Federal Energy Management Program

American Recovery and Reinvestment Act (ARRA)

FEMP Technical Assistance

Installation Management Command – Southeast (IMCOM-SE)

Fast Pyrolysis Technology Demonstration
Fort Bragg, North Carolina #72

Prepared by: Pacific Northwest National Laboratory

September 2010

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Fast Pyrolysis Technology Demonstration Fort Bragg, North Carolina

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Prepared for the U.S. Department of Energy
Federal Energy Management Program
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
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Description of ARRA program

On February 13, 2009, Congress passed the American Recovery and Reinvestment Act (ARRA) of 2009 at the urging of President Obama, who signed it into law 4 days later. A direct response to the economic crisis, the Recovery Act has three immediate goals:

- Create new jobs and save existing ones
- Spur economic activity and invest in long-term growth
- Foster unprecedented levels of accountability and transparency in government spending.[1]

The Federal Energy Management Program (FEMP) facilitates the Federal Government's implementation of sound, cost-effective energy management and investment practices to enhance the nation's energy security and environmental stewardship. To advance that goal and help accelerate agencies' progress, FEMP works to foster collaboration between its Federal agency customers and the U.S. Department of Energy (DOE) national laboratories.

In 2009 and 2010, FEMP used funding from ARRA to facilitate Federal agency access to the broad range of capabilities expertise at the national laboratories. Funds were directed to the national laboratories to assist agencies in making their internal management decisions for investments in energy efficiency and the deployment of renewables, with particular emphasis on assisting with the mandates of the Energy Independence and Security Act of 2007 related to Federal facilities and fleets.

FEMP applied a simple vetting and approval system to quickly allocate work to each of the national laboratories in accordance with FEMP-provided funding. All assistance provided by the national laboratories was in accordance with the requirements of Federal Acquisition Regulation (FAR) Subpart 35.017 and the national laboratories' designation as "Federal Funded Research and Development Center" (FFRDC) facilities.

The Installation Management Command, Southeast won $1.4M in funding from the Environmental Security Technology Certification Program (ESTCP) to construct the equipment and test a fast pyrolysis process to convert wood waste, paper waste, and tree chips into BioOil at the landfill on Fort Bragg, North Carolina. In generic terms, pyrolysis is an ancient technology. Carbonaceous material is subjected to heat in the absence of oxygen and gas, liquid, and solid products occur. However subtle changes in feedstock particle size, reactor configuration, heating rate, temperature, pressure, and feedstock composition can lead to dramatically different partitions between gas, liquid, and char yields. Thorough understanding of pyrolysis phenomena and use of pyrolysis products has been the goal of scientists specializing in the field for more than three decades. This technology demonstration project did not have a Department of Energy national laboratory partner and was in need of technical assistance to define the key technology demonstration performance metrics and testing strategies.

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[1] http://www.recovery.gov/

Introduction

Results from a 2009 Pacific Northwest National Laboratory (PNNL) assessment of renewable energy generation potential in the Southeast revealed that biomass presents the greatest opportunity. The Renewable Oil International LLC was pursuing a demonstration of a fast pyrolysis process to convert wood waste, paper waste, and tree chips into BioOil. The Installation Management Command, Southeast and Environmental Security Technology Certification Program (ESTCP) initiated a project to construct the equipment and test the process at the landfill on Fort Bragg, North Carolina. The process will test the relative efficiency of several feedstocks including wood pallet waste, paper and cardboard waste, and whole tree chips. The resulting BioOil will be tested and analyzed to determine energy content, cost to produce and environmental impact. PNNL was requested to provide technical assistance, which included:

1. Preparing the Technology Demonstration Plan and initial information for the Cost and Performance report,
2. Providing technical review of the process and end products,
3. Defining techniques for measuring feedstock characteristics, BioOil energy balance, and resulting emissions from each feedstock, and
4. Identifying testing laboratories for various BioOil tests needed to determine potential future uses of the end products.

Description of Technology

Fast pyrolysis is the thermochemical conversion of carbonaceous material into a liquid. It involves extremely rapid heating of biomass (as an example) to form vapor, followed by rapid condensation of the vapors into a liquid phase. Typical fast pyrolysis temperatures range from 450°C-600°C. Achieving the heating rates required for fast pyrolysis requires small particles (<10 mm) that are very dry (~10 wt.% moisture), and a reactor configuration that facilitates rapid heat transfer. Biomass, in particular, becomes highly reactive under these conditions; so much so that the resulting liquid continues to react long after it has been generated, causing its viscosity to increase over time. This aging process becomes accelerated if the pyrolysis oil is stored at temperatures above 40°C. Instability and the highly oxygenated nature of pyrolysis oils means that oxygen must be removed (known as upgrading, hydrodeoxygenation, or hydrotreating) must be done before the pyrolysis oil may be used as a blendstock for transportation fuels.

This project's fast pyrolysis system is a 15 ton/day auger pyrolyzer, built by Renewable Oil International (ROI). The unit under construction is a scaled-up version and is based on ROI's experience with a 5 ton/day unit. In addition, ROI has partnered with Tolero Energy LLC to incorporate technology licensed from the University of Georgia, wherein pyrolysis oil is blended with biodiesel to generate a biodiesel blendstock which may be used as-is or further blended with petroleum-derived diesel. A process flow box diagram is shown in Figure 1. Each unit operation of the fast pyrolysis system is shown in green, products are shown in violet, material inputs and streams are grey, and heat streams are yellow.

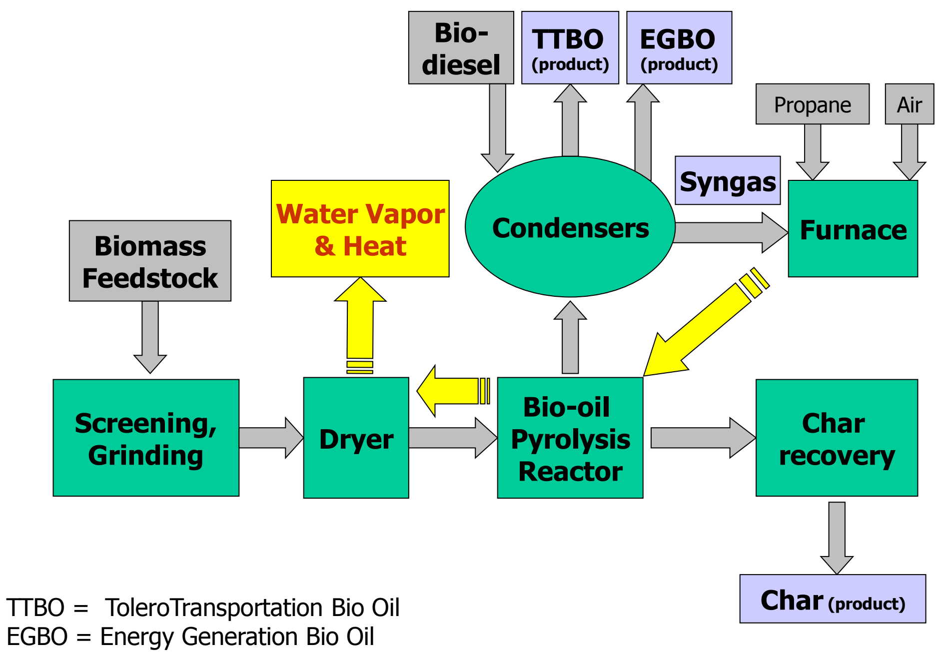


Figure 1. Process Flow Box Diagram

A. Feedstock Preparation

Primary feedstock preparation processing includes grinding the feedstock materials to an appropriate size and sieving. Fast pyrolysis necessitates a high heating rate. Smaller particles facilitate quick heating rates. This system is equipped to handle particles able to pass through a 1/8th inch sieve. Sieving also removes some undesirable materials such as metal and rocks.

B. Feed Bin, Dryer and Cyclone

The feedstock will be metered into the pyrolysis process from a feed bin. Flow rate to the pyrolysis reactor is controlled by metering the wood volumetrically using a slide gate on the front of the feed bin and adjusting the speed of the live bottom conveyor. The slide gate height will be correlated to the product volume on the conveyor, and bulk density for each feedstock will be measured and converted to mass flow using conveyor speed, recorded in real time. The feedstock will then move on conveyors through the dryer and into the pyrolysis reactor.

The dryer will be used for the forest harvesting residues to reduce moisture content from as high as 45% to about 10%. The dryer is designed to handle up to 45% moisture content. Dryer heat will come from the reactor furnace heat exchanger exhaust (i.e., excess process heat from heating the steel shot). Exhaust from the dryer will be vented to a cyclone to remove particulates.

C. Reactor, Furnace and Condensers

Feedstock that is the proper particle size (max particle thickness 1/8-inch) and moisture content (less than or equal to 10%) will be conveyed from the dryer through a rotary airlock and auger into the bio-oil reactor. Simultaneously, steel shot that has been preheated to the correct temperature (400-550 °C) will be injected into the bio-oil reactor and mixed with the biomass to further facilitate heat transfer. Decomposition of the biomass will occur almost instantly upon contact with the hot steel shot. An auger in the bottom of the reactor conveys the char co-product and steel shot from the bio-oil reactor to a char separation system. The char (which is a fine powder) is separated from shot using particle size differences and will be stored in one-ton tote bags or barrels. Bag weight will be monitored over time using platform scales. The steel shot is reheated in the furnace and recycled back to the bio-oil reactor.

The gas and vapor from the reactor are passed through a direct contact condenser system where the gas and vapor come in contact with a cooler (with respect to the gas and vapor stream) biodiesel stream. The biodiesel will facilitate the condensation and absorption of a fraction of the bio-oil, forming the Transportation Bio-Oil (TTBO) product. Biodiesel will be added to the condenser system in a set proportion so as to maintain the desired ratio of bio-oil and biodiesel. The remaining bio-oil will pass through a second condenser, to condense the Energy Generation Bio-Oil (EGBO) product from the gas and vapor stream. The heat transfer fluid streams will be cooled with a liquid-to-air heat exchanger. The products will be piped through volumetric flow meters to their respective storage tanks.

The gas from the reactor (i.e., syngas) will be metered into the furnace burner to heat the steel shot. There is no direct contact between the steel shot and the burning syngas. The syngas is burned in a furnace and the resulting stack gas passed through a heat exchanger to indirectly heat the steel shot. Remaining heat from the heat exchanger will be ducted to the dryer where it is blended with ambient air to cool it to around 250 °F.

The site layout plan and a schematic of the front view are given in Figures 2 and 3.

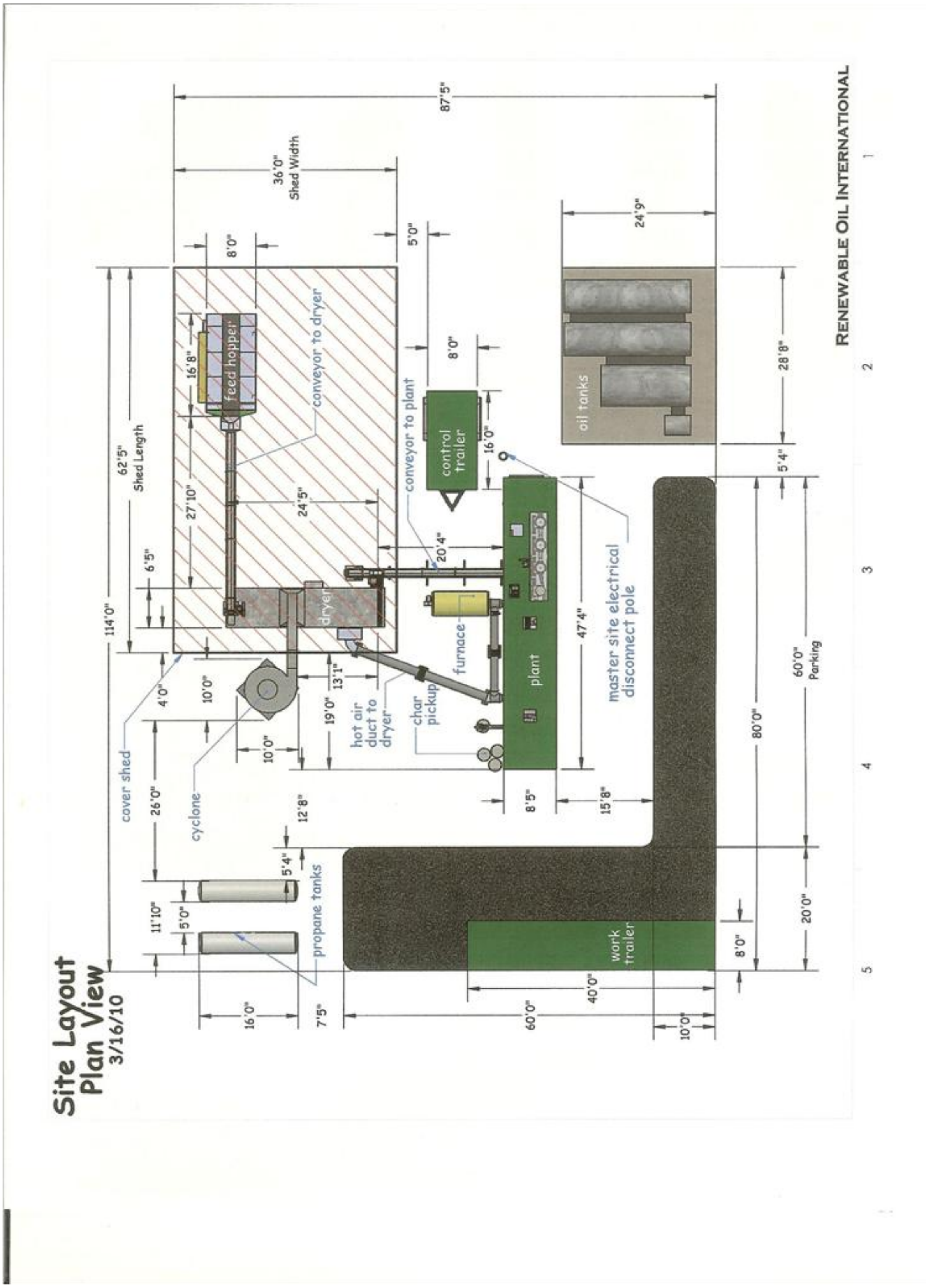


Figure 2. Site layout plan for the ROI fast pyrolysis system

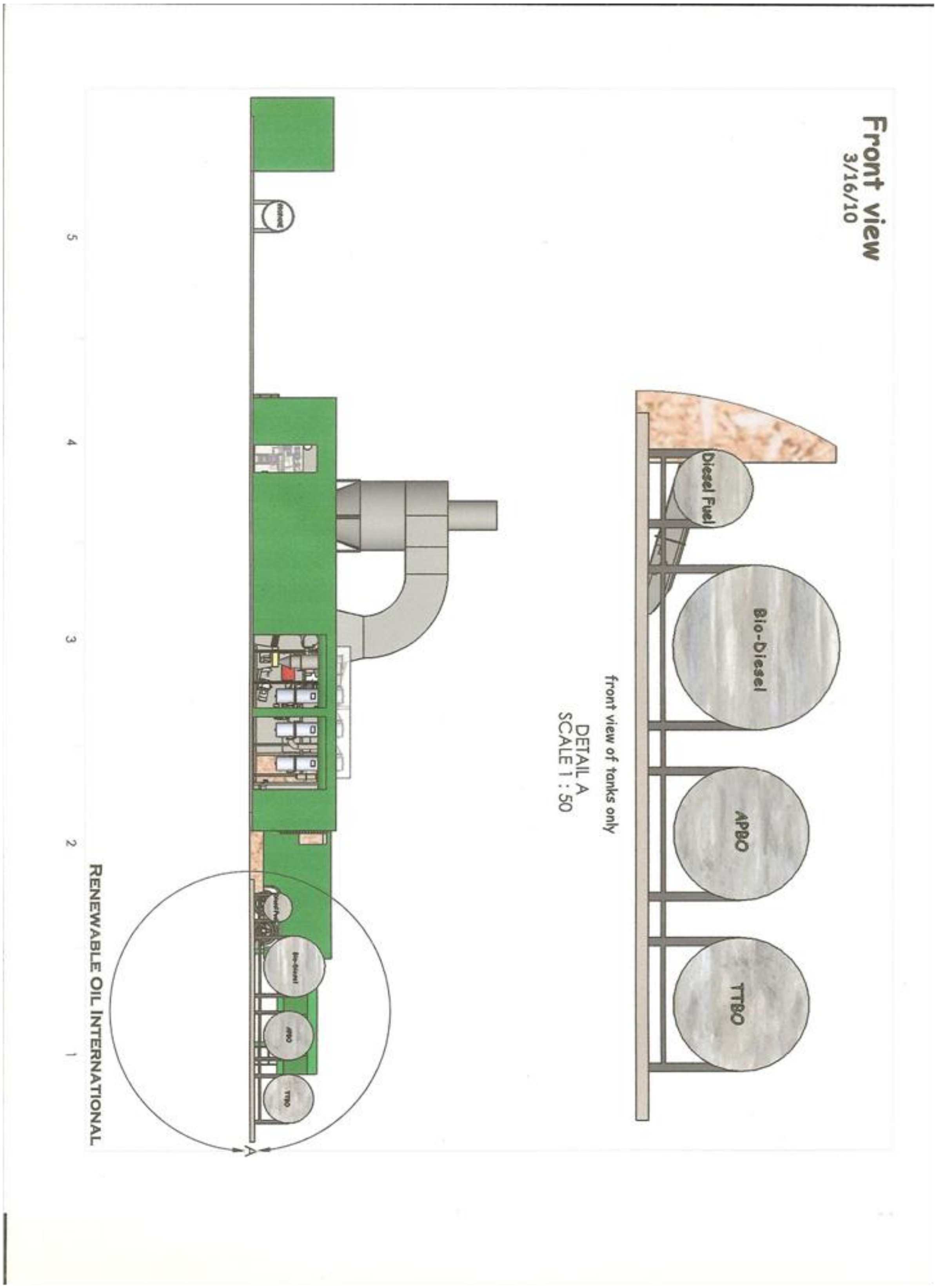


Figure 3. Schematic of the front view of the ROI fast pyrolysis system

Technology Demonstration Plan

One of the major tasks for this project in FY10 was to prepare the detailed Technology Demonstration Plan (TDP) required before the technology demonstration can move forward. An ESTCP TDP describes the planned research and analysis and includes:

- Identification of appropriate metrics by which to evaluate the technology
- Quantitative performance criteria
- Planning appropriate instrumentation and measurement locations
- Identifying entities with capability for performing necessary testing
- Data analysis and quality assurance

PNNL's initial efforts to prepare the TDP included a thorough review of the ROI fast pyrolysis system's mechanical drawings. This resulted in the identification of a significant byproduct stream. Because this type of pyrolysis system has never been built, literature was surveyed to better understand the fractionation of pyrolysis oil products into the "main" product stream and the new "byproduct" stream. It was determined that a large fraction (90% or more) of the pyrolysis oil could go to the byproduct stream. It follows that this stream should be tested as well. These two streams became known as the TTBO and EGBO described above. The TDP was expanded to include testing and quantification of performance criteria for both products.

Metric Identification and Performance Criteria

The goal of ESTCP is to demonstrate and validate promising, innovative, and cost-effective technologies that target the Department of Defenses's high-priority environmental requirements.[2] Validating new technology presents the challenge identifying metrics that are appropriate for the processes and/or products for which standards do not yet exist. Performance criteria should be quantitative and documented to allow for a comparison with standards for a known process and/or product, such as a petroleum-derived analogue, that is expected to be displaced using the new technology or product. Metric identification and performance criteria documentation was a significant effort of the technical assistance project. The performance objectives of the ESTCP project are defined to show the energy balance for each feedstock, as well as environmental performance that meets permit requirements and produces fewer emissions/pollutants than conventional fossil fuel sources. The pyrolysis system's performance will also be evaluated. Performance objectives included in the TDP address feedstock throughput, the ability to handle varying feedstocks, system reliability, and the system's ease of use.

Several data sets are required to perform the above evaluations. A discussion of each Performance Objective, the metric used to determine success, the success criteria, and the respective data requirements follows. This information is also summarized in Table 1**Error! Reference source not found.**.

[2] http://serdp-estcp.org/About-SERDP-and-ESTCP/About-ESTCP

Table 1. Performance Objectives and Metrics

Performance Objective	Metric	Data Requirements	Success Criteria
1. Energetic return on investment (EROI)	a. Comparison of useable acquired energy to the energy expended to acquire the new fuels	i. Energy expended during handling and processing, transport, grinding, drying, and conveying feedstock ii. Energy expended to operate pyrolysis plant iii. Energy acquired in the form of bio-oil (TBO, EGBO), syngas, and char	EROI > 6
2. Liquid product quality	a. EGBO is an appropriate fuel for industrial burners, per ASTM D7544-09	Analyses related to the ASTM standard (see Table 2).	Unit produces EGBO that is comparable to pyrolysis liquid biofuel, as described in ASTM standard D7544-09, Standard Specification for Pyrolysis Liquid Biofuel
	b. TTBO is an appropriate fuel for engines, per ASTM D975	Analyses related to the ASTM standard (see Table 3)	Unit produces TTBO that is comparable to diesel (as described in ASTM D975)
	c. Ultimate analysis and other fuel properties	See Table 4	See Table 4
	d. Combustion Efficiency- boiler	i. Thermal output; ii. Measurements of CO and THCs in burner test stand flue gas; iii. Measurements of carbon in fly ash iv. Flame stability	Emissions measurements are lower or the same as those for petroleum-derived fuel
	e. Combustion Efficiency - engine	Brake Specific Fuel Consumption	183-193 g/bhp-hr

Performance Objective	Metric	Data Requirements	Success Criteria
3. Pyrolysis system can handle feedstocks of varying quality	a. Feedstock moisture and ash content	i. Moisture content of each batch ii. Ash content of resultant bio-oil (TTBO, EGBO) iii. Moisture content of bio-oils	Unit produces bio-oil that meets bio-oil standard (particularly for ash) for feedstocks with moisture content <45%
	b. Feedstock conversion rate	Amount of bio-oil (TBO, EGBO), syngas and char generated per ton of feedstock	50-60 percent dry weight yield of bio-oil
	c. Product energy content	Energy content of bio-oil (TBO, EGBO), syngas and char	EGBO: 76,600 Btu/gal TTBO: 122,000 Btu/gal Char: 1,960 Btu/pound Syngas: 1,575 Btu/pound
4. Environmental performance	a. Air emissions from **test boiler** burning EGBO and petroleum-derived fuel	i. Gallons of fuel/hr ii. Pounds of air pollutants/hr (O_2, CO, CO_2, THC, NO_x, SO_2)	Continuous emissions measurements (CEMs) for bio-oil are lower or the same as those from petroleum-derived fuel
	b. Air emissions from test **engine** burning (TTBO and petroleum-derived fuel)	i. Gallons of fuel/hr ii. Pounds of air pollutants/hr (CO, CO_2, NO_x, PM)	Continuous emissions measurements (CEMs) for bio-oil are lower or the same as those from petroleum-derived fuel, with the exception of NOx
	c. Air emissions from **furnace** operation	i. tons of feedstock/hr ii. lbs of air pollutants/hr	DAQ Air Permit: PM <=2.99 ton/hr SO_2 <=2.3 lb/million Btu heat input
	d. Greenhouse gas analysis	Inventory of inputs, outputs, with applied EPA factors, per federal guidance draft	>50% reduction in greenhouse gas emissions over petroleum-based fuel
5. Fast pyrolysis system and boiler/engine reliability	a. Actual vs. scheduled operating times	i. Hours pyrolysis unit is operational ii. Hours scheduled to operate	90% Equipment availability
	b. Maintenance	Number, type, and cost of scheduled and unscheduled	No unscheduled maintenance actions

Performance Objective	Metric	Data Requirements	Success Criteria
		maintenance actions	
	c. Feedstock throughput	Number of tons of feedstock processed	5 dry tons in 8 hours at steady state operations
	d. Test Burner operations	i. What equipment modifications (e.g., special burner nozzles) or burner adjustments were necessary? ii. What properties of the biofuels mandated the modifications?	Document modifications, adjustments, or additional maintenance to burner test stand operations as a result of using bio-oils
	e. Test Engine operations	i. Hours engine is operational ii. Hours engine is scheduled to operate	Actual operating hours are within +/- 10 percent of scheduled operating hours.
6. Degree of operator expertise required		i. qualifications of operators hired ii. preventive maintenance requirements	Operators with specific on-the-job-training (OJT) are able to operate unit and do required PM

Each performance objective is described in greater detail here.

Objective 1, Energetic Return on Investment (EROI), will assess the overall return on energetic investment (Cleveland C., Costanza R., Hall, C., Kaufmann, R. 1984; Cleveland, 2005; Gagnon, N., Hall, C., Brinker, L., 2009). EROI is defined as the ratio of useable acquired energy to the energy expended to obtain that energy, as shown below.

$$EROI = \frac{Useable\ Acquired\ Energy}{Energy\ Expended}$$

The EROI for crude oil extraction and conversion to liquid fuels is well documented (Cleveland C., Costanza R., Hall, C., Kaufmann, R. 1984; Cleveland, 2005). For this demonstration, the analogous evaluation is an energy balance from biomass collection through bio-oil production, as shown in Figure 4. In Figure 4, the energy expended to collect and convert the biomass is shown in at the bottom of the figure. Useable acquired energy is shown at the top of the figure. Note that energy content of the feedstock (e.g., crude oil, biomass) is not considered an energy expenditure during an EROI evaluation.

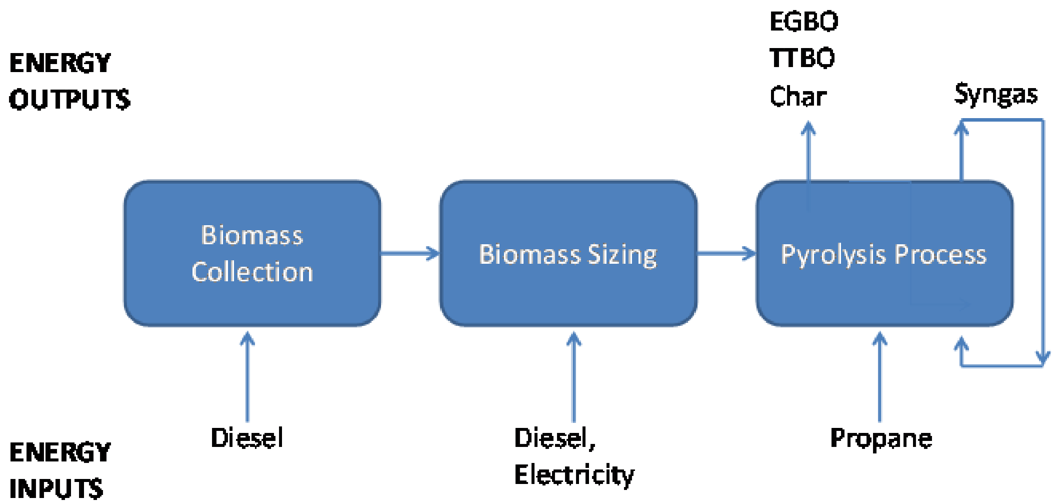


Figure 4. Simplified process flow showing energy inputs and outputs

The success criterion of EROI > 6 provides a comparison between this demonstration and crude oil extraction and conversion to liquid fuels (Cleveland C., Costanza R., Hall, C., Kaufmann, R. 1984; Cleveland, 2005). The EROI for conversion of crude oil to petrol fuels ranges from 6-10 (Cleveland, 2005). Alternative fuels that have been documented (prior to 2005), such as corn ethanol and oil shale have been unable to meet this range (Cleveland, 2005). The target of EROI > 6 was selected for this demonstration.

A 'feedstock' will be defined for the purposes of this analysis as a wood source with a moisture content of ≤ 45 wt.% prior to the drying stage of the pyrolysis process. The feedstock for this demonstration is forest residues. If the feedstock varies significantly in moisture content, the EROI will be calculated for different batches to assess the impact of moisture content on efficiency.

The energy content of the pyrolysis products (bio-oil and char BTU/dry lb of input feedstock) is strongly influenced by the moisture content of material as it enters the reactor. Therefore, field drying will be conducted to the extent possible and then a dryer will used on the front end of the process to reduce the moisture content down to at least 10% on a wet basis. Moisture content of the feedstock will be measured before and after the dryer. Measurements will then be correlated to bio-oil qualities to evaluate overall efficiencies for the moisture contents observed.

Several data sets are required to evaluate the EROI. They are listed below and described, in more detail, in the "Planning Instrumentation Devices and Measurement Locations" section. The first set captures the energy expended to recover the biomass and prepare it for the pyrolysis plant. The second set captures energy expended to operate the pyrolysis plant. The third data set measures the energy output of the pyrolysis products. Measurement locations and the data collected from the pyrolysis plant are shown in a simplified process and instrumentation diagram in the "Planning Instrumentation Devices and Measurement Locations" section.

Metric 1a: EROI

Data Required:

i. Energy expended during handling and processing, transport, grinding, drying and conveying feedstock (Btu/ton of feedstock)

- Processing steps to assess:
  - Collection and transport to pyrolysis unit
  - Initial feedstock screening to remove dirt
  - Grinding to appropriate process feed diameter
  - Screening of ground feedstocks to remove oversized materials and metals
  - Conveying material between feed bins, dryer and pyrolysis unit
- Data for each processing step:
  - Associated tonnage of feedstock handled
  - Estimated fuel or electricity consumed
- Integrated dryer mass input
  - Moisture content of wet biomass
  - Weight of wet biomass
- Integrated dryer mass output
  - Moisture content of dried biomass
- Net dryer energy from waste heat
  - Syngas flow rate, temperature, pressure, composition to shot furnace

ii. Energy expended to operated the Pyrolysis plant

- External energy input
  - Electricity
  - Propane (process startup and auxillary)
  - Rejected heat from furnace (net available to dryer)

iii. Energy acquired

- Pyrolysis mass/energy output
  - Bio-oils (TTBO, EGBO)
    - Volumetric flow, mass density, composition
    - Pyrolysis-oil fraction
    - Energy density of bio-oils (measured in Objective 2)
  - Syngas, mass flow, composition
  - Char, mass flow, composition, energy density
  - Biodiesel volumetric flow to condenser
    - Energy density, specific gravity of biodiesel
    - Mass density
    - Note: While the biodiesel is not an energy output of the process, its contribution to TTBO needs to be measured, so that it can be subtracted from the TTBO for the purposes of calculating the "energy acquired" portion of the EROI

Note that the process is expected to generate a very minimal amount of tar that may plate out on the equipment. This will not be included in the assessment.

Success Criteria: EROI > 6.

Objective 2, Liquid Product Quality, will assess whether the EGBO and TTBO are comparable to other fuels typically burned in the targeted applications (e.g., boilers and engines, respectively). Due to the developing nature of the alternative fuels market and the developmental state of the ROI fast pyrolysis process, there are no recognized standards (e.g., ASTM or ISO) that are directly applicable to the EGBO or the TTBO. Furthermore, different types of boiler and engine services can handle widely different ranges of fuel characteristics. As a result, identification of hard, numerical success criteria is premature for these products. Instead, the characterization data that is typically used for similar types of fuels will be collected to which will understand the range of boilers and engines that will be suited for these fuels.

The EGBO will be characterized using ASTM standard D 7544-09, Standard Specification for Pyrolysis Liquid Biofuel (15 June 09). See Metric 2a.

The TTBO will be characterized using ASTM D975 for Diesel Fuel Oils to determine whether this fuel grade (and thus engines) is a good match for the TTBO. See Metric 2b.

The EGBO and TTBO will be characterized with a limited number of additional analyses that are frequently requested by fuel customers. See Metric 2c.

The combustion efficiency of the bio-oils will also be evaluated for both the boiler (EGBO) and the engine (TTBO) scenarios. See Metrics 2d and 2e.

Metric 2a: <u>EGBO is an Appropriate Fuel for Industrial Burners, per ASTM D7544-09</u>

Data Required:

- Analyses of EGBO as required by the ASTM standard (see Table 2 below).

Success Criteria: Unit produces EGBO that is comparable to pyrolysis liquid biofuel, as described in ASTM Standard D 7544-09, Standard Specification for Pyrolysis Liquid Biofuel, 15 Jun 09, Table 2 below.

Table 2. Pyrolysis Liquid Biofuel Specifications (ASTM D7544-09)

ASTM Standard D 7544-09:	Success Criteria	Test Method
Gross heat of combustion	15 MJ/kg min	ASTM D240
Water content	30% max by mass	ASTM E203
Pyrolysis Solids Content	2.5% max by mass	Annex A-1 to 7544
Kinematic viscosity at 40 °C (without filtering)	125 mm2/s max	D445
Density at 20 °C	1.1-1.3 kg/dm3	D4052

ASTM Standard D 7544-09:	**Success Criteria**	**Test Method**
Sulfur Content	.05% max by mass	D4294
Ash Content	.25% max by mass	D482
pH	Report	E70
Flash point	45 °C min	D93, proc B
Pour point	-9 °C max	D97

Metric 2b: TTBO is appropriate for fuel burned in engines, per ASTM D975

Data Required: Analyses of TTBO as required by the ASTM standard (see Table 3 below).

Success Criteria: Unit produces TTBO that is comparable to diesel (as described in ASTM D975)

Table 3. Standard Specification for Diesel (ASTM D975)

Property	**D975 Success Criteria**	**ASTM Method**
Flash Point (closed cup)	52 min °C	**D93**
Water & Sediment	0.05 max % vol.	**D2709**
Kinematic Viscosity, 40 °C	1.9 - 4.1 mm2/sec.	D 445
Sulfated Ash		D 874
Grade No. 2	0.50 max % mass	D129
Grade No. 2 - Low Sulfur	0.50 max % mass	D2622
Copper Strip Corrosion	No. 3 maximum	D 130
Cetane	40 min	D 613
Cetane Index or Aromaticity	40 min 35 max % vol.	D976 D1319
Cloud Point	**report °C**	**D 2500**
Ramsbottom Carbon Residue	0.35 max mg KOH/gm	D524

Property	**D975 Success Criteria**	**ASTM Method**
Ash	0.01 max % mass	D482
Density, 15 °C	Report	D1298
Pour point	Report	D97
Distillation Temperature, 90% Recovered	282-338 °C	D86
Lubricity, HFRR @ 60 °C	520 max. microns	D6079

D975: http://www.greenfuels.org/biodiesel/tech/ASTM-D975.pdf

Metric 2c: Ultimate analysis and other fuel properties

Data Required: Analysis of EGBO and TTBO according to the methods listed in Table 4.

Success Criteria: EGBO falls within or near the range given for bio-oil, in Table 4 and TTBO falls within or near the range given for biodiesel, in Table 4

Table 4. Ultimate and other fuel property analyses

	Success Criteria	**Test Method**
Ultimate analysis (wt%):		
Carbon (Bio-oil/Biodiesel)	40-46/75-77	UOP866-86
Hydrogen (Bio-oil/Biodiesel)	5-6/12-14	UOP866-86
Oxygen (Bio-oil/Biodiesel)	40-50/11-12	By difference
Nitrogen (Bio-oil/Biodiesel)	0.5-2/4-77ppm	UOP866-86
Sulfur	See "Sulfur Content" in Tables 2 and 3	
Other Criteria:		
Chlorine	Report data	ASTM E256-09
Alkali metals	Report data	ASTM WK21755
Conradson Carbon Residue (CCR)[1], EGBO only	14-23 wt.%	ASTM D189-88
Stability	Report data	IP 378/87/ASTM D4625-

	Success Criteria	Test Method
		86
Total acid number	Report data	UOP565-05
Gross heat of combustion (TTBO only)	~37.8 MJ/kg (for biodiesel) ~17.5 MJ/kg (for pyrolysis oil)[2]	ASTM D240
Water soluble alkalies (sodium and potassium), EGBO only	Report data	

[1]The CCR test method measures residual carbon in heavy liquid fuels and lubricants using destructive distillation

[2]The TTBO will have a lower heating value than biodiesel due to the pyrolysis oil fraction. Once the fraction of pyrolysis oil is known, a weighted average of the the two heating values may be used to compare to the total gross heat of combustion that is measured

Metric 2d: Combustion Efficiency - EGBO

Data Required:

- Thermal output
- Measurements of CO and total hydrocarbons (THCs) in burner test stand flue gas
- Measurements of carbon in fly ash
- Flame stability

Success Criteria: Bio-oils performs as well as or better than petroleum-derived fuel.

Metric 2e: Combustion Efficiency - Engine. Assess the efficiency of the TTBO when burned in a test engine by calculating the Brake Specific Fuel Consumption (BSFC). The BSFC represents the mass rate of fuel consumption divided by the power output of the engine. Given the energy density (calorific value) of the fuel, the BSFC is an indicator of how effectively/efficiently the engine uses that fuel (e.g., energy input -vs- energy output). Calculating the BSFC for the petroleum-derived diesel fuel and the TTBO product will allow direct comparison of the combustion efficiency of these fuels in a diesel engine.

Data Required:

Brake Specific Fuel Consumption

Success Criteria: 183-193 g/bhp-hr (Williams, 2006), determined by dividing the mass of fuel consumed by the power output and time.

Objective 3, Pyrolysis Plant Can Handle Feedstocks of Varying Quality, will demonstrate that the pyrolysis unit can handle a full range of feedstock conditions. The quality of the forest residues feedstock will vary with respect to moisture and dirt. Wet wood increases energy input requirements for the dryer and creates wet bio-oil with reduced energy content. Feedstock quality also depends on the amount and nature of foreign material. Excessive foreign matter can increase the amount of ash in the char and potentially damage the equipment. This information will be critical to understanding processing, handling, and storage requirements for the feedstock.

Metric 3a: Feedstock Moisture and Ash Content

Data Required:

- Moisture (see 1.a.ii) and ash content of each batch of feedstock
- Correlated ash content of resultant bio-oils (see Objective 2, Tables 2 and 3)
- Correlated moisture content of resultant bio-oils (see Objective 2, Tables 2 and 3)

Success Criteria: Unit produces bio-oils that meet the Objective 2 success criteria for ash and moisture content with feedstocks containing up to 45% moisture.

Metric 3b: Feedstock Conversion Rate

Data Required:

- Amount of bio-oils, syngas and char generated (see Metric 1.a.iii) per ton of feedstock (see Metric 1.a.i)

Success Criteria: 50-60 percent dry weight yield of bio-oil

Metric 3c: Product Energy Quality

Data Required:

- Energy content of bio-oils, syngas and char (measured in Objective 2)

Success Criteria: 76,600 Btu/gal for EGBO; 122,000 Btu/gal for TTBO; 1960 Btu/pound char and 1570 Btu/pound syngas. Note: Energy densities for char and syngas are estimates based on CHEMCAD simulation of fast pyrolysis of hybrid poplar. Measured values from the demonstration should be close. Energy densities given for TTBO are based on biodiesel. It is expected the TTBO to have a lower energy density than biodiesel, due to the pyrolysis oil fraction dissolved into it.

Objective 4, Environmental Performance of each Feedstock and Each Fuel, will assess how cleanly the EGBO and TTBO burn in respective test burner and engine labs in comparison with comparable fossil fuels, as well as air releases from the pyrolysis unit.

The pyrolysis plant operations will be assessed using the state air permit limits that would have applied if the unit had been installed at Fort Bragg. The North Carolina Department of Air Quality has issued an air permit (No. 09993R00) for the ROI unit, requiring testing at the drier (ES-1) and the furnace (ES-2). The furnace emission standards are typical combustion standards, which was adopted as metrics for this performance objective.

The EGBO performance in a boiler will be assessed in a bench-scale combustion system operated at Iowa State University. The TTBO performance in an engine will be assessed in a test engine operated by Southwest Research Institute (SwRI)

Metric 4a: Air emissions from burner test stand operation, burning EGBO and petroleum-derived fuel

Data Required:

- Air emissions measurements (continuous emissions monitoring)
  - O_2
  - CO_2
  - CO
  - NO_2
  - SO_2
  - total hydrocarbons (THCs)
  - Particulate matter
  - VOCs
- Mass/volume of fuel burned

Success Criteria: Biofuel burner emissions (on a Btu basis) are equal to or lower than those for emissions/Btu from burning petroleum-derived fuel oil (with the exception of NOx).

Metric 4b: Air emissions from test **engine** operation, for each feedstock (TTBO and petroleum-derived)

Data Required:

- Air emissions measurements under hot-start conditions for the following criteria pollutants
  - CO_2
  - CO
  - NO_x
  - Particulates (continuous emissions monitoring)
- Mass/volume of fuel burned

Success Criteria: Biofuel emissions lower than those for petroleum-derived transportation fuel oil, with the exception of NOx.

Metric 4c: Furnace Emissions, for each feedstock

Data Required: Testing parameters required by the DAQ air permit include:

- tons of feedstock
- weight of products
- PM (furnace)
- SOx (furnace)

Success Criteria: The pyrolysis plant meets air permit requirements:

- PM $\leq$ 2.99 ton/hr (Permit Condition 5)

- SOx $\leq$ 2.3 lb/million Btu heat input (Permit Condition 6)

Metric 4d: Greenhouse Gas analysis

Data Required: See Objective 1

Success Criteria: 50% reduction in greenhouse gas emissions compared with comparable fossil-derived fuel

Objective 5, Fast Pyrolysis System and Boiler/Engine Reliability, will assess the equipment reliability of the pyrolysis system and boiler and engine operations. The ability of the process to handle feedstock at the targeted process capacity will be assessed. The fast pyrolysis unit is designed to handle 15 dry tons per day when operating around the clock. Various factors can impact the ability of a process to meet its claimed capacity, including feedstock quality variability, feedstock availability, operator skill, mechanical reliability, etc. This objective will assess the overall ability of the system and the operators to process feedstock at the capacity rate of the system. It will also provide a platform for reporting maintenance required by the pyrolysis system as well as boiler or engine modifications that may be required to burn the bio-oils produced.

Metric 5a: <u>Actual vs. Scheduled Operating Times</u>

Data Required:

- Hours pyrolysis unit is scheduled to operate
- Hours pyrolysis unit is operational

Success Criteria: 90% equipment availability

Metric 5b: <u>Maintenance</u>

Data Required:

- Number of scheduled and unscheduled maintenance actions
- Types of scheduled and unscheduled maintenance actions
- Costs of scheduled and unscheduled maintenance actions

Success Criteria: Zero unscheduled maintenance actions

Metric 5c: <u>Feedstock Throughput</u>. The pyrolysis process is rated to process 15 dtpd, assuming 24 hr/d operation. The success criteria accordingly is being set at 5 dtpd at steady state operation.

Data Required:

- Number of tons of feedstock processed per 8 hour shift

Success Criteria: 5 dry tons per day at steady state operations

Metric 5d: <u>Test Burner Operations</u>

Data Required:

- Any equipment modifications, burner, or air/fuel adjustments required to operate burner on bio-oils generated
- Properties of the biofuels mandating the modifications

Success Criteria: Documentation of modifications, adjustments, or additional maintenance required for burner test stand operation on bio-oils generated

Metric 5e: Test Engine Operations

Data Required:

- Actual operating hours
- Scheduled operating hours

Success Criteria: Actual operating hours are within +/- 10 percent of scheduled operating hours.

Objective 6, Degree of operator expertise required, will assess the expectation that the unit can be run successfully with two operators with on-the-job training.

Metric 6: Degree of Operator Expertise Required.

Data Required:

- Qualifications of operators hired
- Preventative maintenance requirements

Success Criteria: Operators with specific on-the-job-training are able to operate the unit and do required preventative maintenance

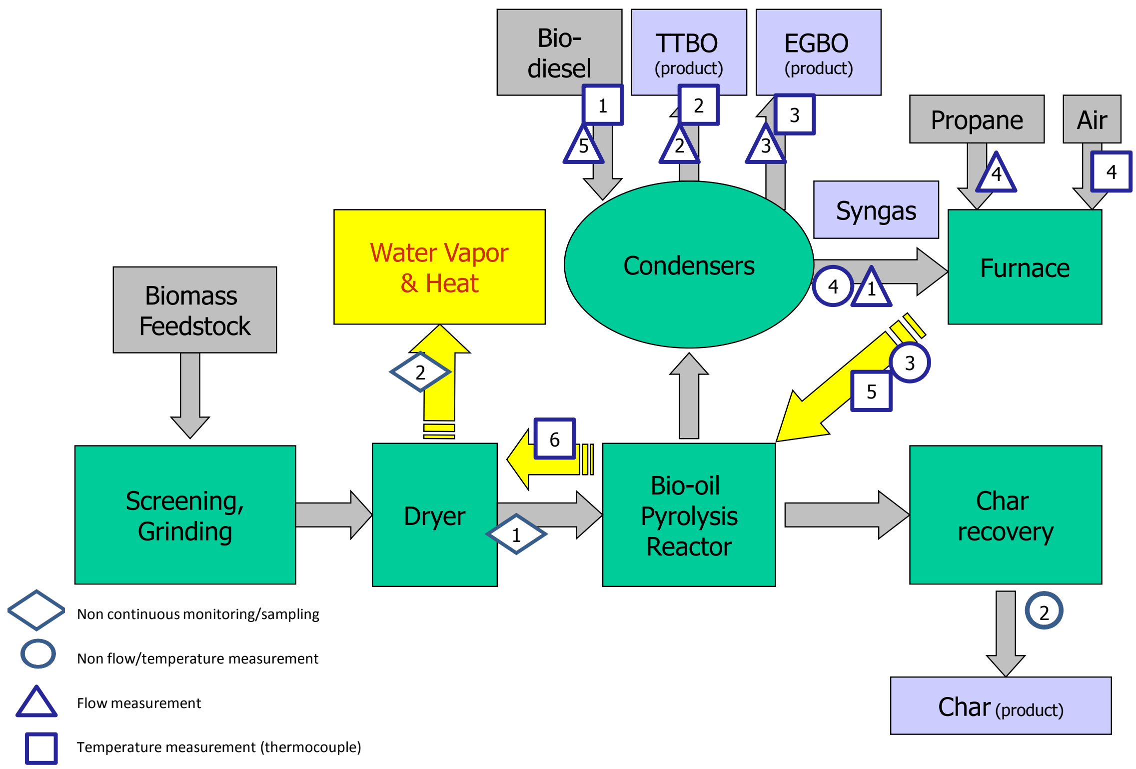
Planning Instrumentation Devices and Measurement Locations

The technical assistance team worked closely with Auburn University and ROI to coordinate an instrumentation strategy with the data required for evaluating performance criteria. Several instruments including scales, thermocouples, volumetric flow meters, and portable gas monitors will be used to collect the data required. A simplified schematic of the process and instrumentation is given in Figure 5.

The list of sensors includes six volumetric flow meters with associated temperature and pressure sensors for correction of flow rates to standard conditions. The net exhaust energy from the furnace will be characterized using fuel flow rates (syngas, propane) and composition plus exhaust oxygen levels (from portable meter measurements) and temperatures. All input energy consumption (electricity, propane, biodiesel) will be metered. The dryer will be sub-metered to determine net electricity consumption of the pyrolysis reactor system.

It is anticipated that one week of data collection, plus one week of preparatory work to wire sensors, integrate data collection hardware, and calibrate equipment will be needed. During each data collection run, the first day will be spent calibrating the input flow rate measurements for the feedstock and prepping the data acquisition system. The remaining days of the week will be used to characterize performance of the reactor system. Measurements will include a starting point for electricity and propane consumption. Once the pyrolysis system has reached a steady operating point, input energy and output products will be totaled and these values used to characterize the startup process. After that point, continuous recording of operating conditions (at one-minute intervals) will be made for the remainder of the operating day.

Those processes not fully instrumented will be measured at periodic intervals. It is likely grab samples at 1-hour intervals will be used to measure feedstock moisture at dryer inlet and outlet conditions) and bulk density. Sampling of the syngas and furnace exhaust streams will be made hourly, as will grab samples of oil products for composition and quality analysis.



1 2 Biomass feed rate to the pyrolysis reactor will be measured using conveyor speed and calibration curves relating feed bin gate opening height to mass per unit length of conveyor. These numbers will be developed through calibrations. Moisture content will be determined through sampling input and output streams at fixed intervals.

2 Emissions from the dryer will be measured by sampling periodically during operation
Char mass flow rate will be measured using electronic scales sampled at known time intervals.

2 3 5 1 2 3 Flow rates (TTBO, EGBO, Biodiesel) will be measured using volumetric flow meters, corrected for temperature.

1 4 Syngas and/or propane flow rate will be measured using a mass flow meter, with periodic sampling of composition (gas bags).

4 4 5 3 Furnace performance will be determined from mass flow rate of propane and gas composition (sampled using a portable gas analyzer) at the exit. Flow rates of air and exhaust gases will be corrected for temperature.

6 Temperature of dryer air will be sampled. Flow rates will not be measured directly, but determined using pre- and post ambient air mix temperatures.

Figure 5. Simplified Process and Instrumentation Diagram

Operational Testing and Sampling Protocol

The technical assistance project was instrumental in fleshing out the operational testing and sampling protocol. Primary operational phases of the demonstration are captured in Phases 3 and 4 of the ESTCP project. Parameter installation points have been selected to enable characterization and documentation of steady-state operation. Table 5 and Table 6 outline the specific parameters, their installation points, and the number and type of devices that will be used to measure each performance objective during each operational stage of the project (i.e., Phases 3 and 4).

Table 5. Phase 3, Pyrolysis Process Operation, Testing, Analysis, and Key Performers

Phase 3: Pyrolysis Process Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
1. Energetic Return on Investment	i. Energy expended during handling and processing to transport, dry, grind, and convey feedstock	Fueling logs for equipment used to move feedstock to pyrolysis site	unknown	Trucks, bobcats, etc. used to convey feedstock. Capture quantity of fuel used by these equipment.	USFS
		Dryer		Mass and moisture content of feedstock at the dryer inlet and outlet	Auburn
		Grinders	In field and at pyrolysis unit	Mass and energy density (proximate analysis) of Biodiesel or electricity used to run grinders [add screening if it requires separate fueling from the grinders]	USFS, Auburn
		Conveyers	At pyrolysis unit	Electricity used to run conveyers. If there is a gen set here, capture the fuel consumed	Auburn
	ii. Energy expended to operate pyrolysis plant	Electricity to pyrolysis unit	Integrating Meter	Sub-metered to separate from dryer requirements	
		Propane to furnace unit	Volumetric flow rate corrected to standard temperature and pressure	Volumetric flow meter, thermocouple temperature, pressure sensor	

Phase 3: Pyrolysis Process Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
				Also ambient air temperature	
		Rejected heat from furnace (net available to dryer)	Temperature, gas composition	Thermocouples (2) and portable gas analyzer	
	iii. Energy acquired (bio-oils, syngas, char, heat)	TTBO, EGBO, Biodiesel	Volumetric flow measurements (2) Temperature corrected to mass equivalent Flow meter for biodiesel Storage tank sample ports (3)	Integrated flow meters at surge tank exits, biodiesel flow sampled at condenser input, temperatures (thermocouples) at each Energy density measurements - see Objective 2	Auburn
		Syngas	Volumetric flow rates, corrected to standard temperature and pressure Syngas sample port	Integrated flow meter at furnace input, plus thermocouple temperature and pressure sensor, composition from hourly samples	Auburn
		Char	Weight, composition, energy density over time	Platform scale on char conveyor dump	Auburn
		Heat	Pre and post ambient air mix temperatures	Thermocouples before and after dryer	Auburn
2. Liquid product	Ultimate analyses	Bio-oils storage	Grab samples hourly	Daily average values from	Auburn

Phase 3: Pyrolysis Process Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
quality	and other fuel properties	tank	from tank sample ports (2)	composite samples	
	Bio-oil fuel characteristics	Bio-oils storage tanks	Sampled hourly from tank sample ports (2)	EGBO – ASTM D7544 analysis TTBO – ASTM D6751 and D975 analysis Daily average values from composite samples	Southwest Research Institute
3. Feedstock quality	Moisture and ash content of each batch of feedstock	Sampled at feedstock weigh bin and exit from integral dryer	Hourly samples	Oven drying (moisture) (see Objective 1), and total organic carbon analysis (ash)	Auburn
4. Environmental performance of each fuel	Furnace emission rates	Furnace	[Phil]	[Phil]	ROI
5. Fast Pyrolysis System and boiler/engine reliability	Hours pyrolysis unit is operational and hours scheduled to operate	Operator's log			ROI
	Number, type, and cost of scheduled and unscheduled maintenance actions	Operator's log			ROI
	Number of dry tons of feedstock	Feed rate measured from	Belt speed from conveyor motor drive,	Mass flow rate calculated from calibration curves	ROI, Auburn

Phase 3: Pyrolysis Process Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
	processed	belt speed, cross-sectional area, and bulk density	bulk density sampled hourly until stable, moisture content sampled hourly	developed using varying gate heights and timed weights from platform scales	
6. Degree of operator expertise required	qualifications of operators hired				ROI
	preventive maintenance requirements	Operator's log			ROI

Table 6. Phase 4, Test Burner and Engine Operation, Testing, Analysis, and Key Performers

Phase 4: Test Burner and Engine Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
2. Liquid product quality	Combustion efficiency	EGBO – burner, fuel inlet, burner outlet, ash collection, thermal output of burner	Unsure	EGBO – burner flame stability (qualitative), mass of carbon injected as fuel and unconsumed carbon in burner exhaust stream (THCs from CEM) and ash, thermal output of burner	Iowa State University
		TTBO – fuel inlet, exhaust stream, power output		TTBO – mass of carbon injected as fuel and unconsumed carbon in diesel exhaust stream (THCs from CEM) and brake power output	Oak Ridge National Laboratory
4. Environmental performance of each fuel	Emission rates	Burner exhaust	CEM	Continuous emissions measurements of criteria pollutants	Iowa State University
		Engine exhaust	CEM	Continuous emissions measurements of criteria pollutants	Oak Ridge National Laboratory
5. Fast Pyrolysis System and boiler/engine reliability	Burner test stand-Identify equipment modifications (e.g., special burner nozzles) or burner adjustments needed	Qualitative			Iowa State University
	Burner test stand-Properties of the	Qualitative			Iowa State University

Phase 4: Test Burner and Engine Operation					
Performance Objective	**Parameter**	**Installation point(s)**	**Number and Type of Devices**	**Brief Description of Device**	**Performer**
	biofuels that mandated test stand modifications				
	Engine-Actual versus scheduled operating hours	Operators log			Oak Ridge National Laboratory

This section describes the samples to be collected during each phase of the project and summarizes the number and types of samples to be collected.

Table 7. Sample Collection

Performance Objective	Parameter	Number and Type of Samples	Sample Method	Schedule
1. EROI	(1) Energy density and moisture content of biomass feedstock	5 daily composite samples	Grab sampling, combined daily to form 5 composites	Hourly grabs
	(2) Mass and energy density, composition of biodiesel, EGBO, TTBO	See PO 2(2)		
	(3) Energy density of char	5 daily composite samples	Grab sampling, combined daily to form 5 composites	Hourly grabs
	(4) Energy density and composition of syngas	Injection volume necessary for clear chromatograph	Grab sampling, combined daily to form 5 composites	Hourly grabs
2. Liquid Product Quality	(1) ASTM standards (D7544, D6571, D975) and other fuel properties	5 daily composite samples	Grab sampling, combined daily to form 5 composites	Hourly
	(2) Boiler combustion efficiency	Determined by testing labs		
	(3) Engine combustion efficiency			
3. Pyrolysis system can handle feedstocks of varying quality	(1) Feedstock moisture and ash content	See PO 1(1)		
	(2) Liquid product moisture and ash content	See PO 2(1)		
	(3) Product energy quality	See PO 2(1)		
4. Environmental performance of each fuel	(1) Emissions	Determined by testing labs		
	(2) Thermal output (boiler) and power			

Performance Objective	Parameter	Number and Type of Samples	Sample Method	Schedule
	output (engine)			
5. Fast pyrolysis system and boiler/engine reliability	No sampling required for these POs.			
6. Degree of operator expertise				
Note: Sample volumes to be determined by testing laboratory requirements.				

Identification of Testing Entities

Product samples (e.g. char, TTBO, EGBO) cannot be adequately analyzed on the processing line and will be shipped to laboratories with capabilities for performing appropriate analysis and. Product properties given in Tables 2-4 including elemental analysis, heating value measurement, and carbon residue potential must be analyzed according to ASTM standards. Southwest Research Institute (SwRI) was identified by the PNNL technical assistance project team as having the equipment and expertise required to perform the testing specified above. Product fuel performance testing is also specified to include emissions monitoring, during fuel consumption and thermal output of the EGBO or brake specific fuel consumption, in the case of the TTBO. Iowa State University capabilities were identified for testing the EGBO in a burner test stand. Oak Ridge National Laboratory and SwRI were identified as having the capability in place for engine testing of the TTBO.

EGBO: Most boilers require some modification to run on efficiently on pyrolysis oil due its high viscosity, ability to suspend solids (e.g. char, polymerization or condensation products), and its rich oxygen content. Modifications may include adjusted air/fuel ratios to account for the highly oxygenated fuel, steam injection to reduce flame temperature, thereby helping to control NO_x, or use of an alternative burner design. The PNNL technical assistance team carefully screened potential test entities to ensure availability of adequate laboratory equipment for burning the EGBO and the capability to capture thermal output and continuous emissions measurement. The following request for bid was sent to potential testing facilities first identified with the assistance of contacts at the USDA and after screening via phone interview:

> *The testing will be of 3 materials: fuel oil #2 (baseline) and bio-oil from 2 different woody feedstocks.*
>
> *At minimum, the following should be captured: thermal output of the bio-oil combustion, CO, CO_2, THC, and NO_x emissions, and quantification of any carbon that winds up in the ash. Modifications (e.g. air/fuel ratio, burner configuration) will be required to use the bio-oil. If possible/affordable the SO_2, PM, VOC, aldehyde, and PAH emissions will be investigated.*
>
> *Some data will need to be provided to enage development of a testing strategy. Measurements will be acquired according to ASTM Standard D7544-09 including: gross heat of combustion, water content, pyrolysis solids content, kinematic viscosity (T = 40°C), density (T = 20°C), sulfur content, ash content, pH, flash point, and pour point. Ultimate analysis will also be obtained.*

TTBO: The TTBO is expected to be directly useable in a diesel engine, with no modifications. The main concern with the engine testing would be to capture emissions under hot-start conditions. After combustion technologies (e.g. catalytic converter) do not become active until they have reached temperatures required by the catalysts. This is achieved some time after being exposed to hot exhaust gases. As exhaust gases pass from the tailpipe, they continue to react and eventually become diluted. For these reasons, it is important that each fuel be tested on the same test stand/dynamometer configuration. The following request for bid was sent out after preliminary telephone interviews:

> *Two fuels, from 2 different feedstocks will be generated. The two fuels are a boiler fuel and a biodiesel-blendstock type fuel, containing a small fraction of pyrolysis oil. They are referred to as EGBO and TTBO, respectively. The capability for capturing the environmental fingerprint associated with using the biodiesel-blendstock (TTBO) in a diesel engine, as well as the brake-specific fuel consumption is needed. The federal (or CARB) diesel tested could be tested under the same conditions.*
>
> *The testing should be performed over an EPA test drive cycle, under hot-start conditions, on the same engine, and with identical after combustion technology (smog control). The pollutants that have been identified for reporting are CO_2, CO, NO_x, and particulates. Can HC speciation (or even simply THC) be captured? This would be required for 3 samples, total, as noted above (TTBO-1, TTBO-2, and federal [or CARB] diesel).*
>
> *ASTM testing is planned (ASTM D6751, D975, and ISO 8217), and access to the results will be available, as needed, to determine the experimental setup, fuel handling requirements, and chemical composition. The TTBO will be characterized using ASTM standard D 6571, Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels. The TTBO will not be a true B100 blend stock because it will have some components of the pyrolysis oil dissolved into it, but this specification assumed to be a good fit for the expected product composition.*

Cost & Performance Prep

The technical assistance team evaluated cost elements necessary to calculate the anticipated life cycle operational costs of deploying the Fast Pyrolysis process. Table 8 contains a summary of the cost elements for the project. Each cost element is subsequently discussed further. In particular, these data will be used to assess the following three valuations:

- Cash flow analysis will use expenses and the value of the produced biofuels to predict how many years it would take before the project shows a positive net cash flow.
- Return on investment (ROI), will determine when the present value of the future cash flows of the pyrolysis unit equals the cost of the unit.
- Cost ($/gal) and ($/Btu) per feedstock will allow for direct comparison to fossil fuel pricing.

Table 8. Cost Element Summary

Cost Element	**Data Tracked During Demo**
Hardware capital costs	• Overall component costs for all installed equipment, including: o Pyrolysis unit components o Dryer components o Feedstock handling and storage equipment o Liquid fuels storage tanks (fuels and products) o Char handling and storage equipment o Environmental control systems o Steel building* o Office trailer* o Other
Hardware lifetime	• Component lifetime • Component replacement cost
Installation costs	• Labor • Shipping • Initial operator training • Site preparation • Pad construction* • Electrical service heavyup* • Steel building installation* • Office trailer installation* • Permitting cost* • Cost of required plans o Contingency plan*

Table 8. Cost Element Summary	
Cost Element	**Data Tracked During Demo**
	○ Environmental assessment*
Operational costs	• Labor of technicians to run and monitor plant • Cost of energy for processing and pyrolysis - Electricity - Propane - Biodiesel • Waste disposal costs, if any • Demonstration monitoring costs - Fuel properties - Feedstock and product quantities consumed and generated - Test burner run - Test engine run • Permit monitoring and compliance costs* - Sampling - Analysis - Reporting • Feedstock costs - Transportation to jobsite ▪ Fuel ▪ Labor - Field chipping/grinding costs * ▪ Fuel ▪ Labor - Storage costs (if any) • Water costs (if any)
Maintenance costs	• Cost and frequency of routine maintenance (labor and materials) • Cost and frequency of non-routine repairs (labor and materials) • Percent downtime
Cost or value of alternative practices for feedstocks	• Estimate based on current mulch prices in Fort Bragg area* • Processing costs

Table 8. Cost Element Summary	
Cost Element	**Data Tracked During Demo**
	• Disposal costs
Fuel cost	Market value of petrochemical fuels that the bio-oil products could replace

*Costs not incurred at shake-down site, but would have been relevant at Fort Bragg and may be relevant at future installations.

Hardware capital costs

Description: Hardware capital costs include the overall component costs for all of the equipment installed at the dem/val site, including the pyrolysis trailer, the dryer and its components, all feedstock handling equipment (including storage), liquid fuel storage tanks, char handling and storage equipment, environmental control systems. These costs will include the engineering design costs and the fabrication costs. A full accounting for these capital costs is necessary to support our understanding of the life cycle costs of this technology.

Data required: ROI will provide a rolled-up cost for the overall hardware capital cost, with a full description of included costs (but not to include a line-by-line cost breakdown).

Data evaluation: The ROI process is in the "early production" phase of development. There are costs imbedded in the capital costs that reflect product development. Subsequent fast pyrolysis units will benefit greatly from this product development work, both in terms of engineering time, process efficiencies, and fabrication costs. Where possible, components of the hardware capital costs that will be less costly in subsequent renditions will be identified. Potential capital costs that could have incurred if the unit had been installed at Fort Bragg will be estimated. These costs may be relevant at future Army installations and should be considered during those deployment decisions.

Hardware lifetime

Description: A full cost assessment considers the hardiness of the equipment - how long is it expected to remain serviceable? While the planned dem/val will be operate over the short term, it is important for the Army to understand the expected lifetime of the equipment, and to be able to calculate a meaningful return on investment. Tied with the previous cost element, this parameter is critical to the life cycle analysis of the process.

Data required: Expected lifetime for each major hardware component. Replacement costs per component.

Data evaluation: ROI will provide an assessment of the expected lifetime of the hardware components. High heat- and high load-bearing components will be scrutinized for wear and stress. Any operational issues identified during process operation will be assessed in terms of the expected lifetime of the hardware.

Installation costs

Description: As listed in Table 9, there are numerous costs associated with the installation of the fast pyrolysis process. Running the dem/val data collection at the shake-down site minimizes some of these costs, as indicated by the asterisked items that would have been relevant at Fort Bragg. These additional costs will be described as relevant to future deployments of the process at other military installations.

Data required: The fabricated components of the fast pyrolysis unit are currently in storage at ROI's facilities. Various costs will be quantitied as they are related to preparing the Alabama shake-down site for operations, shipping the components to the shake-down site, labor to assemble the components and conduct initial shake-down calibration and testing.

Data evaluation: Installation costs will be evaluated as one-time start-up costs. How these costs would change when the dem/val is sited at a military installation (using data developed in preparation for the Fort Bragg deployment) will be examined.

Operational costs

Description: The operational costs include the wide range of costs associated with running the fast pyrolysis unit on a daily basis. Careful documentation and assessment of these costs are critical to the determination of meaningful cash flow analysis, IRR, life cycle analysis, and cost per feedstock calculations.

Data required: See Table 9. Major data requirements include labor, energy input costs, and monitoring costs. Other data requirements that would be more relevant in a full siting of the process would include permit monitoring and compliance costs, as well as feedstock handling costs (minimal for the shake-down site, provided by site owner). Other costs expected to be insignificant include water utility and municipal trash service. Data regarding the variability of these costs over time and any episodicity of the costs will also be captured.

Data evaluation: These diverse costs will be normalized to a common time unit. Significant variability will be noted, and operational cost drivers will examined closely to assess impacts on the overall cost assessment and to identify cost management strategies.

Maintenance costs

Description: These costs include those necessary to keep the process and the site operational. The process operating guide will identify (and provide a schedule for) those routine maintenance activities planned to keep the process equipment clean and functional. Other routine housekeeping costs will be incurred on a regular basis to minimize feedstock losses and health and safety risks. Over the course of the dem/val, non-routine maintenance activities and their associated costs can be tracked.

Data required: Labor and materials associated with routine process and housekeeping maintenance, as well as non-routine maintenance costs.

Data evaluation: Maintenance costs will be normalized to a common time unit. Significant variability will be noted, and any cost drivers will examined closely to assess impacts on the overall cost assessment and to identify cost management strategies.

Cost or value of alternative practices for feedstocks

Description: Today's garrisons work hard to find markets for their wastes and other recyclable spent materials. Over the course of time that this team worked with Fort Bragg, a wide range of alternative management practices were identified, which are being used or considered for the different materials that could have served as fast pyrolysis process feedstocks. Initially Fort Bragg had identified shredded paper from destruction of sensitive paper. The garrison's paper recycling vendor was unwilling to accept this stream because of the particle size distribution. The material was being landfilled at significant cost to the Army. The Fort Bragg pollution prevention team was able to identify an alternative recycling scenario that moved this stream out of the landfill and created a monetary swing from a significant expense to a modest income stream. Similarly, the shredded wood chips have changing alternative uses. Due to the high level of construction at Fort Bragg, there was a high demand for landscaping mulch. Rather than stockpiling woody material, the garrison put the material to use, helping to minimize costs associated with mulch purchase. The value of feedstock will be evaluated for application other than as a feedstock to the fast pyrolysis unit, looking at local market factors and economics.

Data required: Cost or value associated with alternative management of feedstocks.

Data evaluation: The cost or value of alternative management of the feedstock will be considered as part of the operational costs of the system. If the feedstocks are being disposed of currently, the disposal costs would be considered an off-setting expense. Conversely, if the feedstocks are currently bringing in value (e.g., sold as mulch), the lost income stream would be considered an operating expense.

Fuel cost

Description: A critical component of the cost assessment is to compare the cost of the bio-oils with the petrochemical fuels they would replace.

Data required: Market price for diesel and commercial biodiesel, taking into account location, market trends, and seasonal pricing variations.

Data evaluation: Compare the calculated cost per gallon and cost per btu of the EGBO and the TTBO with those of diesel and bio-diesel.

Summary of Project Next Steps

As the ESTCP project moves forward, further technical assistance may be needed during shakedown, sample collection, and data analysis. Scale-up of thermochemical conversion systems can be especially problematic in terms of managing greater thermal mass and the potential for heat and mass transfer regimes that differ significantly from the smaller scale system. The full extent of these effects is not always foreseeable. It is recommended that a chemical engineer, having experience with multiple scales of pyrolysis (or gasification) systems be sought for hands-on, technical assistance.

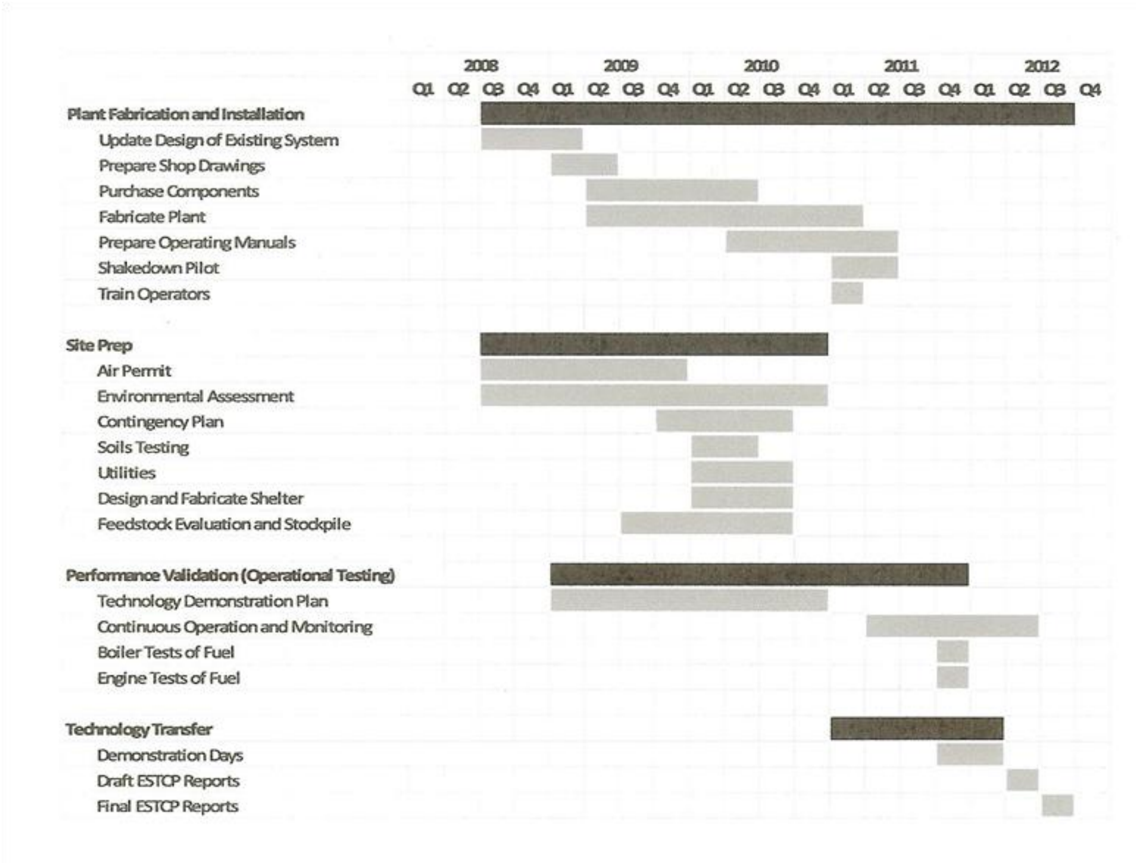


Figure 6 is the current ESTCP project schedule. These dates are likely to change, due to notification on September 29th, 2010 that the Fort Bragg location will no longer be available for the technology demonstration project. Fort Stewart along with Forts Benning, Rucker, and Anniston are the new locations being considered.

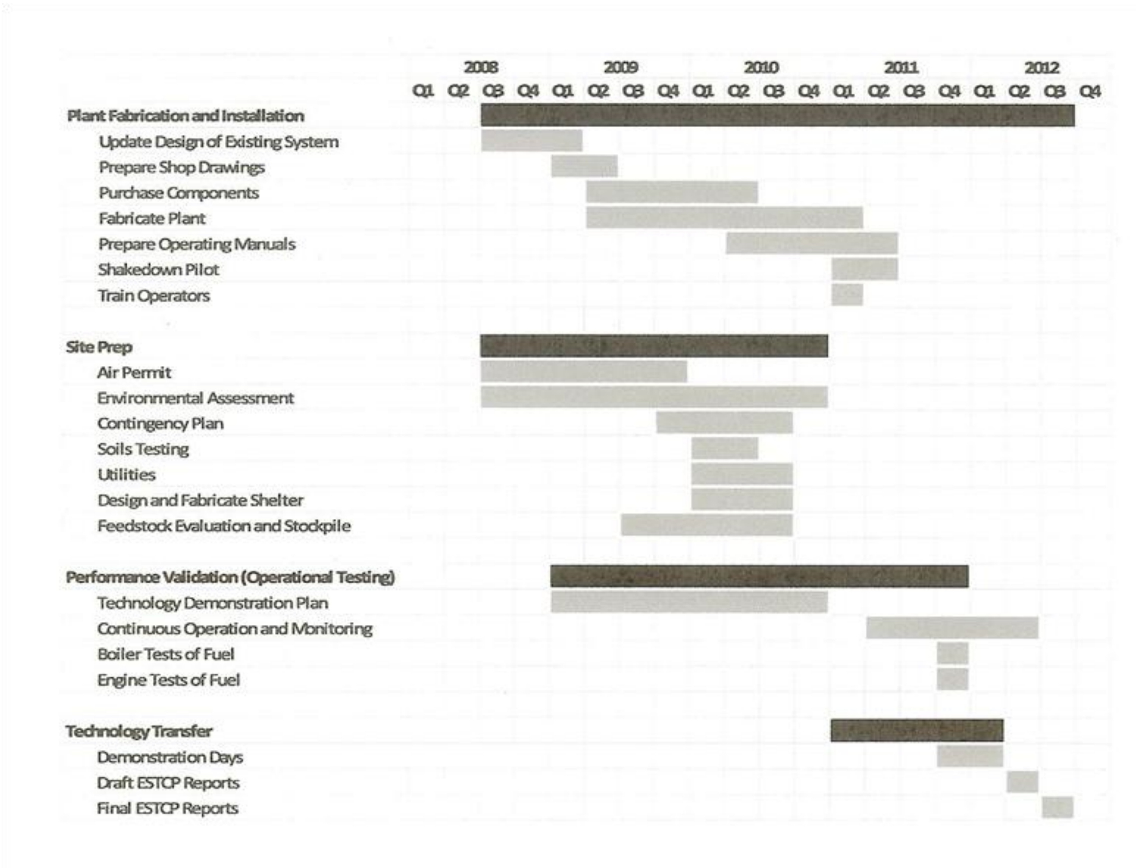


Figure 6. ESTCP Fast Pyrolysis Demonstration Gantt Chart

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