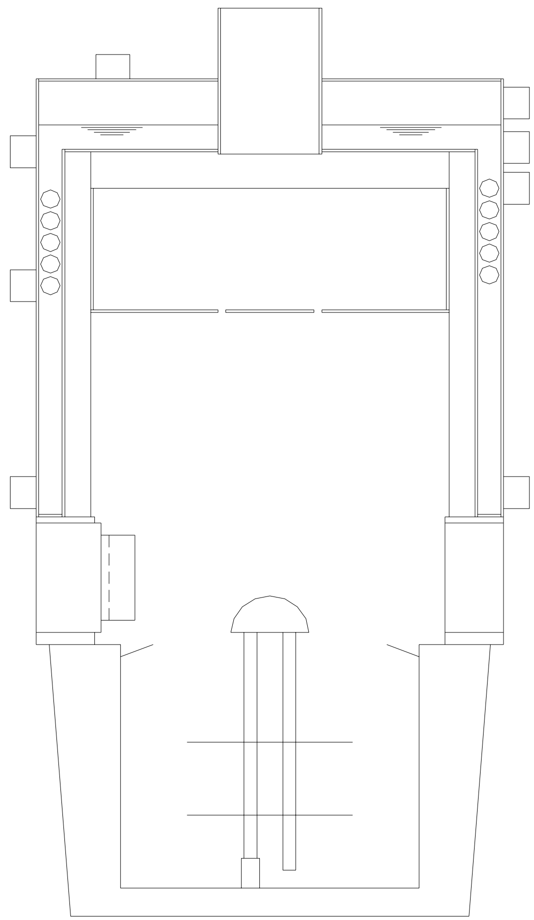

Figure D4: Baffle with Skirt and Skirt 1.5" from Top of Fin

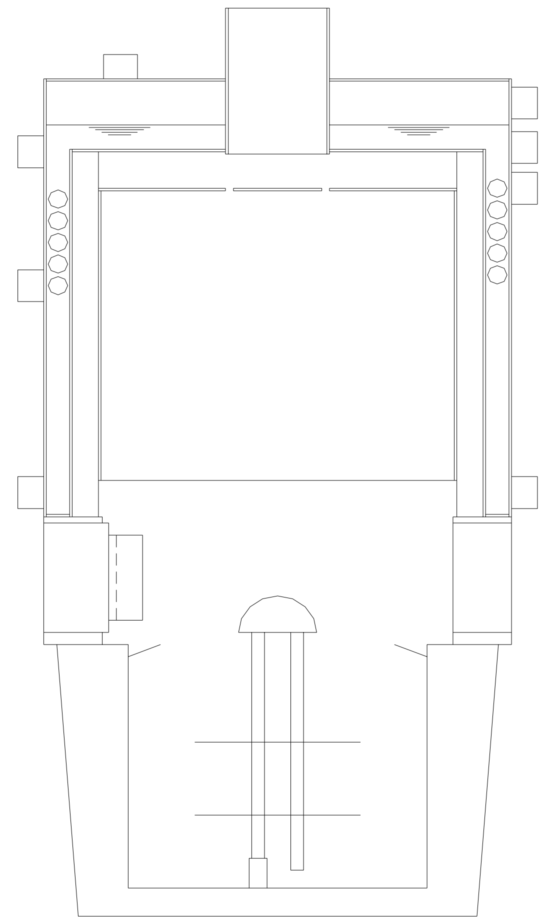

Figure D5: Baffle at Top of 12" Skirt

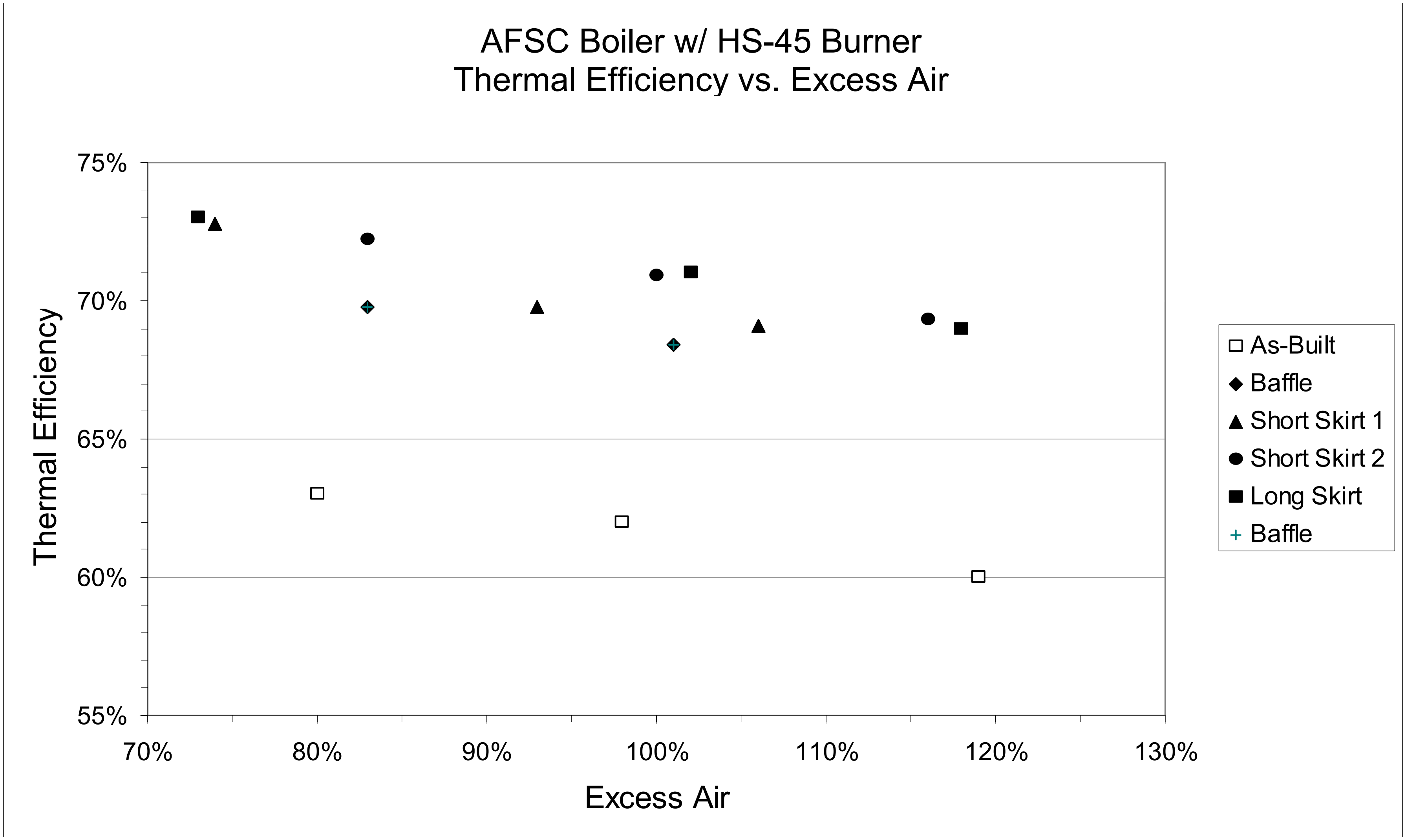

Figure D6: AFSC Boiler w/ HS-45 Burner Thermal Efficiency vs. Excess Air

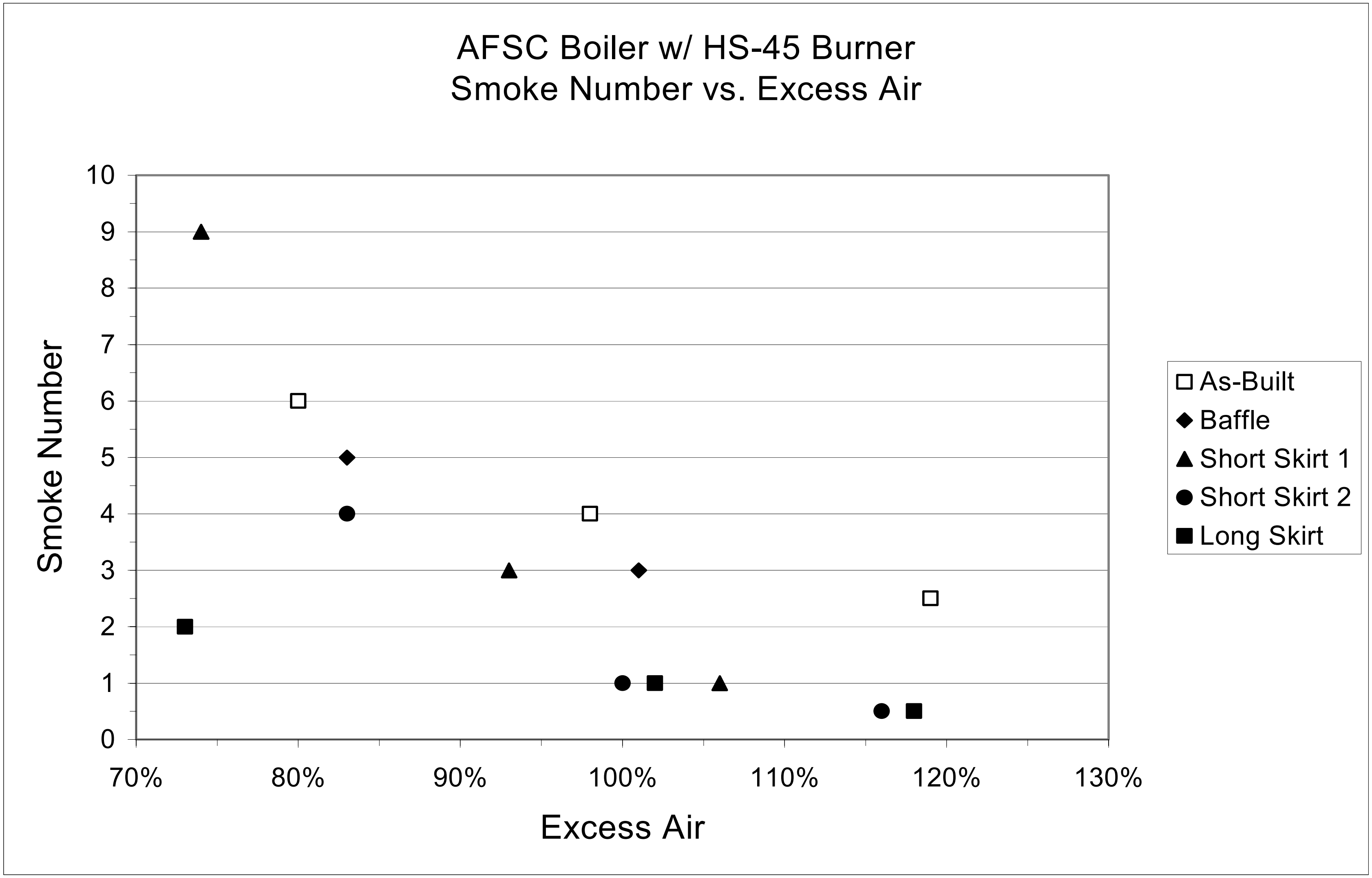

Figure D7: AFSC Boiler w/ HS-45 Burner, Smoke Number vs. Excess Air

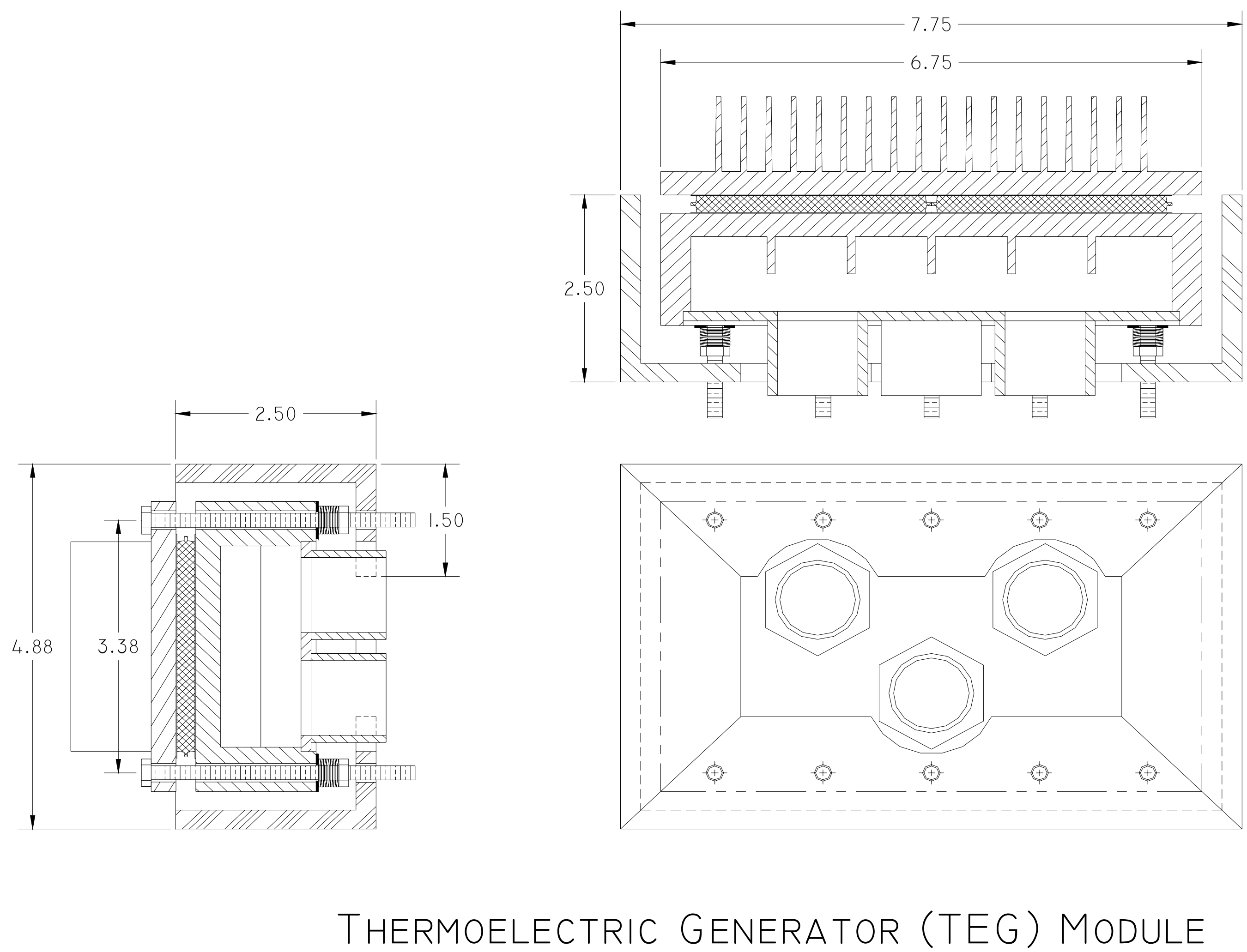

Figure D8: Thermoelectric Generator (TEG) Module