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Energy Research and Development Division

FINAL PROJECT REPORT

Small-Scale Forest Waste Power System

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Small-Scale Forest Waste Power System is the final report for the Small-Scale Forest Waste Power System project (EPC-17-013) conducted by Altex Technologies Corporation. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

After sustainable forest management or logging, piles of forest residue, or slash, are produced within the forest. Forest slash resources are currently a wasted renewable fuel resource that could help California meet renewable portfolio standard goals. Also, forest slash piles represent a significant fire hazard, and are sources of greenhouse gas emissions and pollutants, if simply burned in piles. To mitigate these impacts and increase renewable energy production, a novel and modular Forest Power (FORPOWER) system was developed to convert forest slash to power at an economically viable cost under California Senate Bill (SB) 1122 (Rubio, Chapter 612, Statutes of 2012). The modular power system integrates a simple biomass feeder, doesn't require a syngas cleaner, and uses a compact novel heat exchanger and commercial gas turbine, which results in lower system costs versus conventional systems. In addition, a novel biomass densification system module that compacts slash into logs was developed to reduce forest slash delivery costs to the power module.

The goal of the project was to show how the FORPOWER system, which includes the densification module, supports SB 1122 by cost-effectively converting forest slash to electric power at distributed locations throughout the state close to forest resources. Pilot-scale system biomass test results and analyses under the project showed that an acceptable 4.6-year simple payback could be achieved for a 5 MWe full-scale combined heat and power FORPOWER system, demonstrating the economic viability of the system. In addition to economic benefits, implementing 28 FORPOWER bioenergy modules could reduce greenhouse gas emissions by 1 million tons per year. The gaseous emissions and exhaust opacity from the test system were below San Joaquin Valley Air Pollution Control District regulated limits for biomass boilers. Implementing these environmentally acceptable systems in California would support renewable power standards, reduce the risk of forest fires, and improve forest sustainability.

Keywords: forest slash densification, biomass based directly and indirectly-fired gas turbine, forest slash resources

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EXECUTIVE SUMMARY

Introduction

After sustainable forest management or logging, piles of forest residue, or slash, are produced within the forest. Currently slash is a wasted renewable fuel resource, which if used could help California meet its energy renewable generation goals. Forest slash piles also represent a significant fire hazard to people, property and forests and a source of pollutants if simply burned in piles. To address this issue, California Senate Bill (SB) 1122 (Rubio, Chapter 612, Statutes of 2012) was implemented to promote using this slash to produce power, as approved by California Department of Forestry and Fire Protection or other appropriate state or federal agencies. This legislation focused exclusively on small-scale bioenergy generation facilities producing less than 5 megawatts (MW) of electricity that could be located near forest or agricultural biomass resources.

It is imperative in this investment and legislative climate to explore smaller-scale forest slash biomass electricity technologies that could lower upfront investment and operating costs that will benefit ratepayers economically while reducing fire hazards and pollution.

Project Purpose

This project purpose was to demonstrate a pilot-scale power system that could cost-effectively convert forest slash to electricity called Forest Power (FORPOWER). The overarching goal of the project was to design a commercial-scale FORPOWER bioenergy modules at 3 MW, 5 MW and 10 MW based on the demonstration of a pilot-scale unit using forest slash. The full-scale design and pilot-scale test data evaluated the economic and environmental benefits of this technology.

This technology was set to achieve a projected electric power cost of $.082/kilowatt hour (kWh) for a unit at 5 MW scale with a simple payback of under four years and by using multiple units reduce greenhouse gas (GHG) emissions by more than 1 million tons/year. FORPOWER could attract equipment manufacturer investments to advance commercialization of units for use by power producers by achieving these metrics.

The unique modular FORPOWER technology integrates a simple biomass feeder, separating the particulate-laden biomass fuel combustion products from the clean gas turbine working fluid. In addition, the FORPOWER includes multiple forest slash densification modules that compact the forest slash into dense logs for lower-cost handling, storage, and transport to the bioenergy module that is located some distance from the portable densification modules. Trucks can be filled with dense biomass logs to their weight limit, reducing the number of trips to deliver a given amount of biomass to the bioenergy module, and lowering the cost of delivered biomass and reducing vehicle emissions. The FORPOWER bioenergy module receives the dense logs and reduces the biomass to small particles that are processed partly into bio-oil with the solids burned in a low-emissions combustor and the hot products transferring heat to the gas turbine engine via clean working fluid that then reduces the amount of bio-oil used by the gas turbine combustor. By using this approach, slash can be converted to power without degrading the gas turbine due to ash contamination.

Project Approach

The overall project approach was to design, build, and test a densification system in addition to a pilot-scale demonstration of bioenergy module. The test results from this demonstration were used to design a commercial-scale 3 MW, 5 MW and 10 MW FORPOWER systems to define system capital and operating costs using America Association of Cost Engineers (ACCE) analyses. These cost results were then used to define economic and environmental benefits.

A novel full-scale densification module was constructed and tested to simulate portable features for forest biomass applications of interest to determine the economic benefits of reducing forest slash biomass delivered costs. The densification module used a hydraulically operated cylindrical piston ram that compacted chipped forest slash into dense 11-inch diameter by 6.5-inch-long logs. Prior to combustion in the bioenergy module, these dense logs were reduced in size to 1/8-inch particles that were optimal for the combustor. As with many biomass energy systems, biomass particle feeding into the combustor was initially challenging. By using strategically placed air jets in the feed system, the biomass feed was successfully transformed from the initial dense-phase transport to the diluted-phase transport needed for consistent feeding into the combustor and for stable combustion.

A pilot-scale prototype of a FORPOWER bioenergy module was assembled and tested in Altex's Facility using three types of California forest slash renewable fuel. The project team used the forest slash feedstocks of pine, fir, and white cedar provided by the University of California, Berkeley Blodgett Forest Station at El Dorado County California. The bioenergy module consisted of a multi-stage combustor that was able to control Nitrogen Oxides (NOx), Carbon Monoxide (CO) and particulate emissions to meet stringent California emissions regulations for biomass boilers. Proprietary and commercial analysis tools, established engineering procedures, and conventional materials were used to construct combustors that can safely and effectively withstand the thermal conditions to process biomass. Lastly, a commercially available microturbine was used to generate power from the heat transferred from the biomass hot combustion products.

During the project, a technical advisory committee was formed from staff of the California Energy Commission and Altex, with support from experts in energy system design and combustion equipment marketing, sales and service.

Project Results

The densification and bioenergy prototype modules were able to demonstrate stable operation using tons of forest slash for the pilot-scale demonstration. Using the densification module test equipment, wood waste was densified to a manageable level of 36.5 pounds per cubic feet. With this density, biomass transport trucks to the bioenergy site can be filled to the regulated limit, thereby reducing the number of trips and cost to deliver the feedstock.

The densified biomass was sifted to less than 1/8 inch to power the pilot-scale bioenergy module, achieving the desired NOx and CO emissions. The module was run at various ranges of combustor conditions. Emissions data showed that the bioenergy module met the San Joaquin Valley Air Pollution Control District (SJVAPCD) regulated emission limits for power plants operating on biomass. Meeting these regulations demonstrated that FORPOWER units could be operated in California as these emission limits are currently the most stringent in the state.

The pilot scale demonstration of the bioenergy module was successfully operated; however, the bio-oil which was supposed to provide additional fuel for power generation was insufficient, so a number two distillate oil fuel was utilized. According to literature, test results from a 2.5 MW gas turbine operating on a bio-oil had very similar operating characteristics with the number two distillate oil. These literature test results are encouraging, but future FORPOWER tests should confirm these results on supplemental biofuel. Also, to confirm performance at closer to full-scale, an approximately 1 MW or larger-scale system should be built and tested. At this increased scale, energy losses will be reduced and system efficiencies will be increased.

The full-scale system schematics and flow diagram were designed using the results from the pilot-scale demonstrations. All the subsystems needed such as equipment for building and operating 3 MW, 5 MW and 10 MW plants were designed and identified. The bioenergy module with a standalone system and combined heat and power (CHP) versions of FORPOWER were analyzed. The CHP version of FORPOWER used the combustor exhaust waste heat to produce useful hot water.

The techno-economic model for the power plants were defined using market costs obtained from different vendors, while the costs of construction were determined using a method developed by the AACE. The FORPOWER capital costs were then combined with estimates of operating costs in an economic model developed by University of California at Davis to estimate electricity generation costs for biomass power systems. The model results showed that FORPOWER bioenergy module operating in CHP mode could achieve an acceptable simple payback of 4.6 years for a 5 MW output. A major lesson from this research was that the simple payback is driven by capacity, which means that a 10 MW system will have a faster payback.

Considering the important simple payback parameter, this research showed that a 3 MW, 5 MW and 10 MW scale standalone biomass power plants have payback period of 9, 5.6 and 3 years respectively, while an adding a heat component to the biomass plant can provide a payback of 6.1, 4.6 and 2.5 years. The 10 MW standalone biomass power plant system and a 5 MW or higher CHP power plant met the target cost of electricity (COE) of $.082/kWh.

Total GHG saved for 3 MW, 5 MW and 10 MW plants are 22,800, 38,000 and 76,000 tons/year, respectively. In addition, 3 MW, 5 MW and 10 MW FORPOWER plants have the potential to generate 8 to 18 well-paying jobs in rural areas. These are substantial benefits for building and operating multiple plants. If 28 FORPOWER bioenergy systems were used, the total GHG emissions reduction would be more than 1 million tons per year, consistent with the project target.

FORPOWER has the potential to address SB 1122 targets with acceptable payoff for investors using forest biomass. In addition, since agricultural residues have a lower delivered cost than forest residues, the favorable conclusions for forest residues meeting SB 1122 targets also extend to agricultural residues. This conclusion is based on pilot-scale FORPOWER bioenergy module test results and must be confirmed by larger-scale tests.

Technology/Knowledge/Market Transfer Activities

The knowledge gained from the project would be of interest to many stakeholders. Potential users of FORPOWER include owners of biomass powerplants, forest waste maintenance companies, pellet machine manufacturers, gas turbine manufacturers, and investor-owned and public utilities.

Although sharing this project research at conferences and meetings was constrained by COVID-19, disseminating information through conferences, publications in trade publications and meetings with stakeholders is expected to proceed in the future.

Potential markets for FORPOWER under SB 1122 are forest residue feedstock use up to a total of 50 MW and agricultural residue use up to a total of 90 MW, for a total available market of 140 MW. Under renewable portfolio standards, there is a possibility of 450 MW, but this market will be more cost competitive, and larger systems that exceed the current 5 MW maximum capacity will be needed. In this project, power outputs up to 10 MW were considered. At the 10 MW level, the Levelized Cost of Electricity (LCOE) was significantly lower than 5 MW due to higher engine efficiency and the lower capital cost per output at larger capacities. Larger engines would provide even more competitive power pricing. Table ES-1 provides a list of these substantial markets in tons per year (TPY) inside and outside of California.

Table ES-1: Potential Markets in California and Other Locations in the US

Market	California (TPY)	US (TPY)
Forest biomass wastes.	21.6 Million	154 Million
Agricultural biomass wastes	26.8 Million	144 Million
Urban biomass wastes	37.6 Million	68 Million
Animal feed	12 Million	126 Million

Source: Altex Technologies Corporation

CHAPTER 1: Introduction

Forest slash is currently a wasted renewable fuel resource, which could help California meet its renewable portfolio standard goals by converting it to power. Forest slash piles represent a significant fire hazard to people and properties in California and a source of pollutants if simply burned in piles. To recover renewable energy and reduce forest fire hazards and pollution, a novel and modular Forest Power (FORPOWER) System that consists of a forest densification and bioenergy power production modules were developed to convert forest slash and agricultural residues to power at an economically viable cost to achieve policy Senate Bill (SB) 1122 (Rubio, Chapter 612, Statutes of 2012) [1]. This policy directs electrical corporations to collectively procure at least 250 MW of electric capacity from biomass and biogas projects. In addition, the Bioenergy Market Adjusting Tariff (BioMAT) was established to allow less than 5 MW biomass power plants to enter a pricing agreement with the Investor-Owned-Utilities (IOU).

The overall goal of the project was to design, develop and test a pilot-scale FORPOWER system to be used as a base to project the ability of full-scale systems to generate power at competitive costs using forest wastes, while meeting criteria pollutant requirements, reducing greenhouse gas (GHG) emissions, supporting renewable power standards, reducing forest fire hazards and improving forest sustainability. Specific objectives include development of a biomass densification system that reduces biomass processing and transportation costs and designing full-scale FORPOWER systems that can convert densified forest residues to electric power at a projected cost of $0.082/kWh, have a simple payback of less than four years and for multiple units reduce GHGs by more than 1 million tons per year (TPY).

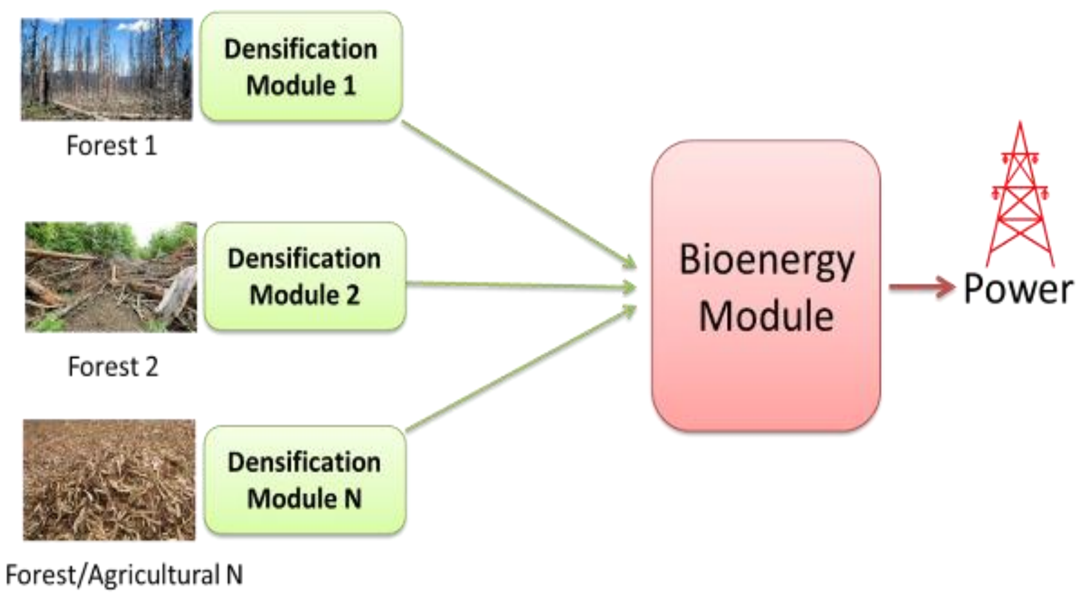
Under the scope of the project, a pilot-scale bioenergy and densification module was developed, fabricated and tested to project a full-scale FORPOWER system design. Biomass feedstocks included pine, white fir and cedar forest residues and wheat straw agricultural residues.

CHAPTER 2: Project Approach

2.1 System Process Overview

The purpose of this study was to apply the learnings from the pilot demonstration using forest wastes, which is depicted as Forest Waste Power System, to design a full-scale biomass power plant biomass power plant design for commercialization. As illustrated in Figure 1, the FORPOWER process may consist of multiple densification modules that convert forest wastes into densified material, which is then transported and fed into a bioenergy module that generates electricity at lower costs. By first densifying the biomass ahead of delivery to the bioenergy module, the logistics handling and transportation costs to deliver the biomass to the bioenergy module are reduced. The bioenergy module uses an indirect and direct-fired gas turbine to reliably produce electric power. This innovative process minimizes the biomass-related contaminants in the gas turbine flow path, reducing the gas turbine maintenance while increasing its system lifetime.

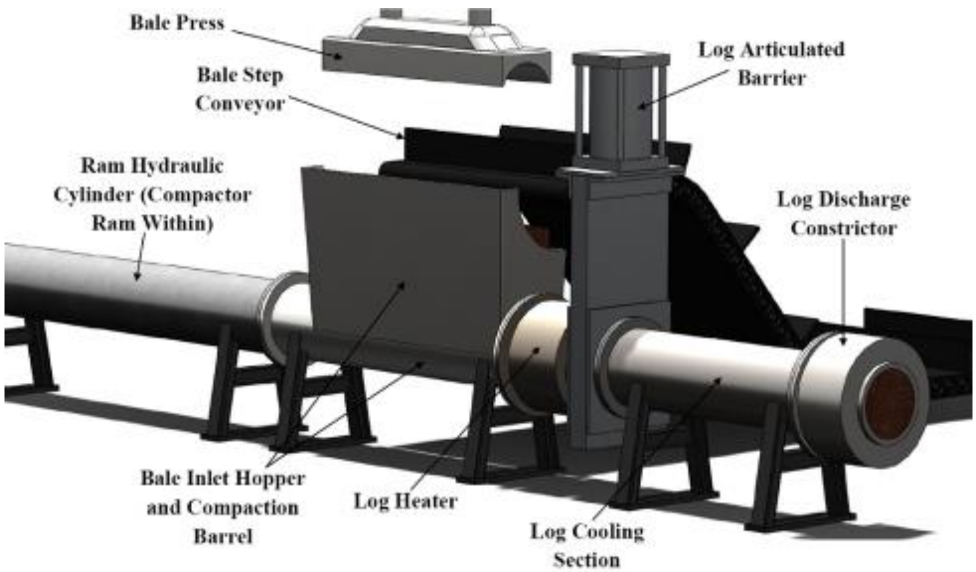
Figure 1: FORPOWER Small-Scale Process



Source: Altex Technologies Corporation

Figure 2 illustrates Biomass Blending and Densification System (BBADS), which has been successful in densifying agricultural residues into 11-inch diameter logs of 40 lbs./cf. density. The BBADS uses a hydraulic ram to compact the biomass against a barrier, where it is heated by a hot oil jacket to a temperature that activates the inherent lignin binder. After a brief holding period, the barrier is opened and the compacted material (7-inch log length) is pushed into a more extended length (50-inch heated length) heating section. After multiple compaction and heating cycles, the originally formed and heated log is pushed into the water-cooled portion (30-inch cooling length) of the tube. At this point, the log is cooled to set the lignin binder. Although the previous process illustrated is for baled agricultural residues, by replacing the feeder with a chipped forest residue feeder and modifying operating conditions, the BBADS can be adapted to forest biomass wood wastes.

Figure 2: BBADS Densification System Rendering

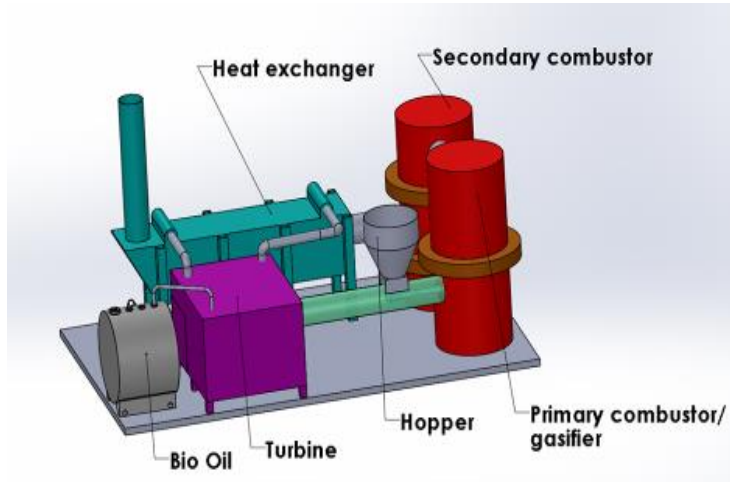


Source: Altex Technologies Corporation

Before the densified forest biomass is used in the bioenergy module, the feedstock will be sifted to 1/8-inch for optimal conversion to power the bioenergy module.

Figure 3 gives a rendering of the bioenergy module that converts densified forest residues to electric power. The module consists of several subsystems, including a primary (cyclonic biomass sub stoichiometric) combustor/gasifier, secondary combustor that cleanly converts the biomass to heat, and heat exchanger (HEX) that captures the biomass combustion heat to help power the gas turbine. Also the working fluid temperature exiting from the heat exchanger is increased by direct firing bio-oil in the gas turbine combustor. By using indirect and direct firing, biomass ash contaminants in the gas turbine working fluid are minimized.

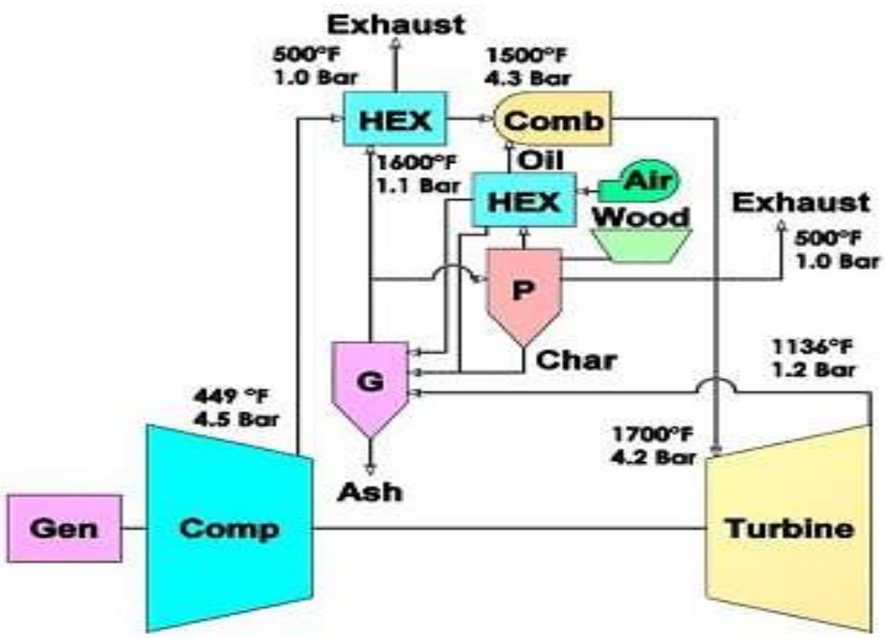
Figure 3: FORPOWER Bioenergy Module Rendering



Source: Altex Technologies Corporation

Figure 4 illustrates the flow diagram of the FORPOWER bioenergy process.

Figure 4: FORPOWER Bioenergy Process Illustration



Source: Altex Technologies Corporation

The FORPOWER biomass conversion process is based on an externally-fired gas turbine technology [2], where the "dirty" fuel combustion products (G to HEX) are separated from the clean air working fluid (Comp to HEX) by a HEX. By using this novel heat exchanger to indirectly heat the gas turbine air working fluid, ash is prevented from contaminating the working fluid and eroding the turbine. Another important advantage of this approach is that the hot air exiting the turbine (Turbine to G) is used as combustion air, where the high temperature helps enhance reaction stability and combustion intensity for low-grade fuels, such as forest slash or char. By using the heat recovered from the hot air, the process is recuperative, which leads to a higher efficiency.

FORPOWER incorporates the cyclone pyrolysis reactor features of the California Energy Commission (CEC)-supported Altex Biomass Conversion to Synthetic Gasoline System (BCSGS process [1], which produces crude fuel oil, non-condensable fuel gas (NCG) and char fuel, with the char and NCG gasified and oxidized in a secondary reactor (G). Products from the reactor provide gas turbine working fluid heating through an Altex advanced and efficient heat exchanger (HEX), called Highly Efficient Low Cost (HELC). By using this novel heat exchanger to indirectly heat the gas turbine air working fluid, ash is prevented from contaminating the working fluid and eroding the turbine. According to recent tests supported by the DOE, this heat exchanger will have 50 percent lower pressure drop and 40 percent lower cost than conventional heat exchangers. This difference will then lower the FORPOWER cost per output [8] supported by the DOE, this heat exchanger will have 50 percent lower pressure drop and 40 percent lower cost than conventional heat exchangers. This difference will then lower the FORPOWER cost per output. Furthermore, tests have shown that the Altex heat exchanger bonding process can be enhanced to reduce the surface corrosion of 316-stainless steel by over an order of magnitude at temperatures of 750 °C, which yields a corrosion resistance consistent with high-nickel content oxidation resistant alloys like Haynes 282, Haynes 230 and Inconel 740 that are 3 to 4 times as costly as 316 stainless steel. Use of this process in FORPOWER lowers the cost of the heat exchanger materials by approximately 50 percent.

The separated and filtered oil from the pyrolysis portion of the reactor (P) will then be introduced into a special gas turbine combustor (Comb), downstream of the heat exchanger (HEX), to boost the heated air to the optimal turbine inlet temperature for high efficiency and power output. This low emissions gas turbine combustor, developed under the CEC's Energy Innovations Small Gran (EISG) program [3], was successfully demonstrated with CEC Public Interest Energy Research (PIER) support in the 100 kWe BBEST gas turbine combined heat and power (CHP) system [4]. By fully implementing the Altex BCSGS process, advanced HELC and BBEST microturbine approaches into the FORPOWER process, the system will have good efficiency and power output levels that will reduce costs per output.

2.2 Pilot-Scale System Process Overview

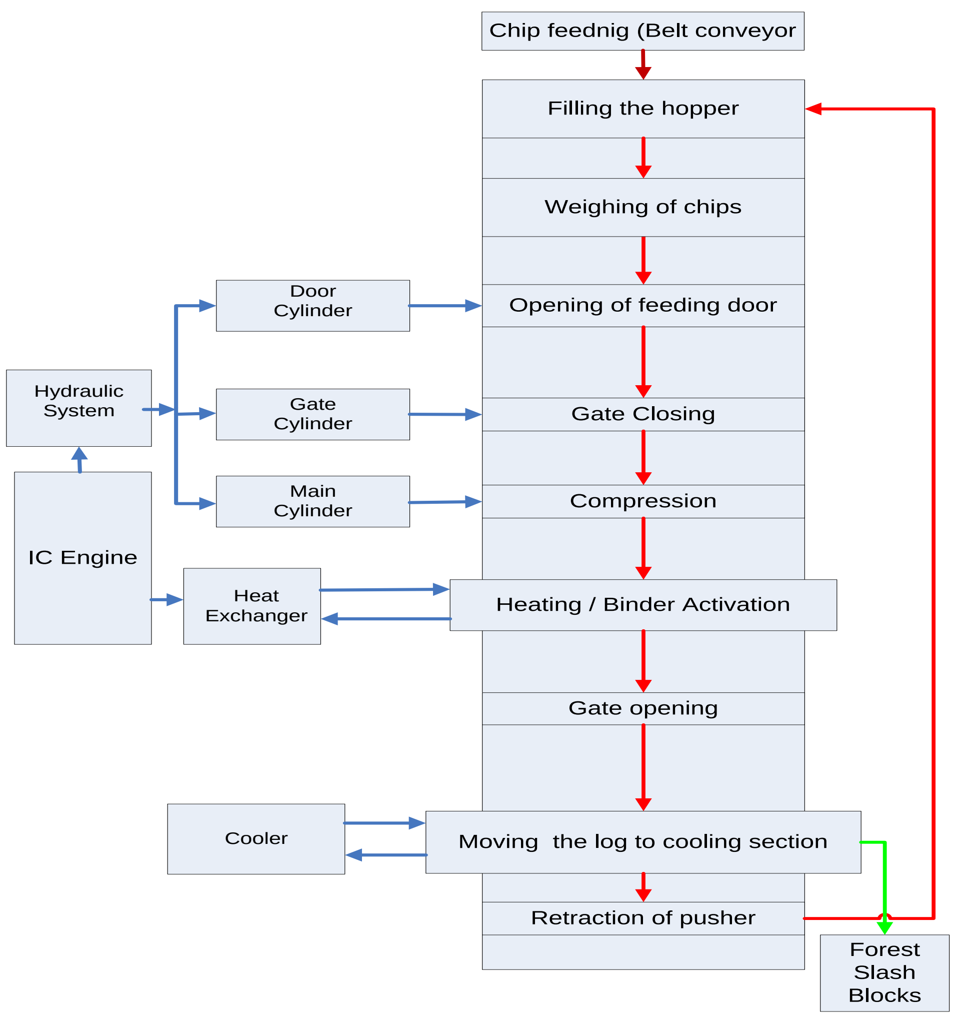
The FORPOWER densification and bioenergy pilot-scale systems were designed, fabricated and tested under this project. The project team developed a pilot scale densification system and bioenergy module to meet budget constraints. The testing of the densification and bioenergy modules were carried out independently, as would occur in normal operation. The pilot-scale bioenergy module test results were then projected to 3 MWe, 5 MWe and 10 MWe system designs and combined with the densification module results to estimate the techno-economic benefits of FORPOWER.

2.2.1 Densification Module

To control FORPOWER project and system development costs, the successfully-tested BBADS biomass densification system design [5] was highly leveraged to create the FORPOWER densification system design that is called Biomass Fuel Blocks (BFB). The key BFB design differences were related to the portability of the system for forest operation, as well as the need to feed chipped forest residues rather than baled agricultural residues, as is used in BBADS.

Through the repetition of a five-step process, logs are produced every 15 seconds. The ram forces are produced by a high-pressure cylinder fed by a positive displacement hydraulic fluid pump that is well proven in compactor use. The compaction zone, ram face and barrier heating needs are provided by a hot oil system that is fired by low-cost biomass in the production system. A thermal oil was used to meet the 200 °C temperature requirement and flow rates were high enough to yield good heat transfer results. For log cooling, a coolant liquid flowing in a jacket surrounding the shell augments the cooling produced by heat soaking into the log interior, promoting evaporation of water. Sufficient vapor exit paths are included over the cooling section length to allow vapor to escape while still retaining the solids at the required compression level. The pilot-scale BBADS equipment design and the process noted were used to successfully produce many tons of logs under the pilot-scale test effort. Figure 5 gives the Block Flow Diagram for the BFB forest biomass densification system.

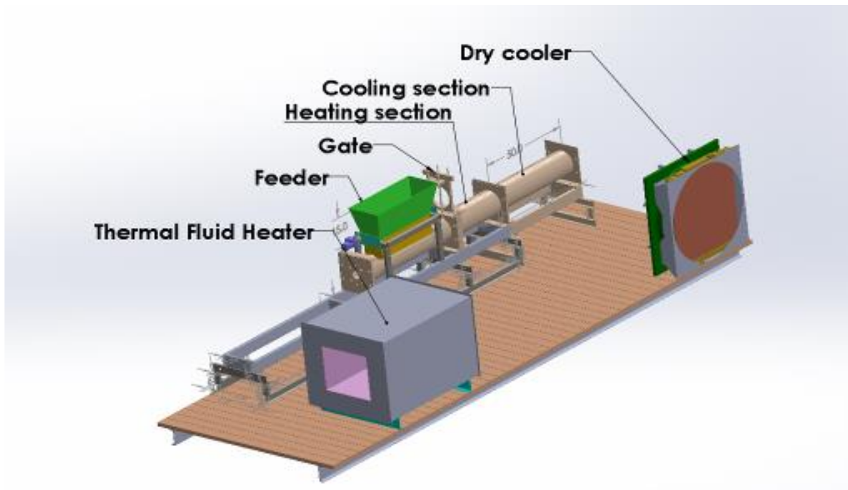
Figure 5: Densification Process Block Diagram



Source: Altex Technologies Corporation

The BFB processes wood chips produced from forest residues using standard chippers. Also, BFB uses the forest tractor engine to drive the hydraulic pressure system for the ram. In addition, the waste heat from the engine is used to heat the wood chips to activate the lignin binder that is needed to create logs. Lastly, a dry cooling system is used in the portable BFB to eliminate water use. These components are highlighted in Figure 6.

Figure 6: Detailed Densification Module Configuration



Source: Altex Technologies Corporation

2.2.2 Pilot-Scale Bioenergy Module

The bioenergy module consists of several major components, including the biomass feeder, bio-oil generator, combustor, heat exchanger and gas turbine that are integrated to create the power production system. As described in the following section, the pilot-scale design follows the full-scale design to generate the needed relevant performance data. However, the biomass throughput was reduced by a factor of approximately 50 from the full-scale system. This capacity reduction was needed to be compatible with available pilot-scale bioenergy module subsystem components that were used in this project to lower development costs. It should be noted that if the mixing and temperature history are properly simulated between the test and full-scale systems, pilot-scale data can be used to design full-scale systems that are many times larger. Systems with significantly larger capacities have been successfully scaled for utility power systems, including nitrogen oxides (NOx) and carbon monoxide (CO) emissions when operating on coal.

2.2.2.1 Biomass Feeder

To supply the sifted feedstock to the cyclone gasifier, a screw based feeder was utilized that consisted of an available biomass hopper, which incorporated a bin stirrer that continuously agitates the material to prevent agglomerates from developing and blocking the feed port at the bottom of the hopper.

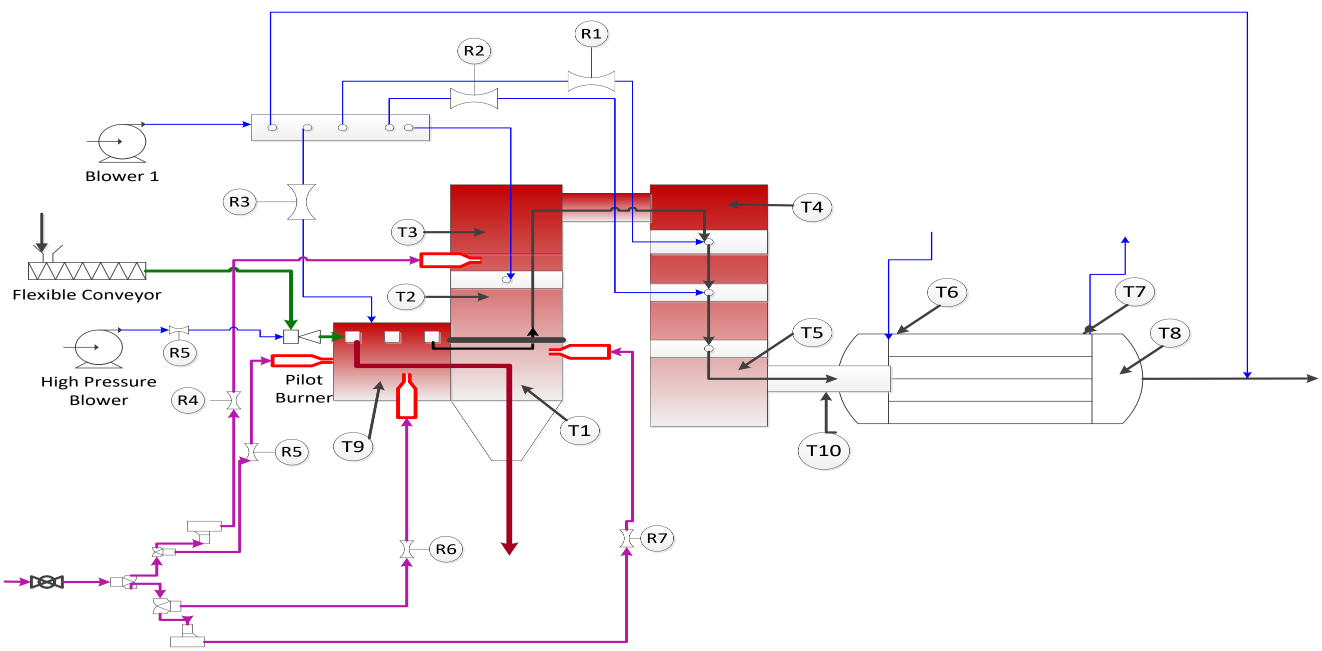
To prepare the biomass for feeding and cyclone firing, the size must be sifted to a top size of 1/8-inch. In the pilot-scale system this was accomplished by an available commercial knife-blade shredder.

To transport the biomass to the cyclone for processing, a flexible feed screw is attached to the bottom of the hopper and by varying screw speed, with a Variable Frequency Drive (VFD), the screw can transport the biomass at a fixed rate up the inclined tube and then drop the biomass into a small hopper attached to the eductor inlet. The material enters the top hopper as a dilute stream and then falls into the commercial eductor, where a high-speed air jet entrains and then tangentially injects the biomass into the cyclone gasifier.

2.2.2.2 Biomass Combustor

Figure 7 gives a process instrumentation diagram (PID) of the pilot-scale bioenergy module showing the major combustor/gasifier components and how they connect with the heat exchanger shown to the right in the figure. At the left of the figure is the near horizontal cyclone gasifier followed by the two towers. Also shown are the various air injection stages, biomass injection and natural gas components for system heat up.

Figure 7: PID for Bioenergy Module



Source: Altex Technologies Corporation

The pilot-scale FORPOWER cyclone combustor/gasifier consists of a nearly horizontal-oriented cyclone that operates under sub-stoichiometric conditions and above the ash fusion temperature, similar to operation of the full-scale gasifier.

The combustor/gasifier firing intensity (residence time) is consistent with that used in the full-scale design. Under nominal conditions, a residence time of 0.1 seconds is specified in the design for good processing of the biomass materials of interest.

A dense and high-temperature refractory is used as the gasifier surface for temperature resistance. Between the high-temperature refractory and the metal shell, a lower conductivity and lower temperature capability refractory is used. The regenerative air passage surrounding the shell in the full-scale design is absent in the pilot-scale design to control test system complexity and cost. A natural gas pilot and burner are built into the design to heat the gasifier ahead of biomass injection.

As with the full-scale design, the biomass is tangentially injected with air into the side of the cyclone. It was anticipated that the high volatile char and biomass fuel would quickly gasify in the reduced oxygen content cyclone. Ash from the biomass would be forced to the cyclone wall and melted under the high temperature reducing conditions. This ash would then flow from the cyclone into the vertical section and then fall into the bottom of the vertical section and into the ash management system. In addition, ash carried over in the gas from the cyclone would fall into the bottom of the vertical section and into the ash management system. By removing ash ahead of the HEX, typical heat transfer surface ash fouling problems with conventional gasifiers are reduced, which reduces expensive maintenance of the heat exchangers, required with conventional approaches.

The ash management system consists of a refractory lined ash collection chamber at the bottom of the gasifier tower that connects with a stainless-steel drum that has a considerable ash holding capacity. Manually-operated rakes are incorporated into the transfer channel to move the ash from the chamber to the stainless-steel drum. The chamber is expected to hold about one run of ash, or 50 pounds of ash, with the drum able to hold multiple days of ash accumulation before cleanout.

The cyclone gasifier produces a syngas that consists of some hydrogen (H2), CO, and methane (CH4) that must be oxidized to water vapor and carbon dioxide prior to the gas entering the heat exchanger. To accomplish this objective, two towers are arranged in series that have air injection to provide the oxygen needed for burnout of the syngas. In addition to burning out the fuel gas, the air is staged to increase the air-to-fuel stoichiometry in the first tower to approximately one to control NOx emissions. This condition, which is the same as that for the full-scale system, previously listed. Based on literature results, this stoichiometry should be maintained over a time period of approximately 0.75-seconds [5]. After this period, gas will enter the second tower, where additional air is injected to bring the stoichiometry to over one and up to 1.3. These conditions are held at approximately 0.5-seconds to burn out all the fuel components ahead of entering the heat exchanger. These conditions are consistent with those specified for the full-scale design.

2.2.2.3 Directly and Indirectly Fired Gas Turbine Engine

A key component is the indirectly and directly-fired Gas Turbine (GT). Given the benefits of this design to FORPOWER, a smaller silo combustor gas turbine design was selected for the pilot-scale test system. Figure 8 is a picture of the 20 kWe gas turbine generator model GTP 30-67 installed in the EMU12/E 20kW electric generation system. The unit was manufactured by Garret Corporation, Air Research Manufacturing Company of Phoenix Arizona that is now a part of Honeywell and is a radial turbomachinery design with a pressure ratio of 4.5.

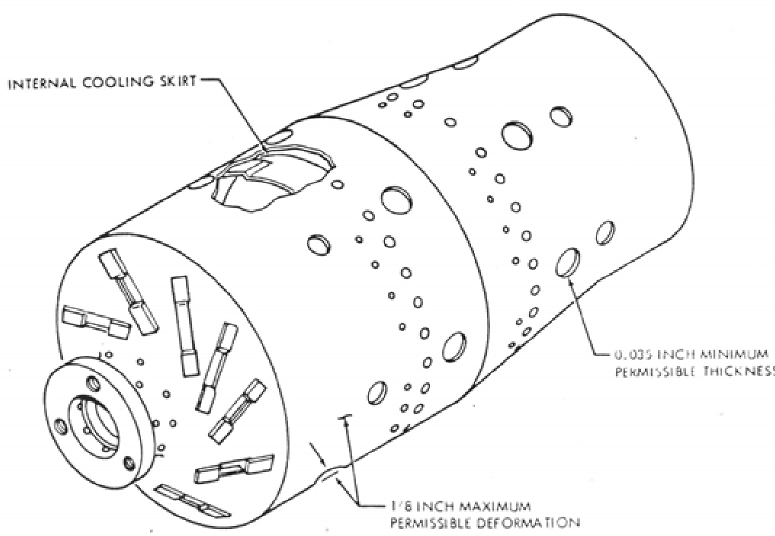
Figure 8: GTP 30-67 Gas Turbine Engine

Source: Altex Technologies Corporation

The system is a 120/230 volts AC, 2 phase, 400 Hz system that is fully self- contained, including fuel tank and battery for starting. The unit is 25” W x 28” H x 60” L and weighs 545 lbs. It is a single-stage radial compressor/turbine on a common shaft, with a silo combustor mounted to the side, as shown at the lower left of the picture in Figure 9. It is fuel flexible and typically operates on JP5, JP4 and kerosene, and can operate on gasoline, diesel or bio-oil fuel. Given the side-mounted silo combustor, this unit is easier to modify for FORPOWER indirect firing than annular type combustor arrangements typical on many gas turbines.

To integrate the GT with the FORPOWER heat exchanger, the compressed air duct was modified to transport the air into the heat exchanger. The heated air was then introduced back into the gas turbine ducting surrounding the silo combustor. The air that flows into the combustor can flow through a series of holes, as illustrated in Figure 9. Fuel is then injected into approximately 22 percent of the air and burned, with the remaining 78 percent of the air being liner cooling and dilution air. The hot mixed gases then flow through the turbine, generating power.

Figure 9: Gas Turbine Combustor Can and Cap Configuration



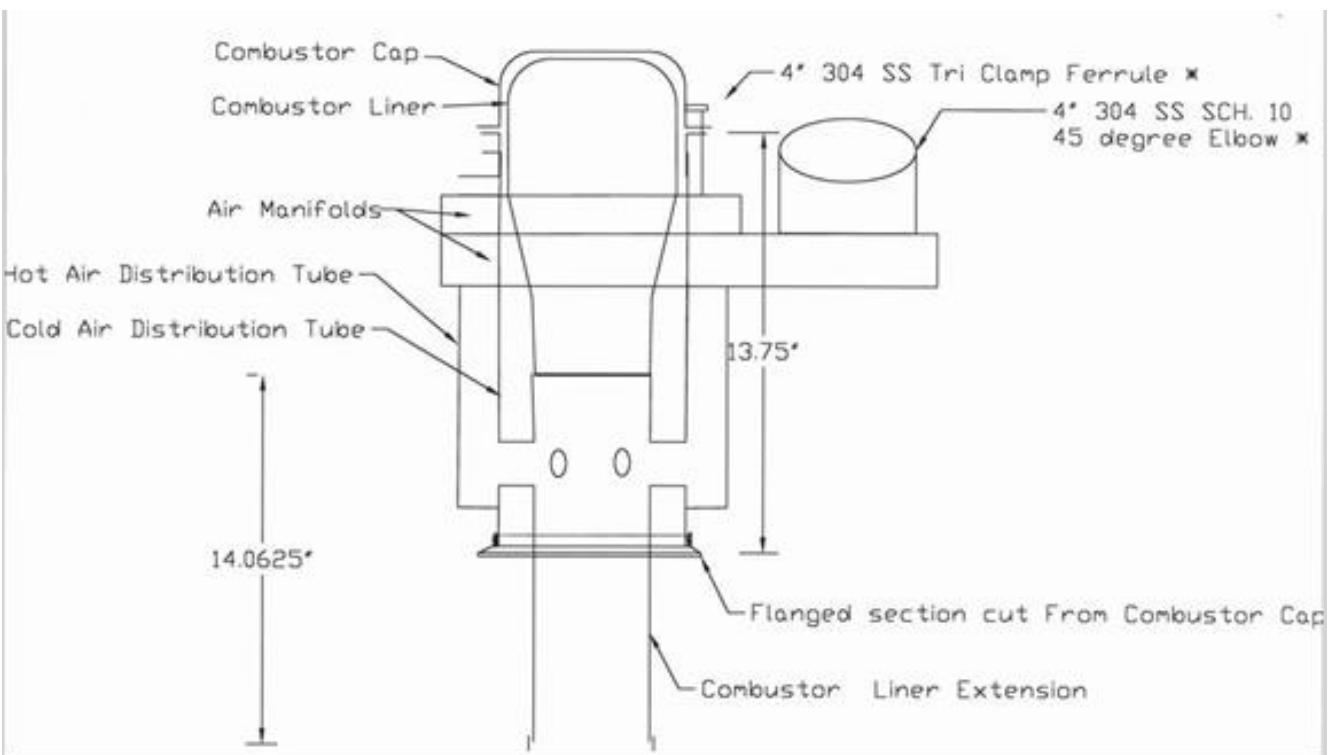
Source: Altex Technologies Corporation

The liner cooling and dilution air flow exceeds the combustion air flow. For control and for startup purposes, it is of interest to maintain the jet fuel combustion system that is then ramped downward as the air is heated by the FORPOWER heat exchanger.

Since the GT controller will automatically cut back on fuel flow as the dilution air is heated, the engine will operate at the required gas turbine inlet temperature in the range of 1,500F, whatever the level of dilution air temperature. Therefore, controlled GT conditions can be achieved at all anticipated dilution air heating levels.

The GT modification shown in Figure 10 was designed to heat the dilution air while bypassing the combustion air. It consists of a compressed "cold" air duct that channels air around the combustion can extension and to the combustion air inlet slots located on the combustor can liner. Simultaneously, the dilution air, which is blocked from entering the combustor can by metal tabs, is routed to a 4-in. diameter tube that is connected to the heat exchanger. A valve and orifice plate are used in this line to measure and control flow to the heat exchanger. After passing though the heat exchanger, the hot air is routed back to the GT through a 4-in. diameter line, where it then flows outside of the cold air duct and then finally through eight ports into the combustion can extension tube.

Figure 10: Gas Turbine Modification to Allow the Heating of Dilution Air



Source: Altex Technologies Corporation

Port velocities allow the hot air to rapidly mix with combustion product gases, producing a uniform temperature gas that enters the turbine. The combustor can extension was designed to use high nickel alloy temperature resistant Inconel 625 to reliably meet high temperature conditions. Lower temperature areas were designed to use 316 SS material to reduce oxidation at high temperature.

2.2.2.4 Combustion Products Heat Exchanger

The compressed air exiting the combustor cap is transported through insulated piping to be further heated by combustion products from wood and char residue forest products in a counter-flow Heat Exchanger (HEX). The compressed air at 400 F enters the half cylindrical manifold at the top and back-end of the HEX. The air flows through internal channels and is heated exiting through the half cylinder manifold at the top front-end of the HEX. Since combustor exhaust gas temperatures are expected to exceed 1800F (982 C), the pilot-scale heat exchanger was constructed of a high nickel alloy, 800 HT, that has long-term corrosion resistance. This alloy is available in limited tube and plate configurations. Therefore, to save time and costs in the buildup of the pilot-scale unit, fins were not used. Instead, a serpentine tube configuration was used. This configuration allows thermal expansion and reduces thermally induced stresses because of temperature cycling. Without the use of fins in the pilot scale heat exchanger the base tube surface area needs to be much larger than the tube area in a finned heat exchanger. This is the reason for the large size of the heat exchanger relative to other components in the pilot scale system. In the full-scale system fins are needed to constrain the scale and cost of the heat exchanger. While the pilot scale heat exchanger configuration is different and larger per heat transfer than the full-scale unit, the Altex heat exchanger model can be used to determine the cost savings when implementing the finned heat exchanger in the full-scale system. Table 1 gives the overall dimensions of the pilot-scale test system heat exchanger.

Table 1: FORPOWER Pilot-Scale HEX Overall Dimensions

Length	Height	Width
Inches	Inches	Inches
87	44	33

Source: Altex Technologies Corporation

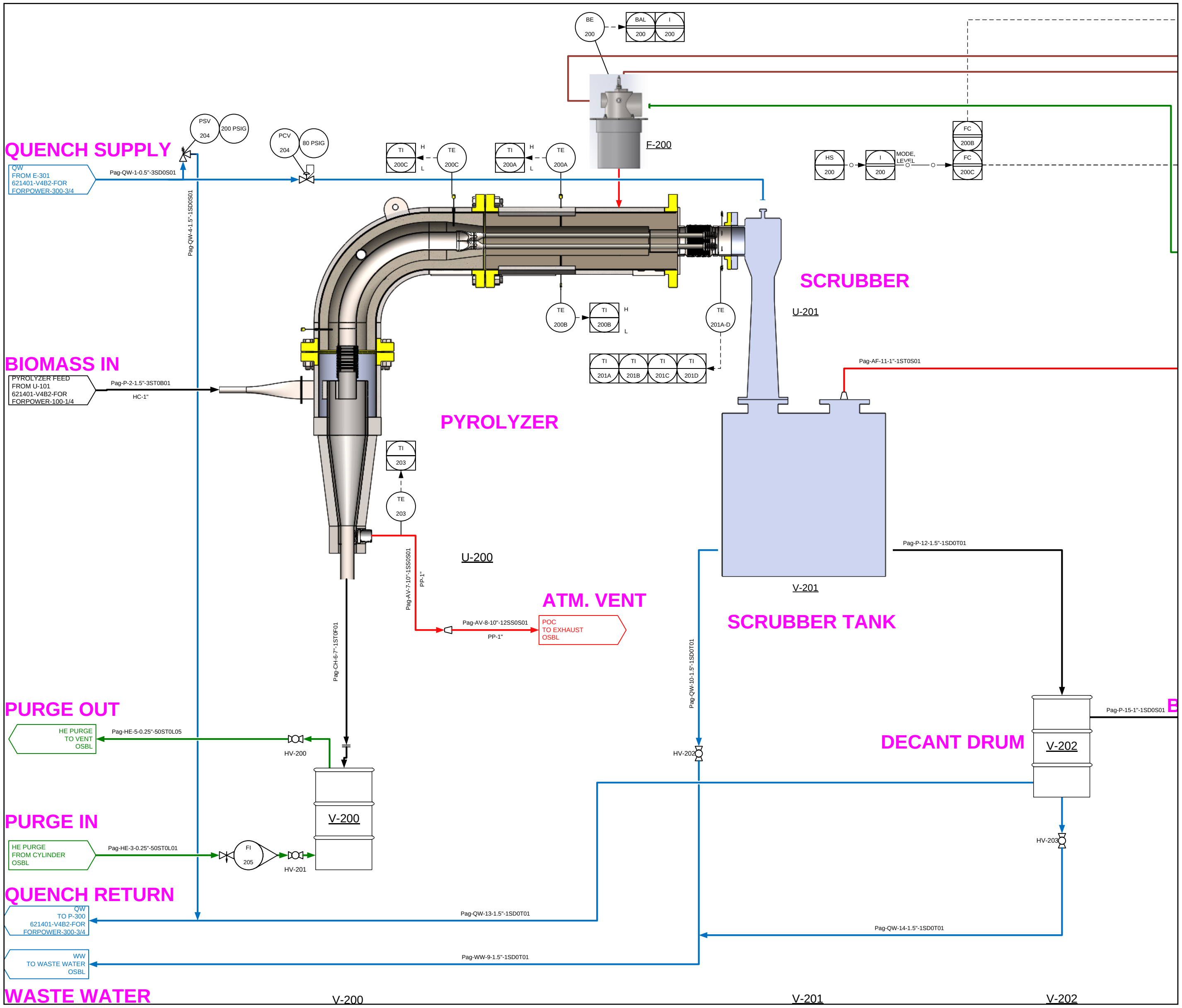
The gas turbine working fluid receives heat from the oxidation of pyrolysis char and biomass combustion that takes place in the gasifier/combustor subsystem. This subsystem consists of a cyclone-based gasifier followed by two towers in which air is sequentially injected to burn out any remaining fuel components and control oxygen availability to the fuel to suppress NOx emissions.

2.2.2.5 Bio-oil Production

As noted, bio-oil is injected into the GT combustor to supplement the indirect biomass driven heating of the GT working fluid. To prepare the bio-oil for pilot scale testing, an available biomass feeder and pyrolysis reactor was modified.

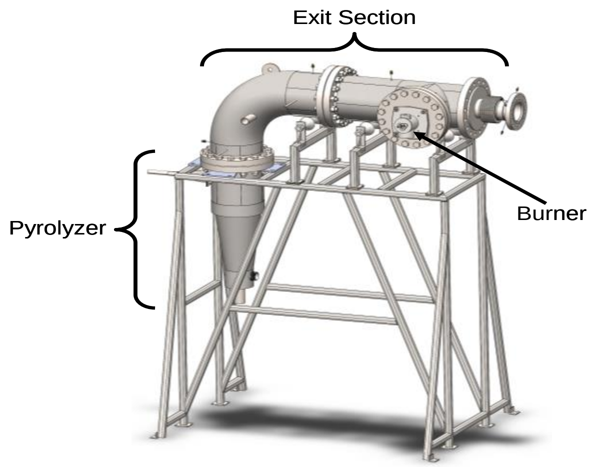
Figure 11 gives the PID of the bio-oil system and Figure 12 gives an illustration of the cyclone pyrolizer design that indirectly and rapidly heats the injected biomass and steam carrier to the needed peak temperature to maximize the yield of bio-oil [6]. The biomass is educted into the cyclone by high pressure superheated steam and is injected tangentially to force the biomass to the hot wall that is heated on the back side by products of combustion. The bio-oil and NCG exits from the top of the cyclone, and char solids exit from the bottom of the cyclone. The bio-oil and NCG are then transported through an isothermal section and into a scrubber that condenses and then separates the bio-oil for use in the gas turbine engine. As shown in Figure 11 a burner is used to heat the isothermal section and pyrolizer to the correct temperature for optimal bio-oil yield.

Figure 11: Bio-Oil Production System PID



Source: Altex Technologies Corporation

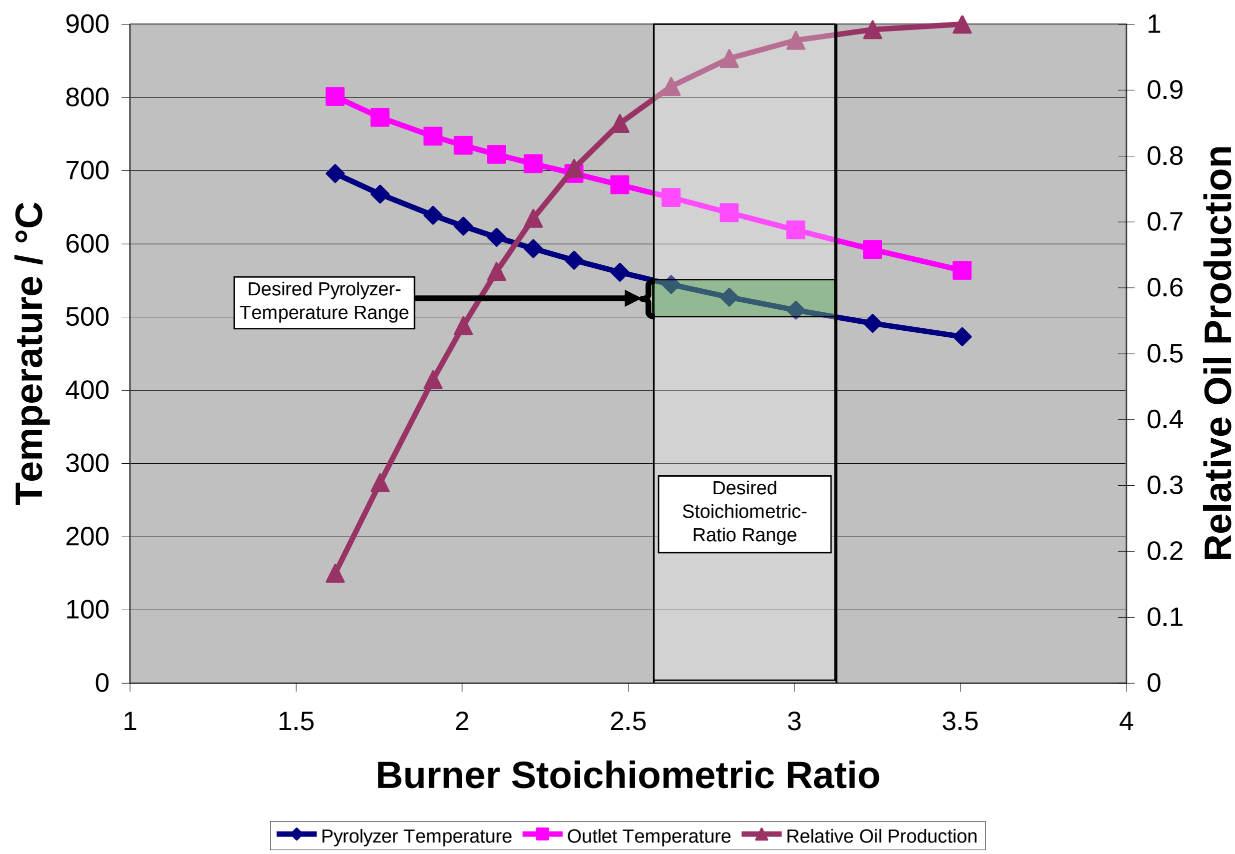
Figure 12: Bio-Oil Production System Illustration



Source: Altex Technologies Corporation

Figure 13 gives ChemCad (a process modeling and simulation software) model predictions for bio-oil yield as a function of burner Stoichiometric Ratio (SR). As shown, a pyrolysis temperature of 500 to 550 °C gives a high yield of bio-oil for the system

Figure 13: CHEMCAD Predictions of Bio-oil Yield Versus Pyrolizer Temperature



Source: Altex Technologies Corporation

CHAPTER 3: Pilot-Scale Testing and Results

3.1 Densification System Test Overview

A densification module was fabricated for testing, as shown in Figure 14. While the system is stationary for testing, all of the components can be mounted on a trailer for portability.

Figure 14: Picture of Feed Hopper and Belt Conveyor Mounted on the BFB Densification System

Source: Altex Technologies Corporation

After fabrication of the densification system, the system was tested to assess the performance of feeder, compaction system, heating system and cooling subsystems. Additional details of these subsystem tests are included in Appendix B. Key results of the densification tests are described in subsequent sections.

3.1.1 Subsystem Test Results

The feeder was tested by feeding the chips from a 12” wide belt conveyor. Along with the feeder, the ancillary test equipment used included a weighing scale with 40 lbs maximum capacity with an accuracy of + 0.167lbs and a stopwatch. During subsequent feeding tests, chips were loaded from a bucket onto the belt conveyor so that the feeding is completed in approximately 10 secs. Tests covered LabView (a data acquisition software) program settings of 6 lbs., 8 lbs. and 10 lbs. feed for each log produced. For each test, the amount of chips delivered into the simulated feeding section was collected and weighed separately. It was found that the feeder can be operated within 2 percent accuracy of the feed set point.

The biomass compaction system was tested using an engine powered hydraulic system. The compaction unit was designed to operate the compactor piston at two different pressures. At a lower pressure of 1000 psi, the compactor ram moves at a speed of 6 inches/sec, with a final pressure of 1800 psi at a speed of 2 inches/sec. The pressure in the hydraulic manifold and the pusher distance moved during operation were recorded during testing. For best operation the two-stage pump pressures were adjusted to 600 psi and 1800 psi for the final testing.

After fabrication, installation and integration of the thermal fluid system with the densification system, it was tested for proper operation. For good quality log/fuel block production, the temperature of oil entering the heating section of the BFB system has to be maintained at 205°C (~400°F). The thermal fluid system was operated and the temperature of oil entering and leaving the heating section of the BFB system and the temperature of hot gases entering the heat exchanger and exiting the system were recorded. The temperature of hot gases entering the heat exchanger was around 560°C, which is compatible with safe operation and longevity of the 304 SS material high efficiency heat exchanger. The temperature of oil entering the heating section of BFB was around 150°C, which is lower than the proper operating temperature of 205°C. Analysis indicated that substantial heat is lost from the surface of the heat exchanger and the uninsulated pipe connections. To correct this problem, the surface of the heat exchanger unit and the pipes were insulated and tests repeated. Test results showed that the proper temperatures could be maintained with the improved insulation.

After fabrication, installation and integration of the BFB cooling system, it was tested for proper operation. For production of good quality logs, the binder has to be cooled down to 45°C to set the binder. Tests showed that the control system circulated the required amount of water to maintain the cooling section below 30°C, which reduces the cooling time, as well as sets the binder.

3.1.2 Feedstock Analysis

Raw materials needed for analyzing the feedstock were received from Blodgett Forest Station, University of California at Berkeley. Dr. Rob York, Manager of the Blodgett Forest Station, prepared the wood chips needed for testing using a commercial chipper. The wood chips consisted of ponderosa pine and were stored in separate sacks. The feedstock analysis is important to understand the impacts of fuel characteristics in system performance.

Small samples were collected for moisture and density measurements using ASABE standard methods, and results are given in Table 2 and Table 3. The moisture content (MC) of Ponderosa Pine is in the range of 12.2 percent to 13.6 percent. The MC of white fir and cedar chips is in the range of 10.5 percent to 11.7 percent. The density of chips was measured by measuring the weight of chips in a 1-gallon plastic container and the results are also given in Table 2 and Table 3.

In addition to moisture measurements that impact the heating value of the biomass, samples were sent to ALS Environmental, 3860 S Palo Verde Road, Suite 302, Tucson, Arizona for proximate and ultimate analysis.

Table 2: Measurement of Moisture of Ponderosa Pine Chips

	Sample 1	Sample 2	Sample 3
MC db	15.6%	13.9%	15.7%
MC as is	13.5%	12.2%	13.6%
Density, lb/cf	13.1	13.3	13.6

Source: Altex Technologies Corporation

Table 3: Measurement of Moisture of White Fir and Cedar

	Sample 1	Sample 2	Sample 3
MC db	13.1%	11.7%	13.3%
MC as is	10.6%	10.5%	11.7%
Density, lb/cf	12.8	13.2	13.5

Source: Altex Technologies Corporation

The proximate and ultimate analyses were carried out as per American Society for Testing and Material (ASTM D121) standards, and the results are given in Table 4, Table 5, and Table 6. For proximate and ultimate analysis, samples were collected from the chips as received from Blodgett Forest Station and the estimated MC was a little higher than the MC of the chips used for making logs. However, all the properties were also given on a moisture-free basis in the tables. From the above feedstock measurements, the pine can be considered a high energy value and low ash fuel relative to the fir and cedar biomass.

Table 4: Results of Proximate Analysis of Raw Material

Raw material	Moisture total	Volatile Matter		Fixed Carbon		Ash	
	wt%	As received wt%	Moist free wt%	As received wt%	Moist free wt%	As received wt%	Moist free wt%
Fir and Cedar	20.41	59.05	74.19	13.67	17.18	6.87	8.63
Pine	14.88	64.20	75.42	19.54	22.95	1.38	1.62

Source: Altex Technologies Corporation

Table 5: Results of Ultimate Analysis of Raw Material

Raw material	Carbon, Moist free wt%	Hydrogen, Moist free wt%	Nitrogen, Moist free wt%	Oxygen, Moist free, Wt %	Sulfur, Moist free wt%
Fir + Cedar	48.96	5.51	0.51	36.84	0.05
Pine	53.45	5.97	0.50	38.41	0.05

Source: Altex Technologies Corporation

Table 6: Results of Testing on Heating Value of Raw Material

Raw material	Heating value, As received Btu/lb	Heating value, Moist free Btu/lb
Fir+Cedar	6,571	8,256
Pine	7,770	9,128

Source: Altex Technologies Corporation

3.1.3 Integrated Densification System Testing

Densification tests were carried out using Ponderosa pine and white fir and cedar materials obtained from Blodgett Forest Station. During testing, the biomass stored in super sacks was transferred into a large tub, as shown in Figure 15, which was then fed to the system by an inclined conveyor belt.

Figure 15: Chips of Prepared Wood Chips Transferred into Large Tubs for Loading into BFB System

Source: Altex Technologies Corporation

During initial conservative testing, only 8 pounds of wood chips were fed into the system each time. But in later testing, 20 pounds of wood chips were loaded each time and these logs were longer than those made in the initial testing. The density and other characteristics of the logs were measured and are given in Table 7.

Table 7: Density of Logs Made During Testing of Densification System

Forest slash material	Density, lb/cf	Average Length, in
Ponderosa Pine, 120 seconds holding time	40.5	6.85
Ponderosa Pine, 45 seconds	36.8	6.90”
Ponderosa Pine, 25 seconds	34.5	7.1
White fir + Cedar, 90 seconds	38.0	6.8
White fir + Cedar, 45 seconds	36.5	7.1

Source: Altex Technologies Corporation

The density of the logs produced was determined by measuring the length and diameter of the logs. The volume of the logs was estimated by considering the logs as cylinders. The density of the log was measured by the ratio of weight to the volume of the log. The estimated density and average length of logs produced during testing are given in the table.

Figure 16: Picture of Logs Made During Testing of the Densification System

Source: Altex Technologies Corporation

The log densities are in the same range as the log densities measured in previous efforts with agricultural residues [5]. The MC of the logs produced were also measured. To make these measurements, samples of approximately 50 grams each were collected from the center and surface of the logs. All samples were mixed thoroughly, and a sample of approximately 20 grams was collected for MC measurement, with results given in Table 8.

Table 8: Moisture Content (MC) of Logs Made Using Densification Equipment

	45 sec Holding time		90 seconds holding time	
Item	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
MC db	14.8%	15.1%	11.3%	11.6%
MC as is	12.9%	13.1%	10.2%	10.4%

Source: Altex Technologies Corporation

As shown, the longer the holding time and thereby heating time, the lower the moisture level. It was difficult to estimate the level of drying that is taking place inside the equipment with the available data. However, some drying was occurring, as identified by some vapor condensation above the emerging logs.

3.1.4 Log Durability Drop Tests

To evaluate the stability of logs during handling, drop tests were carried out that were similar to those applied to agricultural residue logs. The logs were dropped from a height of ten feet onto a concrete floor, and the breakage of the logs was observed.

All the log drop tests were carried out after storing the logs at room temperature for at least three days and the results are given in Table 9. From these results the higher the holding time ahead of the gate, the greater the drop height before the logs break. As the holding time decreases, the throughput capacity of the system increases, but the durability of the logs is reduced. Logs made with 45 seconds holding time can be dropped from a height of 4 feet. However, it was found that log breakage does not severely impact the value of densification.

Table 9: Height of Drop Possible for a Given Hold Time

Forest slash material	Height of drop
Ponderosa Pine, 120 seconds holding time	10 feet
Ponderosa Pine, 45 seconds	4 feet
Ponderosa Pine, 25 seconds	2 feet
White fir + Cedar, 90 seconds	6 feet
White fir + Cedar, 45 seconds	4 feet

Source: Altex Technologies Corporation

It was found that as the drop height is increased, the logs are broken into large dense pieces that do not revert to separate chips. The densities of these pieces are much higher than loose chips. To demonstrate this characteristic, these pieces were loaded into a rectangular container of 14-inch length, 12-inch width and 10-inch height and the weight was measured.

Based on the measured weight and container volume, the density of broken logs, made at a holding time of 45 seconds, was measured to be 31.4 lb/cf, which is nearly 2.5 times higher than the density of wood chips. Therefore, even though the logs did not remain whole after the drop test that exceeded their drop height limit, they did maintain the density and transport cost advantage over chips. This suggests that the 45-seconds holding time is a very conservative time to maintain a densification and transport economic advantage over chips. With further development and testing, shorter holding times will yield higher throughput and more economic advantage.

The appearance of logs made from pine, fir and cedar residues was similar. Also, the appearance of the logs over time was similar. The system was tested over a period of three months.

3.2 Bioenergy Module Test Results

Bioenergy module testing was initiated with component tests that transitioned to integrated system tests using the biomass materials of interest. The total number of test days was 22 with approximately 6 hours per day of test system operation.

3.2.1 Forest Residue Feed Preparation for Testing

In support of bioenergy module testing, logs made from pine, cedar and fir were sized using the available Altex shredder to produce the needed 1/8-inch size biomass supplies for feeding into the combustor/gasifier. The 1/8-inch size biomass has good feeding and processing characteristics with consistent heat output, steady NOx emissions and limited CO emissions.

3.2.2 Testing of Bioenergy System Biomass Feeder

Initial biomass feeding tests with the feeder not connected to the cyclone showed the good potential of the feeder system. These tests developed biomass feed rate versus screw rotational speed calibration curves as well as checked out feeder operation. Figure 17 gives a picture of this feeder with the main biomass hopper in the foreground. Early testing defined how much air flow into the box would be required to produce consistent biomass feeding. During final testing as integrated into the bioenergy system the feeder system worked well giving a steady flow of biomass.

Figure 17: Bioenergy Module Sized Biomass Feeder Subsystem

Source: Altex Technologies Corporation

3.2.3 Combustor/Gasifier System Shakedown Tests

Figure 18 is a picture of the combustor/gasifier test system ready for testing. Initially, the combustor/gasifier was tested with natural gas to check operation of all components using a well-defined and controlled reference fuel. In addition, prior to biomass injection and testing, the system must be heated to the proper operating temperature using natural gas fuel. Therefore, operation on natural gas fuel was proven ahead of biomass testing.

Figure 18: Picture of Bioenergy Test System

Source: Altex Technologies Corporation

During shakedown testing, the fuel and air flows were varied over time to check operability of the unit. The fuel and air flows could be varied without any signs of combustion instability or noise. In addition to operability, it was important to check the gas and air flow measurements against the Testo emissions monitor oxygen (O2) and carbon dioxide (CO2) exhaust stack measurements. Consistency of these measurements indicated that the equipment was properly functioning.

3.2.4 Emissions Using Forest Waste

Ahead of biomass testing, the bioenergy module was fired on fuel fossil gas until biomass operating temperatures were reached. Biomass firing rates, determined from feeder biomass feed rate calibration curves, varied from 760,000 Btu/hr to 1,127,000 Btu/hr for pine and white fir and cedar forest biomass residues. All biomass supplies were sized to 1/8-inch mesh top size. During the testing, the cyclone/gasifier and Tower 1 air flows were varied to characterize the air emissions versus SR in the gasifier/combustor and towers. Tower 1 is where primary burnout occurs and has a limited SR, high temperature and long residence time to achieve the dual objectives of low NOx and good partial burnout of CO, with complete burnout occurring in Tower 2 as a result of further air injection. Conditions in Tower 1 set up the proper temperatures for burnout in Tower 2. Therefore, NOx and CO exit emissions will be driven by conditions in Tower 1. Since emission limits have not been developed for the new technology bioenergy module, the emission test results are compared to the new boiler biomass emissions limits for the San Joaquin Valley Air Pollution Control District (SJVAPCD). For consistency in comparing results, the emissions are corrected to 3 percent O2 in the exhaust.

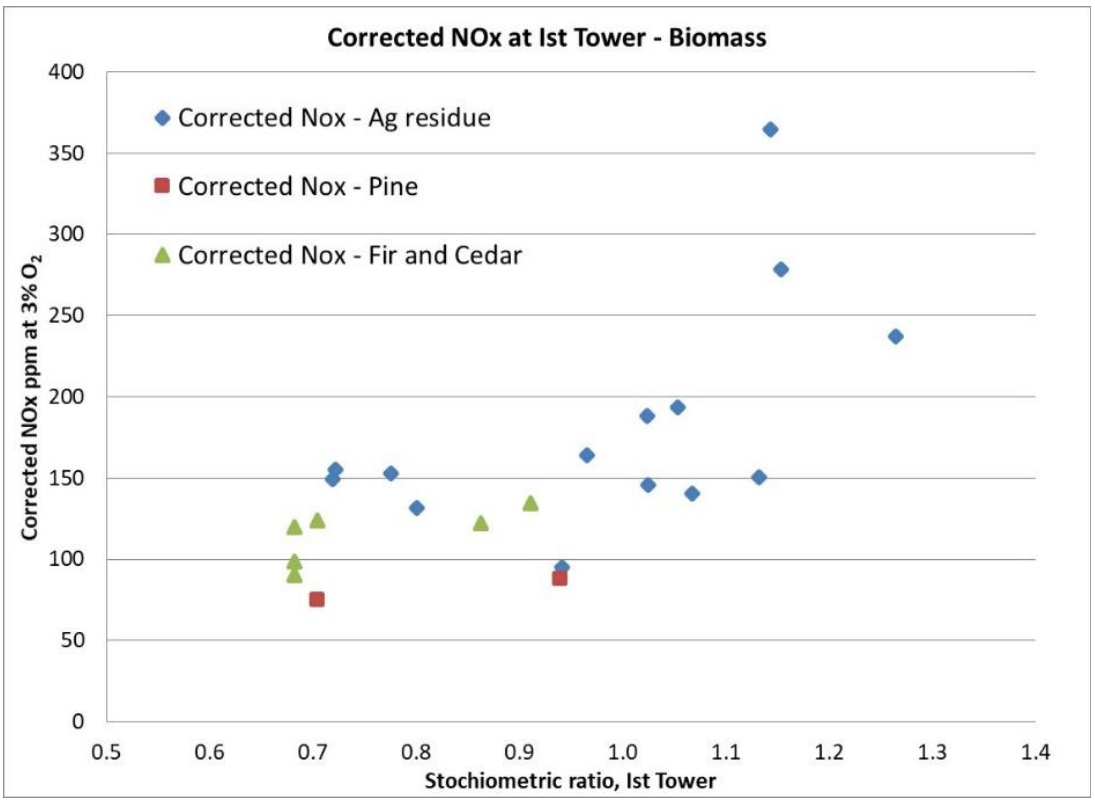
Table 10: SJVAPCD Regulated Boiler Biomass Emissions Limits

Criteria Pollutant	Compliance Limit
NOx	90 ppmv @ 3% O2
CO	400 ppmv @ 3% O2
Opacity	20% (6-minute rolling average) except one 6-minute period/hour not more than 27%

Source: SJVAPCD

Figure 19 gives the NOx emission results, corrected to 3 percent O2, as a function of Tower 1 SR. Plotted are emissions from pine and white fir and cedar residues. For comparison, NOx results from Figure 34 for the wheat straw agricultural residues are also plotted. As shown, NOx is lower for a lower SR, with the lowest NOx achieved at 0.7 SR. Pine, white fir and cedar NOx are below the limit of 90 parts per million volume, dry (ppmvd), as given in Figure 19.

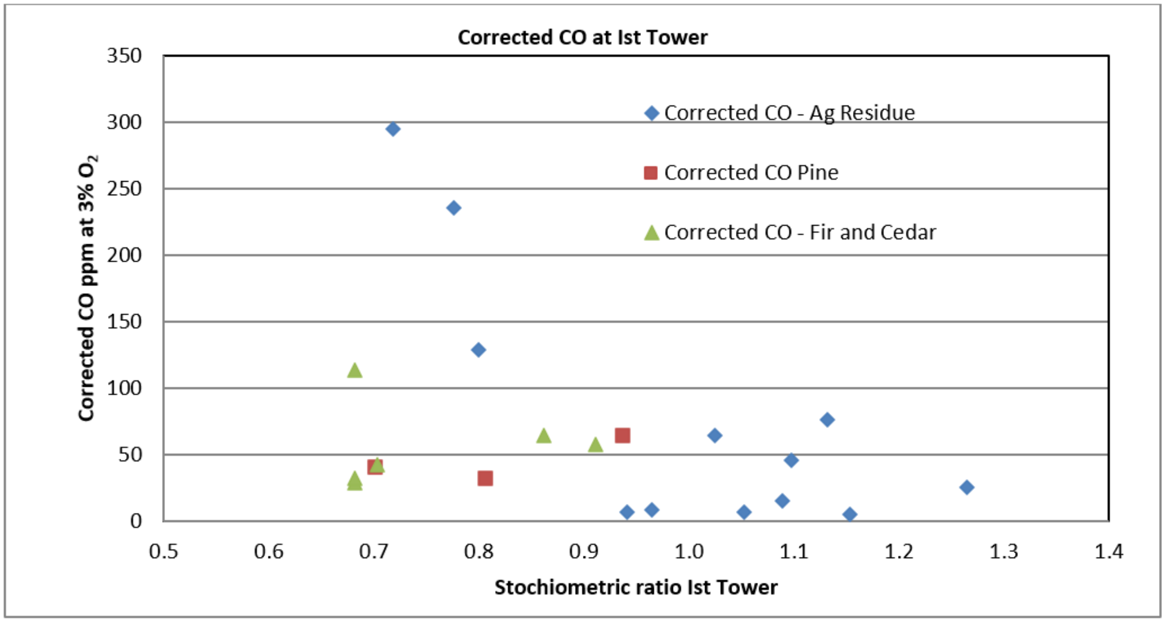
Figure 19: Corrected NOx Emissions for Pine (red symbols), White Fir and Cedar (green) and agricultural Residues (blue)



Source: Altex Technologies Corporation

Relative to CO emissions, Figure 20 gives the CO results as a function of Tower 1 SR. Over the range of SR levels tested, the CO emissions of all biomass were below the CO limit of 400 ppmvd. Pine and white fir and cedar CO emissions were below 150 ppmvd at the lower SR levels of interest for NOx control. CO was as high as 300 ppmvd for wheat straw agricultural residues.

Figure 20: Corrected CO Emissions for Pine (red symbols), White Fir and Cedar (green) and agricultural Residues (blue)



Source: Altex Technologies Corporation

It should be noted that during biomass testing the exhaust opacity was near zero and far below the 20 percent opacity limit from the regulations.

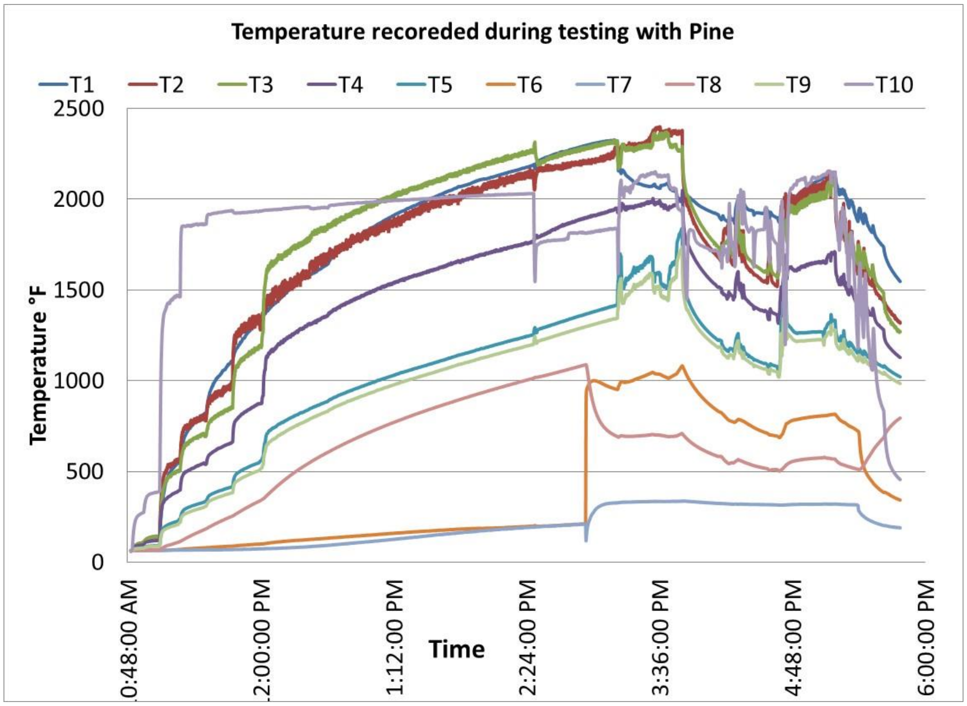
In summary, tests showed that pine and white fir and cedar forest residues could be converted into electrical energy up to the 20 kWe rated power while exhaust emissions were maintained within the SJVAPCD limits.

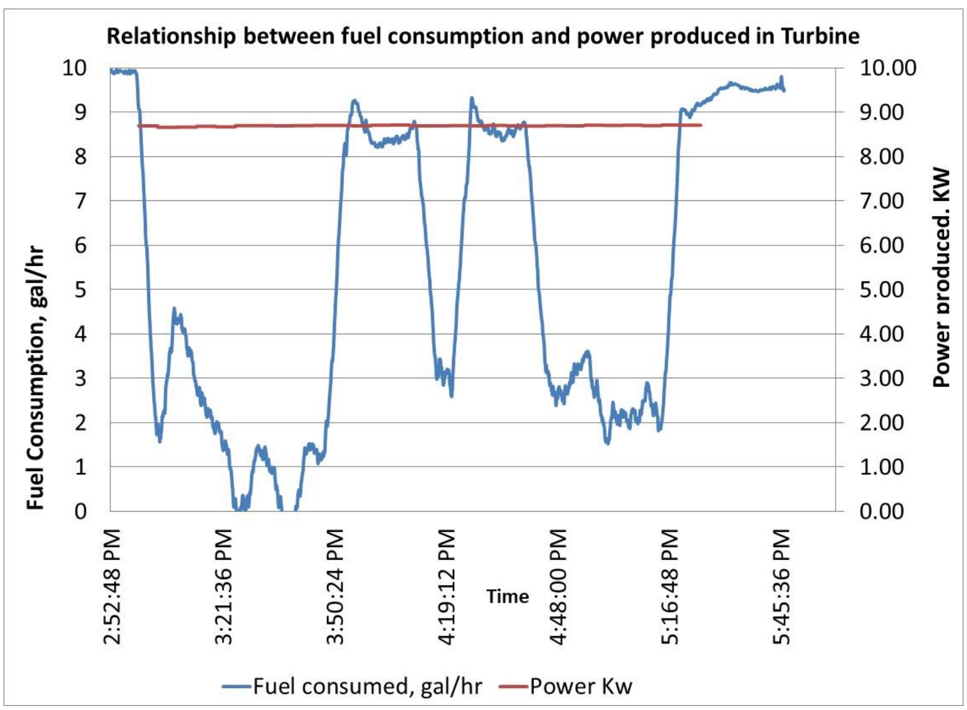
3.2.5 Temperature Analysis of the Gas Turbine

This test demonstrated the indirect firing of the gas turbine using pine forest residues. In this approach, the heat exchanger heat input from biomass firing can offset the liquid fuel need in the gas turbine combustor. In these tests, the target condition was to operate the gas turbine on biomass energy input without any liquid fuel use. This would be a clear demonstration of the principle. Figure 21 shows the FORPOWER temperatures at different locations. As the temperature reached steady state, the gas turbine was operated. A flow meter was installed at the fuel inlet to the gas turbine combustor to measure and record the number 2 distillate simulated bio-oil liquid fuel consumption rate. As the gas turbine was started, two electrical resistance heaters needed to dissipate the electrical power produced, were turned on. During testing, the electrical power produced in the turbine was recorded by measuring the output voltage and current. The fuel consumption is shown as in the turbine as blue lines and the net power produced as red line.

As shown in Figure 21, T6 and T7 are the air temperatures at the outlet of the compressor and the inlet of the gas turbine combustor. The temperature of air at the inlet and outlet of the gas turbine connections to the heat exchanger remained low at around 200F before the engine was started. As the turbine was started at 2:55 p.m. the liquid fuel consumption was around 10 gallons per hour at a power production rate of about 8.8 kWe, as can be seen from Figure 20 bottom. As the temperature of the heat exchanger outlet air (T6) increased to around 1000F, as shown in Figure 21, the fuel consumption rate was reduced to near zero.

Figure 21: Temperature of Turbine Air (top) and the Recorded Fuel Consumption in the Turbine Combustor During Power Production with Pine Biomass Residue (bottom)



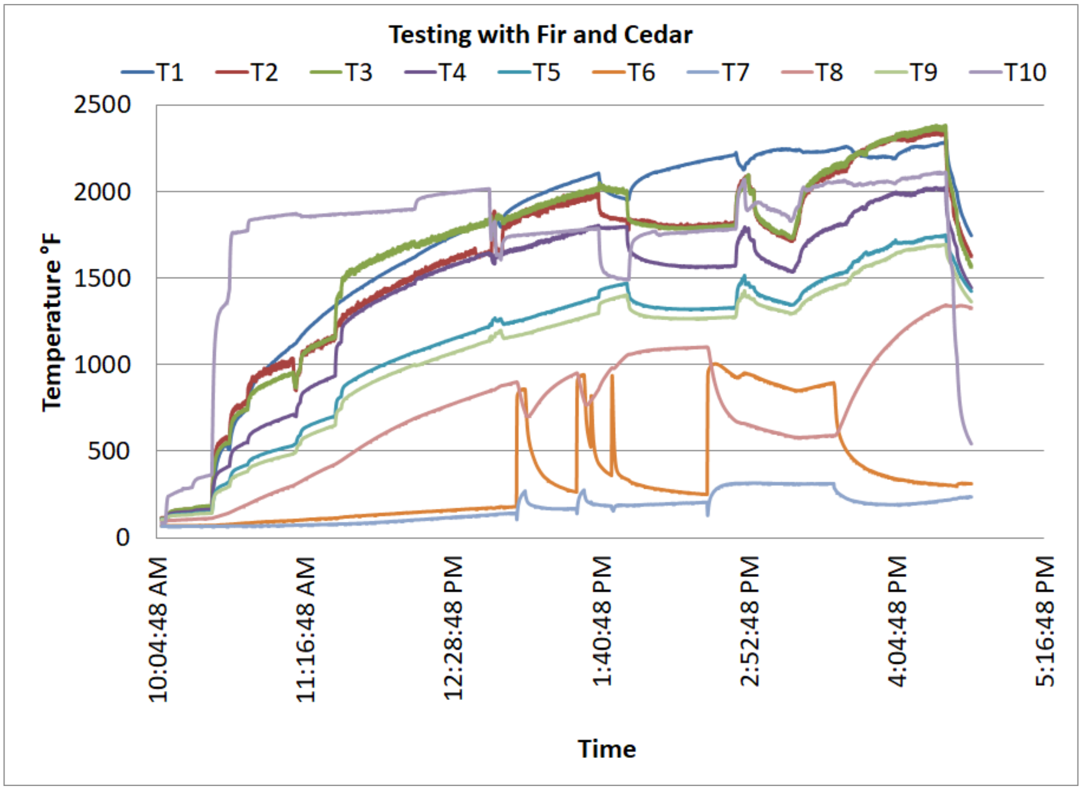


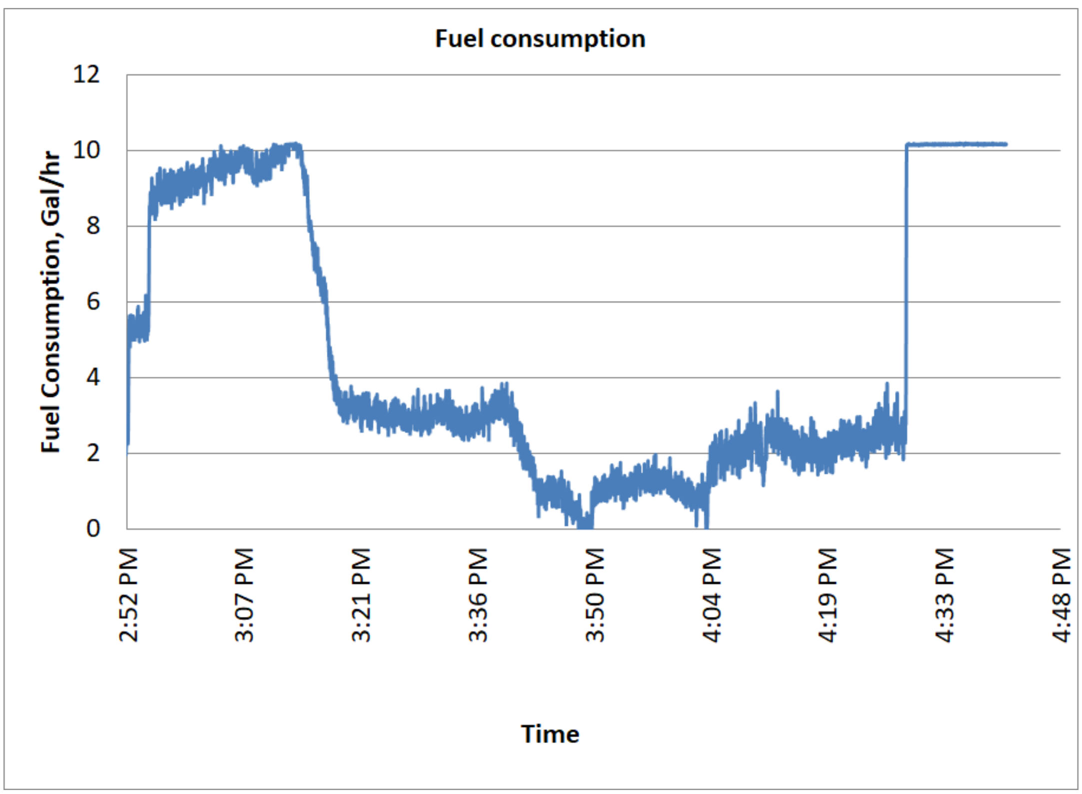
Source: Altex Technologies Corporation

In this case, all the heat needed for electric power production was provided by combustion of pine residues and the heat transferred to the gas turbine working fluid through the heat exchanger. This demonstrates the principle of the FORPOWER indirect firing gas turbine-based power system. At about 4:00 the biomass firing rate was varied, which varied the gas turbine fuel use, as illustrated by the results. At 4:48 the biomass heat input was reduced and the temperature of the outlet air (T6) was reduced to about 750F. This then reduced the fuel use to 2.5 gallons per hour from 8.5 gallons per hour, or a reduction of 60 percent relative to the fuel reduction for 1000F. This indicates that the gas turbine fuel use reduction is linear with the difference between the air outlet and inlet temperature, at an average of .014 gallon per hour per F increase in air temperature. Considering this linear relationship, an air temperature of 1000F, 1350F and 1500F would provide 44 percent, 66 percent and 75 percent of the heat input needed to produce the rated 20 kWe power from the gas turbine. The rest of the heat input is achieved by using bio-oil or other liquid and gaseous fuel in the gas turbine combustor. As noted earlier, the FORPOWER pilot scale, as well as full-scale gas turbine, is fuel flexible and can use a range of liquid and gaseous fuels with proper modifications to the combustor. Therefore, the FORPOWER can be a dual fuel use system with little modification. This indicates the fuel flexibility of FORPOWER and the ability to continue to operate if the biomass portion of the system goes down due to scheduled or unscheduled maintenance. These are important FORPOWER benefits.

Other FORPOWER biomass tests used a mixture of fir and cedar residues, and the results are given in Figure 22. In this case, the fuel consumption rate was around 10 gallons per hour in the initial period. As the gas turbine is operated and the heat exchanger air outlet temperature to the gas turbine reaches 1000F, the fuel consumption rate reaches a near zero level. This result is similar to that for pine biomass. Also, the gas turbine fuel reduction with air temperature increases is .014 gallon per hour per F air temperature increase. This is the same result as with the pine biomass case and shows that the FORPOWER system can be operated by indirect combustion of multiple forest residues to ensure long-term durability of the gas turbine when solid forest residues are used as fuel. Also, from the test data with all the forest biomass, the higher the air temperature out of the heat exchanger the lower the gas turbine combustor liquid fuel use to meet the design point turbine inlet temperature conditions. As above, this liquid fuel use reduction is approximately linear with temperature increases. When bio-oil is used in the combustor, all of the fuel is biomass based and the fuel ratio used does not matter. When the liquid fuel is not derived from biomass, then the liquid fuel use should be minimized for maximum GHG benefits per power output. While the GHG emissions benefits when operating on a non-biomass liquid fuel to the combustor are reduced, the option of a non-bio-oil liquid fuel gives increased flexibility in deploying FORPOWER. These and other test results were used to refine the FORPOWER design parameters and form the basis for determining the performance, economic and emissions benefits of the system.

Figure 22: Temperature of Turbine air (top) and the Gas Turbine Combustor Fuel Consumption During Power Production With Fir and Cedar Tree Residues (bottom)





Source: Altex Technologies Corporation

It should be noted that the available gas turbine design from the 1960s used in the pilot-scale system is very inefficient at 5.2 percent efficiency when new, due to turbomachinery, gearbox and electric generator inefficiencies. Under the same biomass heat conditions, a small-scale gas turbine of 15 percent efficiency would produce 57 kWe. However, the principal heat addition to the gas turbine working fluid through the heat exchanger would still be the same. Scaling the FORPOWER to the 5MWe power needs of the full-scale system with an expected engine efficiency of 29 percent at that scale, the biomass feed rate per kWe would be reduced by a substantial 82 percent from the 20 kW test system. This shows the importance of engine efficiency as system scale is increased. These factors were used in the FORPOWER full-scale system performance and cost evaluations in Chapter 4 and 5 of this report. Given the significant difference in engine architecture, design and efficiency between the pilot and full scale engines, operation at 20 kWe and measurement of engine efficiency was not considered to be relevant to the important projected performance and cost benefits for full scale systems at 3 MWe, 5 MWe and 10 MWe capacities.

CHAPTER 4: Full Scale Design

4.1 BFB Design

Specifications for the full-scale BFB system were defined and results are given in Table 11. These specifications used the BBADS specifications as a base with updates related to the use of forest wood residues rather than agricultural residues. All sub-component design updates were based on these requirements.

Table 11: Full Scale BFB Specifications

Specifications	Value
Capacity, lbs/hr	5000
Diameter of logs, inches	11
Length of logs, inches	9
Cycle time, sec	18
Density of logs, lb/cf	40
Weight per load, lbs	20
Conveyor width, inch	18
Height of chips, inch	6
Conveyor speed, ft/sec	0.65

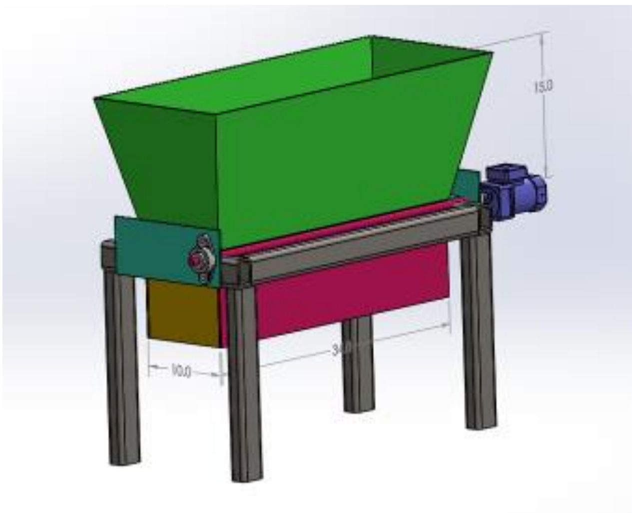
Source: Altex Technologies Corporation

The BFB and BBADS are identical in equipment scale, operating pressure, and cycle. Also, the heating and cooling jackets were similar, with the BFB given a longer heating jacket to provide more heating margin for the chipped forest residues.

The feeder design was updated for forest residue chips, and this design is illustrated in Figure 23. This design uses load cells to activate and open the bottom of the hopper when the total feedstock weight reaches the set target for a single log. By controlling the weight of material going into each log, the log densities are more consistent relative to an input volume target.

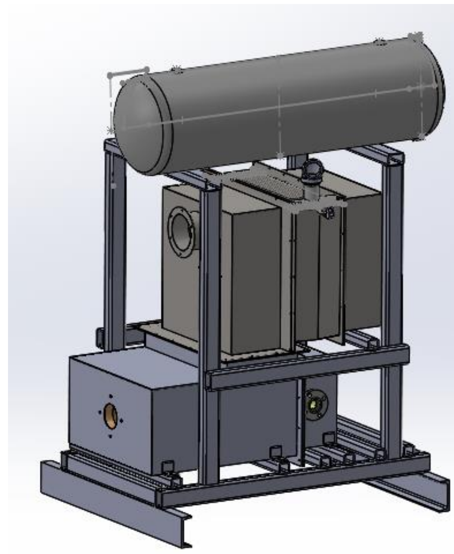
For portability, the heating equipment of BFB needs to be compact and light in weight to enhance mobility within the forest. In addition, the system must also be able to utilize waste heat from the tractor engine exhaust. To accomplish these objectives, the waste heat driven FORPOWER oil heater was designed and is shown in Figure 24. The heater design also incorporates a conventional burner that operates on tractor diesel fuel because the engine cannot provide all of the needed heat for the hot oil. With the combination of engine waste heat and supplemental fuel firing with tractor engine fuel, the hot oil heating needs are met by the system in the figure. Parts exposed to combustion products, including the heat exchanger, are constructed of stainless steel to address corrosion issues. Water availability is very limited and a dry cooling system is used for the portable BFB system. These systems will typically be larger than an evaporative cooling system. To control the size of the cooling heat exchanger, an Altex highly-efficient fin design heat exchanger is utilized that can reduce heat exchanger volume by 50 percent [7]. Integrating these components using established practices completes the full-scale densification module design.

Figure 23: SolidWorks Model of Feeder to be Developed and Installed in the BFB Equipment



Source: Altex Technologies Corporation

Figure 24: Recovery Hot Oil Heater Chamber



Source: Altex Technologies Corporation

4.2 Full Scale Bioenergy Module Design

4.2.1 Directly and Indirectly Fired Gas Turbine Engine

To be consistent with the current SB 1122 5 MWe power requirement, the Siemens 5.1 MWe engine was selected for the full-scale design. An illustration of this engine is given in Figure 5 with the specifications listed in Table 12. As shown in Figure 25, the engine uses multiple "silo" combustors, where the compressed air is routed around the combustor liner and then into the top of the combustor where fuel is injected. The hot gases are then routed through the turbine nozzles and are expanded through the turbine to produce power.

Table 12: 5.1 MWe Gas Turbine Engine Specifications

Component	Characteristics
Power output	5.05 MW€
Frequency	50/60 Hz
Gross Efficiency	30.2
Speed	17,384 rpm
Heat rate	11,914 KJ/KWh
Pressure ratio	14.0:1
Exhaust mass flow	19.5 kg/s

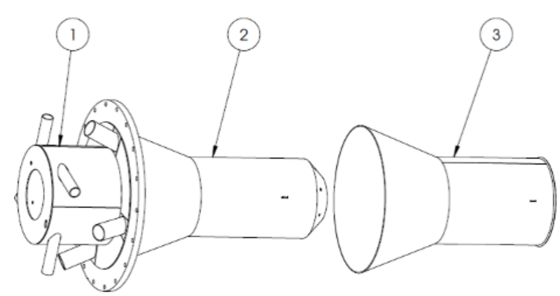
Component	Characteristics
Exhaust temperature	1,013°F
Emissions	<u><</u>25 ppmvd at 15 O2 on fuel gas

Figure 25: SGT-100 Siemens 5.1 MWe Gas Turbine Engine with Silo Combustors

Source: Altex Technologies Corporation

The exhaust gases exit axially. An important advantage of this engine design for FORPOWER is that the accessible silo combustors can be modified to allow indirect firing by replacing the simple combustor head assembly with a modified combustor cap assembly. The modified cap channels the compressed air that cools the liner to an exit that connects with the external Heat Exchanger (HEX). The air is heated in the HEX and then is returned to the cap where the heated air is channeled into the combustor manifold to support fuel oxidation. By having a large manifold, the air velocity is reduced and the flow into the combustor is more uniform. Besides altering the combustion air flow path and temperature, the combustor itself is also modified to allow bio-oil firing. Figure 26 illustrates the special two-stage cyclonic and plug-flow combustor design. The cyclone stage, 1, has four tangential air and fuel entry points that are arranged to create a strongly swirling flow that rapidly mixes fuel and air for good fuel ignition and flame stability.

Figure 26: Two-Stage Low NOx Gas Turbine Combustor Design



Source: Altex Technologies Corporation

In the second stage, 2, an expanded conical section is used to contain four more air and fuel injectors that are arranged to entrain gases from the cyclone portion of the combustor and converge on the axis midway through the second stage of the combustor. This second stage complements the stability of the first stage by optimizing fuel and CO burnout in the second stage. Another benefit of this design is the limitation on NOx emissions.

Under conventional non-premixed combustion conditions, natural gas emissions would be in the range of 80 ppmvd. Furthermore, when firing bio-oil with fuel-bound nitrogen, NOx emissions might be expected to be higher. However, test results for a 2.5 MWe gas turbine operating on biofuel showed that NOx emissions were even lower than those from Number 2 distillate fuel [8]. Furthermore, with the FORPOWER staged air design, lower emissions can possibly be achieved. Tests have shown emissions as low as 5 ppmvd at 100 kWe scale with natural gas.

For bio-oil combustion the fuel will have up to 0.5 percent nitrogen, as listed in Table 13, which can be partially converted to NOx. This will result in higher NOx than with lean premixed natural gas combustion. However, if the combustor is designed to reduce the air flow to the cyclone stage and operate at a cyclone SR (air to fuel ratio divided by the theoretical air to fuel ratio) less than one (such as SR = 0.8), the bio-oil NOx production will be controlled. Literature results [5] support a NOx emissions reduction of more than 50 percent for this type of operation, with acceptable CO emissions as a result of fuel burnout in the oxygen rich (SR>1) second stage.

Table 13: FORPOWER Expected Composition of Pyrolysis Products

Ultimate Analysis (wt%)	Biomass (Forest Residue)	Bio-oil; Complete	Bio-oil; Water Insoluble	Bio-char	Syn-gas by Composition (%)
C	52	38-44	66	75-82	CH_4; 15-40
H	6	7-8	7	2-5	H_2; 5-28
N	0.5	<0.1-0.4	0.3	1-2	CO; 5-20
S	Insignificant	Insignificant	Insignificant	Insignificant	CO_2; 9-46
O	39	48-53	27	14-18	C_2H_6; 0.8-5
Ca, K, Mg, Na	2.5	2-700ppm	Insignificant	ppm level	

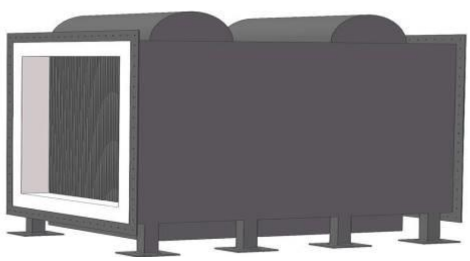
Source: Altex Technologies Corporation

At the end of the second stage, some of the combustion air will flow into the combustor exhaust through dilution air holes that are shown at the end of 2 in the above combustor illustration. This dilution air will reduce the hot gas exiting the combustor to an acceptable turbine inlet temperature. Component 3 was designed to channel the combustor air past the combustor liner as well as into the dilution holes. To inject and atomize the bio-oil, a well-developed and tested air blast atomizer is used. The air blast atomizers use the high-pressure compressor air to impact and destabilize the bio-oil jet and break it into small ligaments that are more rapidly heated and vaporized. With more rapid heating and fuel/air mixing, the soot formation will be suppressed and the flame will be cleaner.

4.2.2 Heat Exchanger

The compressed air exiting the combustor cap is transported through insulated piping to be further heated by wood and char residue forest products-of-combustion in a Heat Exchanger (HEX) illustrated in Figure 27. The HEX is a counter-flow design that maximizes effectiveness. The hot gases enter at the front of the HEX that is to the left in the figure. The compressed air enters the half cylindrical manifold at the top and back-end of the HEX. The air flows through internal channels and is heated and then exits through the half cylinder manifold at the top front-end of the HEX. The design incorporates Altex special fins that augment heat transfer, but still maintain a high thermal efficiency. This is illustrated in Table 14, where the special Altex fin (Enhancement 3) heat transfer and efficiency performance are compared to conventional smooth fins, as well as conventional high-performance louvered and wavy fins. As shown in the table, the Altex special fins have better heat transfer, J (Colburn Modulus dimensionless heat transfer coefficient), as well as thermal efficiency, J/f, (Where f is the dimensionless friction factor) relative to high performance fins [8].

Figure 27: FORPOWER Full-Scale Heat Exchanger Design Illustration



Source: Altex Technologies Corporation

Table 14: Comparison of Conventional and Altex Heat Exchanger Performance

Surface	J	J/f	Efficiency Reduction (%)
Smooth Channel Baseline	.0033	.43	--
Surface Enhancement 1	.0062	.365	15.2
Surface Enhancement 2	.0075	.380	11.6
Surface Enhancement 3	.0148	.365	15.2
Louvered Surface	.009	.225	47.7
Wavy Surface	.0105	.202	53.0

Source: Altex Technologies Corporation

Table 15 gives results of model calculations for the special heat exchanger, including heat transfer, pressure drop, effectiveness and air outlet and maximum metal temperatures, along with an estimate of cost reduction relative to a conventional design. As shown in the table, as the fins per inch is reduced the heat transfer is reduced, but the hot gas side pressure drop is reduced even more. These results illustrate the tradeoffs that were made in the design of these systems. Table 15 gives the overall dimensions for this compact heat exchanger.

Table 15: FORPOWER Full-Scale HEX Dimensions

								CHANGE 8 TO 3
FIN SPACING (1/IN)	8	7	6	5	4	3		-63%
HYDRAULIC DIAMETER (FT)	0.015	0.016	0.018	0.021	0.025	0.029		101%
HEAT TRANSFER (BTU/MIN)	446,206	441,924	428,072	413,627	386,754	345,498		-23%
PRESSURE DROP (IN H2O)	2.83	2.55	1.99	1.66	1.27	0.96		-66%
EFFECTIVENESS	0.83	0.81	0.77	0.74	0.68	0.60		-27%
AIR OUTLET TEMP. (F)	1,261	1,253	1,228	1,202	1,153	1,078		-15%
METAL TEMP. (F)	1,431	1,427	1,414	1,401	1,377	1,339		7%
FRACTION STEEL	0.64	0.64	0.64	0.64	0.64	0.65		-3%
COST REDUCTION (%)	49%	49%	49%	49%	49%	48%		3%

Source: Altex Technologies Corporation

As indicated in Table 15 and Table 16, the gas turbine working fluid receives heat from the oxidation of pyrolysis char and biomass combustion that takes place in the gasifier/combustor subsystem. This subsystem consists of a cyclone-based combustor/gasifier followed by two towers in which air is sequentially injected to burn out any remaining fuel components and control oxygen availability to the fuel to suppress NOx emissions.

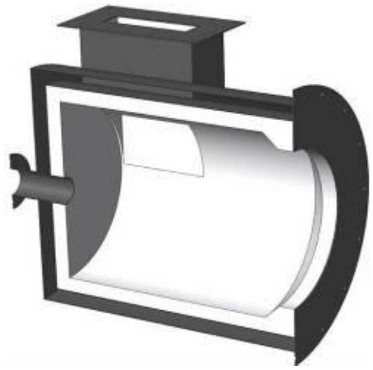
Table 16: FORPOWER Full-Scale HEX Overall Dimensions

Width	Length	Height
Inch	Inch	Inch
110.2	127.6	60

Source: Altex Technologies Corporation

The FORPOWER combustor/gasifier, as illustrated in Figure 28, will consist of a nearly horizontally-oriented cyclone. Due to the high air preheat, the cyclone will operate above the ash fusion temperature. The ash will melt and run out of the cyclone, to an ash quench tank, where it will be converted into a glassy and low-leachability solid. Sub-stoichiometric cyclone operation is also used to convert fuel nitrogen to molecular nitrogen as it evolves from the fuel. The cyclone action in the combustor/gasifier is very beneficial with irregularly sized material because the cyclone will force all material sizes to the wall, where they are retained and "scrubbed" with air until they are completely gasified [9]. Furthermore, besides retaining material for complete gasification, the cyclonic action will constantly re-circulate heat and reacting materials to maintain consistent and vigorous ignition of the incoming biomass material.

Figure 28: FORPOWER Full-Scale Cyclone Gasifier Design Illustration



Source: Altex Technologies Corporation

4.2.3 Biomass Combustor

The high volatile char and biomass fuel will quickly gasify in the reduced oxygen content cyclone. Molten ash slag exits the cyclone, ahead of the vertical section, and drops into a quench tank filled with water. In addition, any ash carried over from the cyclone falls to the bottom of the secondary combustor section and is also transported into the quench tank. Removing ash before the heat exchangers will reduce typical heat transfer surface fouling problems with solid fuel combustion. This reduces expensive maintenance of the heat exchangers required with conventional approaches.

Altex used cyclonic combustor experience gained under the Power from Farm Animals System Technology (PFFAST) project, which processed dairy manure to heat and power to design the cyclone combustor [10]. An important attribute of these designs is the high fuel heat release of 3MMBtu/hrft^3 compared to a typical coal-fired boiler that would have a heat release of 0.06MMBtu/hrft^3, which is 98 percent lower in intensity. Also, a cyclone reactor has considerable flexibility to process a variety of forest waste biomass materials due to strong cyclonic mixing that stabilizes the combustion.

Cyclones have been considered for biomass and coal gasification. Through analysis and a review of cyclone experience [5], it was concluded that a gasifier throughput rate, or residence time of 0.1 second, would be a good operating condition compared to a combustion cyclone residence time of 0.03 seconds. Given the lower airflow requirement of gasification (SR of <0.6), the more conservative residence time still results in a high feedstock throughput and compact reactor. For optimal operation, the cyclone uses tangential air injection to create the needed swirl level for effective and uniform processing of solids and gases within the cyclone. A swirl level of >10 is appropriate for good solid retention. To define specific injector geometries, Altex used available test and design data. As noted, the device will have a cyclone volume consistent with a heat release rate of 1,000,000 Btu/hr ft^3, or a residence time of 0.1 seconds. This high rate is consistent with the highly volatile feedstocks of interest and slagging conditions required for consistent ash removal, and production of the syngas that will be reacted in the combustion towers. Given the high temperature operation, the gasifier will be lined with three inches of high-density refractory (such as Greencast 94, produced by AP Green) for this challenging application. Importantly, the refractory shell is backed by an air passage that recovers heat by preheating the combustion air. This is advantageous from two perspectives. Without this cooling airflow, refractory thickness and system weight would be greatly increased. In fact, for a reasonable wall temperature, an un-cooled chamber would weigh over 100 percent more than the cooled case. Also, preheating the air is beneficial to reaction stability and energy conversion.

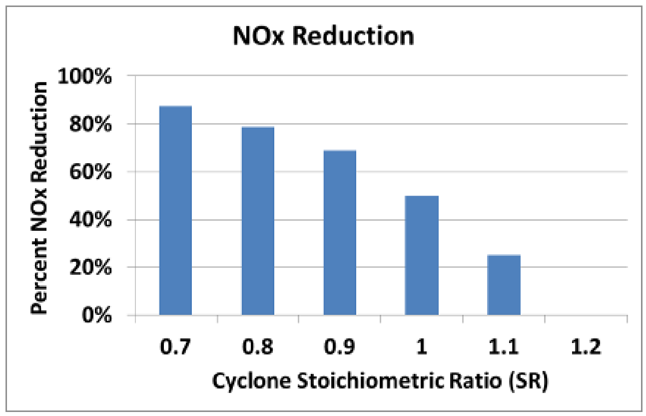
The cyclone gasifier will produce a syngas that will consist of some H2, CO, and CH4 that must be oxidized to water vapor and carbon dioxide prior to the gas entering the heat exchanger. To accomplish this objective, two towers are arranged in series that have air injection to provide the oxygen needed for burnout of the syngas. In addition to burning out the fuel gas, the air is staged to increase the stoichiometry in the first tower to approximately one to control NOx emissions. This condition is listed in Table 17. Based on test results [5], this stoichiometry should be maintained over a time period of approximately 0.75-seconds. After this period, gas will enter the second tower, where additional air is injected to bring the stoichiometry to over one and up to 1.3. These conditions are held at approximately 0.5-seconds to burn out all the fuel components ahead of entering the heat exchanger. Prior experience when processing agricultural biomass materials under these conditions reduced NOx by about 80 percent, as shown in Figure 29.

Table 17: Gasifier/Combustor Target Stoichiometries (SR)

Cyclone SR	Cyclone Tower SR	Exit Tower SR
0.78 – 0.89	0.84 – 0.97	1.1 – 1.3

Source: Altex Technologies Corporation

Figure 29: Cyclone NOx versus Stoichiometric Ratio (SR)



Source: Altex Technologies Corporation

To feed biomass char and biomass into the gasifier, a commercial eductor pump driven by 3 psi air pressure is utilized. To prepare the densified biomass for cyclone firing, the size of the feedstock must be reduced to a top size of 1/8-inch. In the full-scale system, this is accomplished by a commercial knife-blade shredder. By integrating these subsystems with proper piping, the full-scale bioenergy module is created that can be integrated with the densification module to create the FORPOWER system for forest waste to power.

CHAPTER 5: Techno-Economic Analysis

5.1 Densification Module

A detailed economic analysis of the FORPOWER densification module was used to estimate the delivered cost of forest slash to the FORPOWER bioenergy module unit. This delivered feedstock cost was input into the economic evaluation of the bioenergy module to arrive at the cost of electricity (COE) generation and environmental benefits of operation of FORPOWER systems in California. The densification module evaluation was separated from the bioenergy module evaluation because for concentrated forest or agricultural residues and bioenergy modules below 5 MWe capacity, shorter biomass transport distances may not require biomass densification to minimize delivered biomass costs. However, as the biomass becomes more dispersed and the bioenergy module becomes larger, the benefits of densification will become important. Furthermore, it should be noted that the FORPOWER densification process is beneficial for transporting dispersed wood residues to pelletization facilities that produce standard-sized pellets for various combustors, from wood stoves to utility boilers, thereby offsetting the use of coal with renewable wood pellets.

With the expansion of use of the FORPOWER densification module, the number of units produced will increase, thereby reducing the densification module capital cost for forest and agricultural residue.

5.1.1 Economic Analysis of Densification Module

In this economic analysis, the densification modules have two different production capacities, namely, 0.7 tons/hour and 2 tons/hour.

Additional details of the economic analysis are given in Appendix C-1 and only the summary results are given below. To determine the equipment cost of the densification module having 0.7 tons/hour capacity, the actual cost incurred in development of the test system was used. Since only one densification module has been fabricated, the total cost of this prototype unit is high and the cost results are conservative. These costs are listed in Table 18. When BFB densification equipment is fabricated in production unit volumes, particularly if other applications are addressed, then material, fabrication and assembly costs will be significantly lower.

Table 18: Cost of BFB Test System - 0.7 Tons per Hour Capacity

Item No.	Equipment Cost	Qty, Nos.	Price, $	Cost, $
1	Supports and tubular components	1	30,000	30,000
2	Trailer	1	8,000	8,000
3	Heating system	1	13,300	13,300
4	Cooling system	1	2,560	2,560
5	Hydraulic system	1	33,600	33,600

Item No.	Equipment Cost	Qty, Nos.	Price, $	Cost, $
6	Feeder	1	3,000	3,000
7	Control system	1	10,000	10,000
8	Assembly charges	1	20,000	20,000
	Total cost of equipment			120,460

Source: Altex Technologies Corporation

To estimate densification module costs with 2 tons/hour capacity, the costs for the 0.7 tons/hour module were scaled up. For some components, the standard power quotient for costing, as defined by the American Association of Cost Engineers (AACE) [11], was utilized and results are given. For the 2 tons/hour capacity densification module, two tubes of 13.5-inch diameter were used. For scaling up the costs for the larger diameter and capacity, the following formula was used as per Remer and Chai [12].

$\frac{cost_2}{cost_1} = (\frac{size_2}{size_1})^R$ -------(1) where Size is capacity and R is an exponent provided [7].

Since the compaction tube is a pressurized chamber, an exponent of 0.6 is recommended.

The estimated costs for the 2 tons/hour capacity densification module are summarized in Table 19. For Item no. 1 in Table 19, the support sizes have to be increased by a factor of 1.2 and tubular components have to be increased by a factor of 2 to arrive at a cost of $40,670.

Table 19: Cost of BFB System - 2 Tons per Hour Capacity

No.	Equipment Cost	Qty, Nos.	Price, $	Cost, $
1	Supports and tubular components	1	40,670	40,670
2	Trailer	1	8,000	8,000
3	Heating system	1	13,300	13,300
4	Cooling system	1	2,560	2,560
5	Hydraulic system	1	36,600	36,600
6	Feeder, fabrication charges	1	4,500	4,500
7	Control system	1	10,000	10,000
8	Assembly charges	1	30,000	30,000
	Total cost of equipment			145,630

Source: Altex Technologies Corporation

For Item no. 2, only one trailer is needed and the same cost as the 0.7 tons/hour system. For Item no. 3, the heating system costed is capable of providing the heat needed for activation of binder in the 2 ton/hour system and the same cost of $13,300 is used. Similarly, the cooling system for 0.7 tons/hour capacity is also capable of providing necessary cooling needed for 2 tons/hour and cost of $2,560 was used. However, an additional hydraulic compression cylinder and gate cylinder are needed for operation of the 2 tons/hr BFB system. The existing hydraulic power unit is capable of providing the necessary compression pressure needed for operation at 2 tons/hour. Taken together, the hydraulic system cost was increased to $36,600 for the 2 tons per hour capacity. Two feeder hoppers and ancillary components are needed for operation of the feeding system, and the feeding system cost was increased to $4500 for a 2 tons per hour system. The same control system can be used to operate a 2 tons/hr BFB system and a cost of 10,000 was used for this system. Based on experience, an assembly charge of $30,000 is estimated for assembling the 2 tons/hour BFB system. Based on these assumptions, the cost of the 2 tons/hr system was estimated to be $145,630.

5.1.2 Production of Wood Chips Inside the Forest

The fixed and operating costs for producing wood chips inside the forest were estimated and details are given in Appendix C.1.2. For estimation of the fixed cost, the actual cost of purchase and operation of a large Bandit chipper and ancillary equipment, like a belt conveyor, were used. To estimate operating costs, the $3/gallon cost of diesel fuel needed to run the equipment at a rate of 2 tons/hour is used. A capital cost of $130,000 is estimated, as detailed in Appendix C.1.2. For repairs and maintenance, 3 percent of the equipment cost is included as per AACE standard [14]. In addition, the labor cost involved in production of chips at the prevailing cost of $25/hr at the Blodgett Forest Station is also included. Combining the fixed and operating costs, the total cost for production of wood chips inside the forest is estimated to be $35.23/ton or 0.006 cents/kwh. In this estimate, the life of the chipper is assumed to be 10 years. This cost is similar to the cost of collection and processing of wood chips inside the forest of $34 per ton estimated by Springsteen et al, as per the published article from University of California, Agriculture and Natural Resources [13]

5.1.3 Cost of Production of Logs With 2 Tons/hour BFB Capacity

The total fixed cost required for production of dense logs, including the chipper preparation step, is estimated and given in Table 20. Similarly, the total variable cost required for operation of a BFB system and chipper is estimated and given in Table 21. The fuel cost is estimated based on the fuel requirements for testing under this project. The total operating cost is estimated to be $146,669/year.

Table 20: Fixed Cost for Log Production at 2 Tons/Hour

Item No	Item	Quantity	Unit	Unit cost	Amount
1	BFB equipment	1	No.	$ 145,630	$145,630
2	Chipper		No.	$ 130,000	$130,000
	Total				$275,630

Source: Altex Technologies Corporation

Table 21: Operating Cost for Log/fuel Block Production

Item No	Item	Quantity/year	Unit	Unit cost	Amount/year
1	Fuel (Diesel) Chipper	8,000	gallons	3.00	$ 24,000
2	Fuel (Diesel)	4,800	Gallon	$ 3.00	$ 14,400
3	Repairs and Maintenance			3%	$ 8,269

Item No	Item	Quantity/year	Unit	Unit cost	Amount/year
	Labor cost				
4	Operator / Mechanic	2	No.	$ 50,000	$ 100,000
	Total				$ 146,669

Source: Altex Technologies Corporation

Table 22 shows the total production cost combining the depreciation and variable costs. In all cases, the equipment life is assumed to be 10 years. Based on this analysis, the total production cost for this 2 tons/hour case is estimated to be $ 41.88/ton. The dense logs have important transport cost benefits versus chips for the FORPOWER, biofuels and bioenergy markets, as described below. Lastly, this analysis was for a 2 ton/hour capacity unit. For larger BFB units, the cost per ton logs produced is even lower.

Table 22: Total Cost for Log/fuel Block Production

No	Item	Base cost	Rate	Amount/year
1	Total variable cost			$ 146,669
2	Depreciation	$ 275,630	10%	$27,563
Grand Total				$174,232
Total cost of log production per ton				$41.88
Total cost of log production per kwh				$0.011

Source: Altex Technologies Corporation

The estimated cost to produce wood pellets is approximately $80/ton [14]. Therefore, the BFB production cost of $41.88 is 47 percent lower than wood pellet costs. This is a significant saving, even for this small system. Also, for significant shipping distances with widely dispersed biomass residues, log densification has significant advantages over just chipping the material ahead of shipment.

5.1.4 Cost of Transportation of Chips and Dense Logs

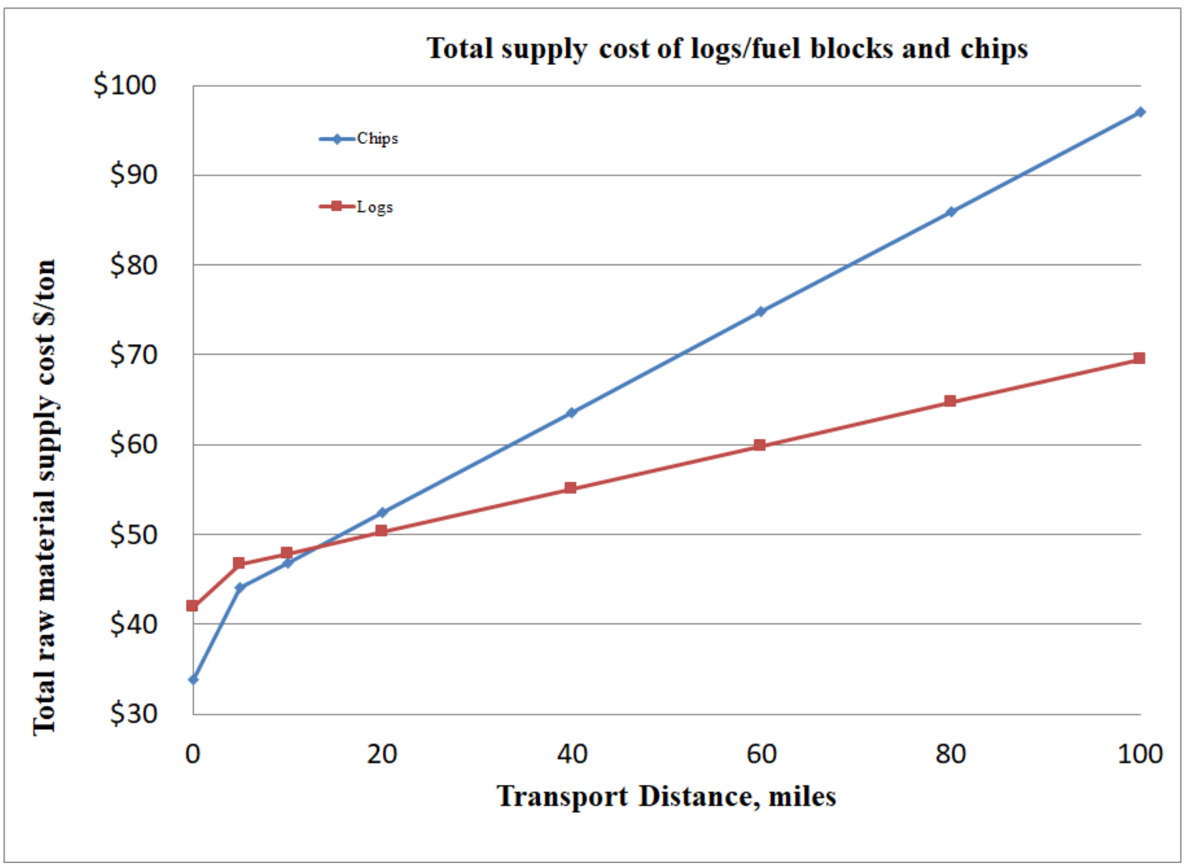
In addition to forest residue preparation costs, the cost of transporting forest residues to FORPOWER bioenergy modules is important to the cost of power production. To estimate biomass transport charges, the cost components included were the truck rental charge of $120/hour and the labor charges involved in loading the slash inside the forest and unloading the slash at the point of use.

In this analysis, it was assumed that the labor hours needed for loading and unloading the biomass is 0.85 hour per truck load and a loaded labor charge of $80/hour. A major factor in the transport cost advantage of BFB logs over chips is that their higher density (over 30lb/cf) can fully load trucks to their regulated limits, whereas the lower chip density (over 12 lb/cf) requires 2.5 as many trips to supply the same weight to the FORPOWER bioenergy plant. These extra trips are a big factor in the delivered cost of biomass. Based on these assumptions, the transport charges for logs or wood chips were estimated for FORPOWER bioenergy plants located at varying transport distances.

It is clear that the delivered cost of forest residue as logs is less than the delivered cost of wood chips when the FORPOWER bioenergy module, biofuel of other bioenergy plants are at a distance of more than 15 miles away from the forest area. When these plants are at a distance of 100 miles, the forest residue logs/fuel blocks can be supplied at a 27 percent lower cost than wood residue chips for approximately the same fuel value. Based on a 1-ton residues per acre availability of forest slash, a 3 MWe scale forest slash can be operated with forest slash supplied from a distance of five miles radius.

For 5MW and 10MW FORPOWER plants, forest residue may have to be supplied from a location within a radius of 20 miles. This provides a 5 percent reduction in biomass delivered cost. By densifying forest slash using FORPOWER technology, raw material can be supplied at a cost of $50/ton even if the FORPOWER plant is located at a distance of 20 miles. It should be noted that the energy value delivered at $50/ton varies with the biomass energy content per pound. For example, the pine, white fir and cedar energy values per pound vary by up to 28 percent, depending on the type and MC of forest residue. Similarly, agricultural or urban biomass energy contents will significantly vary with type, moisture and ash contents. These energy content variations will result in operating and power cost variations, as will be highlighted in Section 5.2.

Figure 30: Comparison of Total Raw Materials Supply Cost



Source: Altex Technologies Corporation

5.2 Bioenergy Module

For the techno-economic evaluation of bioenergy module, the bioenergy module is broken into six different components namely, feed preparation and storage section, feeding section, combustor section, gas turbine engine section, heat exchanger section, and bio-oil production section. The size, type and cost of equipment used in these sections are described in detail in Appendix C.2, along with operating costs and reductions in GHG emissions. These results are summarized in the following sections.

As noted, SB 1122 currently allows power systems up to 5 MWe capacity to participate in the program. In general, the larger the capacity of the system the lower the capital cost per output. Therefore, it was of interest to define the costs for 3 MWe and 10MWe FORPOWER bioenergy modules, as well as the targeted 5 MWe module to assess the impact of capacity on FORPOWER economic benefits. Furthermore, by defining the costs at 10 MWe, the ability of FORPOWER to be competitive outside the SB1122 program could be assessed.

5.2.1 Capital Cost of Bioenergy Modules

For this analysis, biomass is assumed to be received from the forest in the form of logs or chips. As per process calculations using mass and energy balances and engine efficiencies, 4,800 lb/hr, 7,880 lb/hr and 13,580 lb/hr of forest residues are needed for FORPOWER bioenergy module capacities of 3 MWe, 5 MWe and 10 MWe, respectively, at calculated overall plant efficiencies of 23.7 percent, 24 percent and 29 percent. These efficiencies were determined from the nameplate efficiencies on the gas turbine engines reduced by the flue and shell losses from the solid biomass combustion system and parasitic power needs. Based on the engine compressor outlet temperatures and flowrates, the biomass combustor requires 3,200 lb/hr, 5,300 lbs/hr 7,500 lb/hr of forest residues for 3 MWe, 5 MWe and 10 MWe electricity, respectively, with the remaining engine supplemental fuel provided by bio-oil from biomass. The densified forest slash is first reduced to a size less than 1/8" using a shredder or grinder.

A grinder suitable for this kind of operation was identified and the cost of equipment was determined by scaling the purchase price of an available 500 lbs/hr grinder to 3MWe, 5MWe and 10MWe FORPOWER plants, using a capacity scaleup factor of 0.6. Pilot-scale system test results are used for estimating the required capacities of the hopper, injector and screw conveyor, as given above. Purchased costs for a hopper and screw conveyor from Hapman and an injector from Fox Eductors were used with 0.6 scaling factor to estimate costs of \$14,700, \$19,800 and \$ 24,400 for 3MWe, 5MWe and 10MWe equipment, respectively. Similarly, the cost of injector and screw conveyor were estimated. The total solids handling section equipment cost was then estimated to be \$290,300, \$406,200, and \$517,300 for 3MWe, 5MWe and 10MWe plant capacities, respectively, as given in equipment cost Table 23. Costing details are given in Appendix C.2.

Table 23: Bioenergy Module Equipment Cost

Capacity, MWe	**3**	**5**	**10**
Size reduction, lb/hr	3,200	5,300	7,500
Cost of grinder, \$	215,300	290,800	357,000

Capacity, MWe	3	5	10
Belt conveyor			
Forest residue consumption rate, lb/hr	3,201	5,282	7,437
Velocity, ft/min	60	60	60
Cross sectional area	0.074	0.122	0.172
Width, inches	4.5	7	10
Cost basis, $	32,855	58,517	90,493
Total cost, $	32,900	58,600	90,500
Hopper, Ground forest residue			
Density, lb/cf	18	18	18
Capacity, cf	71	117	165
width, feet	6	8	9
height, feet	4	4	4
Cost basis, $/ 8 cubic feet	3,950	3,950	3,950
Cost of hopper, $	14,700	19,800	24,400
Injector (Eductor and blower)			
Capacity, lb/hr	3,201	5,282	7,437
Cost basis, $/250 lb/hr	971	971	971
Cost of injector, $	4,500	6,100	7,500
Screw conveyor			
Capacity, lb/hr	3,201	5,282	7,437
Cost basis $/300 lb/hr	5,517	5,517	5,517
Actual cost, $	22,900	30,900	37,900
total cost of solids handling section, $	290,300	406,200	517,300

Source: Altex Technologies Corporation

Based on net power available and ease of integration with FORPOWER heat exchangers, the SGT-A05 model turbine manufactured by Siemens was selected for the 3MWe FORPOWER system.

The salient operating conditions that are important for the FORPOWER application are given in Table 24. To define the installed cost of this 3 MWe engine, cost results for an installed 5 MWe simple cycle gas turbine engine [15] were scaled using 0.6 power scaling factor and converting the 2008 dollars to 2020 dollars using the cost inflation index. The cost of installed turbine on a turnkey basis was estimated to be $6,203,900.

Table 24: Selected Turbine Engine Operating Characteristics 3, 5 and 10 MWe FORPOWER System

Engine model	SGT-A05	SGT-100	SGT-400
Net Power (MWe)	3	5	10
Power (MWe)	4	5	13
Flow (Kg/sec)	15.4	20.9	39.4
Pressure ratio	10.3	13.7	16.8
Compressor outlet temp (F)	727.0	850.0	946.0
Efficiency	29.7%	30.6%	39.4%

Engine model	SGT-A05	SGT-100	SGT-400
Exhaust Temperature, F	1040	1006	1031
Flow rate, lb/hr	121,968	165,528	312,048
Heat rate, KJ/KWh	12,137	11,914	9,500
Heat rate, btu/hr	46,014,620	60,978,375	116,154,973
Turbine inlet temperature, F	1,991	2,038	2,300

Source: https://www.siemens-energy.com/global/en/offerings/power-generation/gasturbines.html

For a 5 MWe FORPOWER system, the SGT-100 turbine engine manufactured by Siemens was selected for integration with the 5MWe FORPOWER system. As applied in the 3 MWe engine case, the installed cost of the 5 MWe engine used the results in reference 4 without the need for scaling. The total cost of installed turbine on a turnkey basis was estimated to be $8,428,880.

For a 10MW FORPOWER system, SGT-400 turbine engine manufactured by Siemens was selected based on the net power available and also favorable operating conditions suitable for integration with custom built heat exchanger. The salient operating conditions that are important for FORPOWER application is given in the table.

The cost of the 10 MW turbine used results from reference 4 scaled up using the 0.6 power factor and considering escalation from 2008 to 2020 dollars. The cost for the installed engine on a turnkey basis was estimated to be $12,775,800.

Combustor

Using significant experience in designing and building combustors, an innovative combustor with cyclonic, primary and secondary combustion chambers was designed and fabricated for pilot scale testing. This successfully tested unit was used as a basis for sizing and costing full-scale FORPOWER combustors. For sizing the combustor, pilot-scale test results that defined composition and temperature histories were used. Since, the test results showed that the forest slash was combusted with emission levels lower than the biomass power plant limits in California, the test results were used to scale the sizes of the cyclone, first and secondary combustion towers, as given in Table 25. The $54,000 cost for building the 300 KW thermal test unit was used with the 0.6 power scaling to estimate the cost of combustors for 3MW, 5MW and 10MW combustion systems. These costs were $274,000, $372,500 and $565,000, respectively.

Table 25: Sizing and Cost Details of Combustor Section

Power generation capacity	3MW	5MW	10MW
System capacity, MMBtu/hr	40	61	93
Biomass combustor feed rate, lb/hr	3,201	5,282	7,437
Biomass combustor feed rate, tons/hr	1.6	2.6	3.7
Biomass combustion rate, tons/day	38	63	89
Mass flow rate, lb/hr	23,619	38,965	54,864
Volume flow rate, cfs	94	155	218
Residence time, sec (Based on cold air flow rate)	4.7	4.7	4.7

Power generation capacity	3MW	5MW	10MW
Volume of reactor, cu ft	441	727	1,023
Tower dia, ft	4	4	5
Cross sectional area	126	182	205
Tower height, ft	6	8	8
L/D ratio	1.81	1.90	1.61
Pressure, atm	1	1	1
Number of towers	2	2	2
Cost basis, per tower $/200 KW	54,000	54,000	54,000
Total cost, $	274,000	372,500	565,000

Source: Altex Technologies Corporation

Heat Exchanger

In the FORPOWER system, the heat exchanger is designed as a unit having three sections, namely: high temperature heat exchanger, main heat exchanger and recuperator heat exchanger. The hot combustion gases exiting the combustor enter the hot side of the high temperature heat exchanger section, pass through the main heat exchanger and exit the recuperator heat exchanger. The compressed air (process air side) from the turbine compressor enters the process gas inlet side of the main heat exchanger through the manifold, passes through the high temperature heat exchanger and exits through the manifold located in the high temperature heat exchanger section. The hot compressed gas exiting the manifold then enters the turbine combustor. The heating of compressed air occurs in the high temperature and main heat exchanger in a counter-flow configuration. The heat exchanger sections are designed to ensure that metal temperatures do not exceed the allowable temperature of the material used in the different sections. The high temperature heat exchanger is designed and built using Inconel 625. Using the engine defined air inlet temperature and the needed heat exchanger outlet temperature, the sizes of costs of the heat exchangers were determined with costs of $113,400, $164,500 and $215,400 for 3 MWe, 5 MWe and 10 MWe plant capacities, respectively. Details of the estimates are given in Appendix C.2.4.

Bio-oil System

Bio oil production from forest slash is well-proven technology and DOE has published detailed techno-economic analysis on production of bio-oil [16]. The total bio-oil requirement for operation of 3MWe, 5MWe and 10MWe FORPOWER system was estimated at 17.8, 27.6 and 68.6 million BTU/hr of heat. These inputs translate to 1.6, 2.6 and 3.2 tons/hour for 3Mwe, 5Mwe and 10Mwe, respectively. The maximum achievable yield of bio-oil production forest slash was estimated to be 59.9% [5]. To provide the required supplemental heat, 0.69, 1.07 and 2.66 tons/hour of biomass must be processed for 3MWe, 5MWe and 10MWe capacities, respectively. From the DOE report [5], the equipment cost of a 200 tons/day bio-oil plant is $8.8 Million. By scaling down the equipment cost using the 0.6 power exponent the costs are $2.09 Million, $2.72 Million, and $4.69 Million required for purchasing the feeding, pyrolysis, condensation and other equipment used in the bio-oil production section of 3MWe, 5MWe and 10MWe FORPOWER plants, respectively. Details of these estimates are given in Appendix C.2.5.

5.2.2 Total Installed Cost of 3MW FORPOWER Bioenergy Module (Power only and CHP)

The estimated equipment costs for the six different FORPOWER sections were utilized to estimate the total installed cost of FORPOWER plants by including the direct and indirect costs. The total direct costs includes, cost of installation, instrumentation and controls, piping and insulation, electrical costs, building costs, yard improvement costs, facility services, and land. These costs are location and industry specific, and since the exact locations are not yet available, the range of these costs, as per reference [3] and inputs received form commercial contractors, were used. By including the direct and indirect development costs, the installed total capital cost of 3MWe scale FORPOWER system with power only mode was estimated to be $11.35 Million, which corresponds to $3,784.67 per kw required for a 3MWe scale FORPOWER plant, as listed in Table 26. In comparing similar kinds of biomass power plants, these costs are found to be reasonable and used to estimate the cost of electricity production in terms of $/kWe given in reference [17] of this report. For the 3MWe CHP case the cost of sub-systems from 1-6 remains the same as power only system. The equipment cost for heat recovery heat exchanger was estimated and included as subsystem 7 and the result is given in Table 27.

Table 26: Total Installed Equipment Cost of a 3 MWe FORPOWER System (Power only)

No.	Name	No. of Skid	Total FOB Cost	Total Direct Cost	Total Indirect Cost	TIC (Total installed Cost)
#1	Feed Preparation and storage	1	$ 248,200	$440,555	$74,460	$ 763,215
#2	Feeding	1	$ 41,500	$73,662	$12,450	$ 127,613
#3	Combustor	1	$ 495,000	$913,275	$148,500	$1,556,775
#4	Heat exchanger	1	$ 198,067	$444,660	$59,420	$ 702,148
#5	Turbine	1	$ 6,203,900	$-	$-	$6,203,900
#6	Bio oil production	1	$ 2,092,400	$-	$-	$2,092,400
	Total cost			*Total Cost of FORPOWER*	*plant:*	$11,354,000
					$/KW	$ 3,785

Source: Altex Technologies Corporation

Table 27: Total Installed Equipment Cost of a 3 MWe FORPOWER System (CHP)

No.	Name	Number of Skid	Total FOB Cost	Total Direct Cost	Total Indirect Cost	TIC (Total installed Cost)
#1	Feed Preparation and storage	1	$ 248,200	$440,555	$74,460	$763,215
#2	Feeding	1	$ 41,500	$73,663	$12,450	$127,613
#3	Combustor	1	$ 495,000	$913,275	$148,500	$1,556,775
#4	Heat exchanger	1	$ 198,067	$444,660	$59,420	$702,147
#5	Turbine	1	$ 6,203,900	$ -	$ -	$6,203,900
#6	Bio oil production	1	$ 2,092,400	$ -	$ -	$2,092,400
#7	Heat Recovery Hex	1	$ 198,067	$444,660	$59,420	$702,147
	Total cost			Total Cost of FORPOWER plant:		$12,056,000
					$/kWe	$4,019

Source: Altex Technologies Corporation

5.2.3 Total Installed Costs of 3 MWe, 5 MWe and 10 MWe FORPOWER Bioenergy Modules (Power Only and CHP)

Similar to the installed equipment costs for 3 MWe, 5MWe and 10 MWe power only and CHP bioenergy modules were estimated and these results are given in Table 28. Details for these estimates are given in Appendix C.2.6 to C.2.8.

Table 28: Power Only and CHP Bioenergy Module Capital Costs for 3, 5 and 10 MWe

Power (MWe)	3	5	10
Power Only ($)	11,354,000	15,549,000	23,540,000
Power Only ($/KWe)	3,785	3,110	2,354
CHP ($)	12,056,000	16,563,000	24,831,000
CHP ($/KWe)	4,019	3,313	2,483

Source: Altex Technologies Corporation

5.2.4 Operating Costs of 3 MWe, 5 MWe and 10 MWe FORPOWER Bioenergy Modules (Power Only and CHP)

Variable operations costs, beyond delivered biomass fuel costs, include the cost of water, waste disposal expenses, chemicals, and gases used for ancillary equipment, lubricants and consumables. In addition, major maintenance cost includes scheduled major overall expenses, spare parts for balance of plant (BOP). In the FORPOWER plant, there is no need for large quantities of water for cooling. It is difficult to accurately estimate these costs for a new power plant, therefore, a nominal cost of $1.65/MWh was used that is similar to that for conventional biomass power plants [18]. Based on this assumed rate, the variable operation and maintenance cost for 3MWe, 5MWe and 10MWe FORPOWER plants were estimated to be $41,580/year, $69,300/year and $138,600/year, respectively. These values were used in the energy cost calculations in terms of $/kwh.

The types of personnel needed for successful operation of FORPOWER system were identified and the wages for these personnel were taken from the published wage data available at https://www.bls.gov/oes/current/oes_ca.htm#43-0000. Accordingly, the variable labor costs for 3MWe, 5MWe and 10MWe FORPOWER systems were estimated to be $413,500/year, $614,440/year and $974,020/year and included with 50 percent benefits in the energy cost calculations in terms of $/kwh.

FORPOWER plants produce ash and disposal cost varies from $3 to $5/ton min to $20 to $40/ton max depending on the distance and method of transport (https://www.acaa-usa.org/aboutcoalash/ccpfaqs.aspx#Q13). In certain cases, ash can generate income if ash is used as by-products for making construction materials and other items. However, in the analysis an amount of $20/per ton was used as an expenditure for disposal of ash. The cost of ash disposal for 3MWe, 5MWe and 10MWe plants were estimated to be $16,135/year, $26,620/year and $37,480/year, respectively, and included in the energy cost calculations in terms of $/kwh.

5.3 BFB and Bioenergy Module

The estimated FORPOWER bioenergy module capital and operating costs were used to calculate power cost in $/kWh. The established Excel modelling tool developed and published by UC Davis, available at: https://biomass.ucdavis.edu/tools/energy-cost-calculator/, was utilized to calculate LCOE values for 3MWe, 5 MWe and 10 MWe power only and CHP bioenergy modules. For the CHP estimates the cost of operating a waste heat driven exhaust heat exchanger was added to the capital cost and a fuel reduction credit for producing hot water was removed from the operating cost. The LCOE values for all the capacities and biomass fuel types for all cases were then compared to the SB 1122 maximum purchase price of $.1997/kWh to define simple payback in years. Forest and agricultural residue cost and GHG reduction benefits of deploying FORPOWER were estimated and summarized below. Details of these estimates are given in Appendix C.3.6.

5.3.1 FORPOWER System Power Production Costs

The cost estimation procedure used the same UC Davis model and a consistent set of financial parameters for all cases. The procedure and parameters are illustrated below for the 3 MWe case. Details for this 3 MWe case, and 5 MWe and 10 MWe power only and CHP cases, are given in Appendix C.3 (C.3.1 to C.3.3). The capital costs and $/kWe used for all cases are previously provided.

Table 29 gives the system parameters that are needed to estimate LCOE. High hours of operation, considering only maintenance down time, is required for maximum plant payoff. Overall plant efficiencies of 23.7%, 24% and 29% were calculated for 3 MWe, 5 MWe and 10 MWe plants, respectively, which then defined fuel consumption rates. These efficiencies were determined from the nameplate efficiencies on the gas turbine engines reduced by the flue and shell losses from the solid biomass combustion system and parasitic power needs.

Table 29: Electrical and Fuel—Base Year: 3 MWe FORPOWER Plant (Power Only)

Net Plant Capacity (kWe)	3,000
Capacity Factor (%)	85
Annual Hours	7,446
Net Station Efficiency (%)	23.7
Fuel Heating Value (kJ/kg)	18,608
Fuel Consumption Rate (t/h)	2.40
Fuel Ash Concentration (%)	6
Annual Generation (kWh)	22,338,000
Capital cost per net capacity ($/kWe)	3,785
Annual Fuel Consumption (t/y)	17,853
Annual Ash Disposal (t/y)	1,071

Source: Altex Technologies Corporation

Table 30 gives important expenses that are incurred during a year for successful operation of a FORPOWER plant. The major expenditure of $620,295 is incurred as wages for the 3MWe FORPOWER system. Insurance and property tax are the next major expenditures that are incurred to generate 3 MWe of electricity.

Table 30: Expenses—Base year: 3MWe FORPOWER plant (Power Only)

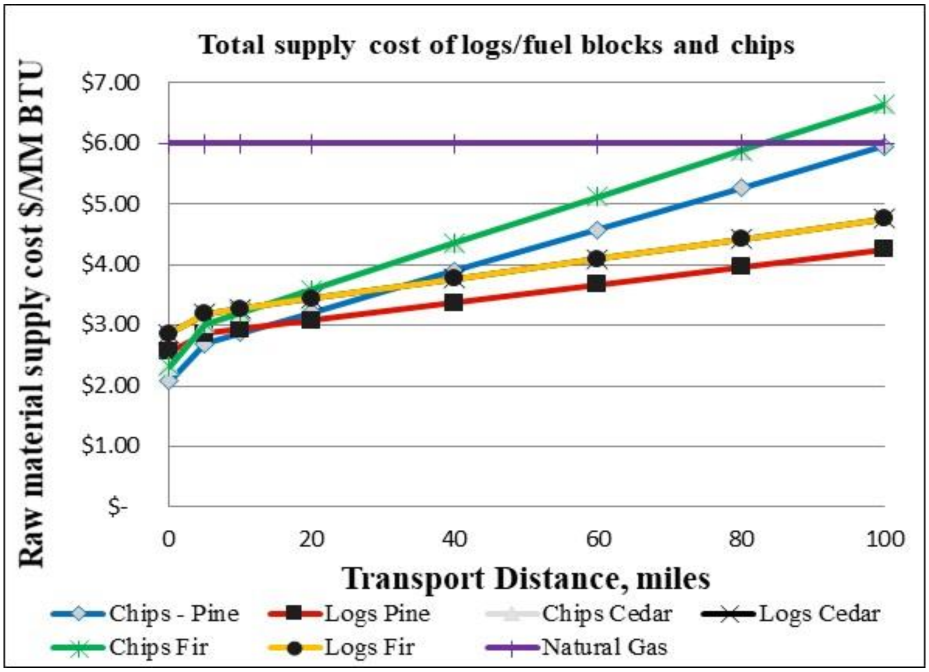
Item	Value	($/kWh-net electrical)
Fuel Cost ($/t)	44.10	0.0352
Labor Cost ($/y)	620,295	0.0278
Maintenance Cost ($/y)	41,580	0.0019
Insurance/Property Tax ($/y)	397,390	0.0178
Utilities ($/y)	81,481	0.0036
Ash Disposal ($/y)—use negative value for sales	21,423	0.0010
Management/Administration ($/y)	62,030	0.0028
Other Operating Expenses ($/y)	18,609	0.0008
Total Non-Fuel Expenses ($/kWh)	1,242,808	0.0556
Total Expenses Including Fuel ($/y)	2,030,106	0.0909

Source: Altex Technologies Corporation

All the subsystems including the turbine likely have a total life of more than 20 years and will have value after continuously running for 20 years. However, to be conservative, a straight-line method of depreciation was assumed and the FORPOWER system has zero value at the end of twenty years. Based on the parameters given in Table 31 to Table 33 the cash flow that can be achieved in running a FORPOWER system is calculated with the model and results are given in Appendix C.3.1 (a), Table C-36.

Figure 31 illustrates the slightly lower cost per delivered energy of the chipped material. For more dispersed forest resources that will require longer transport distances to the bioenergy plant, the biomass log form will have a significant cost advantage versus chipped material.

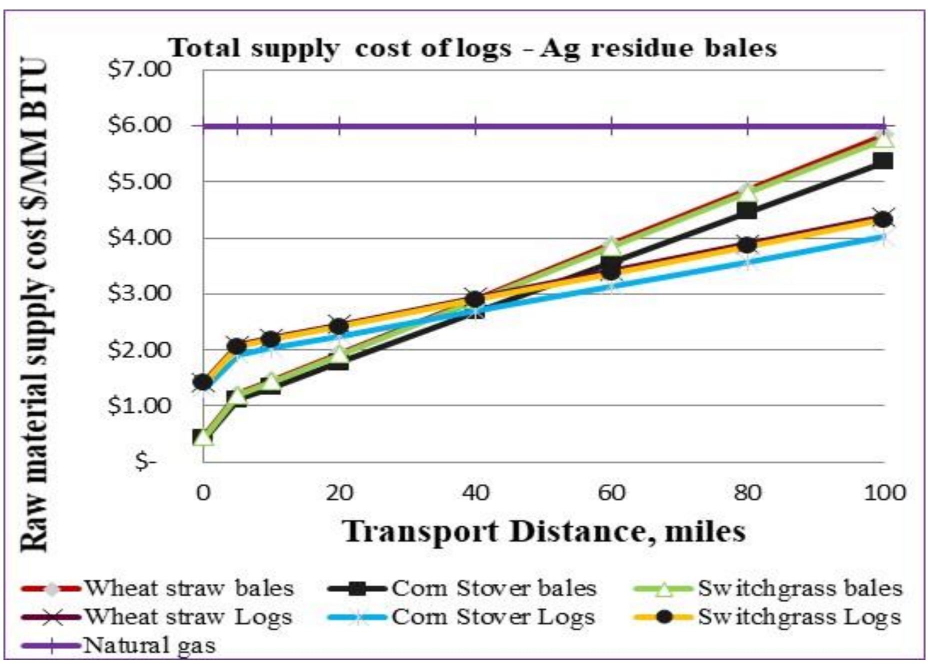
Figure 31: Forest Residue Delivered Cost per Energy



Source: Altex Technologies Corporation

Note that in all cases, the delivered energy cost of forest residues is significantly below the assumed California natural gas delivered fuel price of $6/MMBtu. It should also be noted that agricultural biomass has a lower cost than forest biomass, as shown in Figure 32, and this lower cost will reduce FORPOWER simple payback for the additional 90 MWe total capacity allowed for agricultural biomass under SB 1122.

Figure 32: Agricultural Residue Delivered Cost per Energy



Source: Altex Technologies Corporation

Table 31: Tax, Escalation/Inflation and Other Income Assumptions: 3MWe FORPOWER Plant (Power Only)

Taxes	
Federal Tax Rate (%)	34.00
State Tax Rate (%)	9.60
Production Tax Credit ($/kWh)	0.012
Combined Tax Rate (%)	40.34
Income other than energy	
Capacity Payment ($/kW-y)	100
Interest Rate on Debt Reserve (%/y)	7.50
Annual Capacity Payment ($/y)	300,000
Annual Debt Reserve Interest ($/y)	51,248
Escalation/Inflation	
General Inflation (%/y)	2.10
Escalation—Fuel (%/y)	2.10
Escalation for Production Tax Credit	2.10
Escalation—Other (%/y)	2.10

Source: Altex Technologies Corporation

Table 32: Assumptions on Financing: 3MWe FORPOWER Plant (Power Only)

Debt ratio (%)	75.00
Equity ratio (%)	25.00
Interest Rate on Debt (%/y)	5.00
Economic Life (y)	20
Cost of equity (%/y)	15.00
Cost of Money (%/y)	3.50
Total Cost of Plant ($)	11,354,000
Total Equity Cost ($)	2,838,500
Total Debt Cost ($)	8,515,500
Capital Recovery Factor (Equity)	0.1598
Capital Recovery Factor (Debt)	0.0802
Annual Equity Recovery ($/y)	453,483
Annual Debt Payment ($/y)	683,306
Debt Reserve ($)	683,306

Source: Altex Technologies Corporation

A wholesale maximum power purchase price of $0.1997, as per BIOMAT auction price under SB1122, is offered by California utilities for generation of electricity from forest slash. Since this purchase price is higher than the estimated LCOEs for all cases in Table 33, payback is then possible for all FORPOWER cases estimated. The simple payback period is calculated by dividing the capital cost for the plant by the $0.1997 maximum purchase price of power minus the LCOE with the difference multiplied by the number of kWh per year. This gives the number of years to payback the capital investment.

As shown in Table 33, higher capacity and the use of CHP significantly reduce LCOEs. The higher energy content pine has only a 3 percent LCOE advantage over white fir and cedar. Using agricultural biomass will have a more significant cost advantage. Using the cash flow, the LCOE cost to produce electricity is calculated as $0.1471/KW for the 3 MWe case. Using the consistent set of financial parameters, the model was used to calculate LCOEs for all forest residue biomass fuels at capacities of 3 MWe, 5MWe and 10 MWe for power only and CHP cases and results are given in Table 33.

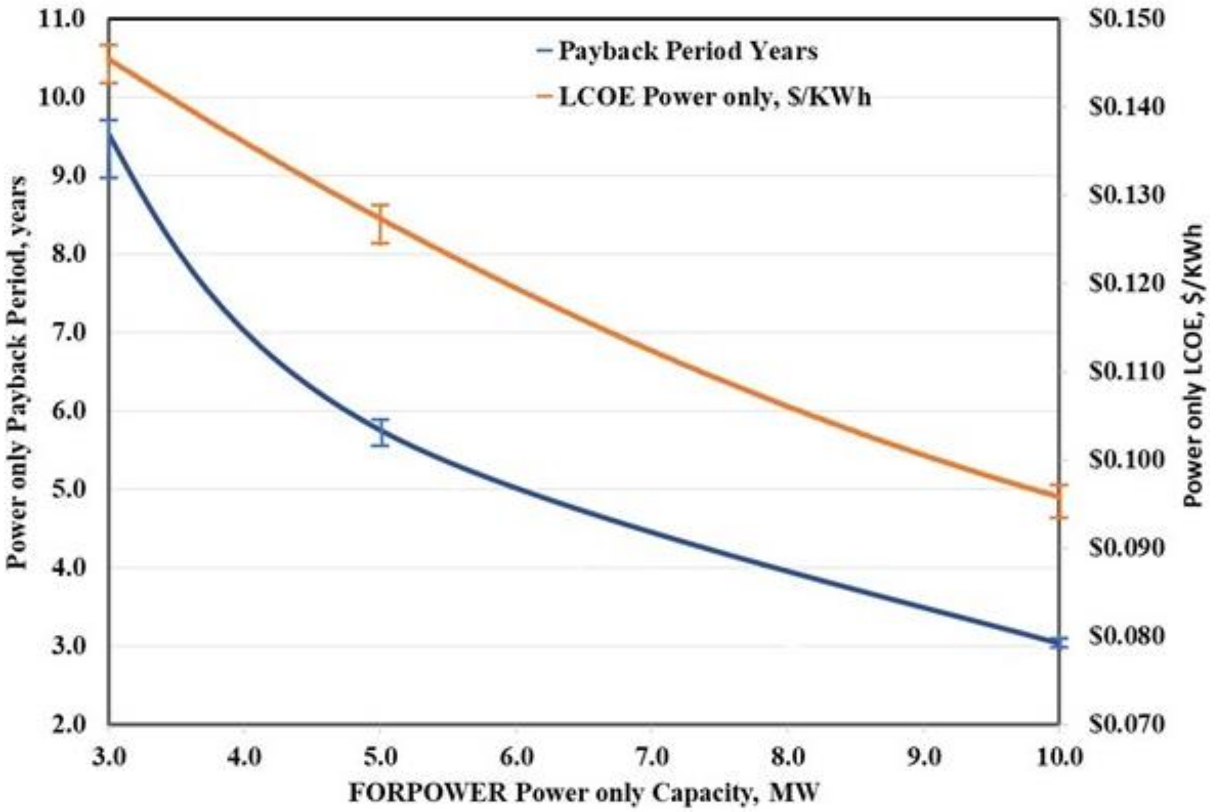
Table 33: LCOE and Estimated Payback Period for 3MWe, 5MWe, and 10MWe Scale FORPOWER System

Capacity, MW	Rawmaterial	LCOE (Power only)	LCOE (CHP)	Simple payback period, years FORPOWER CHP	Simple payback period, years FORPOWER (Power only)
3	Pine - Chips	$ 0.143	$ 0.111	6.1	9.0
5	Pine - Chips	$ 0.125	$ 0.101	4.5	5.5
10	Pine - Chips	$ 0.093	$ 0.067	2.5	3.0
3	Cedar - Chips	$ 0.147	$ 0.115	6.4	9.7
5	Cedar - Chips	$ 0.129	$ 0.106	4.7	5.9
10	Cedar - Chips	$ 0.097	$ 0.071	2.6	3.1
3	White fir - Chips	$ 0.147	$ 0.115	6.4	9.7
5	White fir - Chips	$ 0.129	$ 0.106	4.7	5.9
10	White fir - Chips	$ 0.097	$ 0.071	2.6	3.1
3	Pine- Logs	$ 0.145	$ 0.113	6.3	9.3
5	Pine- Logs	$ 0.126	$ 0.103	4.6	5.7
10	Pine- Logs	$ 0.094	$ 0.068	2.5	3.0
3	Cedar - logs	$ 0.149	$ 0.117	6.6	10.1
5	Cedar - logs	$ 0.131	$ 0.108	4.8	6.0
10	Cedar - logs	$ 0.098	$ 0.072	2.6	3.1
3	White fir - Logs	$ 0.149	$ 0.117	6.6	10.1
5	White fir - Logs	$ 0.131	$ 0.108	4.8	6.0
10	White fir - Logs	$ 0.098	$ 0.072	2.6	3.1

Source: Altex Technologies Corporation

Figure 33 shows the variation of FORPOWER power-only mode LCOE and Payback Period with an average forest residue feedstock cost over a range of system capacities. As shown in the figure, the LCOE and payback significantly decrease with increases in system capacity. The brackets on the lines indicate the span in LCOE and payback for the range of forest residues costs tested. The impact of forest residue costs on LCOE and payback is small compared to the impact of system capacity on LCOE and payback.

Figure 33: Effect of FORPOWER Power Only System Capacity on LCOE and Payback Period

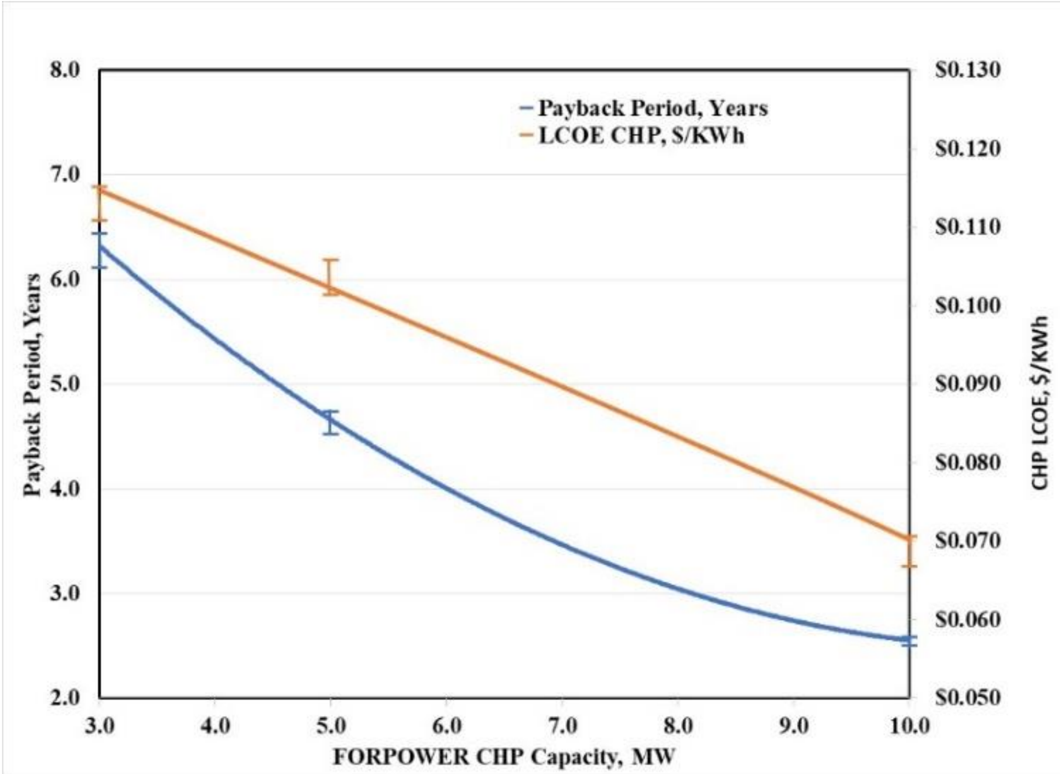


Source: Altex Technologies Corporation

The 3 MWe capacity system has an unattractive payback of over nine years. At 5 MWe, the payback is 5.6 years, which is acceptable for some investors. At 10 MWe capacity, the payback is an attractive 3.0 years. However, the 10 MWe capacity is beyond the current SB 1122 limit of 5 MWe for participation in the program. By including larger capacities under SB 1122, paybacks will be reduced below 5.6 years. As an alternative to this approach the CHP mode, where both hot water and power are produced, can be implemented to reduce payback for 5 MWe capacity systems.

Figure 34 shows the CHP mode FORPOWER LCOE and payback variation with capacity. The payback period is an acceptable 4.6 years with 5MWe production capacity, with a very attractive payback period of only 2.5 years at 10 MWe capacity.

Figure 34: Effect of FORPOWER CHP System Capacity on LCOE and Payback Period



Source: Altex Technologies Corporation

At the initiation of the project, some aggressive economic and GHG emissions targets were identified, and these are listed in the first column in Table 40. In the second column are the estimated economic and GHG results for a 5MWe FORPOWER system with CHP. As shown, the estimated LCOE is about 29 percent higher than the initial project target of $.082/kWh. This then leads to a simple payback of 4.6 years, which exceeds the project target of four years by 15 percent. This difference is not that great and a 4.6-year payback would be acceptable to investors. As noted above, a higher capacity reduces the LCOE and payback. The third column in Table 34 gives the capacities required to hit the LCOE and payback targets. As shown, the four-year payback target is achieved if the capacity is increased to 6 MWe.

Table 34: Comparison of Economic Estimates and GHG Reductions to Project Targets

Objectives	Project Target	Forest Residues-5Mwe	Capacity to Hit Target	Agricultural Residues-5MWe
LCOE ($/kWh)	.082	.106	8 MWe	.082
Simple Payback (yrs)	<4	4.6	6 MWe	3.8
GHG Emissions (MMT/yr)	1MMt/yr	1MMt/yr	5 MWe	1MMt/yr

Source: Altex Technologies Corporation

5.3.2 Environmental Benefits

In this analysis, it is assumed that FORPOWER systems can cover the targeted 140 Mwe total electricity generation needs from Category II and III fuel sources, namely forest slash and agricultural biomass under SB1122. To achieve this, 28 FORPOWER plants of 5MWe scale will be built over a period of seven years as per Table 35. With this type of deployment, it will be possible to reduce GHG emissions by more than 1 million tons/year, meeting the project goal. In addition, FORPOWER systems can generate more than 560 well-paying jobs and eliminate the need for forest treatment costs in approximately 600 sq miles of forest. Based on avoiding incurring cost for fire treatment, the roughly estimated cost savings is approximately $249 million. Combined with the economic benefits described in Section 5.3.1 these benefits support the further development and ultimately the use of FORPOWER in California.

Table 35: Environmental and Socio-economic Benefits of FORPOWR System

	Years after start				
Year	**3**	**4**	**5**	**6**	**7**
FORPOWER 5MW	1	7	14	21	28
Base electricity produced by FOR POWER, MWe	5	35	70	105	140
Annual revenues from electricity, $	7,434,831	52,043,817	104,087,634	156,131,451	208,175,268
Total heat produced, MMBtu/hr	33	228	456	684	912
Savings in fuel cost, $	1,455,361	10,187,530	20,375,059	30,562,589	40,750,118
Direct jobs	20	140	280	420	560
GHG reduction from electricity production, tons/year	35,145	246,016	492,032	738,048	984,063
GHG reduction from fuel savings, tons/year	2,132	14,923	29,846	44,769	59,692
Total GHG reduction, tons/year	37,277	260,939	521,878	782,817	1,043,755
Avoided forest fire treatment area, sq miles	21.5	150.8	301.6	452.4	603.2
Avoided forest fire treatment cost,$	8,892,342	62,246,395	124,492,790	186,739,185	248,985,580

Source: Altex Technologies Corporation

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

The knowledge gained from the project would be of interest to many stakeholders. These potential users of FORPOWER results are listed in Table 36. The potential markets for FORPOWER under SB 1122 are forest residue feedstock use up to 50 MWe total. In this project, power outputs up to 10 MWe were considered and costed. At the 10 MWe level, the LCOEs were significantly lower than at 5 MWe, due to higher engine efficiency at increased capacity and the lower capital cost per output at larger capacities. Larger engines over 20 MWe would provide even more competitive power pricing.

Table 36: Potential Users of FORPOWER

Densification Module	Bioenergy Module
▪ Biomass powerplants ▪ Pelletization plants ▪ Animal feed exporters ▪ Waste collection companies ▪ Forest waste maintenance companies ▪ Agricultural waste collection companies ▪ Pellet production companies ▪ Hydraulic compactor equipment manufacturers ▪ Burner and heat exchanger manufacturers ▪ Pellet machine manufacturers	▪ IOUs that support SB 1122 ▪ Non-IOU utilities ▪ Industries that need process hot water ▪ Power companies that promote renewable power ▪ Gas turbine manufacturers ▪ Feeding equipment manufacturers ▪ Heat exchanger manufacturers ▪ Reactor and furnace manufacturers

Source: Altex Technologies Corporation

Table 37 provides a list of these biomass resources inside and outside of California. These markets could all be addressed by the FORPOWER densification module alone or in combination with the densification module. Together, there are many opportunities for deploying FORPOWER densification and bioenergy modules within and outside of California. In addition, FORPOWER can be used outside of the US and in many countries that are now focusing on renewable energy.

Table 37: Potential Biomass Resources in California and Other Locations

Market	California (TPY)	US (TPY)
Forest biomass wastes.	21.6 Million	154 Million
Agricultural biomass wastes	26.8 Million	144 Million
Urban biomass wastes	37.6 Million	68 Million
Animal feed	12 Million	126 Million

Source: Altex Technologies Corporation

Technology transfer activities under the project were expected to proceed once test results showed the performance and emissions potential of FORPOWER versus conventional technologies. Performance and economic benefits show that FORPOWER has potential to address the many markets listed. However, these results were only obtained recently and COVID-19 constraints limited the transfer of knowledge from the project to the many stakeholders. As the pandemic threat recedes, the plan is to disseminate project knowledge to stakeholders through multiple potential paths, including those listed in Table 38.

Table 38: FORPOWER Knowledge Dissemination Paths and Status

Path	Status
• Renewable energy conference presentations and posters • Publication of articles in trade magazines • Preparation and distribution of information sheets and brochures • Direct contacts with high-potential stakeholders	• 2018 EPIC Symposium Presentation • Discussed FORPOWER benefits with over two-dozen potential stakeholders

Source: Altex Technologies Corporation

This dissemination work will be planned and executed following the FORPOWER project completion. To date, only limited knowledge dissemination work has been and includes:

- Contacts with UC Davis and UC Berkeley researchers on the use of FORPOWER densification to facilitate agricultural and forest biomass transport and storage at low cost.
- Contacts with multiple animal feed exporters on the use of FORPOWER densification potential in this market.
- Meeting with animal feed exporter on the implementation and cost of FORPOWER densification versus conventional overseas transport.
- Attended wood pelletization conference and met with pelletization company staff and consultants on FORPOWER densification module potential support in that industry.
- Met with dairy farmers and association president on the interest in employing FORPOWER to consume dairy manure waste and produce power.
- Met with and discussed FORPOWER potential to cleanly consume forest wastes and produce power with UCB Blodgett Forest Station Manager.
- Contact with boiler and economizer manufacturer representatives on the CHP markets and opportunities for FORPOWER bioenergy module.
- Prepared FORPOWER presentation for 2018 EPIC Symposium and supported the meeting, contacting many attendees on the potential for FORPOWER to consume forest and agricultural residues and produce electric power.

In the coming months, additional contacts and presentations will be made to further disseminate the FORPOWER results that were developed under this project.

CHAPTER 7: Benefits to Ratepayers

An important benefit of this project and research to ratepayers is the reduction of forest fire danger to people, property and infrastructure by utilizing high hazard forest waste. However, the quantification of this benefit is not straightforward and depends on many factors. SB1122 has defined the amount of forest slash that can be used in the production of power and the price of that power that will be acceptable to the California IOUs.

In all of these cases, GHG emissions would be reduced versus burning fossil fuels, thereby benefitting local communities. Lastly, the reduction of open burning of forest and agricultural residues will reduce criteria pollutants, including NOx, CO and Particulate Matter (PM). Reduction of these pollutants are beneficial to the health of local populations.

CHAPTER 8: Lesson Learned, Conclusions and Recommendations

8.1 Lesson Learned

During the project, multiple lessons were learned spanning from those related to product regulations to testing and reporting results. Many of the lessons learned were minor and specific to Altex and not easy, or useful, to transfer to other organizations and stakeholders. Some of these lessons can be gleaned from other sections of the report. In this section, only the major lessons learned will be listed and discussed for the benefit of other organizations and stakeholders. These could be helpful in the duplication of this, or closely aligned, work.

8.1.1 Regulations and Requirements

In any development, the product requirements must be well defined at the beginning of the effort and the product must be developed to meet all requirements, including safety, efficiency and environmental and other regulated requirements. With hard work and the right technology, these can be met. However, if these external requirements and regulations are changed in the wrong direction during the project, the development could be a wasted effort.

Related to environmental regulations, the unique FORPOWER design does not easily fit into available air pollution source categories. Without a specific FORPOWER emissions target, Altex identified the biomass-fired boiler regulations as the closest available regulation that could be applied to FORPOWER. This regulated emissions limit was used as the performance target. During the project, the biomass-fired boiler regulated emissions target was updated that then reduced the margin between the measured emissions and the new regulated target. This was unanticipated and could have made the development effort irrelevant if the new regulations were set significantly below the FORPOWER measured emissions. Fortunately, FORPOWER met these new emissions target. The lesson learned from this experience is that during development product requirements and regulations could change, and to control the risk of not creating a marketable product, significant flexibility and contingency has to be built into the product during the development stage and beyond.

8.1.2 Optimistic Budget and Schedule

The development of a new product has many risks and the probability of the plans being executed on budget and time are low if significant contingencies are not included. Many previously unknowns are uncovered during the development effort and need to be addressed to move forward. This requires additional budget and time relative to an optimistic plan. This is particularly the case for complex systems that require the development of many components needed to operate the system at the proposed performance level. While it is possible that during system development component performances may fall short of targets.

In the case of FORPOWER, the bioenergy module required the implementation and successful operation of ten new and significant subsystems. If each had a probability of success of 80%, the probability of the total system being successful would be 10%. The lessons learned is that for complex systems that require development of many components, budgeting and scheduling should be conservative to avoid disappointing the customer and the developer. With more time and money, progress can be made, but if that is not available at the outset then the full system development should not be undertaken. Instead a component-by-component development should be pursued in stages to build confidence toward the complete system development. To help guide this planning, a risk registry should be developed along with mitigation strategies to reduce or eliminate risks. This registry should be updated at regular intervals (e.g. monthly) to capture evolving risks and corrections. Lastly, the developers and development partners should have similar levels of risk tolerance to avoid disappointment.

8.1.3 Resources

Over the period of multiple years, project resources can change in unexpected ways. These could be infrastructure resources, as well as staff resources. Altex was faced with an expiring facility lease with a landlord who was proceeding on a plan to tear down the Altex facility and build a five-story office building to significantly increase rental income. Altex managed to delay the move, at some expense to Altex, to allow the completion of Altex tests. Project staffing for FORPOWER included PI, mechanical, chemical and electrical engineers, various technicians, managers and consultants. These varied somewhat over the length of the project, requiring additional training and qualification of different positions. Also, expertise had to be transferred for some critical needs to keep the project on track. With these changes, working relationships had to be restarted and efficient ways of working together had to be established. These changes increased costs and delayed work that was not covered in the optimistic budget and schedule project plans. In addition, staff changes at the development partner also had to be accommodated, resulting in some inefficiencies and delays. The lesson learned is to build resources backup, including having trained staff to take over if a staff member leaves the company or project. Unfortunately, this risk reduction strategy requires more company investment and thereby requires even higher project budgets and longer schedules to cover this need for backup and extra training.

8.1.4 Technology Development

There were multiple lessons learned during technology development under the project. Some significant lessons were:

- Biomass materials are very heterogenous and lack the level of classification and specifications applied to other fuels, such as coal, petroleum liquids or natural gas. In addition, the biomass gathering method can entrap dirt and debris and skew the material properties from typical levels. Rain and snow can drastically change energy value and microbial decay can impact both energy content and handling characteristics. If materials are improperly stored, particularly if they are stored over a considerable period, significant property changes are possible. This then requires a system that is very flexible to adapt to changing feedstock supply characteristics.

While energy content is very important, flowability of the material represents an even bigger hurdle to the basic operability of the system. The lesson learned is to carefully specify and test biomass supplies to ensure their relevance in testing and, once acquired, protect the supplies from weather to avoid biomass property drift.

- Biomass materials are difficult to handle, transport and feed into processes designed to extract energy from the biomass. During feeding of biomass into FORPOWER reactors, the biomass dense phase (i.e. pile of sized material) must be transformed into a dilute phase (i.e. rapidly-moving flow of air with dispersed biomass particles). This is particularly challenging for small-scale test systems where surface-to-volume ratios are high and the probability of plugging of flow passages is also high. During the project, it was learned that jets of air could be successfully used to disperse the biomass transported in the dense phase, by a screw feeder, into a dilute phase compatible with injection into the FORPOWER reactor. Also, stirrers for biomass feed hoppers were useful to avoid bridging of material and uneven feeding. With these fixes, feeding challenges were overcome and operation became smoother. The lesson is that biomass materials have challenging feeding problems and even best practices will not easily work for small test systems. In development, expect some biomass feeding problems and build in budget and schedule contingencies to address these problems.
- While operation became smoother with improvements in biomass feeding, there was still some variation in feed rate over time that could impact emissions, particularly if the O_2 level in the exhaust decreased to a low level. At these conditions, CO became excessive. During the FORPOWER testing, the CO challenge was ultimately addressed by modulating the combustion air fan as the exhaust O_2 level varied. The lesson learned was that exhaust O_2 levels needed to be consistently maintained at a level where CO was acceptable and efficiency high. While FORPOWER testing used manual exhaust O_2 control by modulating the air fan, this approach could be automated using an exhaust O_2 sensor and a controls program that would modulate the air fan speeds to maintain the selected O_2.
- To save project funds, available used equipment were utilized where possible. While most of the available equipment operated as expected and allowed needed data to be obtained that characterized the FORPOWER process, some equipment required repairs during the testing phase. This added costs and delayed testing. The lesson learned is to include in the risk registry the unscheduled repair work for used equipment, and the expected budget and schedule increases to cover these efforts to ensure operation of the test system.

The above focused on problems and the needed corrective actions to continue project development and testing. In general, many development and test problems can be overcome with additional budget and schedule. Many FORPOWER efforts went right during the effort and supported the technical feasibility of FORPOWER and the conditions under which the concept is economically viable. These efforts have been documented in various other sections of this report.

8.2 Densification Module Conclusions

Log densities from 36.5 lb/cf to 36.8 lb/cf were produced from pine, white fir and cedar slash, which is approximately 2.5 times the density of wood chips. Successful testing of the pilot-scale system with portable features supports that the densification equipment can be manufactured as a portable system for operation inside or at the boundary of the forest. Development of a portable densification system has synergies with commercially-available forest maintenance equipment, with the expectation that forest compatible tractors can be integrated with the densification system.

Using log production test data and analysis, the cost of forest slash dense logs was estimated to be $42/ton to deliver them to FORPOWER bioenergy modules, which is below chipped forest slash delivered cost. For one ton per acre per year forest residues availability, transport distances are short and the feedstocks transport cost reduction benefit is 5 percent for a 5 MWe system. However, for more dispersed residues with one-half ton per acre availability the transport cost reduction is 10 percent. Lastly, for a one ton per acre residue availability and a power system of 30 MWe the densification transport cost reduction is a significant 19 percent. It is concluded from this study that it is possible to build and economically operate multiple densification systems to support FORPOWER plants with capacities that cover SB 1122 that is limited to 5 MWe.

8.3 Bioenergy Module Conclusions

Stable feeding and processing of biomass was achieved and NOx and CO emissions and exhaust opacity levels were recorded for a range of primary and secondary combustor stoichiometric ratios.

Forest residue test conditions were found where emissions for biomass were below the SJVAPCD regulated limits for boilers operating on biomass. Meeting these regulations supports that FORPOWER units could be operated in California without the need for expensive post combustion emissions controls, such as Selective Catalytic Reduction. Using the pilot-scale test results, full-scale system dimensions and air and fuel flows were defined for costing purposes. All the subsystems needed for building and operating 3MW, 5MW and 10MW plants were designed, equipment was sized, and commercial equipment identified. Power only and CHP versions of FORPOWER were analyzed. The CHP version would produce hot water as well as power to improve overall system efficiency. Component costs were obtained from different vendors and the costs of building FORPOWER plants were determined using a method developed by the AACE. The FORPOWER capital costs were then combined with estimates of operating costs in an economic model developed by UC Davis to estimate electricity generation costs.

8.4 Recommendations

A pilot-scale FORPOWER system has been designed, developed and tested that consists of a densification module and a bioenergy module that receives the densified biomass and burns the biomass to drive an indirectly- and directly-fired gas turbine that produces power. The densification system was successfully tested using forest slash materials, including pine, fir and cedar received from Blodgett Forest Station. To show biomass feedstock flexibility, wheat straw agricultural residues were also successfully tested. The pilot-scale bioenergy module was designed, developed and tested to prove that electricity can be generated from forest slash and agricultural residues. Pilot-scale system tests and analyses have shown the technical and economic feasibility of FORPOWER. To successfully commercialize this technology, the following additional work is recommended:

- Use California forest survey data to develop a number of densification site scenarios in California that would define the FORPOWER deployment opportunity and determine the impact on forest fire risk and forest sustainability.
- Use California agricultural biomass survey data to define agricultural co-feedstock opportunities and determine the economic impact on FORPOWER deployment.
- Identify design weaknesses in the densification and bioenergy modules and recommend strategies to improve throughput and quality and reduce costs.
- Develop, fabricate and test a portable forest residue densification module that can be towed by a tractor to strategic locations within the forest.
- Test additional forest residues, as well as urban tree trimmings and agricultural residues.
- Design, develop and test a larger-scale bioenergy module to prove operation at a larger scale with government funding support and community cooperation.
- Design, develop and test a 5 MWe-scale beta bioenergy module to prove operation at full scale with a range of forest and agricultural residues.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
$MM	Million dollars
AACE	American Association of Cost Engineers
BBADS	Biomass Blending and Densification System
BCSGS	Biomass Conversion to Synthetic Gasoline System
BFB	Biomass Fuel Blocks system
Btu	British thermal unit, a measure of heat energy
Cf	Cubic feet
CH4	Methane
CHEMCAD	Process modelling and simulation software
CHP	Combined heat and power
CO	Carbon monoxide, an unstable gas causing health hazards to humans
CO2	Carbon dioxide
COE	Cost of Electricity
COVID-19	CoronaVirus Disease – 19
EPIC	Electric Program Investment Charge Program
F	Degrees Fahrenheit
FORPOWER	small-scale FOREST POWER system
GHG	Greenhouse gas
GT	Gas turbine
H2	Hydrogen
HELC	Highly Efficient Low Cost
HEX	Heat exchanger
KWe	Kilowatt of electricity
LabVIEW	Data acquisition software
lb/hr	Pounds per hour
LCOE	Levelized Cost of Electricity
MC	Moisture content
MMt	Million metric tons
MWe	Megawatt of electricity
NCG	Non-condensable fuel gas
NOx	Nitrous oxide, an unstable gas causing health hazards to humans
O2	Oxygen

Term	Definition
PFD	Process flow diagram
PID	Process instrumentation diagram
ppm	parts per million
ppmv	parts per million volume
ppmvd	Parts per million volume, dry
SJVAQMPCD	San Joaquin Valley Air Quality Management Pollution Control District
Slash	Piles of forest residue generated as a result of sustainable forest management or logging
SR	Stoichiometric Ratio
Testo	Emission gas analyzer
TPD	Tons per day
TPY	Tons per year
UC	University of California

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