Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT

WASTE VEGETABLE OIL DRIVEN COMBINED HEAT AND POWER FOR FAST FOOD RESTAURANTS

Prepared for: California Energy Commission
Prepared by: Altex Technologies Corporation

ALTEX TECHNOLOGIES CORPORATION

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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Waste Vegetable Oil Driven Combine Heat and Power for Fast Food Restaurants is the final report for the project (grant number PIR-09-016) conducted by Altex Technologies, Inc. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies Program.

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ABSTRACT

Altex converted its proven fuel-cell-based combined heat and power (CHP) system to operate on waste vegetable oil (WVO) produced by restaurant fryers. Altex collected WVO from several sources in California and tested the fuel cell system's critical components, catalyst, and materials on these WVO samples. These tests identified the required modifications to the system that were implemented to create the WVO-CHP. Data was then used to develop a WVO preprocessing, filtration, and delivery system that fed clean WVO to the reformer portion of the fuel cell CHP system, where it was converted to a hydrogen-rich reformate suitable for the fuel-cell. A beta unit was developed and demonstrated in the laboratory, and then successfully installed and operated at a commercial field site, using WVO generated at the site.

The WVO-CHP system can use 100 gallons of WVO produced weekly by a typical fast-food restaurant, and produce 5 kWe of electricity and 10-12 kW of heat in the form of hot water for the restaurant's operation. This WVO-CHP will provide California's 30,000 restaurants a technology with the potential to reduce the sector's energy demand, local emissions and carbon foot print. If the WVO-CHP system is installed and used in half of the state's fast food restaurants, the annual load on the electricity grid would be reduced by up to 65 MW. In addition, the project addresses AB 32 by the potential for reduction of 1 million tons of CO_2 annually based on the expected market penetration.

Keywords: California Energy Commission, combined heat and power, waste vegetable oil, fuel cell, reformer on-site generation

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EXECUTIVE SUMMARY

Introduction

There are more than 30,000 fast-food establishments in California and 230,000 nationwide. Each year these establishments produce 12 million tons of CO_2 in California, and more than 89 million tons of CO_2 nationwide. Typically, each restaurant produces enough waste vegetable oil to power a 5-kWe (electric) combined heat and power system that can offset the restaurant's heating and electricity demands, reducing the restaurant's carbon footprint. However, there are currently no combined heat and power (CHP) technologies that can convert the waste vegetable oil into heat and power while also meeting California's CARB 2007 emission targets.

This report summarizes the results of an RD&D project that was executed to overcome these challenges. Altex developed and tested a 5-kWe nominal fuel-cell based CHP system that demonstrated an 82 percent overall thermal efficiency. This CHP system combines the proven Altex Compact, Robust, and Reliable Reformer technology with a High Temperature Proton Exchange Membrane fuel cell stack.

Project Process

Altex converted the Altex CORE Reformer, which normally functions on petroleum based distillate fuels, to a waste vegetable oil reformer. Reformer components were modified to process the waste vegetable oil and covert it to approximately 75 percent hydrogen, 1percent carbon monoxide (CO), with the balance carbon dioxide (CO_2), which has been shown to be suitable for High Temperature Proton Exchange Membrane fuel cells. Altex also developed preprocessor to prepare and clean impurities from the waste vegetable oil. The preprocessor and reformer were tested and proven on a variety of waste vegetable oil. The reformer was integrated with a nominal 5 kWe fuel cell to produce the waste vegetable oil-CHP. The system produces 4-5 kWe. The system also includes heat exchangers that recover the system heat to produce 12 kWt (thermal) as hot water. The system was connected to the grid at Altex and tested before installing at the Silicon Valley field test site. The waste vegetable oil from the site's cafeterias was used to operate the system at Altex and at the site.

Conclusions and Recommendations

Based on laboratory test results that simulated field operation, and the field tests, the waste vegetable oil-CHP showed the potential to:

- Produce more than 4 kwe grid connected electricity and more than 12 kw hot water from the waste vegetable oil generated at the site
- Have more than 82 percent system efficiency.
- Meet CARB 2007 emission requirements.
- Meet a three-year payback period when replacing grid electricity and a natural-gas fired hot-water heating system.
- Penetrate a large market consisting of fast food restaurants and establishments with cafeterias that produce the waste vegetable oil.

Benefits to California

The waste vegetable oil-driven CHP will provide California ratepayers, energy experts, and policymakers with a state-of-the-art CHP breakthrough which will help integrate renewable resources into state's electricity supply portfolio. This waste vegetable oil-CHP can provide California's 30,000 restaurants with a technology that has the potential to reduce the sector's energy demand and save each restaurant $4,850 a year. If the waste vegetable oil-CHP system is installed and used in half of the state's fast food restaurants, the annual load on the electricity grid would be reduced by up to 65 MW.

The environmental aspects of the CHP system will benefit Californians through environmentally sound energy generation that reduces greenhouse gas emissions and less fuel use. In particular, the project addresses AB 32 by the reducing 1 million tons of CO_2 annually with the expected market penetration. Additionally, because the system emits very low levels of pollution, it will reduce NOx and CO compared to the amount of useful output.

CHAPTER 1: Project Definition

1.1 Project and System Description

Altex converted its proven fuel-cell-based combined heat and power (CHP) system to operate on the waste vegetable oil (WVO) that is produced by restaurant fryers. The CHP system uses a 100 gallons of WVO produced weekly by a typical fast-food restaurant, and produces around 5 kWe electricity and 10 kWt (thermal) heat in the form of hot water for the restaurant's operation. A beta unit was developed and tested at Altex and at a Silicon Valley field test site.

The Altex CHP system was originally developed to work on diesel fuel or jet fuel. To modify the system to operate on WVO, Altex collected samples of WVO from several sources in California and tested the fuel cell critical system components, catalyst, and materials on these samples. Using these data, a WVO preprocessing, filtration, and delivery system was developed that feeds clean WVO to the reformer portion of the CHP, where the WVO is converted to a hydrogen-rich reformate suitable for the fuel-cell stack. These tests identified the required modifications to the system, which were then implemented. With these modifications, the team assembled the CHP system, connected it to the grid and tested it at Altex to simulate the field conditions. Altex then installed the system in the field, connected it to the grid, and successfully completed testing.

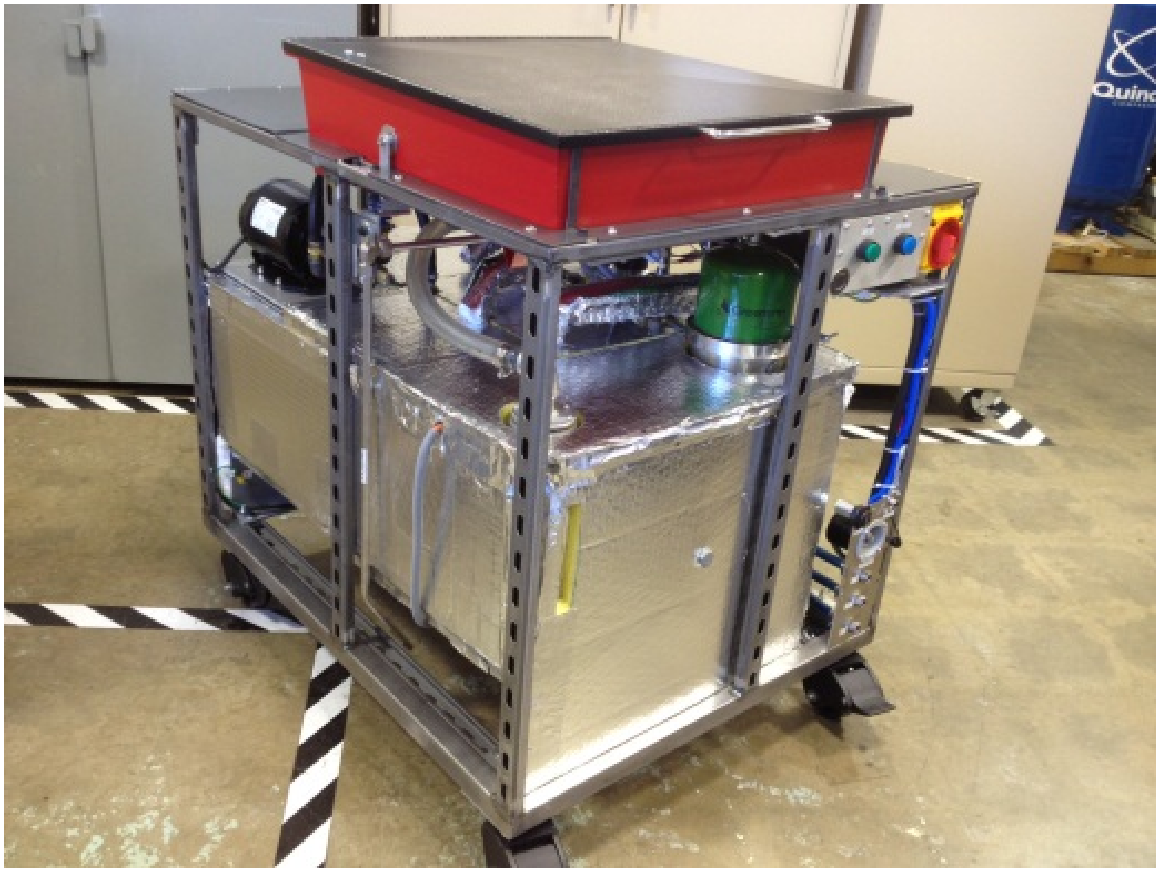
Simulated field testing in the laboratory and field testing demonstrate that the WVO-CHP operates as designed. The system converts waste vegetable oils into 75 percent hydrogen and 1 percent CO, with balance CO_2 that is fed into a 5kWe High Temperature PEM (HTPEM) fuel cell. WVO-CHP converts waste and used fryer oil into electricity and hot water that can be used to save the establishment natural gas and electricity. The project successfully developed and demonstrated the WVO-CHP concept.

1.2 Preprocessor Design and Fabrication

Altex designed and fabricated a Waste Vegetable Oil Preprocessor that filters out the fryer oil particles and impurities (Figure 1). The preprocessor is designed to process 30 gallons of WVO in four hours (Table 1). This capacity is optimum for a typical oil replacement cycle with minimum labor application. Fryer oil is simply emptied into the mesh screen located on the top. This screen collects large pieces of food and impurities, letting the oil pass through. The oil is re-circulated through a heated tank and lines and a filter that separates the gum-like impurities. Although these impurities are a small fraction of the oil (typically 300 grams for 30 gallons, or 0.3 percent), they will plug the reformer lines, if not separated.

The final system design was selected after evaluating several design scenarios, including ozonation, centrifuge separation and filtering. The evaluation criteria included: pumping power, heating energy, cost, complexity, maintenance, and development time. Based on this evaluation, which was supported by testing, Altex chose a cycle consisting of a centrifuge with one stage of 100 micron filtering. Testing has shown that running the centrifuge for four hours while the tank is full (30 gallons) is sufficient to filter out enough impurities that downstream clogging is avoided.

Figure 1: WVO Preprocessor



Source: Altex Technologies, Inc.

Table 1: WVO Preprocessor Specifications

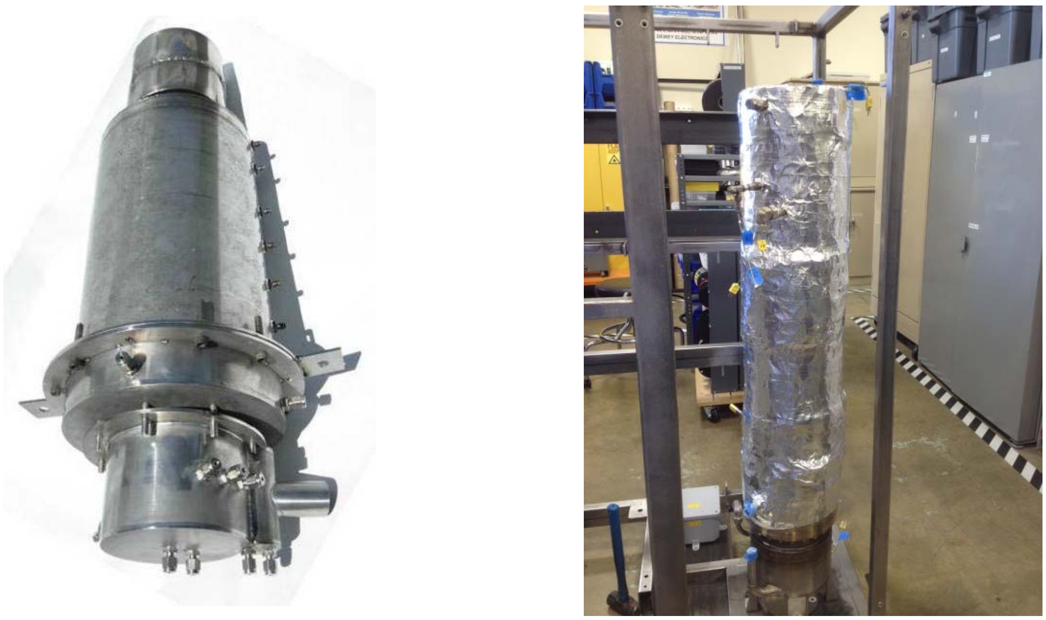
Parameter	Specification
Tank Capacity, gallons	30
Preprocessing time, hours	4
Residue, grams/gallon	30 grams/gallon
Power, W	500
Energy usage, W-hr/gallon	70

Source: Altex Technologies, Inc.

1.3 Reformer Design and Fabrication

The reformer design was based on the Altex CORE Reformer (Figure 2). It includes the burner, prereformer, reformer, WGS reactor, and a boiler. The heat required for the steam reforming is produced by the cyclonic burner that is located at the bottom. Certain design modifications, particularly to the burner and mixing zones, were made to design and fabricate the WVO Reformer. These modifications were defined by testing the reformer components.

Figure 2: 5 kWe CORE Reformer (left) used as the basis for developing the WVO Reformer (right)



Source: Altex Technologies, Inc.

Figure 3 shows the CORE Reformer burner (left) and the modified WVO Reformer burner (right). The WVO burner is four times taller than the CORE Reformer burner, which was developed to be light and compact for mobile applications and operation on JP-8 and diesel fuel. Initially the CORE burner was tested using WVO, but the WVO had to be preheated to a high temperature for the burner to operate properly. Tests were then performed at different preheat temperature and operating conditions. Initially higher air pre heat temperatures (550°C) were investigated, but this resulted in oil cracking and fouling in the burner. Through tests and analysis, the optimum operating conditions were defined and the CORE burner was operated continuously for six hours per day for two days and then disassembled for inspection. The inspection found that the burner was clean and functional. However, as testing continued, engineers discovered difficulties in ignition and output from the burner. Also, the high preheat requirement increased the parasitic power. Given the long term operational difficulties and large power consumption, Altex redesigned the burner to better use the thermo-physical properties of the WVO. The redesign reduced the electric power consumption and eliminated the long-term restart problems.

Figure 3: CORE burner (left) and the WVO burner (right)


Source: Altex Technologies, Inc.

The Altex CORE Reformer uses highly efficient steam reforming. The reformer's mixing zone is designed to maintain an optimum temperature range for the fuel and steam to remain in the vapor state and mix together. Early in the project, a micro reactor was set up to test the reformer catalyst on the WVO and also to define the optimum mixing conditions. These tests indicated that the optimum WVO mixing zone temperature was higher than the CORE Reformer design temperature. Therefore, the mixing zone was redesigned to have more heat exchange surface area to maintain the mixing zone at the proper temperature. This further added to the height of the WVO Reformer.

The reformer uses pumps and blowers to supply fuel, water and air to its components. A fuel pump and a water pump supply fuel and water to the reformer and a separate pump and a blower supply fuel and air to the burner. These Balance of Plant (BOP) components were also selected verified and assembled using the CORE Reformer control system and software. Figure 4 shows the BOP and control panels used in the final system assembly. The reformer was tested on WVO and all of its BOP and the control system were verified before installing them into the system frame. These tests verified that the WVO reformer produces 74% Hydrogen, 25% Carbon Dioxide, with the balance of <1% Carbon Monoxide and <1% Methane. This reformate composition is suitable for the High Temperature PEM (HTPEM) fuel cell.

Figure 4: WVO Reformer BOP and control panel

Source: Altex Technologies, Inc.

1.4 Stack Assembly

The WVO-CHP uses a 5 kWe HTPEM fuel cell. Before assembly of the stack into the system frame, the HTPEM fuel cell stack performance was verified on an Altex test stand using hydrogen as the fuel. Staff installed the stack in the test stand and connected lines for the anode, cathode, and coolant. The system was tested with Altex's LabVIEW-based control system, which was then adapted for use in the final integrated system. After verifying stack operation, technicians assembled it into the frame (Figure 5).

Figure 5: Fuel cell stack assembly

Source: Altex Technologies, Inc.

1.5 Control System Design and Fabrication

1.5.1 Control System Hardware

The main controller for the WVO is a National instrument cRio chassis (NI-9474). The chassis is equipped with eight modules, including temperature measurement, Analog Inputs and Outputs, Digital Inputs and Outputs, and RS-485 communication. The control program is written in LabVIEW and resides in the chassis memory, so the system can be a stand-alone system.

Currently a laptop is used as a User Interface (UI) that is connected to the cRio chassis through an Ethernet connection. The use of laptop makes it easy to update the software, as the system is being tested and finalized. The laptop can easily be replaced by an industrial Human-Machine Interface (HMI) or start/stop pushbuttons for easy stand-alone operation.

1.5.2 Control System Software

The control software for WVO-CHP system is written in LabVIEW graphical programming platform. The control software has two components. The main component resides in the National Instrument cRio chassis, and controls all components of the system by reading sensors and applies outputs to the actuators. The main component keeps track of the changes in system parameters and acts accordingly to keep the system running at pre-specified or communicated set-points. The other component of control software is the User Interface (UI), which is written in LabVIEW to be compatible with the laptop for now, but can be easily translated onto a commercially available touchscreen for mass production. The communication to the main controller is provided through an Ethernet connection, allowing for simple integration into a building management system for larger industrial facilities, or intranet integration for a restaurant installation. The UI also provides historical charts, alarm annunciation, a command and control panel, data-logging, and graphical-and-numerical representation of the process parameters.

1.6 Electrical System Design and Assembly

The heart of the electrical system is the grid-tied inverter. The inverter selection was a challenge, since the inverter had to be approved by State of California for grid connection, be compatible with the fuel cell output voltage, have single phase 208v output, and provide 5kW electric output. Most of the inverters in the market available at this scale have been built specifically for solar panel systems, and they lack the needed flexibility. After a comprehensive study of the inverters approved by the State of the California for grid connection, an inverter from Sustainable Energy Technologies (SUNERGY LV-208), was found to match the desired criteria (Figure 6). The control system communicates to the inverter through a RS-485 Modbus.

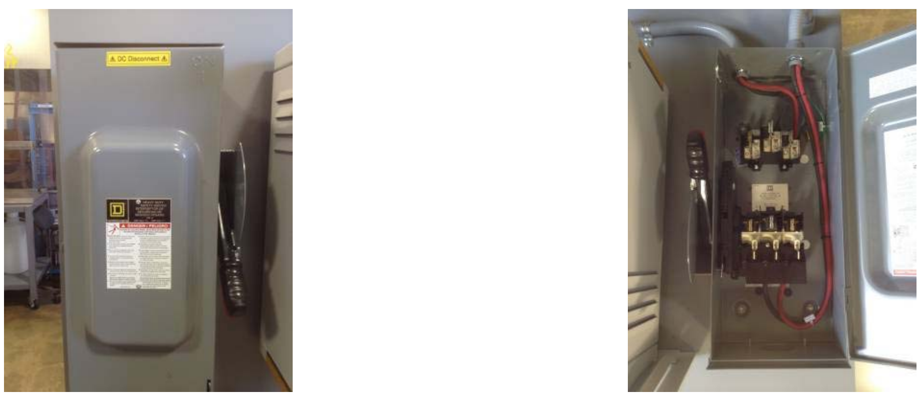
Altex designed an interface circuit to monitor fuel cell parameters at a 1 Hz sampling rate, which is three times faster than the rate provided by the as-delivered Inverter. For more protection, a fused manual disconnect switch (DC Disconnect Switch) is located between the interface box and the inverter (Figure 7). An Uninterruptable Power Supply is included, to allow a safe system shut down in case of a power outage. The control system also includes an emergency shutdown algorithm to disconnect power from the system in case of an emergency situation.

The WVO-CHP system is connected to the grid through a junction box and two separate manual disconnect switches. The junction box (Figure 8) and one of the disconnect switches are placed on the WVO Front Electrical Panel (Figure 9) while the other disconnect switch is wall mounted at both the Altex lab and the demonstration site. All cables and fuses are sized based on national and international standards. Inside the junction box, a wattmeter measures the net power and energy that the system delivers to the grid. The control and monitoring system has access to power and energy data through the RS-485 Modbus communication.

Figure 6: System Inverter

Source: Altex Technologies, Inc.

Figure 7: DC Disconnect Box



Source: Altex Technologies, Inc.

Figure 8: Junction Box

Source: Altex Technologies, Inc.

Figure 9: Front Electrical Panel

Source: Altex Technologies, Inc.

1.7 Additional System Components

The WVO-CHP system has additional components that enable the major components, described previously, to operate as intended. They include the fuel tank, water tank, boiler, and condensers that are used to make the WVO steam reforming water neutral. Multiple heat exchangers recover the heat at strategic locations and heat approximately 8 liter/min (2 gpm) city water to 40 °C at full load. Figure 10 shows some examples of these components. The POC heat exchanger is located at the right top. This device is used to decrease the temperature of the exhaust stream so the water is condensed and separated in the knock out tank located at the bottom right. Using city water as the source, this heat exchanger brings the POC temperature to almost room temperature (such as 23°C, with city inlet water temperature of 18°C). A similar approach is applied to the fuel cell exhaust. The fuel cell exit heat exchanger is visible on the left side.

Figure 10: POC heat exchanger/condenser and water knock out tank

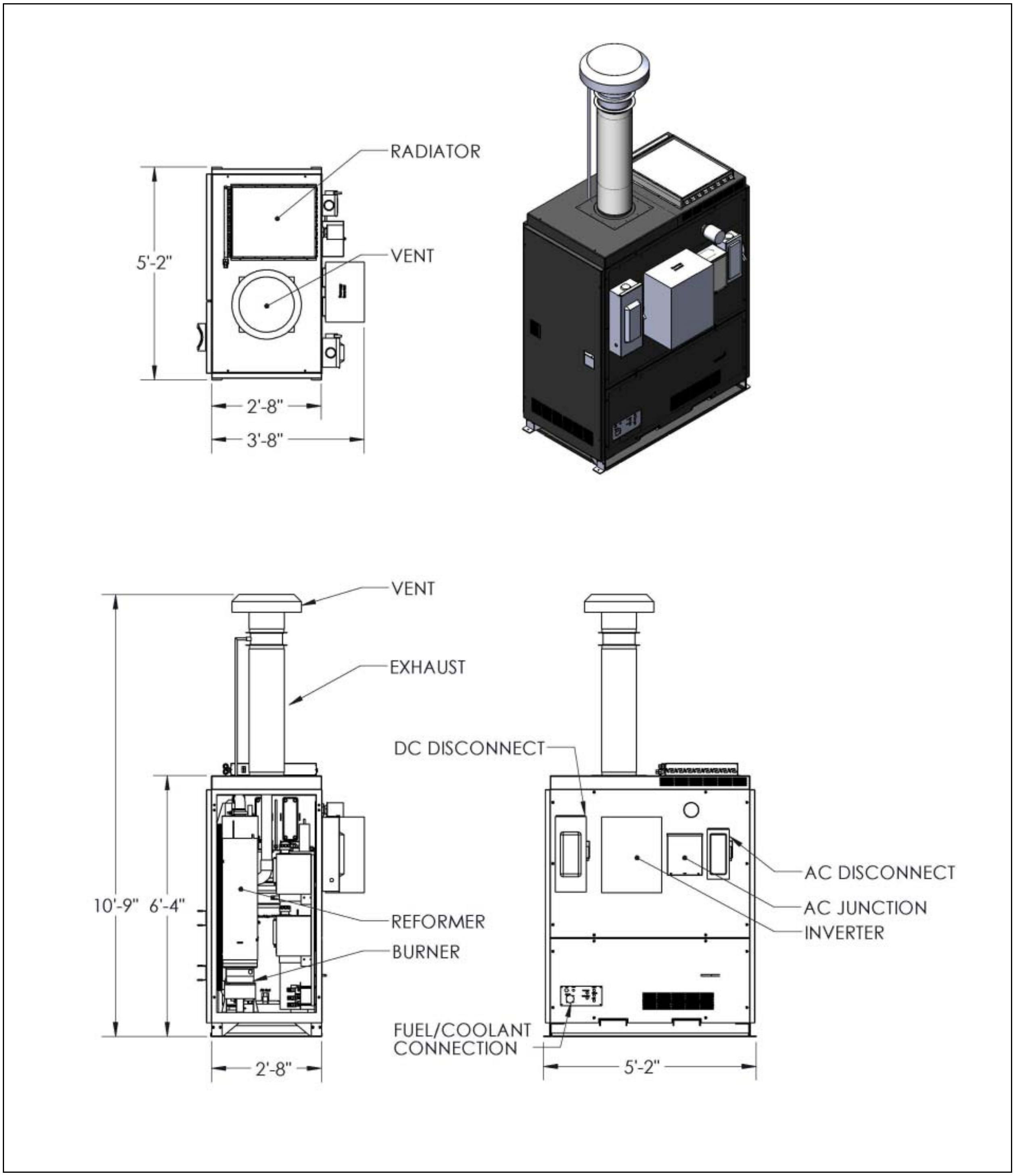
Source: Altex Technologies, Inc.

1.8 System Assembly

The assembly of the WVO-CHP system used the same approach that Altex uses in assembling all its power system deliverables. The 3-D CAD models utilized in the design and manufacturing of the key custom components are combined with 3-D CAD models of the BOP equipment, framing, and tubing to create a CAD model of the entire system. This enables better documentation of the fabrication of the system from components and subsystems.

Figure 11 shows the 3-D CAD model of the entire WVO-CHP system with covers and hood installed. The system is designed to have easy access to all major components. Figure 12 shows the WVO-CHP system assembly process that followed the stepwise CAD assembly drawings and detailed process flow diagrams. The assembly included insulating tubing and wiring, and harnessing and securing the components and subsystems to the frame. During assembly, Altex technicians leak checked all the connecting tubes and verified all electrical and control wiring. Before assembly, each subsystem was individually tested for performance and functionality over the entire range of operation. Following these tests, the system cabinet skins were installed for final testing. Figure 13 shows the WVO-CHP at an Altex test station.

Figure 11: CAD model of the WVO-CHP System



Source: Altex Technologies, Inc.

Figure 12: WVO CHP System Assembly Process

Source: Altex Technologies, Inc.

Figure 13: Fully assembled WVO CHP System at Altex Test Station

Source: Altex Technologies, Inc.

CHAPTER 2: Lab Testing

Testing at Altex included validation of components and materials, followed by subsystem and system testing. The system was also grid connected at Altex and tested while simulating the field conditions before shipping the unit to the field.

2.1 Subcomponent Testing

2.1.1 WVO Testing

Sample oils from different establishments were collected and analyzed. Sources included oils from chicken, fish, and burgers fryers/establishments. Fresh vegetable oils corresponding to the used oils were also acquired. Altex also approached and received products from Salinas Tallow, which collects and processes used cooking oil around the entire San Francisco Bay Area. Salinas Tallow produces a clean refined used oil product from the waste oil that is of proper specification to be directly fed into the fuel cell system. Inspection of oil samples indicated that preprocessing would be required to prepare the oil for use in the WVO Reformer. Initially an ozonation process was considered.

Ozonation tends to reduce the average molecular weight of the oil, eventually making it less viscous and more flammable. Approximately three liters of WVO was heated and rough filtered with a commercial grease paper filter. The oil was converted to a fine emulsion by stir-adding 5%-10% water to the WVO by volume. Then ozone was bubbled into the emulsion through a fine stainless steel bubbler head. The temperature of the emulsion was maintained at 35-50°C. This resulted in a small quantity of white precipitate that was removed in a filter. Figure 14 shows untreated (left) and treated oils at 3 hour treatment intervals. A baseline Altex cyclonic burner was used to evaluate untreated and treated oils. Tests showed that the burner operated better with the treated oil. However, the ozonation option was not implemented due to its cost and complexity. A simpler process of filtering and preheating the oil eliminated the need for additional hardware and complexity, resulting in simpler system integration.

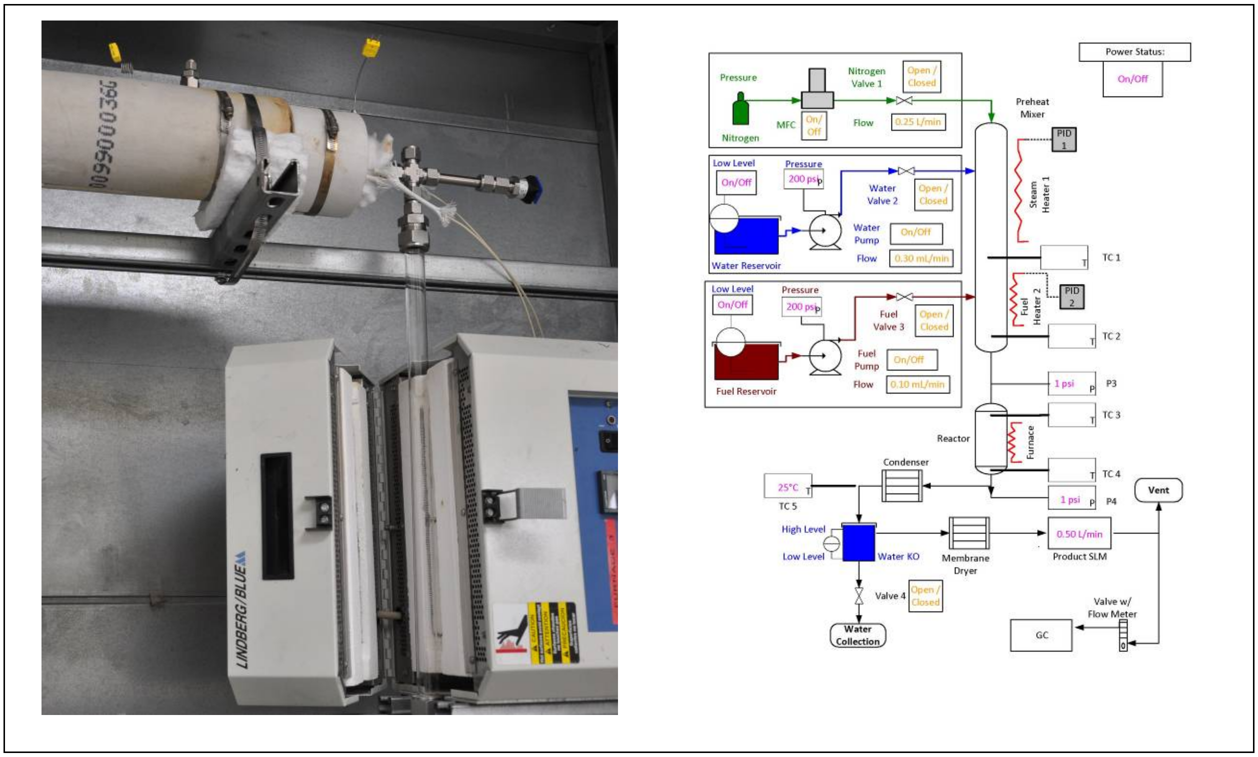
Figure 14: Oil test samples after ozonation pretreatment

Source: Altex Technologies, Inc.

2.1.2 Micro Reactor Testing

Before fabricating the main components, Altex used a micro reactor to test the catalysts and define the operating conditions of the reformer components. Figure 15 shows main components of the reactor (left) and its process flow diagram (right). It includes a preheated mixer where oil and water mix (the horizontal insulated section in Figure 15) and then are reformed to hydrogen rich reformate in the presence of catalyst in the vertical section of the reactor. The clear catalyst tube and clamshell furnace allow for visual inspection of the catalyst bed. The system includes all the safety mechanisms, including nitrogen purge for shut down.

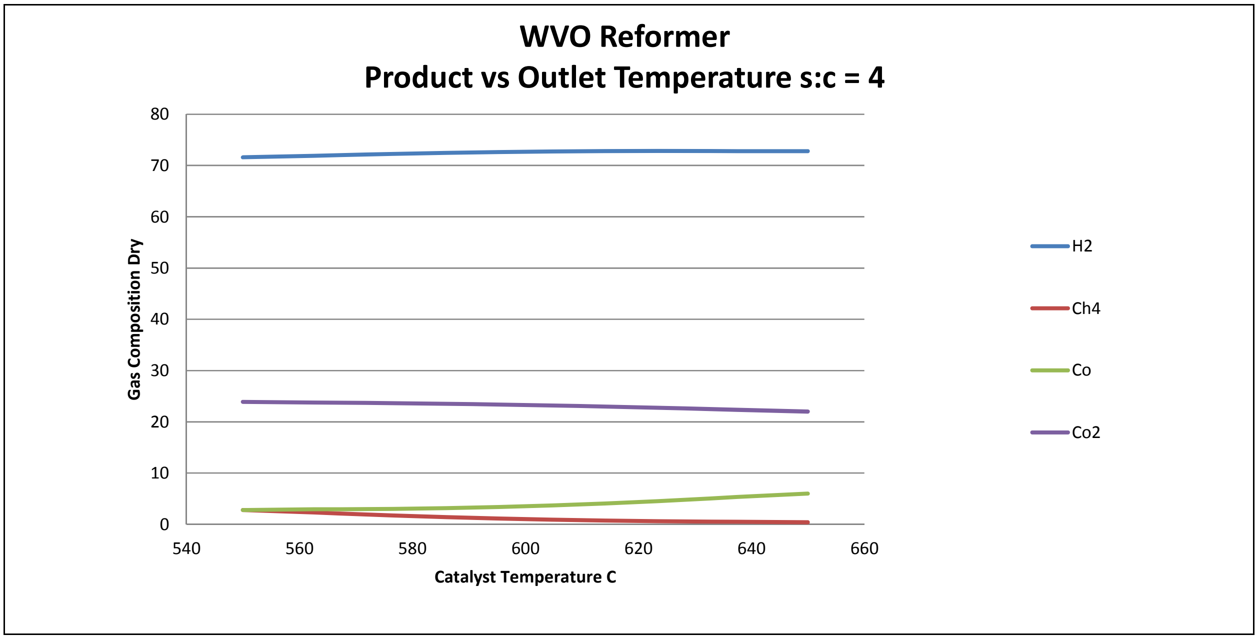
Figure 15: Micro reactor test set up



Source: Altex Technologies, Inc.

Sample reformer product gas composition results are shown in Figure 16. Good hydrogen selectivity was obtained. As shown in Figure 16, the reformate composition contains approximately 74% hydrogen. This is high hydrogen selectivity from WVO and the level is consistent with the hydrogen selectivity Altex has obtained processing JP-8 and biofuels for Army fuel cell power systems. Note that the composition is also consistent with chemical equilibrium calculations. As expected, as the temperature increases, the methane concentration is reduced and CO increases. In the Altex reformer, the temperature is raised to a temperature where methane is completely converted to CO and hydrogen. The shift portion of the WVO Reformer (not included in the micro reactor) reduces the CO to less than 1%.

Figure 16: Micro reactor composition versus temperature



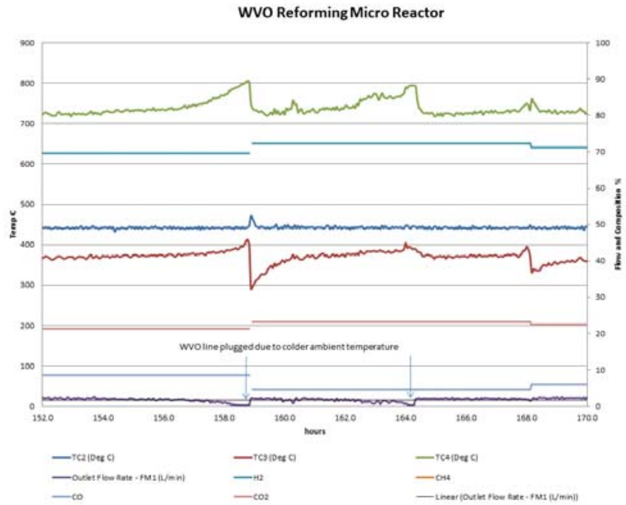
Source: Altex Technologies, Inc.

In addition to characterizing the catalyst and defining the operating conditions, Altex used the micro reactor to define other system design parameters. For example, through long-term catalyst testing, Altex continuously refined a system, which used a heated tank and heated recirculation WVO lines to ensure steady fluid delivery. The micro scale of the test amplified the challenges of pumping WVO. A section of the long-term data is shown in Figure 17. The temperature zones, and the rate of the reformate flow, were measured by a flow meter, and during this testing the WVO line plugged at low ambient temperatures. The pump was able to clear the blockage, but during that period the hydrogen flow rate dropped and the system temperatures increased. This result was not acceptable for the final system, and the design was upgraded to include larger diameter heated tubes for the WVO fuel delivery in the full scale system.

2.1.3 Burner Testing

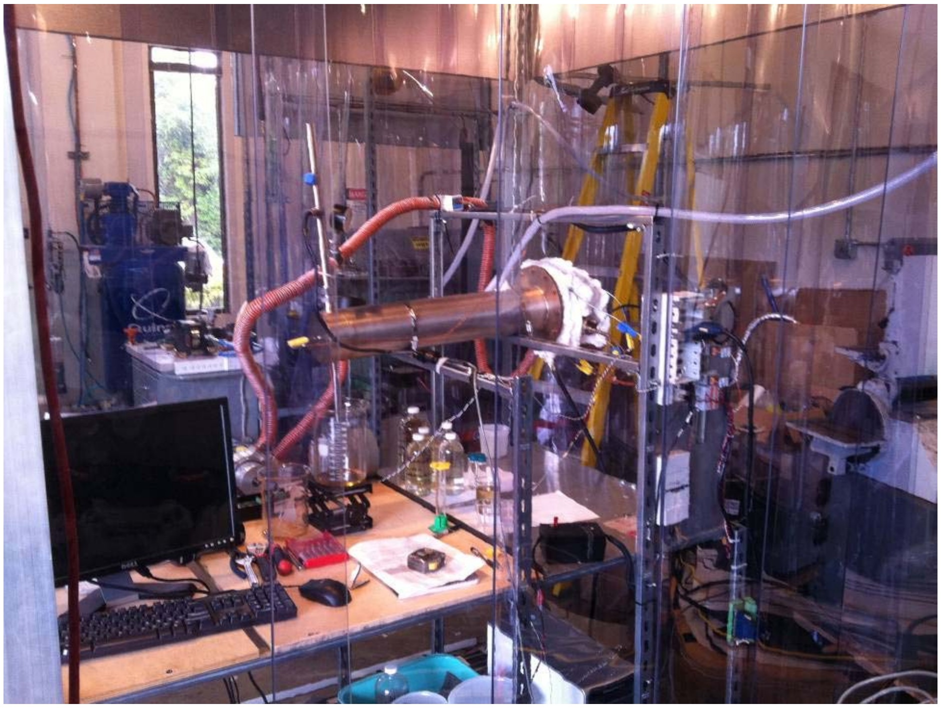
The CORE Reformer, which the WVO Reformer is based on, uses a cyclonic micro burner that is compact and light. This burner was developed for portable Auxiliary Power Units (APU) systems and has been proven to operate on JP-8 and diesel fuel. Initially tests were performed with this burner. A full-scale burner test set up, cost shared by the Army, was used for these tests.

Figure 17: Snap Shot of the micro reactor long term testing



Source: Altex Technologies, Inc.

Figure 18: Burner Test Facility

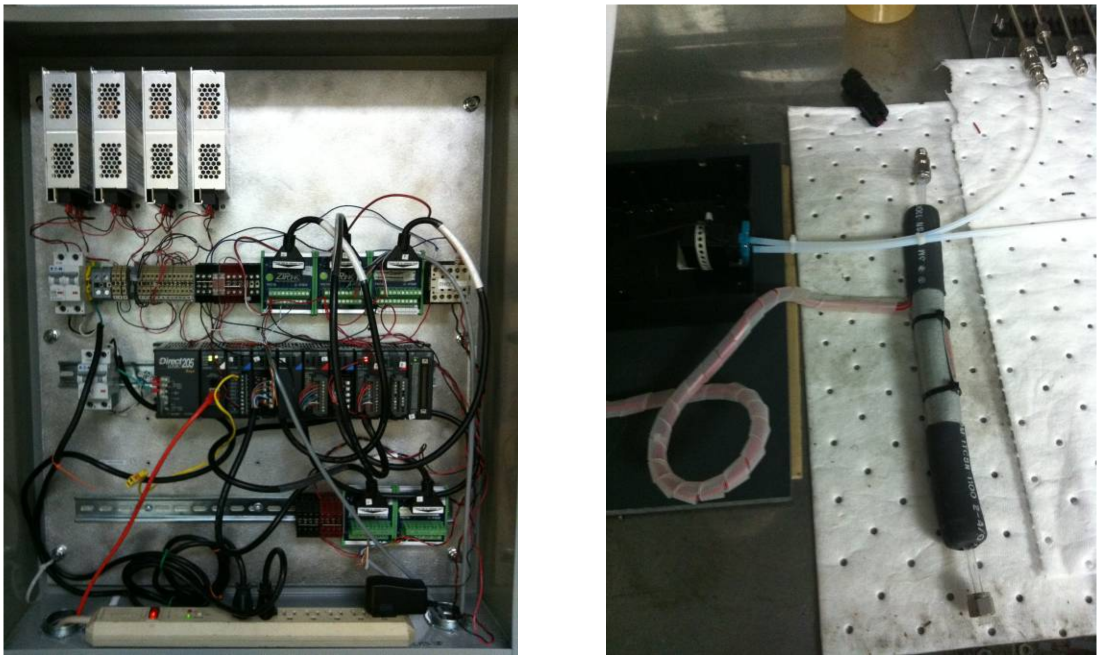


Source: Altex Technologies, Inc.

2.1.4 BOP Testing

Well characterized pumps and blowers are necessary to achieve good control for the burner and reformer. To accomplish this objective, pumps and blowers are tested to define their flow versus the pump current and voltage. Altex used a cost-shared test stand to characterize the WVO-CHP pumps. The test stand, shown in Figure 19, allowed for controlled flow and pump parameters while capturing the flow rate data using both a flow meter and highly accurate scale. The set up was modified with a heated line to keep the WVO at the desired temperature. The heated line and a miniature pump are shown on the right hand side of Figure 19.

Figure 19: Pump characterization set up with a heated line (right)



Source: Altex Technologies, Inc.

2.2 Reformer Testing

The long term catalyst test data defined the ideal process conditions for the WVO Reformer. These data showed that the WVO reforming process requires different temperatures than the JP-8 reforming process. The reformer components were modified to meet these different temperature requirements. An integrated WVO Reformer was tested to verify its operation before its integration into the power system.

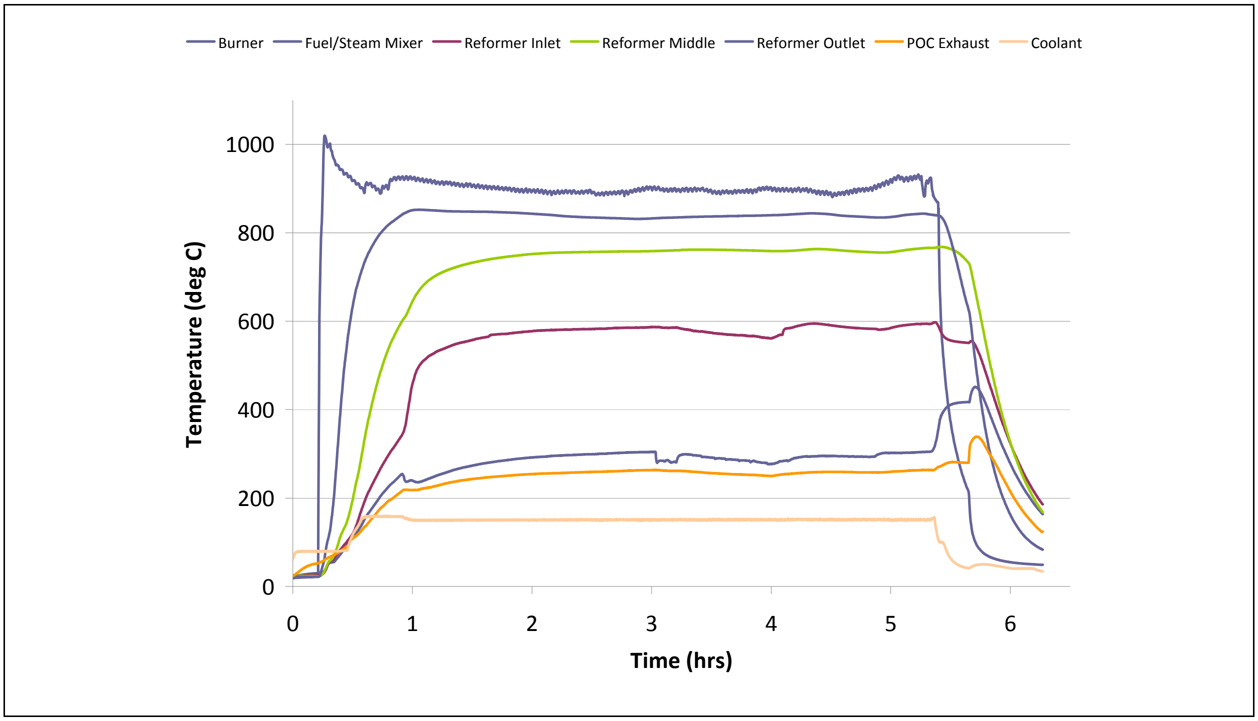
Figure 20 shows the WVO Reformer test station. This set up was designed to verify the control system and the reformer BOP.

Figure 20: Reformer test set up

Source: Altex Technologies, Inc.

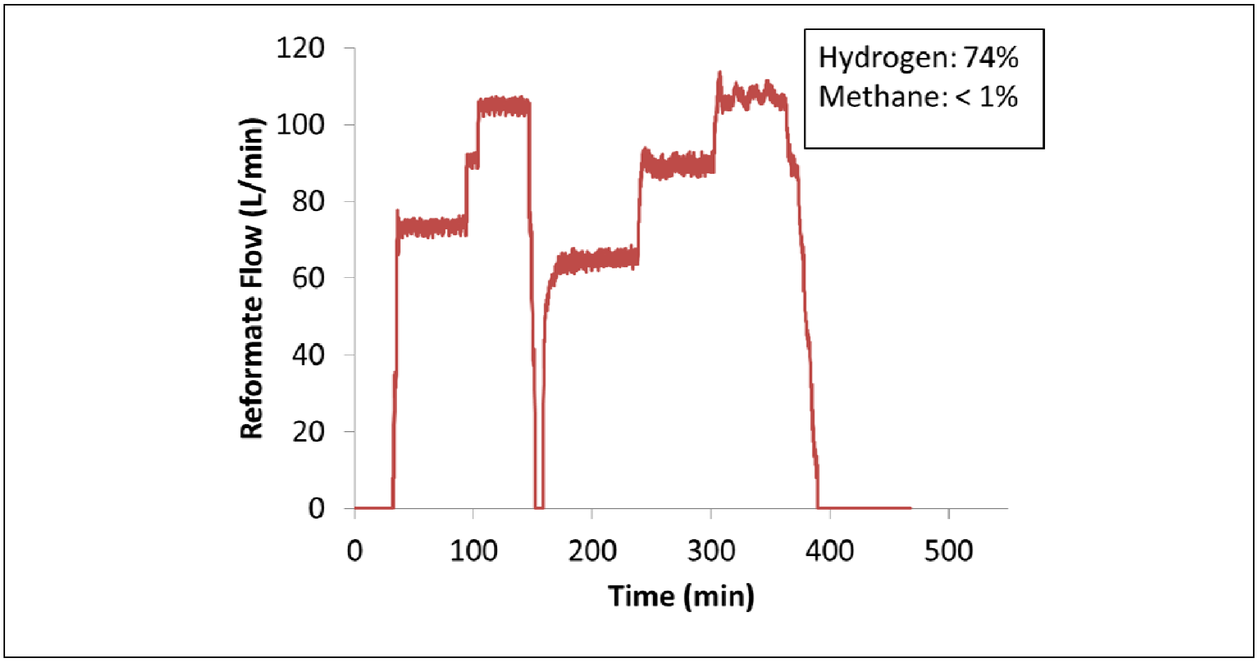
Figure 21shows sample temperature data for a one day test run. As shown, all zones have uniform temperature profile, indicative of stable operation. To verify the system, initially the reformer was tested on JP-8 and then switched to WVO. Sample results are shown in Figure 22. In this case, for first 150 minutes of testing, JP-8 was used to define a reference performance target. Following the reforming of JP-8, the flow was paused and switched to the waste vegetable oil. The test continued using similar flow rates and the performance was comparable. Throughout the test, 100% conversion was observed and the average composition was 74% Hydrogen, 25% Carbon Dioxide, with the balance of <1% Carbon Monoxide and <1% Methane. This reformate composition is consistent with that achieved on JP-8 and is suitable for the high temperature PEM fuel cell that is used for this system. These tests proved the reformer component before integrating it with the fuel cell stack prior to support stack verification testing.

Figure 21: Reformer test data (temperature)



Source: Altex Technologies, Inc.

Figure 22: Reformer test data (reformate flow)



Source: Altex Technologies, Inc.

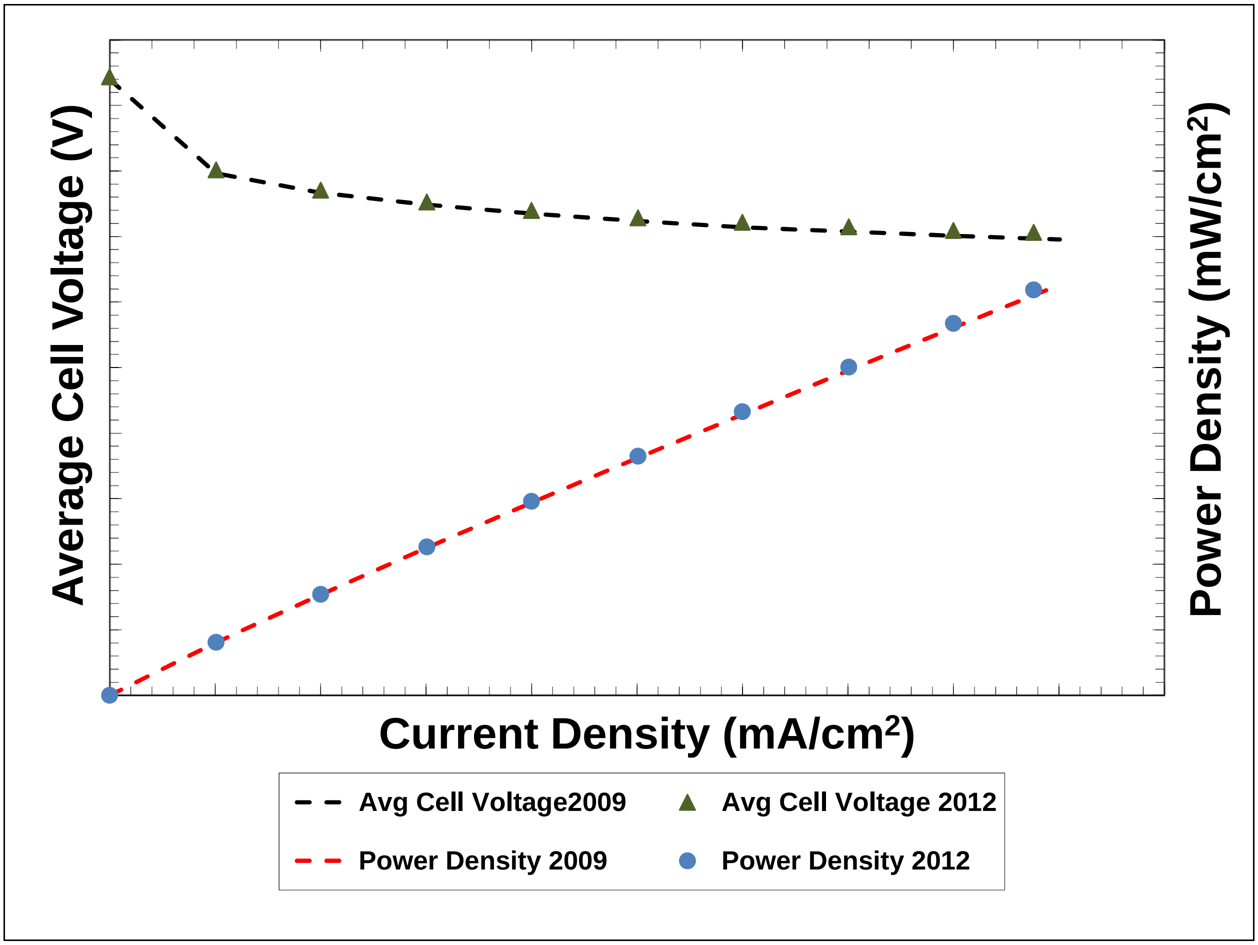
2.3 Stack Verification Testing

As previously discussed, the WVO reformer produced 74% Hydrogen, 25% Carbon Dioxide, with the balance of <1% Carbon Monoxide and <1% Methane. This reformate composition is suitable for the HTPEM fuel cell. A cost shared stack was verified before integrating it with the reformer. In the past, this stack has been tested on hydrogen and reformate with similar composition as the WVO reformer. To verify the stack, it was tested on hydrogen and its performance was compared to past data. The fuel cell stack installed in the test station is shown in Figure 23. This Figure also shows the load bank used in the test stand on the left. The stack test data is shown in Figure 24. The data are plotted along with the previous stack data to assess the WVO-CHP stack's health. Current and past performance data are shown to be the same, verifying performance prior to installing the stack in the WVO-CHP system.

Figure 23: Stack verification test station

Source: Altex Technologies, Inc.

Figure 24: Stack verification test result



Source: Altex Technologies, Inc.

2.4 System Testing

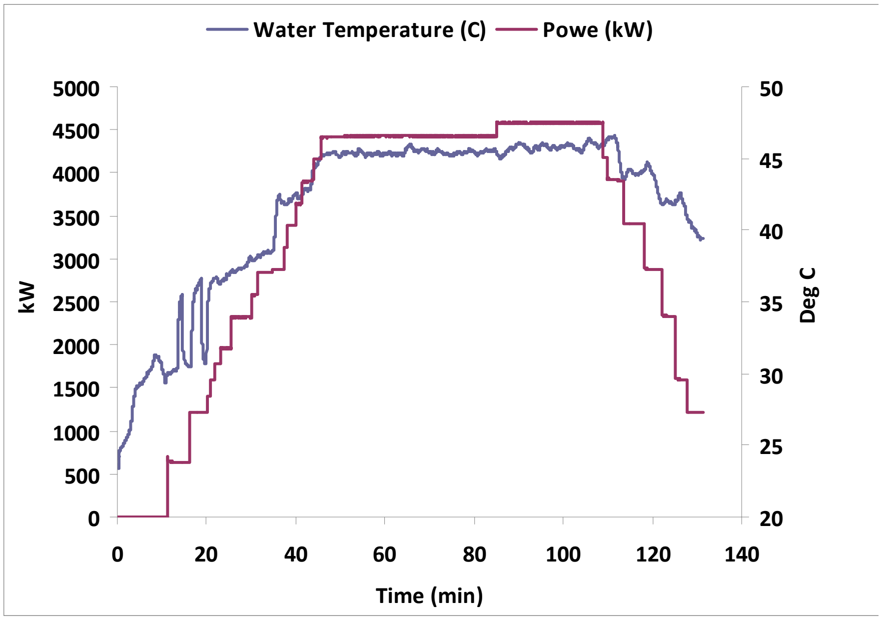
Shake down tests were performed after system assembly. Figure 25 shows the installed system during testing. During these tests, system components were monitored with a laptop that was also used to store the data. These tests proved the integrated system assembly and prepared it for grid tied simulated field and actual field testing.

Figure 25. Completed WVO-CORE system prepared for shakedown testing

Source: Altex Technologies, Inc.

During the shake down tests, the system was started and its power was gradually increased while all component functions and performances were monitored. These tests used WVO that was collected from the chosen field demonstration site. The WVO was preprocessed in the WVO Preprocessor and then was fed into the reformer, where it was converted to 75% hydrogen, minimal CO, and approximately 25% CO_2. While the system is designed to produce 1-2% CO that is compatible with the HTPEM fuel cell that is used in the system, the CO level produced was undetectable by a gas chromatograph. It is anticipated that as the system accumulates operating time, the CO level will reach its design level. No major issues were encountered during shake down tests. The system, as installed at Altex, is shown in Figure 26 with a sample test result. Note that for these shake down tests the system load was measured by an electronic load, as the system was not yet grid tied. These tests prepared the system for inspections that were performed before connecting the system to the grid.

Figure 26. System Shakedown Test

WVO-CHP system test setup at Altex	
WVO-CHP system shakedown sample test results	

Source: Altex Technologies, Inc.

CHAPTER 3:
Field Demonstration

3.1 Demonstration Site Selection

The principal factor in the site selection was support and interest from the host in participating in the demonstration of a new and unique technology. Criteria also evaluated were:

- The availability of space
- Ownership of the space
- Ease of access to the facility for installation
- Availability of wvo for analysis and laboratory testing prior to field testing
- Future access to the facility to document performance and energy savings.

Several sites were evaluated against these criteria. These included Salinas Tallow, several local Fish–and-Chips and hamburger restaurants. None of these entities met the above criteria. In most cases, the business owners were interested in the project but did not own the property and could not sign off on the project. In these cases, the property owner did not have any incentive to participate. Site visits were performed and in all cases, there was not a proper location for the equipment. Space was identified as a major hurdle that limited the interest from building owners at any cost.

Based on Mr. Edalati's helpful suggestions and contacts from another Energy Commission project, Altex secured a site at a Silicon Valley company with multiple cafeterias and proper facilities for the Altex equipment to be securely installed without impacting the day to day business. This company is familiar with energy and R&D projects and thus was supportive of hosting the field tests for the WVO-CHP system. The site host wishes to remain anonymous at this time, and the use of their name is not allowed in reporting, without their written permission.

Altex and the site host entered into a Facilities Service Agreement and Sub Contract to complete the field testing. Altex secured the site at no cost to the project, other than the installation and permitting cost and the site owner agreed to provide the WVO at no cost.

3.2 Field Test Planning, Permitting, and Installation

Altex engaged a site-approved electrical contractor to install the WVO-CHP system at the site. The team attended three site survey meetings in planning the installation. The plan called for the electrical contractor to install new electrical service to the designated system space and connect the electric service to the California-approved grid tie inverter that is part of the Altex WVO-CHP system. The space provided was outside, and a temporary security fence with rain tent were planned to secure and protect the Altex equipment. All the site work was planned while the system was going through the simulated field testing at Altex. As part of the site agreement, the site personnel would inspect the system while it was being tested at Altex under simulated field conditions.

3.3 Simulated Field Testing

As agreed with the site, Altex performed simulated field tests at Altex that were observed by the site personnel before installing the unit at the site. The simulated field testing also required permitting and a PG&E interconnect review, inspection, and approval. All these activities occurred in the city of Sunnyvale, where Altex is located. Below is the list of activities that were completed.

- Site plan preparation
- Single line diagram
- Permit application
- Net inter-connection application

After submitting the proper documents to the city of Sunnyvale, Altex answered the city's questions, and the city granted the permit to install the system. Because the site was inside a laboratory, Altex installed an exhaust hood to properly exhaust the WVO-CHP exhaust flow. The exhaust had proper safety mechanisms required by building codes and the exhaust was indicated on the permit application drawings, as shown in Figure 27. The lab setup also included CO and hydrogen detectors, and also an E Stop outside the curtained hood. After inspection by the city's hazard, fire and building inspectors, the permit was signed off and the system was tested.

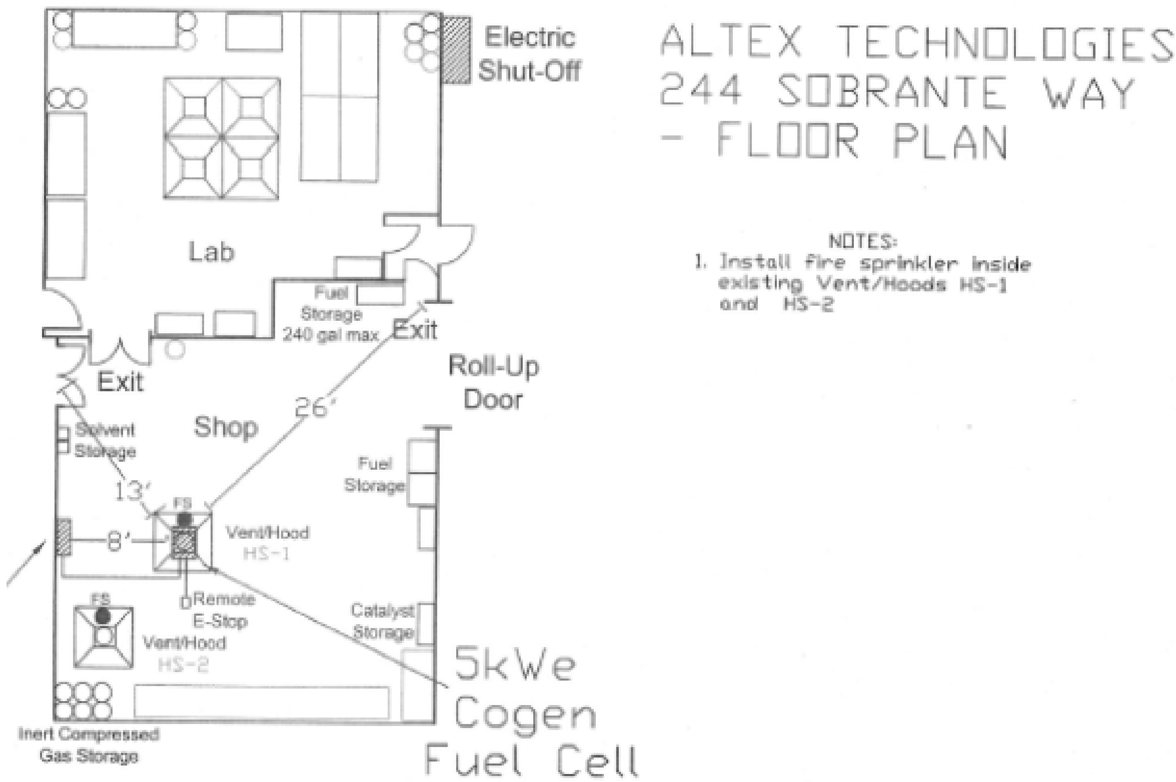
The installation process at Altex also included a Net Interconnection application with PG&E. This application was submitted after changing Altex PG&E billing methods to be compatible with the PG&E rules and regulations for interconnect permission. This permit required an on-site inspection that was planned and executed. Upon this visit, the system was run and was disconnected from the grid by the inspector to assess the system's proper and safe shut down. The system passed the test.

3.4 Simulated Field Test Data

For simulated field testing, the system was grid connected and tested. Figure 28 shows the grid connected system set up at Altex. Since the site does not use the hot water produced by the heat portion of this CHP system, a water loop system was fabricated to cool and recycle the water. This system is also shown in Figure 28. Testing continued for a month. During simulated field testing, the field site representatives witnessed the system operation and performance. This visit assured them that the system was properly packaged and was ready for delivery to their site. Also, during the field simulated testing, Energy Commission personnel, including the program manager, visited Altex for a project review. The system operation was also demonstrated during this visit.

Figure 29 shows sample test data from the simulated field testing. Testing was performed daily and the system was shut down after testing was competed to comply with Altex safety rules and the issued municipal permit. System operation starts with the burner that heats all system components. This startup also coincides with the system generating hot water, as shown by the leading curve on Figure 29 charts. The trailing curves show the power that was generated by the fuel cell after the reformer and fuel cell components were at proper temperature to start generating power. All of these processes are automated, however, for the simulated field testing, the system was occasionally run in semi-automatic mode to characterize different parameters during each test. The system generated more than 4 kWe and hot water, reaching the design goal. The system is flexible in term of hot water generation. Between 6 kWt to 14 kWt were generated on different days. This is because the burner can be operated across a wide range and the system is designed to convert all of the burner's excess heat into hot water. This flexibility allows matching a site's hot water demand.

Figure 27: Site Plan for Simulated Field Testing at Altex



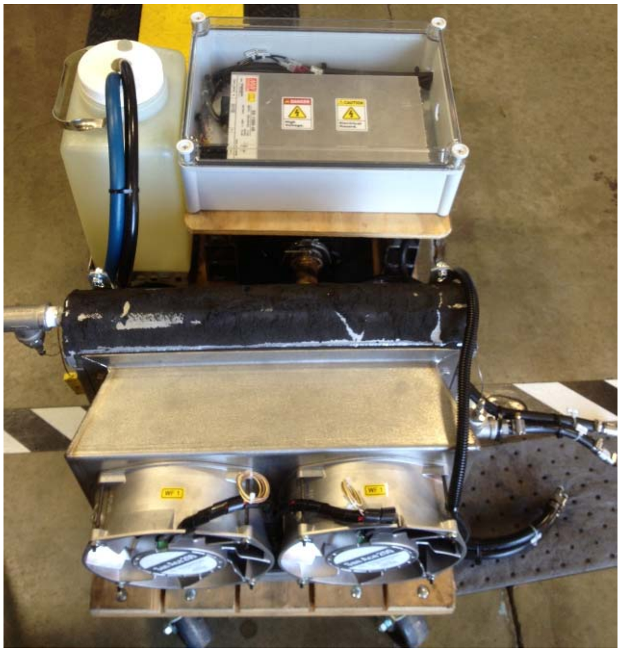
Source: Altex Technologies, Inc.

Figure 28. Grid connected simulated field test set pp (top) and the water loop (bottom)

(a)

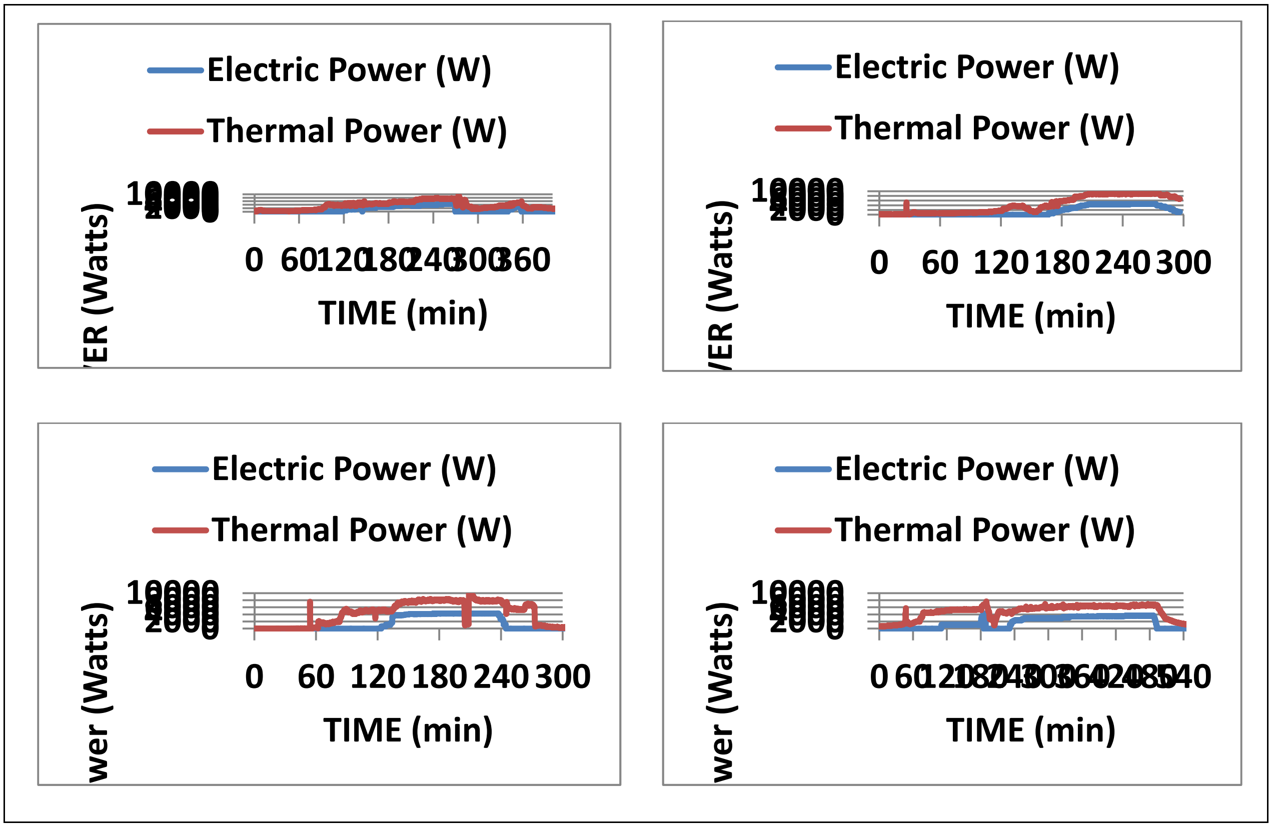
Grid connected WVO CHP systems

(b)



Demonstration site water cooling loop system

Figure 29. Grid connected simulated field test data



Source: Altex Technologies, Inc.

3.5 Site Demonstration

After successfully completing the simulated field testing, Altex coordinated the delivery and installation of the system at the demonstration site's designated location. Since the location was outdoors, a fence was installed prior to system delivery, to protect the system. Figure 30 shows a few pictures of the system delivery (top row) and installation at the site (bottom row). As shown in the lower right picture, the system was anchored to the ground on a steel plate for seismic protection, and an exhaust was installed to safely discharge the system flue gases. Not visible in the picture are the electrical conduit, electrical box, and the code-legal interface to the site's electrical grid connection.

Figure 30. System Delivery to and Installation at the Site

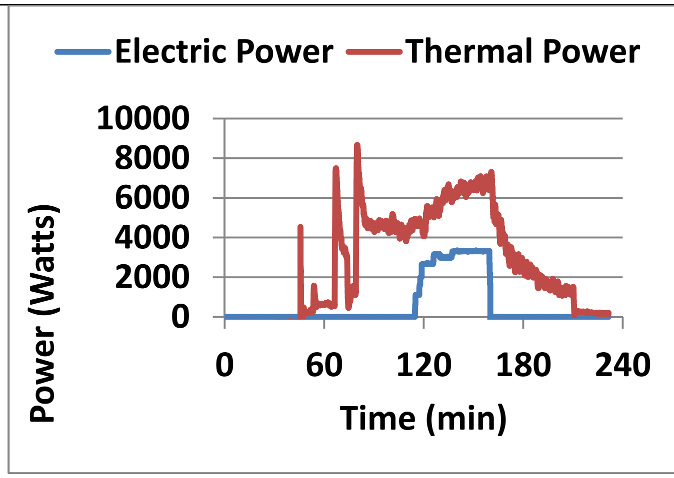
Source: Altex Technologies, Inc.

The system assembly at the site followed the site permit instructions. To ensure that the system meets the permit requirements, the system went through shakedown tests to verify the function of the emergency shut down, normal shut down, exhaust low flow safety, and other safety features. Figure 31 shows shake down sample test data in preparation for the inspection. These tests were limited in duration to comply with the permit. These tests were followed by a successful Hazardous Materials inspection and municipal permit sign off. Following this inspection, longer term tests were conducted. However, since the system is not UL listed as yet, the permit does not allow unattended testing. To comply with the permit and the Altex Safe

Operating Procedure, testing was limited to manageable durations, when two staff members could be present. Figure 32 shows sample 8-hour and 24-hour site data after municipal permit sign off. Although two staff were present, the testing was planned to be continuous and automatic, to assess the system's automatic operation for future unattended use. This was achieved except for one down due to staff rotation during the 24-hour test. As shown, the system operates consistently and produces power and hot water using the site WVO. These test data prove the systems operation at the demonstration site.

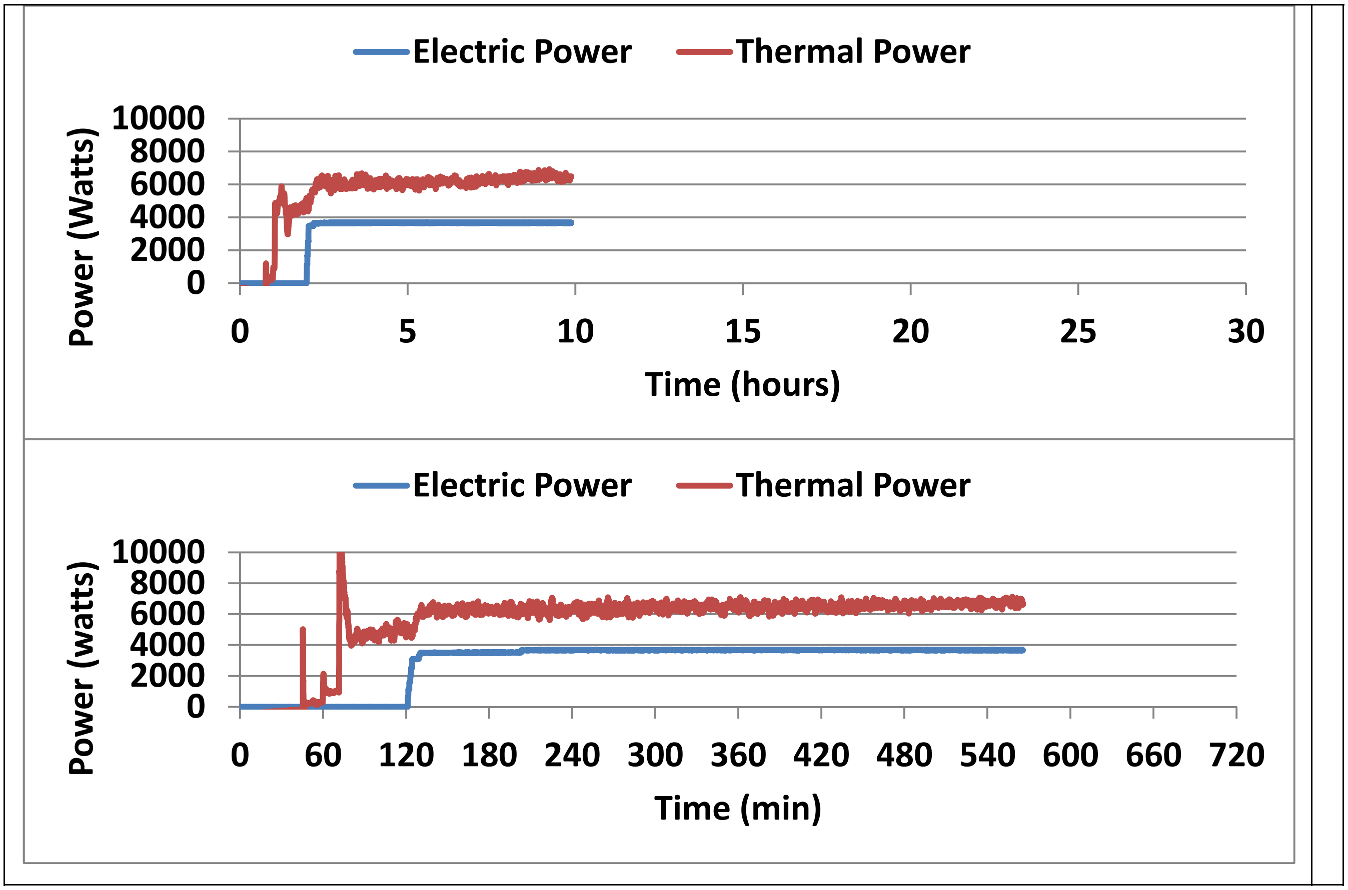
Note that the demonstration site data are similar to the grid-connected test data collected during the simulated field testing at Altex (e.g. Figure 29). This similarity allows further grid-connected testing at Altex, where more cost effective testing could be conducted and the system can be showcased to potential interested parties. This is planned.

Figure 31. System and Shakedown Test Data at the Demonstration Site



Source: Altex Technologies, Inc.

Figure 32. Demonstration Site Grid-Connected Test Data



3.6 System Evaluation

As previously discussed, Altex developed the WVO-CHP system, connected it to the grid, and successfully operated it on waste vegetable oil. The operational test data were used to evaluate the WVO-CHP system against the system design targets. Table 2 compares the system targets to what was achieved. As shown, the key targets were met.

The system was grid connected and was operated at 208 VAC up to 4 kWe. The system was used to produce up to 14000 Watts (47000 Btu/hr) hot water at 115°F. Since the system has a burner, even more hot water and/or higher temperature water can be produced. However, since the project emphasis was on electrical power generation and grid connectivity, no attempt was made to optimize the water heating subsystem.

A key requirement of the system was operation on WVO. This was achieved and the WVO collected from the site cafeteria provided the fuel for both simulated field and field tests. This success was partially due to the WVO Preprocessor that was developed under the project.

The system consistently achieved over 80% overall efficiency. This efficiency is the CHP efficiency and is based on the sum of the heat and electrical outputs (Combined Heat and

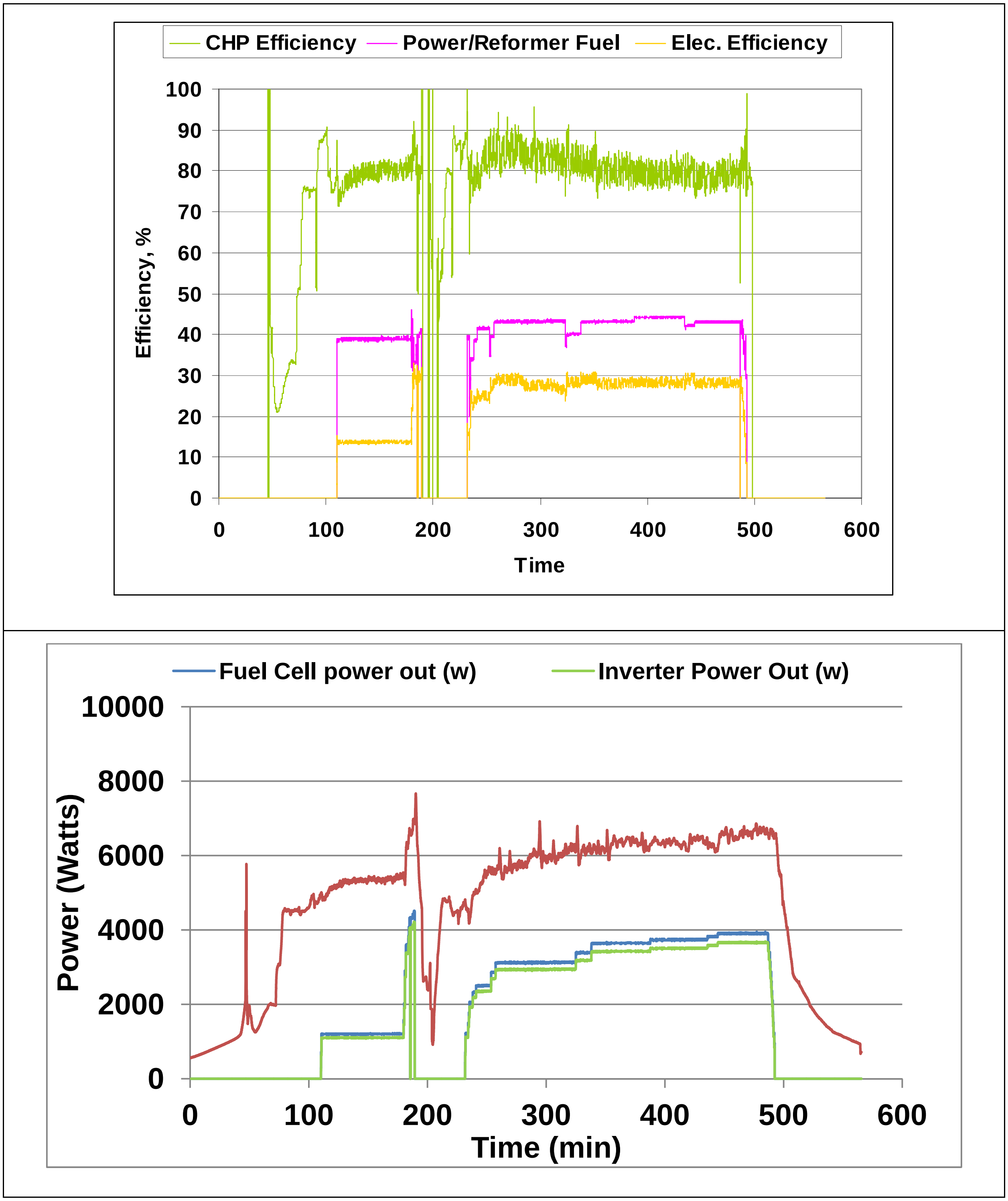
Power-CHP) divided by the total fuel consumed. Sample efficiency graphs are shown in Figures 33 - 35. The top graph of these figures shows the overall or the CHP efficiency, as defined above and also shows the load variation (lower graph), as the system is started and ramped in power. The CHP efficiency is consistently around 80%, and surpasses this target. This high efficiency, combined with using waste vegetable oil as the fuel, will provide considerable benefit to the user and the site.

Table 2: WVO-CHP Status Vs Target

Parameter	System Targets	System Status/Achieved
Electrical Output	4 kW @ 120/240VAC, grid compatible	4 kW@ 120/240VAC, grid compatible
Heat Output	Up to 45,000 BTU/h @ 150°F	45,000 BTU/h @ 115°F
Fuel	Waste vegetable oil	Waste vegetable oil
Overall Efficiency	>80%	>80%
Electrical Efficiency	40%	44% (reformer fuel only), 30% (total fuel)
NOx	<0.07 lb/MWh	<0.07 lb/MWh
CO	<0.1 lb/MWh	~0.1 lb/MWh
VOC	<0.02 lb/MWh	Did not measure but expected to pass
PM	Undetectable	Did not measure but expected to be undetectable

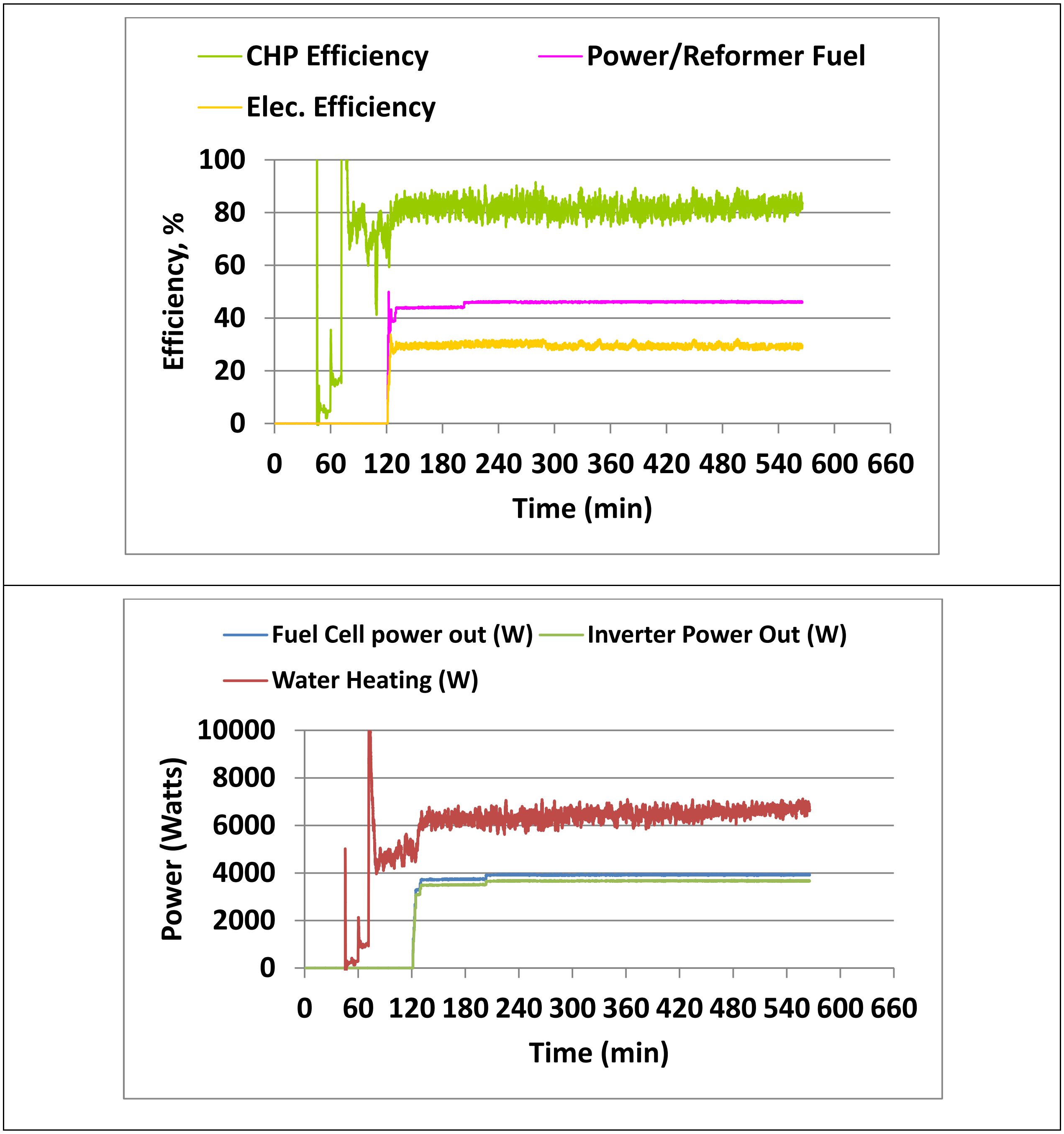
As shown in Table 2, the target electrical efficiency is 40%. Calculating an accurate electrical efficiency requires measurement of the fuel that is used to produce the reformate and the resulting power. This was not possible because the WVO-CHP has a burner that is the source of heat for the reformer as well as the hot water. But the portion of the burner heat (and the corresponding fuel flow) that is used to produce the reformate is not known and an accurate electrical efficiency cannot be determined. For this reason two electrical efficiencies are plotted in Figure 33 and Figure 34. The curve that is around 30% is marked as electrical efficiency. To calculate this efficiency the sum of the fuel flow to the reformer and to the burner was used as a basis. This is the true definition of the electrical efficiency, if the system is fully optimized for electrical power generation and the system waste heat is used to generate the hot water. However, the system water heating subsystem was not fully optimized. Figure 33 and Figure 34 also show a graph with an efficiency value around 44%, which is calculated by using the fuel flow to the reformer as the basis. The true electrical efficiency is between these two curves, i.e. between 30% and 44%.

Figure 33. WVO-CHP System Efficiency and Output (simulated field test)



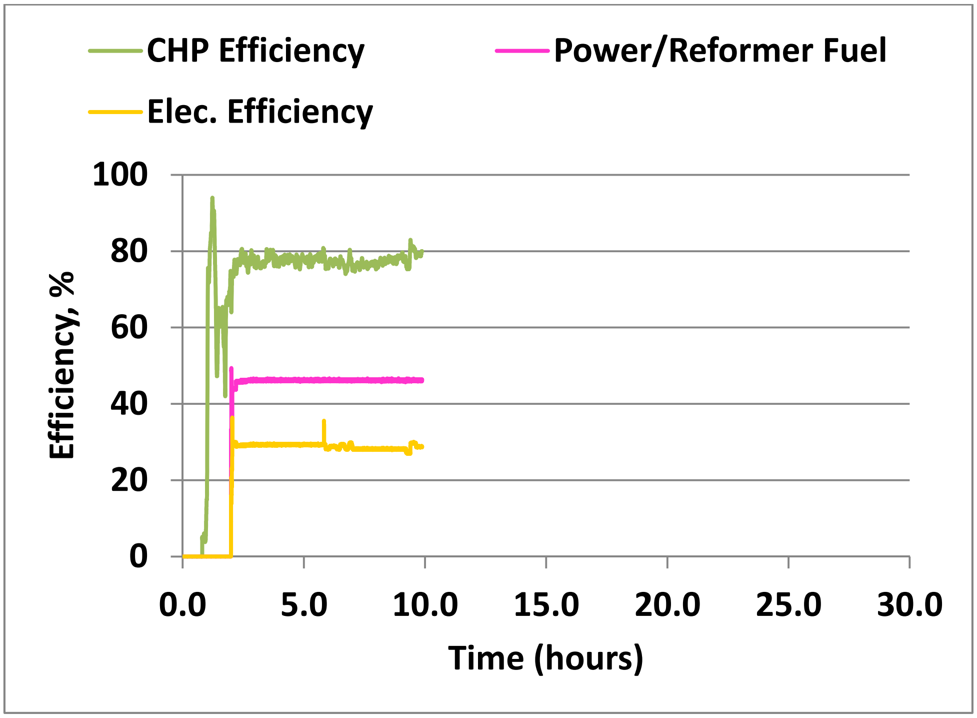
Source: Altex Technologies, Inc.

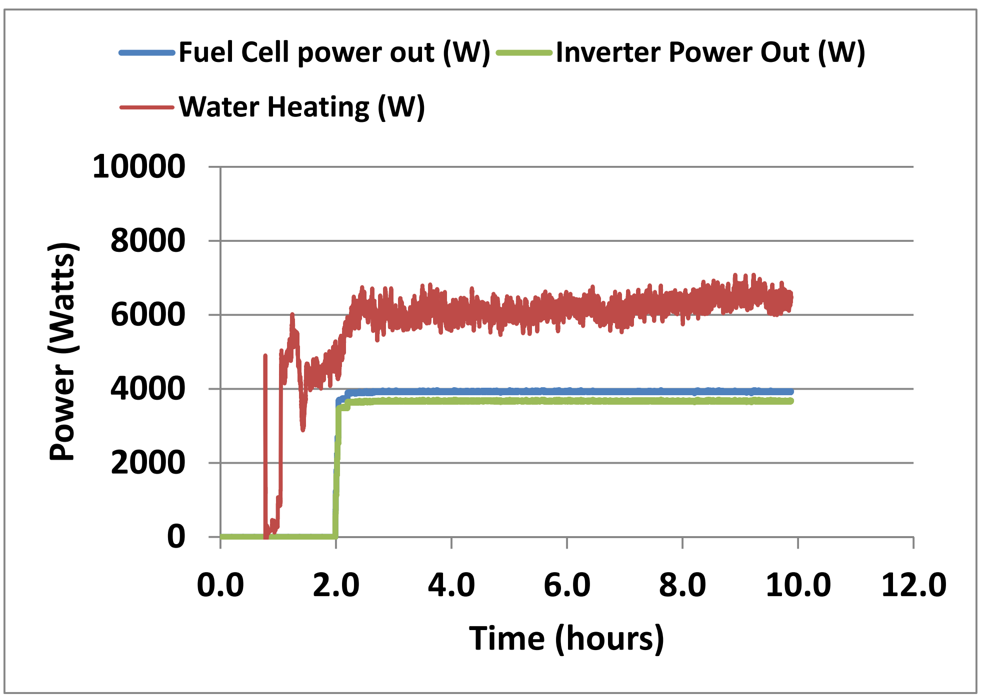
Figure 34. WVO-CHP System Efficiency and Output (field test_8 hours)



Source: Altex Technologies, Inc.

Figure 35. WVO-CHP System Efficiency and Output (field test_24 Hours)





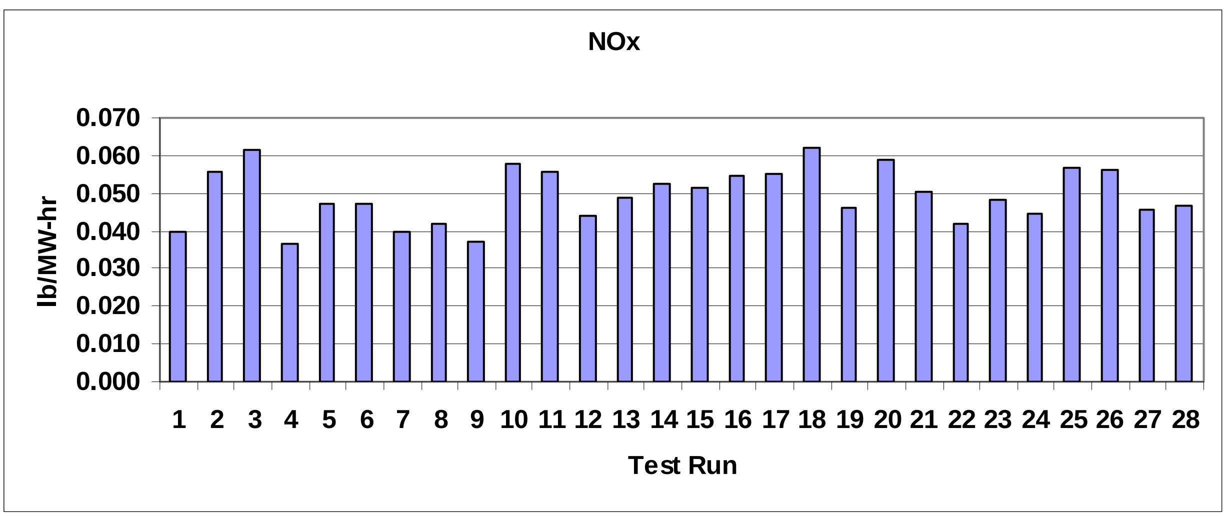
The WVO-CHP is targeted to meet CARB 2007 emissions limits. During testing, NOx and CO were measured and converted to lb/MWhr using the California Air Resource Board (CARB) DG certification work sheets[1]. Sample data are shown in Figure 36 and Figure 37.

As shown, NOx is consistently below the CARB limit of 0.07lb/MW-hr. The CO average is below the CARB limit of 0.1 lb/MW-hr, however, there are occasional CO breakthroughs that are above the limit. Work is required to optimize the burner for consistent compliance. VOC and PM were not measured but for this type of system they are normally in compliance when CO is.

As discussed in Section 1.3, to covert the Altex reformer for the WVO-CHP application, a new burner was developed with the capability to operate on WVO. Because of limitations in schedule and funding, no attempt was made to optimize the burner for emissions performance. Altex has 25 years of experience in developing low NOx burners and is confident that the current WVO-CHP burner can be modified easily to meet CARB 2007 under all scenarios.

The certification work sheet was also used to arrive at the Energy Efficiency. This data is shown in Figure 38. As shown, the Energy Efficiency is 83%-85%. This high efficiency, combined with the use of waste vegetable oil as the fuel, will provide considerable benefit to the user and the site and benefit Californians through environmentally sound energy generation that results in reduced greenhouse gas emissions and less fuel use.

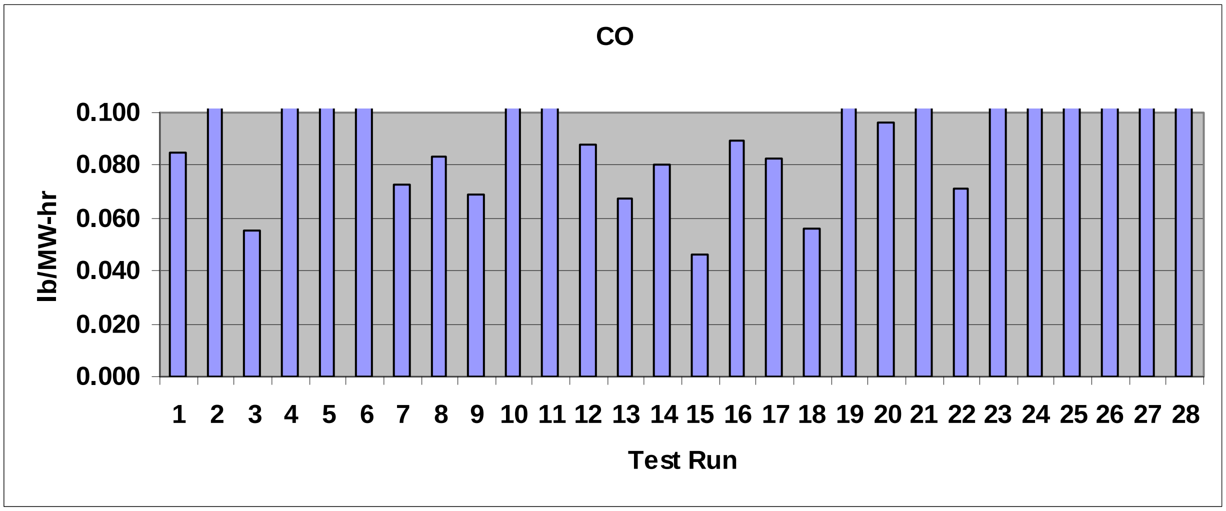
Figure 36. WVO CHP NOx data



Source: Altex Technologies, Inc.

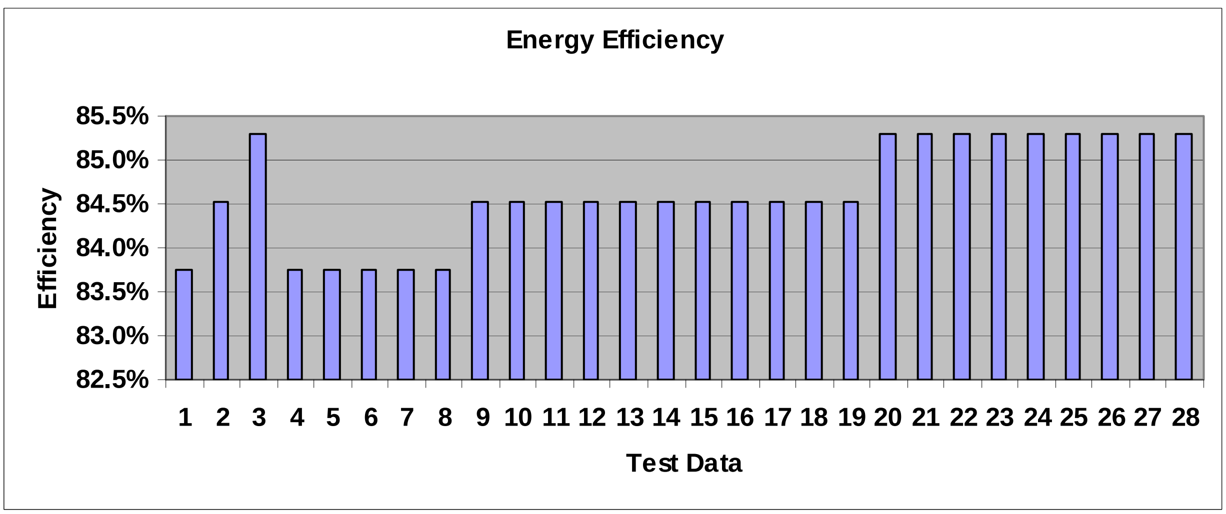
[1] http://www.arb.ca.gov/energy/dg/certification_calculation_tool.xls

Figure 37. WVO CHP CO data



Source: Altex Technologies, Inc.

Figure 38. WVO CHP Energy Efficiency



Source: Altex Technologies, Inc.

CHAPTER 4: Technology-Transfer and Production Plan

4.1 Technology-Transfer Plan

To maximize the beneficial impact of this project, the knowledge gained from the execution of the project, including experimental results and lessons learned, is being made available to the public. To ensure that the results of the project are disseminated to key stakeholders and decision makers, a technology transfer plan has been developed and is being implemented.

The technology-transfer plan has two main avenues for public dissemination and one transfer of technology to potential commercialization partners.

The first avenue in public dissemination is through this final report and project fact sheets. In addition to the description of the project, its rationale, and its execution, key experimental results are included in the main section of the final report, which is publicly available.

The second avenue in public dissemination is through industry and technical conferences. For example, Altex routinely presents results of activities through presentations and panel discussions at various professional conferences including the annual Fuel Cell Seminar, American Chemical Society and American Institute of Chemical Engineers national meetings, and other topical conferences that discuss fuel cells, climate change, and alternative energy. Altex has already listed the WVO-CHP among its fuel cell project portfolios.

The technology transfer plan also includes transferring the result of the project to the key decision makers in potential commercialization partners. Altex is preparing a list of potential commercialization partners. These include:

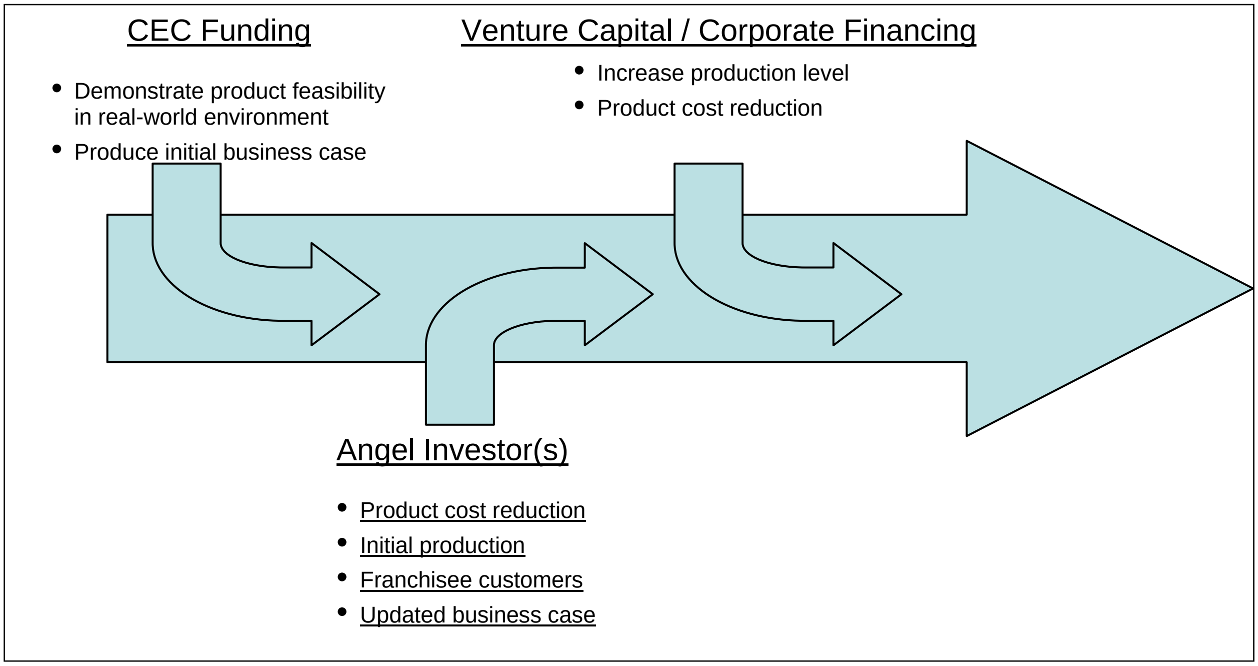
- Large companies with cafeterias, including the selected site
- Fast food restaurant chains
- Fuel cell manufactures
- Investors

An executive summary of the project success is being sent to the potential commercialization partners.

4.2 Production-Readiness Plan

Figure 39 outlines the commercialization path. Through this project, the Energy Commission funding allowed demonstrating the product feasibility in a real world environment. The system is available at Altex to be showcased to attract investors for commercialization. Angel, Venture and Corporate investors are being targeted. Altex is also investing towards the WVO-CHP commercialization. Currently this investment is used for attracting other investors, and product cost reduction. The cost reduction also benefits from other Altex fuel cell projects. The cost reduction is aimed at reducing the manufacturing and material cost of the reformer. Under the project, a packed bed reformer was used, and its cost is being reduced by using wash coated, stamped reactors that are amendable to low cost manufacturing. This process was implemented successfully last year. Also, work has been initiated to convert the precious metal-containing catalyst to a non precious metal catalyst.

Figure 39. Commercialization plan



The cost reduction strategy will reduce the payback period. To achieve market introduction, the payback period for the WVO-CHP must be reduced to less than five years. For significant market penetration, this payback period needs to be reduced to three years or less. These targets are summarized in Table 3.

Table 3. Goals for price and performance for WVO-CHP Commercialization.

Year	Market Position	Unit Price	Efficiency electric/system	Payback Period* No incentives	Payback Period* With incentives
2015	Early adaptors	$100,000	40% / 82%	8 years	5 years
2015	Market Introduction	$41,000	40% / 82%	4. years	2. years
2018	Market Penetration	$26,000	40% / 82%	3 years	1 years

*Payback period estimated assuming electricity at $0.15/kWh, natural gas at $8/MMBTU

Incentives reduce the payback, but uncertainties exist regarding the continued availability of incentives and the price of natural gas. To achieve introduction into the market beyond early adopters, either the payback period without incentives must be attractive on its own, or the payback period with incentives needs to be within a time frame over which these uncertainties are minimized. For this reason, the research team chose five years without incentives and two years with incentives as maximum payback periods for market introduction. These payback periods correspond to a capital cost of $41,000, which corresponds to a price reduction of 32%.

For extensive market penetration, even shorter payback periods are required, particularly without incentives, since significant market penetration would theoretically imply that incentives are not needed. Therefore, a reasonable capital cost would be one that reduces the payback period to three years or less without incentives. This corresponds to a capital cost of $26,000, which corresponds to a further price reduction of 37% (57% from the current status). If incentives remain in place, this capital cost reduces the payback period to less than one year. Such a short payback period would greatly drive market penetration, but once incentives go away, the system is still viable economically.

The performance of the current design is expected to meet the needs for market introduction and market commercialization. In particular, the 82% overall efficiency is sufficiently high to not pose any barrier to market penetration. However, any increase in efficiency (electrical or overall) contributes to reduction in payback period through increased energy production for the same amount of fuel. Additionally, efficiency increases can reduce the size and/or cost of some system components, which can result in capital-cost reduction.

Figure 40 presents a graph (on left) showing the reduction in capital cost, and the payback period. With these cost estimates, a Mansfield-Blackman model of market penetration was used to predict the degree of market penetration.[2] The industry specific parameters for the Mansfield-Blackman model are the “Z-factor” that measures an industry’s typical risk averseness, a profitability index that was estimated as an industry payback period divided by the payback period of the WVO-CHP, and an investment index that is a ratio of the investment required for the technology to the total assets of the firm.

The Z-factor chosen for the model was -0.1. This is a less risk averse rating than that for large-scale breweries (Z=-0.3), but significantly more risk averse than that for aerospace firms (Z=0.3). An industry-acceptable payback period of five years was used with an investment index of 0.027 given a capital cost of $41,000 and typical net worth requirements for fast-food franchisees of $1.5 million per store. It should be noted that at this level of investment index, the model is relatively insensitive to the investment index and capital cost affects market penetration through the payback period.

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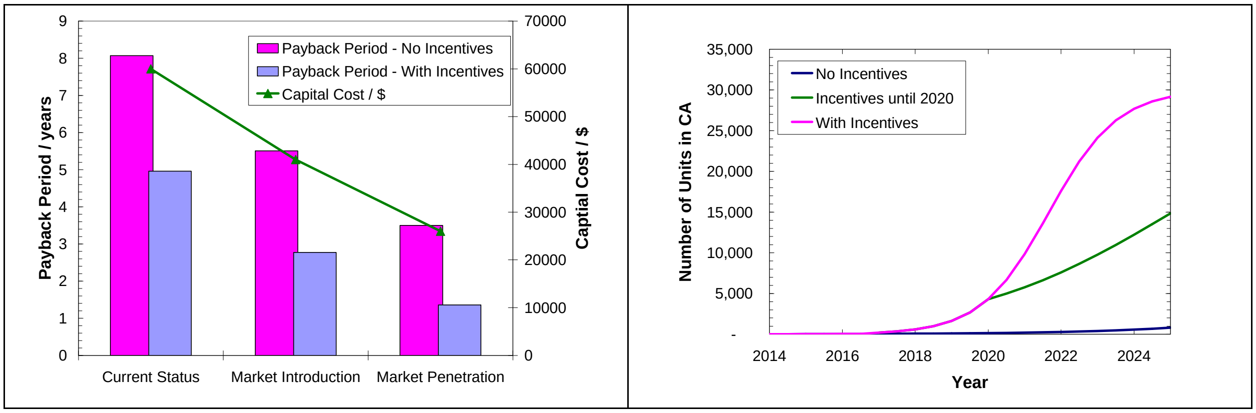
[2] “Review of Methods for Forecasting the Market Penetration of New Technologies,” S. T. Gilshannon amd D. R. Brown, Pacific Northwest National Laboratory, PNNL-11428, UC-900, December 1996

The results of the model using the above assumptions are presented in Figure 40 (right) for three cases. The first case is when current incentives are available at their current value through at least 2020, the second is when incentives are rescinded in 2020, and the third is when no incentives exist. The market penetration predicted by the model for these cases was 29,000, 13,000, and 2,600 units, respectively. It should be noted that the second case is a more realistic assumption since once a technology gains appreciable market share, there is great pressure to reduce and/or eliminate such incentives. However, there is still measurable market penetration for the worse-case scenario.

Figure 40. Payback vs capital cost (left) and market size (right)



The results of this project, the cost reduction strategy and the market study are being used to develop a business plan for attracting the necessary investment to commercialize WVO-CHP.

GLOSSARY

Specific terms and acronyms used throughout this report are defined as follows:

Term/Acronym	**Definition**
BOP	Balance of Plan
Btu	British Thermal Unit, 1 Btu= 1. 055 kilo Joules to convert Btu/hr to watts divide the value by 3.41
CAD	Computer Aided Design
CARB	California Air Resource Board
CHP	Combined Heat and Power
CORE	Compact Reliable and Robust Reformer
DC	Direct Current
DG	Distributed Generation
EPA	Environmental Protection Agency
HMI	Human-Machine Interface
HTPEM	High-temperature polymer-electrolyte membrane
MMBtu	Million British Thermal Units, 1 MMBtu = 293.3 kWhr
NI	National Instrument
PIER	Public Interest Energy Research
RD&D	Research, Development, and Demonstration
RS	Recommended Standard
UI	User Interface
WVO	Waste Vegetable Oil
WVO-CHP	Waste Vegetable Oil fueled Combined Heat and Power