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Clean Transportation Program

FINAL PROJECT REPORT

Biomass Conversion to Synthetic Gasoline System

Prepared for: California Energy Commission

Prepared by: Altex Technologies Corporation

ALTEX TECHNOLOGIES CORPORATION

Gavin Newsom, Governor

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Mehdi Namazian
Tahmina Imam
Nehru Chevanan
Kenneth Lux
Primary Author(s)

Altex Technologies, Inc.
244 Sobrante Way
Sunnyvale, CA 94086
408-328-8300
Altex Website (www.altextech.com)

Agreement Number: ARV-15-009

Taiying Zhang
Project Manager

Elizabeth John
Office Manager
ADVANCED FUELS AND TECHNOLOGIES OFFICE

Kevin Barker
Deputy Director
FUELS AND TRANSPORTATION

Drew Bohan
Executive Director

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-14-602 to support biofuel early and precommercial technology development. In response to PON-14-602, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards on June 24, 2015, and the agreement was executed as ARV-15-009 on December 9, 2015.

ABSTRACT

This project sought to develop a biomass conversion to synthetic gasoline system that produces gasoline from cellulosic biomass at less than $2.00 per gallon and with a carbon intensity of less than 30 grams of carbon dioxide equivalent per megajoule. The research team achieved the project goals by demonstrating that the fuel cost for a 3,000-barrels-per-day plant is less than $2.00 per gallon, and the plant is economical based on the return on investment. At a sales price of $3.50/gallon gasoline, the internal rate of return on equity varies between 30 percent to 45 percent, depending on the biomass feedstock price. The well-to-wake life-cycle analysis showed that the biomass conversion to synthetic gasoline system biogasoline carbon footprint is negative. This value should be compared with the carbon footprint of the petroleum gasoline. A key achievement under this project was to develop a catalyst that operates at a relatively low pressure and produces a fuel with a similar distillation curve and carbon number distribution to those of commercial gasoline. The catalyst was demonstrated in a fuel production reactor with one-barrel-per-day gasoline production capability.

Keywords: California Energy Commission, biomass, gasoline, catalyst, low cost, low GHG

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EXECUTIVE SUMMARY

In 2010, nearly 28 million vehicles in California consumed roughly 14 billion gallons of gasoline and 3.3 billion gallons of diesel and produced about 150 million tons of greenhouse gas (GHG) emissions. The State of California has developed aggressive targets and plans for reducing these and other GHG emissions by implementing several legislative and executive initiatives, such as Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), the Alternative Fuel Plan in response to Assembly Bill 1007 (Pavley, Chapter 371, Statutes of 2005), and Reducing California's Petroleum Dependence, in response to Assembly Bill 2076 (Shelley, Chapter 936, Statutes of 2000). These biomass-based goals of these initiatives, combined with the fact that 80 percent of the transportation fuel consumed in California is gasoline, make it clear that the greatest impact on GHG emissions can be made by producing a cost-competitive, biomass-based fuel that replaces gasoline. This project sought to develop a biomass conversion to synthetic gasoline system (BCSGS) that produces gasoline from cellulosic biomass at less than \$2 per gallon and with a carbon intensity of less than 30 grams of carbon dioxide (CO_2) equivalent per megajoule (gCO_2e/MJ.)

The system was built from a system that was being developed concurrently under support from the U.S. Department of Energy (U.S. DOE) that was targeting JP-8 production, from a feed of mixed coal and cellulosic biomass. The system design and the equipment were adapted from this cost-shared system by the addition of a pure biomass feed system and additional fuel production reactor with a new catalyst specifically developed for gasoline. In addition, the plant design and life-cycle modeling of the system highly leveraged the work performed under the U.S. DOE cost-shared project.

Under the project, the research team fabricated and verified the biomass feed system and the fuel-production reactor. The team developed a gasoline-specific catalyst that produces gasoline at atmospheric and relatively low pressures, contributing to the low cost of the fuel. A full-scale-2,000-ton-per-day system plant was designed and used to perform economic and life-cycle analyses to determine the plant and fuel costs and GHG emissions. The biofuel-gasoline production cost is projected to be \$1.80/gal at \$55/ton of delivered biomass to the plant. The life-cycle analysis (LCA) shows that the system biogasoline carbon footprint is negative, saving 22.7 kilograms of CO_2 per gallon or 50 pounds of CO_2 per gallon if system gasoline were used instead of petroleum-based gasoline. This value should be compared with the carbon footprint of the petroleum gasoline that is 93 grams of CO_2 equivalent per megajoule. This substantial difference in CO_2 emissions clearly shows the benefit of the system process and has the potential of eliminating the entire 150 million tons of annual vehicular GHG emissions and enabling negative vehicular GHG emissions in California by use of system biofuel versus petroleum-based gasoline.

Based on laboratory tests, plant design, analysis, the biomass-conversion-to-synthetic-gasoline system showed the potential to convert biomass to gasoline using the catalyst developed and optimized under this project and to produce less than \$2 per gallon of gasoline at a 2,000-ton-per-day system plant scale at \$55/ton biomass cost. The BCSGS has the potential to drastically undercut the capital investment and the fuel price of competing biomass to biofuel technologies (i.e., gasification plus Fischer-Tropsch [FT] synthesis). This goal was achieved

with the projected gasoline cost of $1.8 per gallon of biofuel with a negative carbon footprint that has the potential of eliminating the entire GHG emissions related to the gasoline use in California.

CHAPTER 1: Project Definition

1.1 Project and Process Description and Background

This project sought to develop a biomass-conversion-to-synthetic-gasoline system (BCSGS) that produces gasoline from cellulosic biomass, at less than $2 per gallon and with a carbon intensity of less than 30 grams CO_2e/MJ. This goal was achieved by operating a lab-scale BCSGS; producing drop-in, or interchangeable, gasoline; designing a 2,000-ton-per-day or 3,000-barrel-per-day (BPD) BCSGS plant; and verifying the fuel cost and carbon footprint.

The BCSGS was built off a system that was being developed concurrently under support from the U.S.DOE (Contract No. DE-FE0023663) that was targeting JP-8 production from a feed of mixed coal and cellulosic biomass. The BCSGS design and the equipment were adapted from this cost-shared system by adding a pure biomass feed system and a fuel production reactor with a new catalyst specifically developed for gasoline. In addition, the plant design and life-cycle modeling of the BCSGS highly leveraged the work performed under the U.S. DOE cost-shared project.

The research team achieved the goals of the project by demonstrating that the fuel production cost for a 2,000-ton-per-day plant is less than $2 per gallon, and the plant is economical based on the return on investment. At a sales price of $3.5/gal, the internal rate of return on equity (IRROE) varies between 30 percent and 45 percent with variable feedstock prices. The well-to-wake LCA showed that the BCSGS biogasoline carbon footprint is negative (-77 gCO_2e/MJ). This value should be compared with the carbon footprint of the petroleum gasoline that is +93 gCO_2e/MJ. This substantial difference in the CO_2 emissions clearly shows the benefit of the BCSGS process. The economics and environmental benefits of the BCSGS are due to the BCSGS innovative process that is described below.

1.1.1 BCSGS Process

BCSGS is a transformative technology that overcomes the technical and economic barriers that exist in converting biomass to a synthetic gasoline. While gasification followed by FT synthesis has been technically successful to produce a synthetic fuel from biomass,[1] the associated cost is high, mainly due to the high temperatures required in the process and the need to hydrocrack the waxes produced during FT synthesis.[2] Alternative approaches that use

1 *Cost and Performance Baseline for Fossil Energy Plants Volume 4: CTL via F-T Synthesis*, DOE/NETL Contract No. DE-FE0004001.

2 Tarka, T.J., 2011. DOE/NETL-2012/1542. Office of Strategic Energy Analysis and Planning, National Energy Technology Laboratory, DOE.

pyrolysis,[3] to convert the biomass to bio-oil have technical and cost difficulties. These difficulties are due, in large part, to the presence of oxygen in the bio-oil. Because of the presence of oxygen, high-cost hydrotreating is required to convert the bio-oil to synthetic fuel.

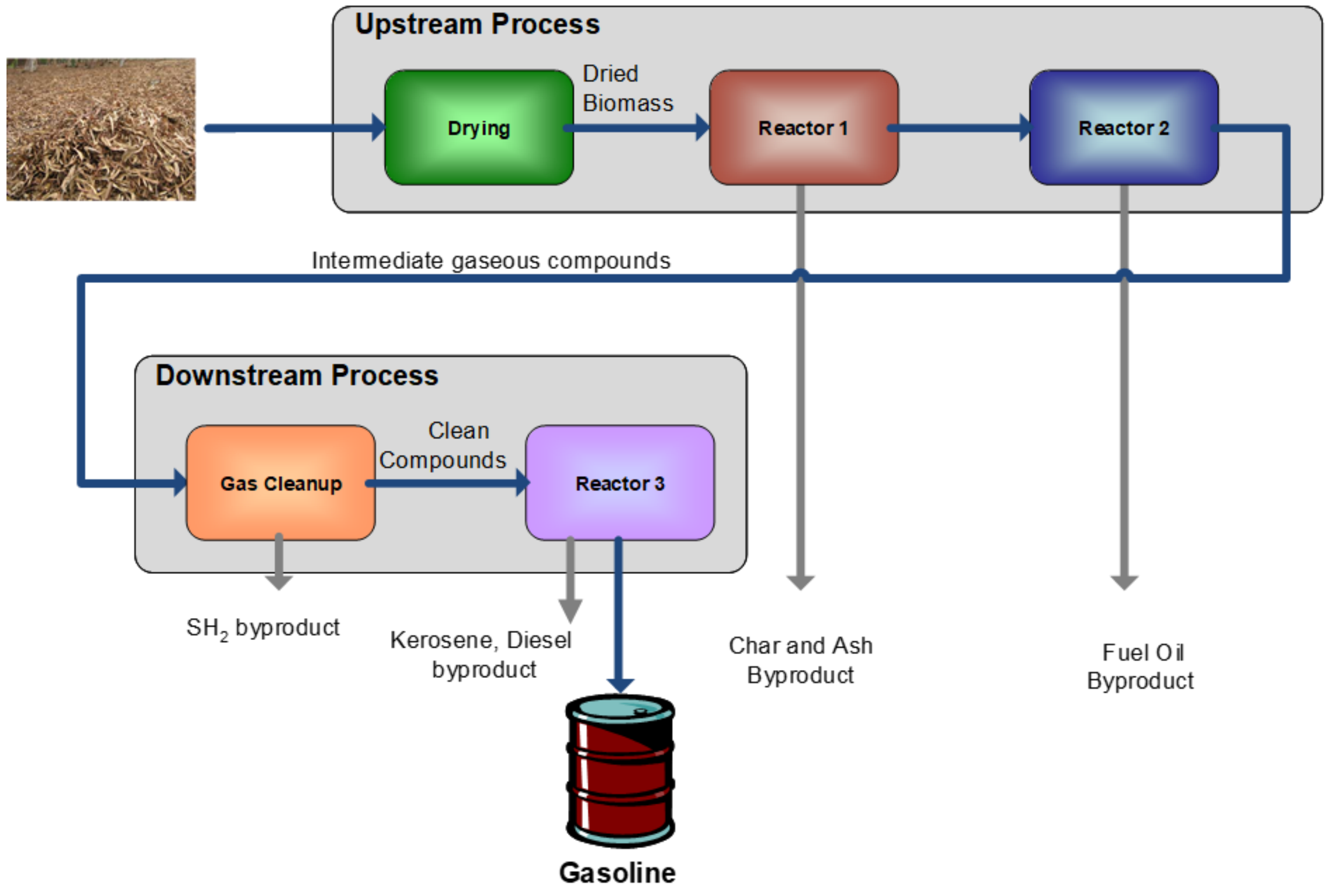
The Altex BCSGS is an innovative and patented process that combines the best aspects of gasification/FT synthesis and fast pyrolysis while avoiding the hurdles associated with these approaches.[4] Similar to FT synthesis, the process uses gaseous intermediates to build a high-quality synthetic fuel but uses lower temperatures and more reactive intermediates. This leads to less expensive unit operations and an elimination of the formation of FT waxes that require hydrocracking. Similar to fast pyrolysis, the process operates at lower temperatures than gasification but removes the oxygen in the feed as carbon monoxide and CO_2 that can be removed before or slipped through the reactors that produce the fuel from the highly reactive intermediates. This process produces a liquid that does not need to be deoxygenated through hydrotreating. In this way, the BCSGS process operates at lower temperatures to reduce equipment costs while eliminating the need for hydrotreating or hydrocracking. In turn, eliminating the need for hydrotreating or hydrocracking eliminates the need for production of high-pressure hydrogen with the associated costs and GHG emissions. These attributes reduce the capital and operating costs of the BCSGS process as compared to classical gasification/FT synthesis or pyrolysis/bio-oil-hydrotreating. As a result, BCSGS can produce a cost-competitive drop-in fuel.

Figure 1 is a block diagram for the BCSGS. Logistically, the process is split into two sections: an upstream process and a downstream process. In the noncatalytic upstream process, the biomass feed is converted into gaseous intermediate products while separating the oxygen in the feedstock from these intermediate products. The intermediates are highly reactive and can be readily converted to a liquid fuel in the downstream catalytic process. If needed, in the upstream process, the feed is dried to a targeted moisture content before being sent to Reactor 1. In this reactor, the feed is converted to a pyrogas consisting of steam and volatile hydrocarbons, while char and ash are recovered as solid by-products from this reactor. This solid material is a valuable by-product that can be sold as a renewable solid fuel to industry. The product of Reactor 1 is directly fed into Reactor 2, where the volatile hydrocarbons are converted into the reactive intermediates before it is cooled and split into a light oil stream and product gases. The light oil by-product is similar to heating oil and can be sold through heating-industry channels. The product gases are sent to the downstream process to build the desired fuel catalytically from the reactive intermediates.

3 Pacific Northwest National Laboratory. 2009. *Production of Gasoline and Diesel From Biomass via Fast Pyrolysis, Hydrotreating, and Hydrocracking: A Design Case.*

4 U.S. Patent 9,199,889 B2.

Figure 1: Block Diagram of the BCSGS Process to Convert Biomass into Gasoline



Source: Altex Technologies Corporation

In the downstream process, the product gases from the upstream process are cleaned using industry-standard gas-cleanup approaches. The reactive intermediates in the clean gases are then used as building blocks of gasoline in Reactor 3. Through the control of the operating conditions in Reactor 3 (*e.g.*, space velocity, selected catalyst, reactor recycle ratio), the carbon-number distribution of the product can be tailored to match that of the desired fuel. This is demonstrated in Figure 2, which shows that by tailoring the catalyst and the conditions of Reactor 3, a fuel matching the gasoline distillation curve can be produced. These data was collected under a U.S. DOE supported project that used lab-scale equipment developed under the Defense Advanced Research Projects Agency (DARPA) project,[5] to convert lignocellulosic biomass to gasoline.[6]

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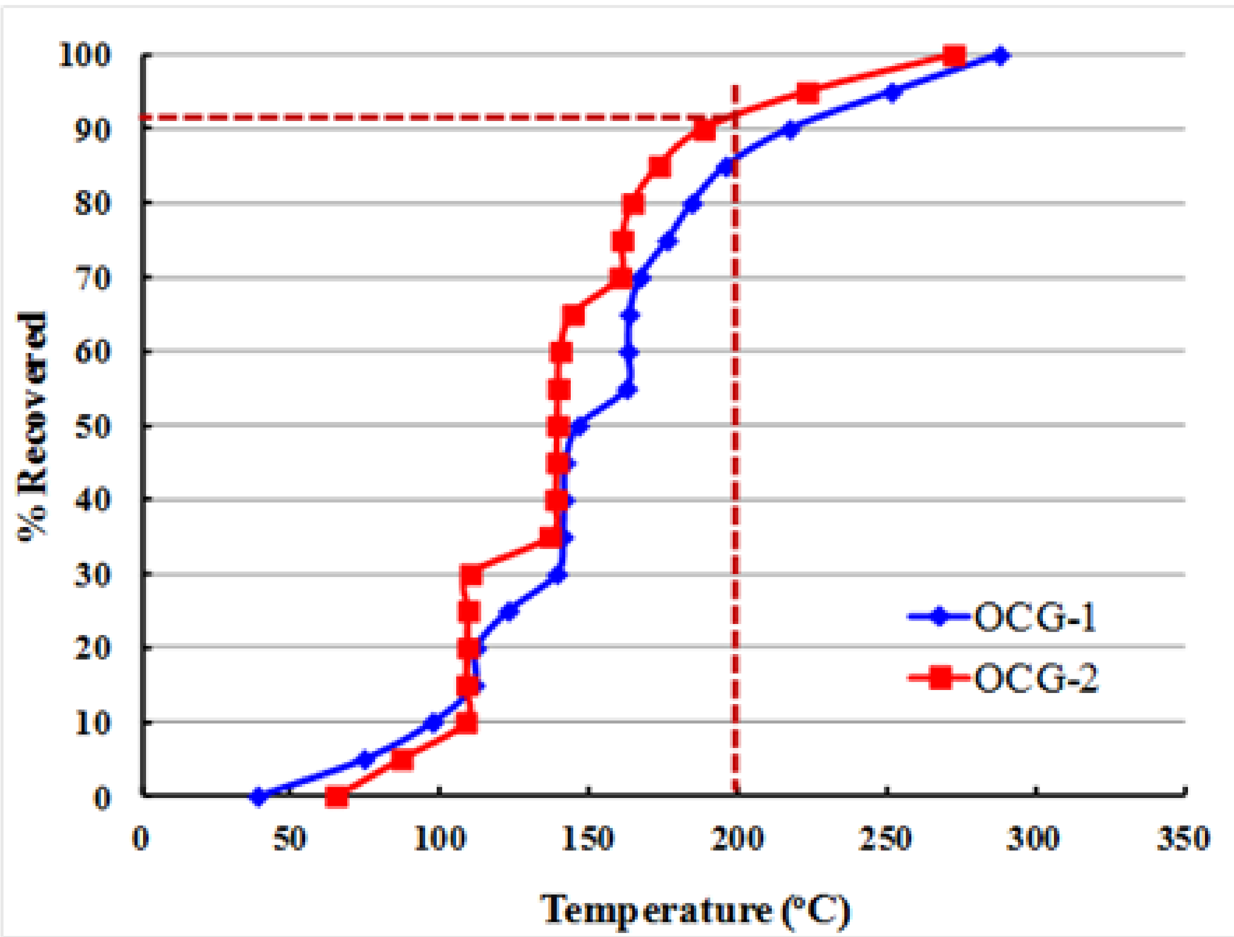
5 Altex Final Report on « Clean and Low-Cost (CALC) Coal to Jet Fuel Conversion Process » DRAPA Contract HR0011-09-C-0092

6 Altex Final Report on « Infrastructure Compatible Biofuel Production System for Lignocellulosic Biomass DOE Contract No. DE-SC0006466

1.1.2 Basis of the BCSGS Process

The base technology was first developed under a DARPA project that was awarded to Altex in response to a competitive RFP for developing transformative coal-to-liquid processes that overcome the limitations of the current technologies, which are mainly high capital costs and high GHG emissions. BCSGS overcomes these limitations through the novel thermochemical process that operates at moderate temperatures (versus gasification and FT), removes oxygen, and does not require hydrogen for hydrotreating (unlike bio-oil followed by hydrotreating).[6]

Figure 2: The Synthetic Gasoline ASTM D2887-Distillation-Curve Produced by the BCSGS Using Two Catalysts



Catalyst	Liquid yield (%)	Product percentage (%)	
		b.p. < 200 °C	b.p. > 200 °C
OCG-1	27	85	15
OCG-2	35	92	8

Source: Altex Technologies Corporation

The goals of the DARPA project were to show the feasibility of this transformative technology in the lab by converting low-rank coal to JP-8 for military applications,[7] and to use the data to show the process's economics feasibility. This was achieved and a lab-scale system was built and tested and a fuel matching the JP-8 distillation curve was produced. Under the DARPA project, the research team used test data and designed a 100,000-BPD refinery was designed. A Class 4 cost estimate and economic analysis were performed that showed that JP-8 can be produced for less than $1.5 per gallon. This cost was later confirmed under a U.S. DOE project in which coal and biomass were mixed to reduce the GHG emissions of the syn-JP-8 to below that of petroleum-based JP-8. Under this project, titled greenhouse-gas-reduced coal-and-biomass-to-liquid-based jet fuel (GHGR-CBTL), a techno-economic analysis was conducted. In addition, an LCA model produced in collaboration with Argonne National Laboratory and a GHGR-CBTL module was added to the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model. These techno-economic analyses and LCA models were used as the basis for developing the BCSGS economics and LCA.

1.1.3 Viability of the Process

As discussed above the base of the BCSGS technology was developed under DARPA and U.S. DOE support to overcome economics barriers of technologies like FT. This development was achieved under the U.S. DOE-supported greenhouse-gas-reduced (GHGR) project when the cost of the GHGR-CBTL plant was compared with an FT plant with similar assumptions. The techno-economic analysis was performed following U.S. DOE guidelines that included a 40,000-BPD plant output. The research team developed and evaluated a matrix of plant configurations. The scenarios included capturing or venting CO_2 to estimate the cost of CO_2 capturing. A baseline case with CO_2 capture was included and was compared with a similar FT baseline case that has been studied by U.S. DOE with similar assumptions. The results are shown in Figure 3 that compares the total overnight cost and Equivalent Crude Oil price for GHGR-CBTL with those calculated from the results of the U.S. DOE/National Energy Technology Laboratory FT-liquids baseline case.[8] As shown the GHGR-CBTL total overnight cost and equivalent crude oil are 62 percent and 69 percent of the total overnight cost and equivalent crude oil for the U.S. DOE FT-liquids baseline case, respectively. This result shows that the economics of the GHGR-CBTL, which is the basis for the BCSGS, are significantly better than a gasification/FT process.

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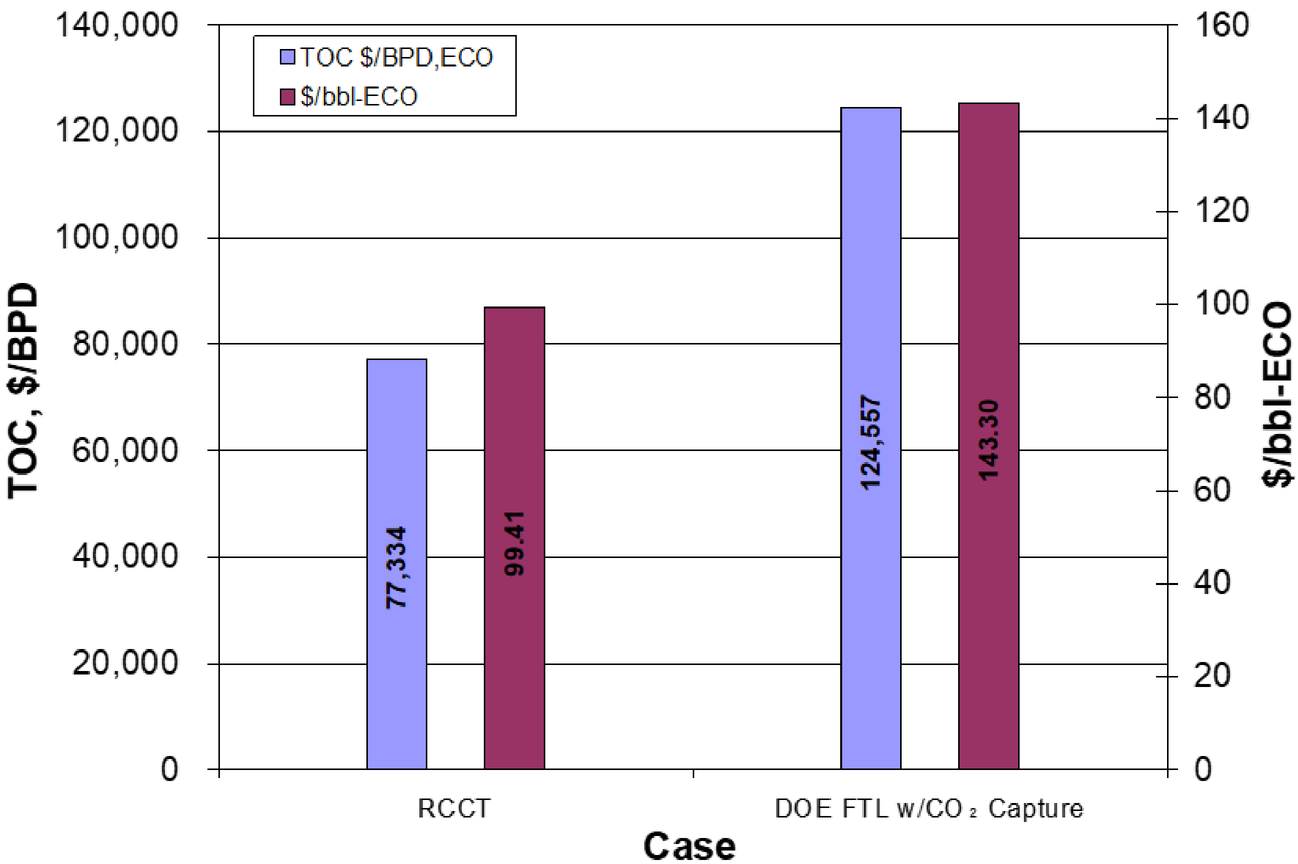
7 Note that JP-8 used by the DOD is very similar to Jet A-1 Jet A, which are used for civilian aircraft.

8 *Cost and Performance Baseline for Fossil Energy Plants Volume 4: CTL via F-T Synthesis*, DOE/NETL Contract No. DE-FE0004001

Figure 3: Comparison of Total Overnight Costs and Equivalent Crude Oil Prices for GHGR-CBTL and the U.S. DOE/ National Energy Technology Laboratory FT-Liquids Baseline Case



Source: Altex Technologies Corporation

Equivalent crude oil prices in the U.S. DOE model reflect a 20 percent IRROE. In other words, the equivalent crude oil is the price that the fuel needs to be sold to have 20 percent rate of return in investment. To get an idea of the cost of fuel production without the profit margin included, one can look at the equivalent crude oil price and the equivalent petroleum jet price for the case where the IRROE is 0 percent. The case for 0 percent IRROE resulted in JP-8 *cost* of $1.57/gallon of fuel.

Further support for the viability of the BCSGS process is that under the cost shared GHGR project, detailed equipment costs were defined. Most importantly, equipment was identified that is already used for unit operations in commercial chemical industries that could be adapted into the BCSGS process. In particular, ethylene production from the steam cracking of hydrocarbon feedstocks, including heavy feedstocks, is one of the largest chemical industries in the world. Certain unit operations of this industry can be adapted to BCSGS, indicating that the process and the equipment associated with the process are readily available at the large scales needed for significant fuel production. In addition, fuel production reactors used in the BCSGS process are well known and have been commercialized for use with both heterogeneous and homogeneous catalysts (*e.g.*, Shell Higher Olefin Process, Dimersol processes), although these operate at higher pressures (>550 pounds per square inch gauge [PSIG]) than the BCSGS catalysts. This means that there are drop-in replacements for the BCSGS fuel production reactor that are commercially available. Using two processes that are so well developed and commercialized greatly reduces the risk of the BCSGS process.

With this background and parallel activities, the BCSGS project was executed and the results are described in the following chapter.

CHAPTER 2: Project Accomplishments

2.1 Feedstock Acquisition

2.1.1 Introduction

Under the U.S. DOE cost-shared project, the research team executed a subcontract with University of California, Davis (UC Davis). Under this subcontract, UC Davis supplied 20 tons of switchgrass, wheat straw, and corn stover for testing purposes. The Altex and UC Davis relationship builds upon previous efforts under which Altex worked with UC Davis in testing the Biomass Blending and Densification System equipment that compacts loose biomass feedstock to high-density (~40 lbs./ft3) logs.[9,10] Under these efforts, UC Davis supplied to Altex more than 20 tons of agricultural residues for testing. Altex used its previously built working relationship with UC Davis to identify and acquire the feedstock for BCSGS. In addition, for certain feedstocks, UC Davis provided data to conduct the LCA of carbon intensity. These data are being included in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) model of carbon intensity developed by Argonne National Laboratory, another subcontractor under the cost shared GHGR project.

2.1.2 Feed Stock Identification

BCSGS is feedstock flexible. To show this flexibility, three types of biomass were identified to be used for testing under BCSGS—switchgrass, corn stover, and wheat straw. These biomass feedstocks were selected because they are readily or potentially available and they are good candidates in terms of low cost and low maintenance for conversion to biofuels, specifically gasoline under BCSGS.

The availability of these selected feedstocks in California and the United States are listed in Table 1, and the related compositions are listed in Table 2.

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9 Kelly, J. Chevanan, N., and Miller, G.,2012 Monthly progress reports on California Energy Project on "Demonstration of full scale Densification System", PIER Grant No. PIR-11-021.

10 Kelly, J, Chevenan, N and George Miller "Biomass Blending And Densification System" Reports on DOE Contract No. DE-FG02-08ER85187.

Table 1: California and U.S. Availability of Selected Biomass Feedstocks

Agricultural crop	Total California Production, Million ton (bone dry)/year[11]	Total US Production, Million ton (bone dry)/year[12]
Corn stover	0.2	24.0
Wheat straw	0.4	6.0
Switchgrass, projected	0.4[13]	1.0
All agricultural residue	5.0	144.0

Source: Altex Technologies Corporation

Table 2: Carbon, Hydrogen, and Nitrogen Content Present in the Biomass

Sl.NO	Biomass material	Carbon	Hydrogen	Nitrogen
1	Switchgrass(14)	46.6%	5.3%	0.5%
2	Wheat straw(10)	44.4%	5.87%	1.35%
3	Corn Stover(15)	46.7%	6.3%	0.8%

Source: Altex Technologies Corporation

U.S. DOE has identified Switchgrass as a high-potential energy crop.[16] At UC Davis, six lowland and five upland ecotypes of switchgrass were evaluated. Lowland ecotypes are taller, and coarser, have a more bunch-type growth habit, and may be more rapid growing than upland ecotypes. In contrast, upland ecotypes are found in drier upland sites and tend to be finer stemmed and lower yielding. Results from research at UC Davis (a completely randomized block design with six replications) have shown that with lowland ecotypes, biomass yields up

11 University of California, Davis, "An Assessment of Biomass Resources in California, 2007, 2010 and 2020," Final Report, California Energy Commission, December 2008, CEC-500-2013-052

12 Perlack, R, D., Wright, L, L., Turhollow, A, F., Graham, R, L., and Erback, D, C., 2005, Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. Joint study report of Department of Energy and Department of Agriculture.

13 Estimated from Figure 4 of Fujin, Y., et al. GCB Bioenergy (2014) **6**, 672–686 for a price of $50/ton ($55/ton).

14 Wu, M., Wu, Y., and Wang, M., "Mobility Chains Analysis of Technologies for Passenger Cars and Light-Duty Vehicles Fueled with Biofuels: Application of the GREET Model to the Role of Biomass in America's Energy Future (RBAEF) Project", Argonne National Laboratory Report No. ANL/ESD/07-11, May 2005

15 Capunitan, J. et al. Fuel 95 (2012) 563–572

16 Historical Perspective on How and Why Switchgrass was Selected as a "Model" High-Potential Energy Crop, ORNL/TM-2007/109 (https://www1.eere.energy.gov/bioenergy/pdfs/ornl_switchgrass.pdf)

to 17 tons per acre (38 tons/hectare) could be achieved. This amount is an excellent yield that makes this biomass as a promising energy crop.

Wheat is the major small grain grown in more than 500,000 acres in California. Unlike other straws, wheat straw is sturdy and very strong. Hence, it is not used as a bedding material and is generally considered waste. Disposal of the wheat straw produced in California is a big problem. Farmers are paying for removal of straw from the field. Using this low-value and readily available biomass as a feedstock will eliminate problems in receiving biomass throughout the year in a commercial-scale BCSGS plant. Hence, wheat straw is considered a good candidate for BCSGS leading to production of biofuel (e.g., gasoline) within California (Figure 4).

Besides producing large quantities of wheat straw, the United States is the top corn producer in the world. The cornfield residues in the form of stalks, leaves, and cobs that remain in fields after harvesting are referred as corn stover. According to a 2005 CEC report, California produces about 5 million tons per year of field crop residues, principally as cereal straws and corn stover.[17] Because of the high ash content, this material is not used in direct biomass power generation, but it is a good candidate for thermal conversion in biofuels production in BCSGS.

Figure 4: The Biomass Densification Equipment in BCSGS Full-Scale Plant for Densifying the Feedstocks to Minimize Feedstock Transportation Cost and Energy

Source: Altex Technologies Corporation

17 "Biomass Resource Assessment in California, In Support Of the2005 Integrated Energy Policy Report", CEC-500-2005-066-D (http://www.energy.ca.gov/2005publications/CEC-500-2005-066/CEC-500-2005-066-D.PDF)

In the commercial-scale BCSGS plant, all three selected biomass materials would be densified in the field and transported to the BCSGS plant. This would reduce raw-material costs by lowering the feedstock-transportation costs in the BCSGS plants.[9,10] Altex has produced densified logs using more than 10 tons of these three biomass materials using biomass densification equipment, as shown in Figure 4. This figure shows the biomass densification equipment while being field-tested at UC Davis under support from the CEC.[9] Figure 5 shows pictures of densified logs produced from switchgrass, corn stover, and wheat straw. Densifying these residues using the biomass densification process has potential to reduce the logistics cost involved in transportation of biomass from the field to the BCSGS plant.

Figure 5: Densified Feedstock Logs; A) Switchgrass, B) Corn Stover, and C) Wheat Straw

Source: Altex Technologies Corporation

2.1.3 Feedstock Acquisition

The initial acquisition amounts of the biomass feedstocks were based on one month of testing in the BCSGS system. This testing requires 7.5 tons of biomass. The research team requested UC Davis harvest, bale, and supply 7.5 tons of biomass, including switchgrass, corn stover, and wheat straw. BCSGS requires particles size of about 1 millimeter for efficient thermal conversion of the biomass in pyrolysis. Altex has contacted several companies to obtain quotes for size reduction of the biomass feed. Based on the quotes received and company capabilities, Altex selected Hazen Research and Andritz to be used for biomass sizing in BCSGS. Because of their lower cost, Andritz was the final selection to size and bag the biomass. Under cost-shared activities, 7.5 tons of biomass were transported from UC Davis to Andritz where they were ground, then were shipped to Altex in super sacks. Figure 6 shows the super sacks and the bulk bag unloader that is part of the BCSGS feed system.

Figure 6: Feedstock Biomass Super Sacks (Left) Designed for the Bulk-Bag Unloader (Right)

Source: Altex Technologies Corporations

2.1.4 Feedstock Acquisition Summary

The BCSGS feedstocks were identified and acquired. Three biomass feedstocks were selected for testing in the BCSGS system based on the feedstocks being available, having a low cost, and having the potential to alleviate farm-maintenance issues. The selected feedstocks were switchgrass, corn stover, and wheat straw. These three feedstocks have also been densified into 40 lbs./ft^3 logs using Altex biomass densification field equipment that would be part of the BCSGS full-scale plant. By densifying the loose biomass in the field, biomass densification reduces biomass transportation costs and energy use. Upon Altex request, UC Davis prepared 7.5 tons of the feedstock and shipped this to Andritz to be sized for use in BCSGS. Work is underway at Andritz to size and bag the biomass feedstock. The sized biomass will be shipped to Altex in super sacks designed to be used in the bulk-bag unloader of the BCSGS feed system. With these activities, the feedstock identification and acquisition, planned under the BCSGS project, is completed.

2.2 BCSGS Plant Design

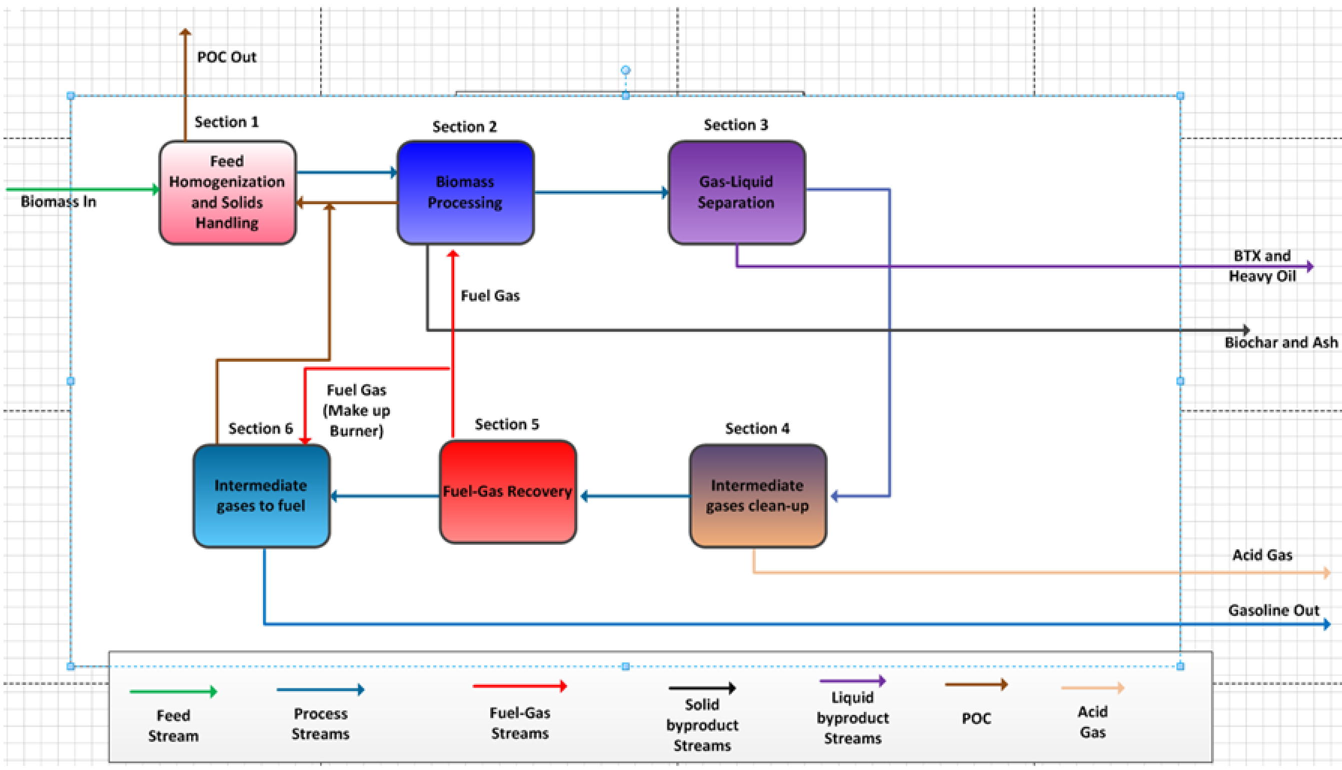
2.2.1 Introduction

CHEMCAD was used to design the full-scale 2,000-ton-per-day biomass feed plant which produces around 3000-BPD of gasoline. The design was based on the cost-shared GHGR-CBTL, 50,000-BPD plant design. The design was used to develop economics, and LCA models and determine the full-scale plant and fuel cost and carbon intensity.

2.2.2 Plant Design, Fuel Cost, and Life Cycle Analysis

The BCSGS process is illustrated in the block diagram of Figure 7. The process is broken down into six sections. Section 1 handles feed-sizing and uniform distribution of the biomass. Section 2 processes the biomass into an intermediate product stream. Section 3 separates any high-molecular weight byproducts that are formed in Section 2 from the intermediate gases. Section 4 uses industry-standard gas-cleanup approaches to remove CO_2, NH3, and hydrogen sulfide. Section 5 prepares the gas-mixture for downstream-processing by compressing the stream to the required-mild-pressure, pre-heat to reaction temperature, and adjust weight hourly space velocity (WHSV) for highest product yield. Section 6 processes the olefins at Altex-defined conditions to liquid biofuel with a carbon number distribution as that of gasoline. The non-condensable fuel gases from Section 5 are used for heating of Section 2 and 6.

Figure 7: Block Flow Diagram of the Altex-BCSGS



Source: Altex Technologies Corporation

For the heat and mass balance, the research team selected a 2,000-ton-per-day BCSGS plant. The 2,000-ton-per-day plant size is the baseline plant size that is used by the U.S. DOE and for which there are economics data available for comparison.[18,19] Based on this plant size, and cost shared data, the research team used the CHEMCAD process simulation to prepare the

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18 *Cost and Performance Baseline for Fossil Energy Plants Volume 4: CTL via F-T Synthesis*, DOE/NETL Contract No. DE-FE0004001.

19 DOE Contract No. DE-FG02-08ER85187.

mass and energy balance. The CHEMCAD simulation results of the BCSGS plant design are summarized in the following section. These results were transferred to the BCSGS process flow diagrams (PFDs) for cost updates and equipment sizing. The authors performed a detailed economic analysis using a standard class 4 cost model for the chemical industry developed by the Association for the Advancement of Cost Engineering. For this task, some of the capital costs were obtained from outside vendors, while the proprietary/custom equipment and the operating costs are determined in support of the cost model tools. Further, the team performed a well-to-wake process analysis using the GREET® model for LCA of the BCSGS plant. The LCA is updated to show the CO_2 emissions throughout the BCSGS plant.

2.2.3 Plant Design

Using the U.S. DOE cost shared GHGR model as a base, the research team completed the 2,000-ton-per-day BCSGS plant design. The CHEMCAD simulation results of unit-op design variables, stream flow rates, operating conditions, and heat duties from upstream, intermediate, and downstream processes were updated and optimized for BCSGS. Table summarizes the design changes and updates to the GHGR plant design to generate the CHEMCAD process simulations model of the BCSGS plant. The different plant design sections with the respective components and changes are listed in Table .

Table 3: BCSGS Design Changes by Process-Sections

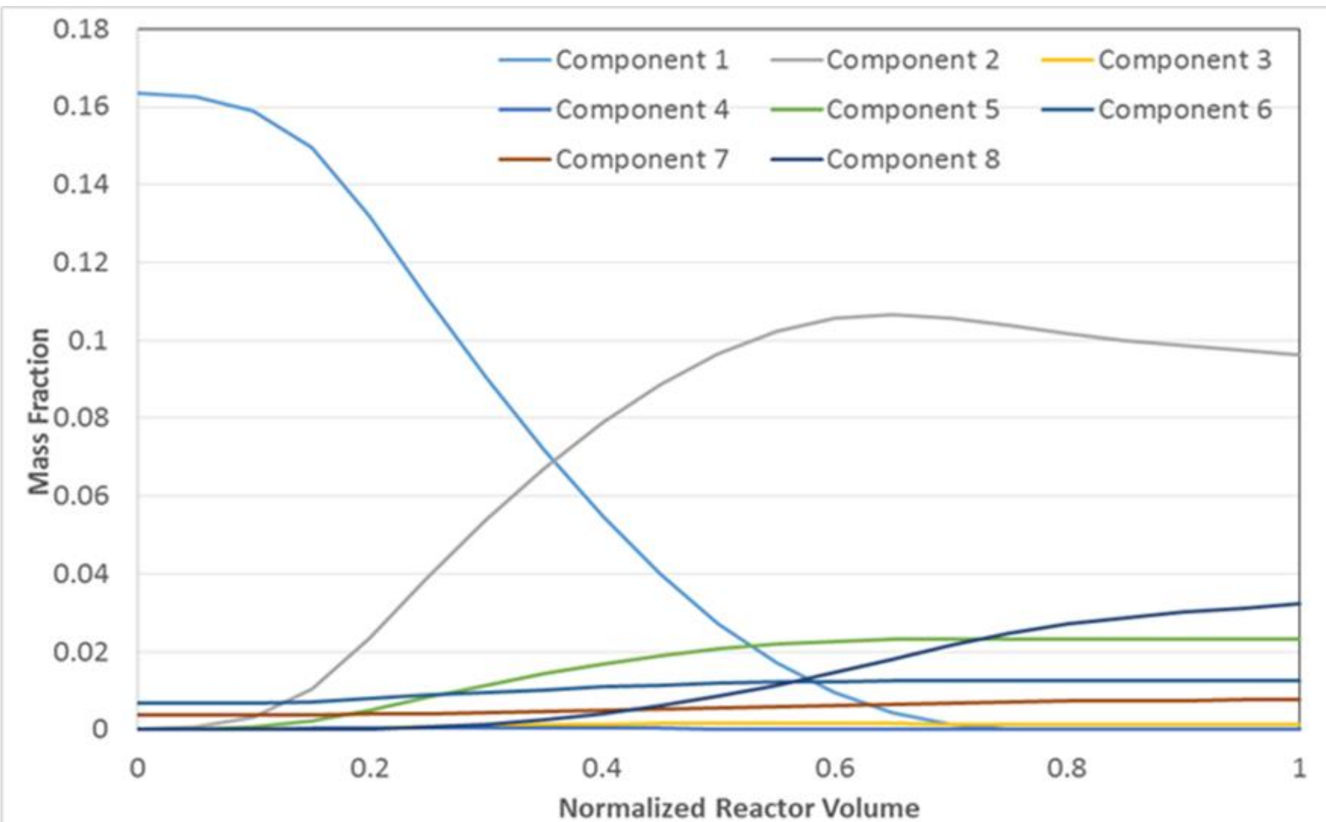
Plant Design Sections	GHGR Components/Properties	BCSGS Design changes
Feed System	Dryer	Eliminated
	Grinder	Added with particle distribution updates
Intermediate Processing	Coal conversion	Eliminated
	Biomass conversion	Optimized
	Heat duties	Updated
Gas-Liquid Separation	Fractionator	Sized
	Reflux boiler	Optimized
Gas clean-up	Recycle loops	Optimization in progress
Downstream processing	Heat duties	Updated
	Reactors	Optimized
Gasoline Recovery	Fractionator	Optimized for gasoline

Source: Altex Technologies Corporation

As shown in Table , the dryer that was used in the GHGR was eliminated from the feed-system section. Biomass as received contains 10 to 13 percent moisture and is ideal for the Altex biomass-processing reactors. Thus, further drying is not necessary. The feed grinder was updated with particle size distribution of 200 to 900 micrometers. In the intermediate-processing section, biomass conversion and reactor heat duties were optimized. The GHGR coal processing was eliminated from the design. In the gas-liquid-separation section, the fractionation was sized and optimized to separate and collect any aromatics/fuel-oil from the process-gases. In the gas-clean-up section, where CO_2 and H_2S are removed from the process gas stream, the recycle streams were optimized. Both in the downstream-processing and gasoline-recovery section, heat duties and reactions for fuel-production (gasoline) were optimized. These updates to CHEMCAD completed the BCSGS-design for the 2,000-ton-per-day plant.

With the completed BCSGS plant design, stream flow rates and unit-op heat duties were used to specify the energy requirements and design variables of each reactor or unit op. Sample simulation results from upstream and downstream processes are presented in Figure 8 and Figure 9, respectively. Figure 8 is an example of the mass fraction of different hydrocarbon components in Section 2. The model allows variation of the process conditions (temperature, pressure, WHSV, etc.) and physical dimensions (volume, length, diameter etc.) to maximize the desired components. For example, as shown in Figure 8, component-2 (a desired-product for maximizing the gasoline yield) is maximum at 0.65 normalized reactor volume. This type of analysis was used to maximize yield and define the best operating conditions for the corresponding sections.

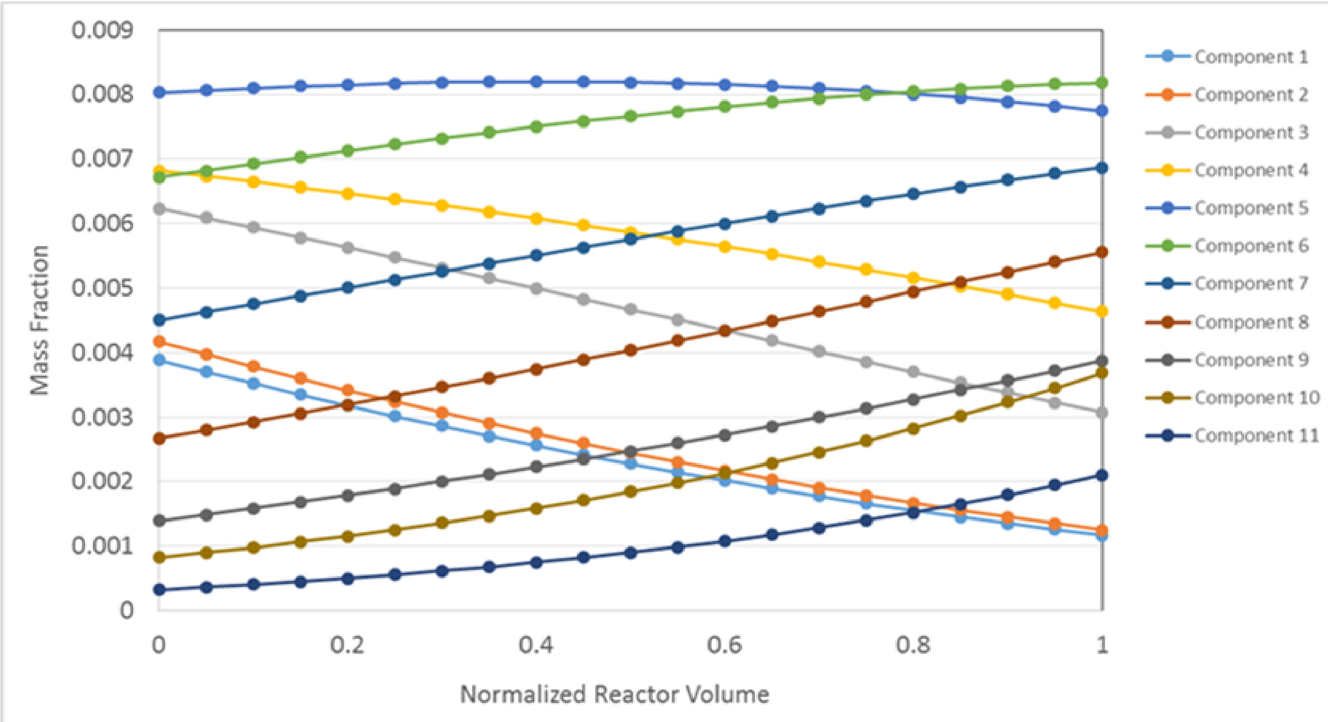
Figure 8: Simulation Results of Different Hydrocarbon Components in an Upstream Unit-Op



Source: Altex Technologies Corporation

Figure 9 is an example of the Altex-simulated-profile of Section 6 (Figure 7). The complex multi-reaction process is simulated to optimize the desired end-products by varying the reactor volume, as shown in Figure 9. For example, the optimum mix for Components 4 and 5 occurred at a normalized volume of 0.55. Using this simulation, the research team determined the optimum unit-op design criteria for each process.

Figure 9: Simulation Results of an Altex-Downstream Unit-Op Profile



Source: Altex Technologies Corporation

The updated CHEMCAD flow sheets were transferred and documented in Microsoft Excel®, and these data were linked to the plant PFD in Visio, as shown in Figure 10. The stream composition and properties in combination with sized-heat exchangers were updated for mass and energy balances and cost estimates for use in the technical and economic analysis. In addition, the recycle rates throughout the process was optimized and verified for best heat and energy utilization for the BCSGS plant. The updated PFD-sheets shown in Figure 10 allows easy access by Altex engineers to further specify, design, and cost equipment without the need to access the CHEMCAD model. Further, cost analyses were performed on the equipment in all sections and are discussed in the later sections.

2.2.4 Plant and Fuel Cost

The research team performed a detailed economic analysis was performed using a standard Class 4 cost model for the chemical industry developed by the Association for the Advancement of Cost Engineering. For this task, some of the capital cost for the designed capacity was obtained from outside vendors, while the proprietary/custom equipment and the operating costs were determined in support of the cost model in CHEMCAD and other online-engineering-tools.[20] Table 4 shows the equipment costs. Note that these are the uninstalled equipment cost and the installation and other factors are discussed later and are included in Table 5.

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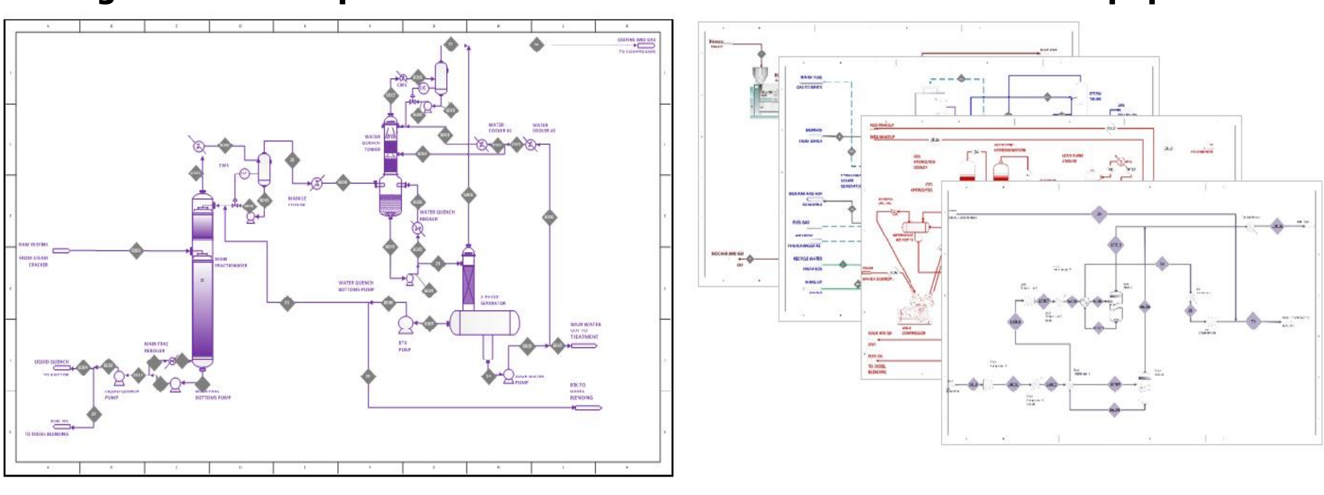
20 Peters, M.S., Plant Design and Economics for Chemical Engineers, 5/e.

Figure 10: PFD Updated with CHEMCAD Data and Used to Cost Equipment



Source: Altex Technologies Corporation

Table 4: Equipment-Cost for a 2,000-Ton-Per-Day BCSGS Plant[18,19,20]

Plant Section	Equipment Cost
Feed handling	$3,200,000
Intermediate production	$19,397,454
Gas-liquid separation	$2,902,086
Gas cleanup	$11,385,057
Fuel-gas recovery	$1,337,500
Fuel production	$1,715,493
Utilities	$196,016
Total	**40,133,607**

Source: Altex Technologies Corporation

The feed system cost was based on an actual estimated-quote from Rotochopper.[21] The basis of the estimation was the feed-flow of 2,000-tons-per-day and the optimum-particle size of the feed for BCSGS. The quote included a two-stage feed-system; primary grinding to initially size the biomass, and a secondary hammer mill grinding to ensure fine particle size distribution of the biomass including the intermediate conveying system. The intermediate production section includes the reactor water-vessels, water cooling pump, and vessel, and steam-generator-and-

21 Rotochopper Inc. (https://www.rotochopper.com/)

drum cost.[19] The gas-liquid separation and gas cleanup sections are based on the GHGR-CBTL design, where the fractionator was sized and reflux boiler was optimized under the gas-liquid separation-and-recycle loops were optimized under the gas cleanup section for 2,000-ton-per-day biomass processing.[18,19,20]

The fuel-gas recovery section had a significant cost reduction. The work performed under the project, specially related to the catalyst, showed that the planned complex-cryogenic-system, which was originally planned, could be replaced with a lower-cost compressor-unit. The compressor is sufficient to raise the pressure needed for BCSGS-catalyst peak performance for fuel-production (Figure 25). Also, the previous need for concentrating the intermediate gases-feed by cryogenic was eliminated by downstream processing condition optimization (Table). The cryogenic section elimination resulted in one less operator, reducing the operating cost as well. Further, the fuel production section had a cost reduction due to elimination of cyclization and diesel fractionation due to final fuel production in the range of gasoline. Testing under this project showed that the fuel produced had desired carbon-number distribution similar to gasoline under American Society for Testing and Materials (ASTM) D2887; simulated distillation. Therefore, the elimination of cyclization and diesel fractionation resulted in elimination of the unit operations; i) cyclization feed pump and reactor, and ii) the diesel fractionator, condenser, reflux vessel, pump, fractionator reboiler and vessel, and bottom pump respectively. The utilities did not have many updates. With these cost elements updates in the cost model, the total direct and indirect costs and total capital investment for the 2,000-ton-per-day BCSGS plant has been updated as shown in Table 5.

Based upon the cost model, the purchased equipment cost of $40.13 million from Table 4 was used to arrive at the installed cost and total capital need as presented in Table 5. The detailed Class 4 cost analysis used the listed cost factors in Table 5 for the various direct and indirect costs as presented. These factors are based on U.S. DOE baseline studies.[18,19] The total direct cost is $98.3 million and the indirect cost is $49.8 million, as presented in Table 5. As a result, the BCSGS would require a fixed capital investment of $148 million and a total capital investment of $155 million, as shown in Table 5.

Table 6 shows the breakdown of production costs and the costs per gallon. For this analysis, all associated costs, including feed material and labor costs are included. The first cost element is the cost of the raw material. A baseline biomass delivered cost of $55.00 per ton is assumed. The cost of the labor is based on five shift-operators and three shifts per day. To arrive at the total cost, including the capital cost, a conservative 20-year straight-line deprecation of the capital cost is assumed. Combining these cost elements, the bio-gasoline production cost is $1.799 per gallon with depreciation and $1.62 per gallon without depreciation. This cost analysis shows that the BCSGS operation is economically feasible as this is even below the U.S. DOE target for biofuel cost of $3.00 per gallon.

Table 5: Installed-Cost Summary for a 2,000-Ton-Per-Day BCSGS Plant[18-20]

BCSGS 2,000-TPD Plant	FOB Cost Factor	Cost Million $
Direct Costs		
Purchased equipment, E'		40.13
Delivery, fraction of E'	0.00	0.00
Subtotal: delivered equipment		40.13
Purchased equipment installation	0.39	15.65
Instrumentation & Controls (installed)	0.25	10.03
Piping (installed)	0.30	12.04
Electrical systems (installed)	0.10	4.01
Buildings (including services)	0.29	11.64
Yard improvements	0.12	4.82
Service facilities (installed)	0.00	0.00
Total direct costs	1.45	98.32
Indirect Costs		
Engineering and supervision	0.32	12.84
Construction expenses	0.34	13.64
Legal expenses	0.04	1.61
Contractor's fee	0.17	6.82
Contingency	0.37	14.85
Total indirect costs	1.24	49.76
Fixed capital investment (FCI)		148.08
Working capital (WC)	0.05	7.40
Total capital investment (TCI)		155.48

Source: Altex Technologies Corporation

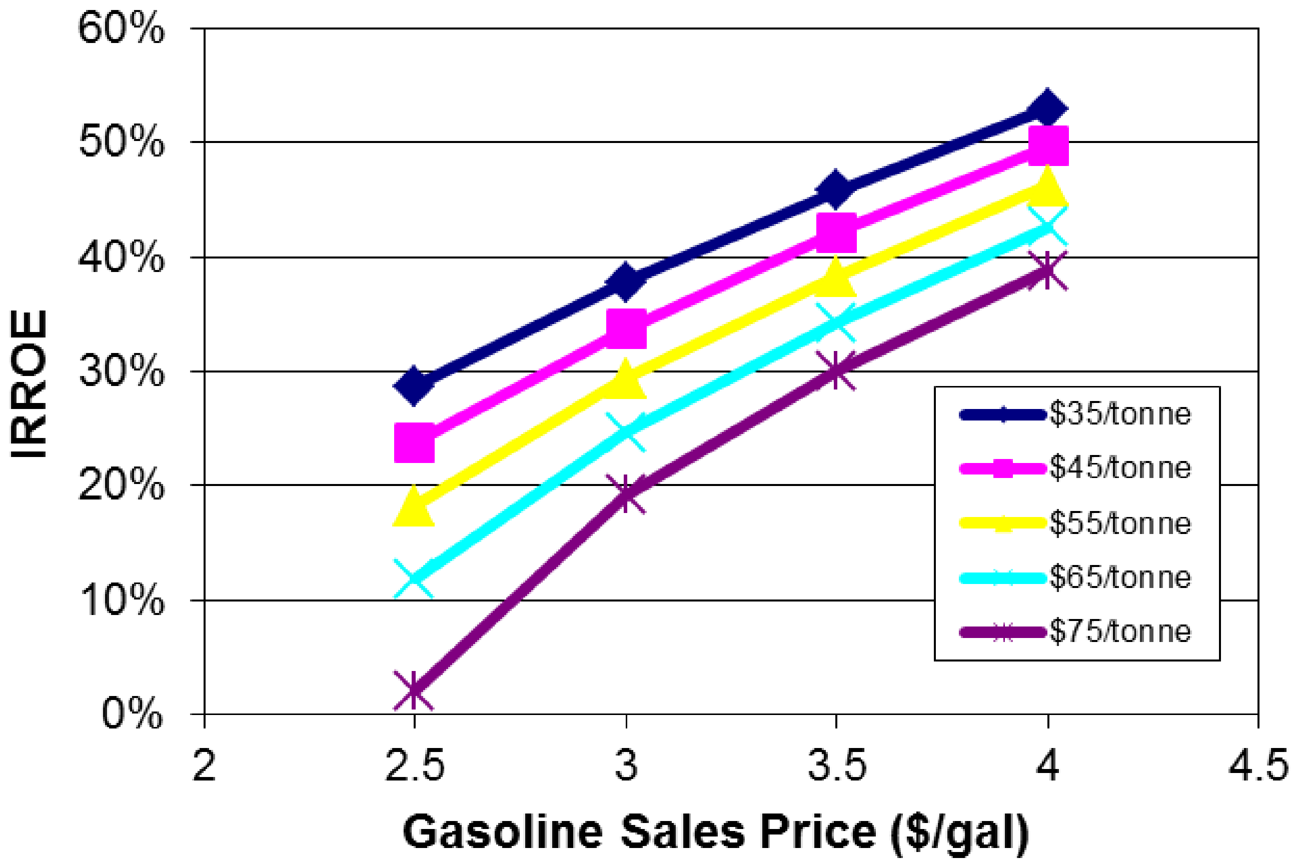
Table 6: Breakdown of Production Costs

Item	Cost Factor	Basis	Basis, MM$/y	Cost, MM$/y	Cost, $/gal
Raw materials				40.15	0.973
Operating labor				1.176	0.029
Operating supervision	64.34%	operating labor	1.18	0.757	0.018
Utilities				8.531	0.207
Maintenance and repairs	0.02	FCI	145.88	2.918	0.071
Operating supplies	0.15	maintenance & repair	2.918	0.438	0.011
Laboratory charges	16.78%	operating labor	1.176	0.197	0.005
Royalties	0.01	c_o	66.850	0.669	0.016
Catalysts and solvents	0	--		0.000	0.000
			Variable cost =	**54.836**	**1.329**
Taxes (property)	0.01	FCI	145.883	1.459	0.035
Insurance	0.01	FCI	145.883	1.459	0.035
Rent	0	FCI	145.883	0.000	0.000
Depreciation	Calculated separately				
			Fixed Charges =	**2.918**	**0.071**
Plant overhead, general	0.6	labor, supervision and maintenance	4.851	2.910	0.071
			Plant Overhead =	**2.910**	**0.071**
			Manufacturing cost =	**60.664**	**1.470**
Administration	3.50%	labor, supervision and maintenance	4.851	0.170	0.004
Distribution & selling	0.05	c_o	66.850	3.343	0.081
Research & Development	0.04	c_o	66.850	2.674	0.065
			General Expenses =	**6.186**	**0.150**
TOTAL PRODUCT COST WITHOUT DEPRECIATION *(1st year)* = c_o				**66.850**	**1.620**
TOTAL PRODUCT COST WITH DEPRECIATION *(1st year)* = c_o				**74.254**	**1.799**

Source: Altex Technologies Corporation

The research team performed a sensitivity analysis and the results, in terms of IRROE, are shown in Figure 11. As shown, for this sensitivity analysis, the feedstock price varied from $35 to $75/ton and the effect of the gasoline selling price on the IRROE was determined. This cost model assumed, three years plant construction period, 20 years depreciation, a debt/equity ratio of 60/40, loan terms of 6 percent over 20-years, inflation rate of 2 percent, discount rate of 20 percent, tax rate of 35 percent, and minimum debt-service coverage ratio of 1.3. The cash flow analysis shows that the minimum fuel sale price needed to obtain a debt-service coverage ratio of 1.3 for reasonable financing structures is $2.5/gallon. With the updated BCSGS capital costs, this is 15 cents/gallon less than previously shown. At a conservative sales price of \$3.5/gallon biofuel; gasoline sale price, the IRROE varies between 30 to 45 percent with variable feedstock prices, as shown in Figure 11. This high IRROE makes BCSGS attractive to commercial scale up production of biofuel; gasoline.

Figure 11: IRROE to Gasoline Price with Variable Biomass Price from \$35-\$75/Ton



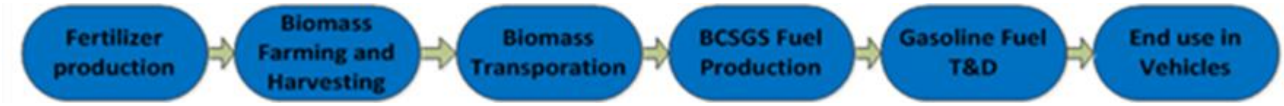
Source: Altex Technologies Corporation

2.2.5 Life Cycle Analysis

In collaboration with Argonne National Laboratory, the laboratory's GREET® model was further developed under the GHGR cost-shared project to include a module for the GHGR process so that a complete Well-to-Wake LCA could be conducted for the GHGR process with the GREET® model. Because this module was designed to handle feeds with different proportions of biomass and coal, it included the case where the feed was 100 percent-biomass. This enabled to determine the LCA assessment for the BCSGS at 100 percent biomass with minor modifications to the model.

As shown in Figure 12, the BCSGS Well-to-Wake analysis includes production and transportation of biomass-feed that consists of fertilizer production, biomass farming, harvesting, and transportation, (ii) production of BCSGS-fuel and its transportation and distribution, and (iii) combustion of the biofuel in transportation vehicles.

Figure 12: BCSGS Well-to-Wake Analysis



Source: Altex Technologies Corporation

The material flow into the BCSGS plant included 100 percent biomass. The biomass data were provided by UC Davis. Altex also has provided material and energy flow for biomass densification that is part of the biomass cycle. Table 7 is a sample data set that summarizes the energy and material flows associated with cultivating and harvesting these biomass types within California.

Table 7: Summary of LCA Data for Biomass Applicable to BCSGS

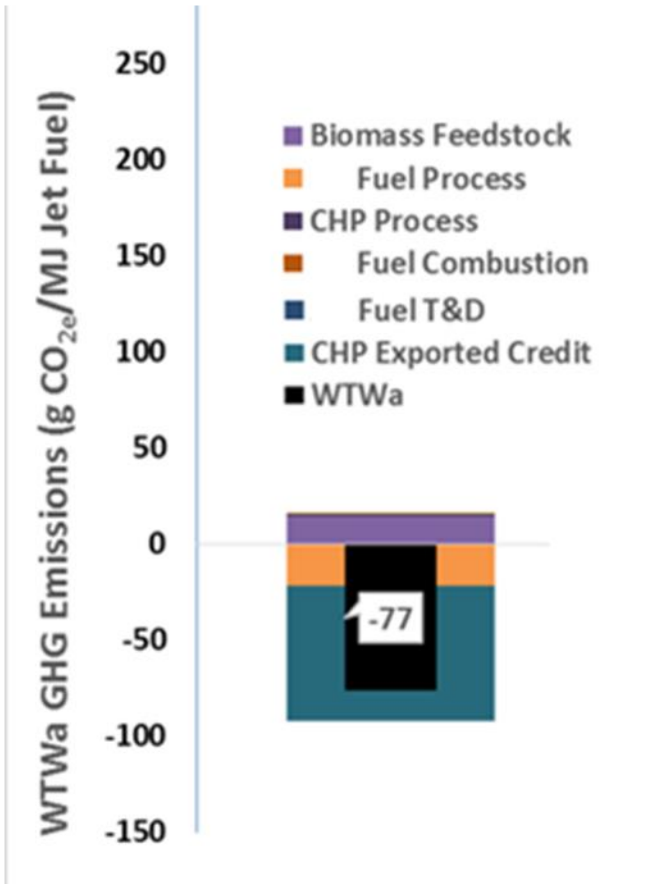
	Source: GREET® Corn (per bushel)	Source: CA Corn study (San Jose) Corn (per bushel)	Source: GREET® Corn Stover (per dry ton collected)	Source: GREET® Switchgrass (per dry ton)
Farming Energy Use: Btu	9,608	11,133	247,053	177,700
Fertilizer Use				
Grams of Nitrogen	423	567	7,000	7,300
Grams of P_2O5	146	58	2,000	100
Grams of K_2O	151		12,000	200
Grams of $CaCO_3$	1,150			
Pesticide Use				
Grams of Herbicide	7	0.01		28
Grams of Insecticide	0.06	0.10		
Water Consumption Factor (gallons/bushel)	146	5,576		

Source: Altex Technologies Corporation

From Table 7, in addition to reporting the average material and energy flows for corn production in the US per GREET®, the regional specific data for corn harvested in San Jose, California was included by tapping into UC Davis cost studies. This data was used in the BCSGS LCA model.

This data was updated to show the CO_2 emissions throughout the well-to-wake process of the GREET® model. As shown in Figure 13, factors considered to calculate the GHG emissions are; biomass feedstock-CO_2 consumption, CO_2-release from fuel-processing,-transportation,-and-distribution, and-combustion, and the combined-heat-and-power used in the process and sold as electricity for credit from bio-char. Even though fuel combustion produces the largest CO_2 emission, as shown in Figure 13, larger amounts of the CO_2 are credited due to renewable biomass,-biochar,-and-fuel that results in negative balance of 77 gCO_2e/MJ BCSGS-fuel for wheat straw. This drastic difference in CO_2 emissions clearly shows the benefit of the BCSGS plant that uses 100 percent biomass. Argonne National Laboratory is also developing the biomass transportation model to compare heavy duty trucks and railway as a mode for biomass transportation to verify CO_2 emissions for both cases.

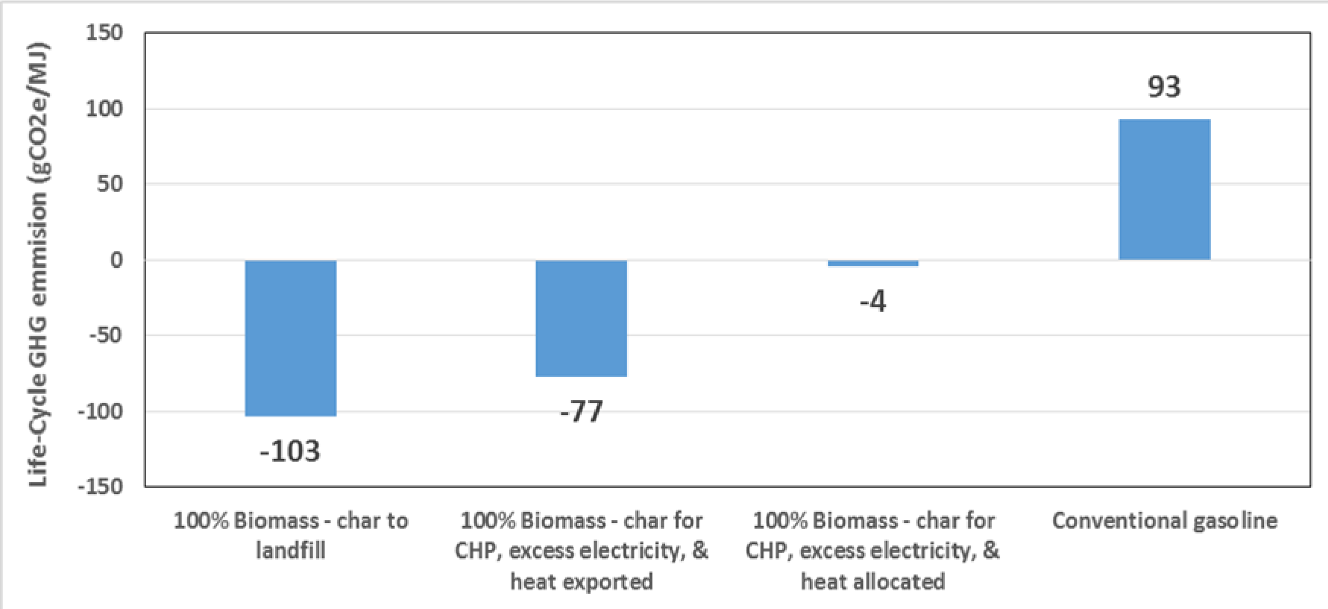
Figure 13: LCA-data on GHG Emissions for 100 Percent Biomass with the Option to use Bio-Char for Heat and Power and Sell Excess Electricity



Source: Altex Technologies Corporation

Further, Argonne National Laboratory has updated the LCA, including energy utilization from recycles, conversion factors for electricity, natural gas emissions, and water usage provided by Altex. These cost shared activities cover a larger plant with varying biomass mixes, including 100 percent biomass as in BCSGS. Three different cases using 100 percent biomass with the option of char to landfill, char for combined-heat-and-power, excess electricity and heat exported-and-discarded are compared to conventional gasoline production for their respective CO_2 emissions, as shown Figure 14. All cases using wheat straw show ranges of -4 to -103 gCO_2e/MJ BCSGS-fuel versus 93 gCO_2e/MJ conventional gasoline. This drastic difference in CO_2 emissions clearly shows the benefit of the BCSGS plant that uses 100 percent biomass.

Figure 14: GHG Emissions from Biofuel; Gasoline versus Conventional Gasoline



Source: Altex Technologies Corporation

To evaluate the effect of different feedstocks on the carbon footprint of the BCSGS process, similar analyses were carried out using corn stover and switchgrass as the feedstocks. These results are summarized in Table 8.

Table 8: Well-to-Wake GHG Footprints for Different Feedstocks and Different Char Uses (gCO_2e/MJ)

Feedstock	Wheat Straw	Switchgrass	Corn Stover
Sell char for electricity	-3.7	-6.7	-10
Sell char for Combined-Heat-and-Power	-77	-81	-88
Bury char in landfill	-103	-108	-114

Source: Altex Technologies Corporation

Table 8 shows that the use of the char has a significant impact on the GHG footprint of the process. However, in all of the feedstocks and char-use scenarios, the GHG footprint is negative. Additionally, although wheat straw has the lowest well-to-plant GHG footprint (89,000 gCO_2e/dry-ton vs. 107,000 and 142,000 gCO_2e/dry-ton for corn stover and switchgrass, respectively), the negative GHG footprint of the conversion of biomass to fuel and its combustion dominates the well-to-wake GHG footprint. Additionally, the higher carbon content in the switchgrass and corn stover leads to the BCSGS system producing more fuel per dry-ton of switchgrass or corn stover than for wheat straw. This leads to a significant decrease in the GHG emissions per MJ of fuel for these two feedstocks. To be conservative, we have chosen the wheat straw as the baseline case that, as shown in Table 8, produces the largest GHG footprint.

2.2.6 Plant Design Summary

A full-scale-2,000-ton-per-day BCSGS plant was designed, and used to perform economics, and LCA to determine the plant-and-fuel cost, and the GHG emissions. CHEMCAD was used to design the 2,000-ton-per-day plant. The mass and energy balance data from CHEMCAD was transferred to PFD for costing and equipment sizing.

Based upon the Class 4 cost model, the BCSGS plant would require a fixed capital investment of $148 million and a total capital investment of $155 million, including working capital. Combining these cost elements and the operating costs, the biofuel; gasoline production cost is $1.80 per gallon with depreciation. The cash flow analysis shows that the minimum fuel sale price needed to obtain a debt-service coverage ratio of 1.3 for reasonable financing structures is $2.5/gallon. At a conservative sales price of $3.5/gallon biofuel; gasoline sale price, the IRROE varies between 30 percent and 45 percent with variable feedstock prices.

The LCA includes GHG emissions from feedstock cultivation, harvesting, and transportation, conversion of the biomass feedstock into fuel, transportation and distribution of the fuel, combustion of the liquid transportation fuel, and from the options for char disposition (*i.e.*, burying the char in a landfill, selling it for electricity generation, or selling it for combined-heat-and-power applications). Even though, fuel combustion produces the largest CO_2 emissions, larger amounts of CO_2 credits are obtained due to use of renewable biomass and a portion of the carbon in the biomass being converted to char that is either buried as a form of carbon sequestration in solid form, or burned to offset GHG emissions from electricity sourced from the grid. This results in a negative balance of GHG emissions. The BCSGS bio-gasoline carbon footprint is negative (-77 gCO_2e/MJ). This is compared with the carbon footprint of the petroleum gasoline that is +93 gCO_2e/MJ. This substantial difference in the CO_2 emissions clearly shows the benefit of the BCSGS process.

2.3 BCSGS Test System Design

The goal of this activity was to identify and implement the needed system design modifications to a U.S. DOE cost-shared GHGR-test-system for BCSGS project. This was accomplished, and design modifications were made to the test system design that makes it applicable to BCSGS.

The BCSGS block flow diagram follows the plant flow diagram of Figure 7. The same block flow diagram applies to GHGR. However, the feed material and the product fuel are different. CHEMCAD simulations for design and performance analysis were performed for both the BCSGS and GHGR systems. This analysis, in combination with comprehensive studies of biomass (BCSGS feedstock) flow properties and a broad range of downstream testing to produce gasoline at Altex, showed that modifications are required to the feed system (Section 1) and to the Olefin-to-Fuel production reactor (Section 6).

After Section 1, the BCSGS-solid-feed is converted to a gaseous mixture similar to that obtained with GHGR. This mixture is then processed the same way as in GHGR. As a result, no changes are required to Sections 2, Section 3, or Section 4.

Section 5 is a commercial gas clean up system that has been selected to clean the gases produced from the biomass-coal mix (feedstock for GHGR) that have more impurities than the gases that are produced from biomass (feedstock for BCSGS). Therefore, it will also work for the biomass-only feed that produces a cleaner gas mixture.

The clean gas from this unit (Section 5) is converted to liquid fuel in Section 6. For BCSGS, the target fuel is gasoline, while the target fuel for GHGR is jet fuel. As a result, some modifications are required to the Sections 1 and Section 6. Details of these modifications are described below.

2.3.1. Feed-System Modifications

The feed-system PFD is shown in Figure and its major components are listed in Table 9. The feed system transfers solid material filled in a super sack from a bulk bag unloader via a flexible screw conveyor (U-100), which feeds into a hopper (U-101). The hopper feeds into two rotary valves (U-102 and U-103). The rotary valves feed into a feed-purge-separator (U-104) that is situated on the top of an eductor (A-100). Superheated steam is the motive-force to feed the solids in to the reactor in section 200. The steam feed has a bypass to account for changes in steam for the required solid flow. The feed system design was based on a proven feed system that Unitel Technologies, the Altex industrial partner and subcontractor under the project, developed. This feed system was proven in the field on sawdust and based on Unitel experience was applicable to coal/biomass feed. However, modifications were needed to apply the unit design for courses biomass feedstock at Altex.

Table 9: Feed-System Components and the Needed Modifications

Tag No form PFD	Description	Modifications
U-100	Bulk Bag Unloader w conveyor	None
U-101	Hopper	Steeper cone
U-102	Rotary Valve	Increase size
U-103	Rotary Valve	Increase size
U-104	Feed Purge Separator	Steeper cone
A-100	Eductor	Increase suction inlet size
F-101A/B, F-102A/B	Purge Vent Filters	None
N/A	Particle uniformity	Material sieving

Source: Altex Technologies Corporation

These modifications were identified based on testing followability of the material and also interactions with the feed system components manufacturers. For example, Table shows the followability parameters for the BCSGS three biomass materials and the GHGR mix of coal/biomass. These tests were performed at Iowa State University, College of Agricultural and Life Sciences. As shown, the coal/biomass mixture has a much higher followability, as indicated by the mass of the flow of the material through the test system after 5 seconds. In addition, the cohesion is a measure of the initial force required for particles to segregate and flow. In a gravity-fed hopper, the force causing the segregation of particles for overcoming the cohesion is the self-weight of the ground material itself, which depends on the bulk density of material. Hence, we can take the ratio of bulk density to cohesion as a parameter for understanding the flow properties of the ground biomass versus the coal/biomass. This ratio is extracted from the Table 10 data, below, and plotted in Figure 15. As shown, the coal biomass mix has the highest ratio, consistent with its better followability. In other words, the weight of the mix above the potential cohesion location helps to overcome the cohesion and flow the material downward. Accordingly, experiments carried out at Altex have shown that the coal/mix had a better flowability than the biomass and agitation of biomass material that was required for all three biomass materials to segregate and flow from conical hoppers into flow lines. These tests and additional tests at Altex defined the needed modifications to the feed system.

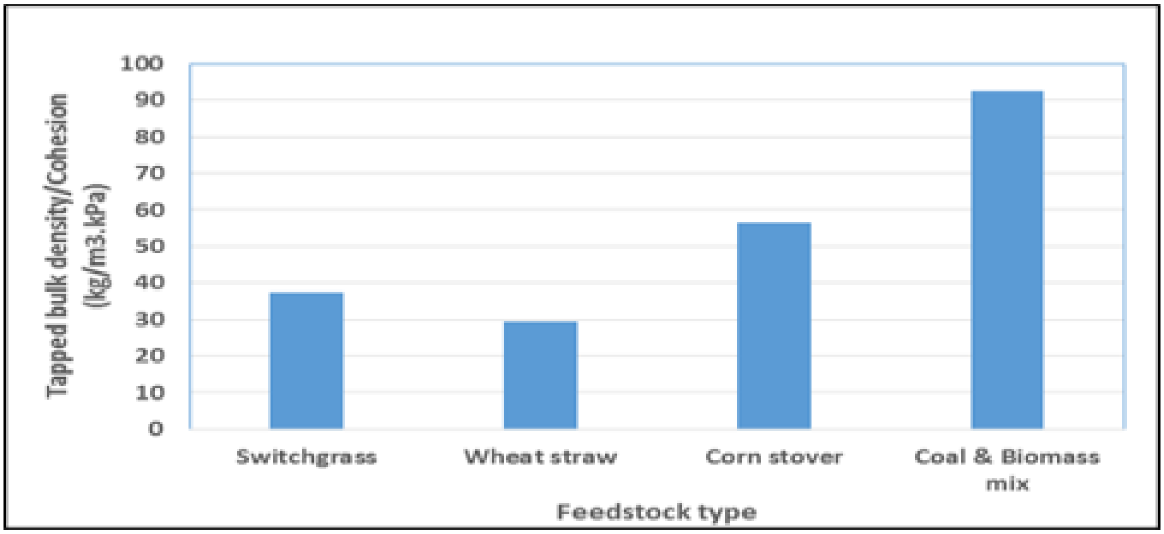
The research team initial performed testing to define the design parameters with the ground biomass that was available at Altex. This material was ground to a 1/8-inch size. Although they were ordered to be sized to 1/8 of inch mesh, there were longer than 1/8-inch straws in the ground biomass. This is evident from Figure 16, which shows the material under a shear stress. Longer straws are visible that most likely have passed the sizing mechanism at a straight angle. This issue was communicated with the new grinding partner, Andritz, who made sure that their grinding and follow-on sieving was effective in capturing the longer straws. This was achieved and the ground biomass received from Andritz was much finer. Nevertheless, the design-upgrade test activities used the available non-uniform biomass. As a result, design is conservative and can handle coarser material.

Table 10: Flowability Properties of Ground Biomass and Coal & Biomass Mix

Sl. No	Measured property	Switchgrass	Wheat straw	Corn stover	Coal and Biomass mix	
1	Loose Bulk density (kg/m^3)	205	111	219	440	Multi-phase flow calculations
2	Tapped bulk density (kg/m^3)	248	135	265	555	
3	Mass flow after 5 sec, grams	137	37	113	4,037	Critical steady flowrate
4	Angle of internal friction, deg	44	55	68	68	
5	Cohesion, kPa	6.6	4.6	4.7	6	

Source: Altex Technologies Corporation and Iowa State University, Department of Agricultural and Biosystems Engineering

Figure 15: Followability Measure of the Material



Source: Altex Technologies Corporation

Figure 16: Direct Shear Test Unit for Measuring Shear Stress

Source: Iowa State University, College of Agricultural and Life Sciences, College of Engineering

Table 9 shows the modifications that were implemented. As shown, the bulk-bag unloader (U100) from the cost-shared equipment is applicable to the BCSGS project. To ensure the applicability of U-100 to BCSGS, a sample of the biomass was supplied to Flexicon, the equipment manufacturer. Flexicon examined this material to ensure that the design of U-100 works with the biomass to be used in the project. To ensure the operation at full-scale, a super sack of sized biomass was delivered to Flexicon who successfully tested the bulk bag unloader (U-100) before shipping it to Altex.

The hoppers (U-101 and U-104) are generally applicable to all feed material provided that the cone angle and discharge ports are properly designed for feed material that is more difficult to feed. Since the biomass has lower density, non-uniform shape, and a larger angle of repose in comparison to the biomass-coal mixture it makes biomass the more difficult of the two materials to feed.

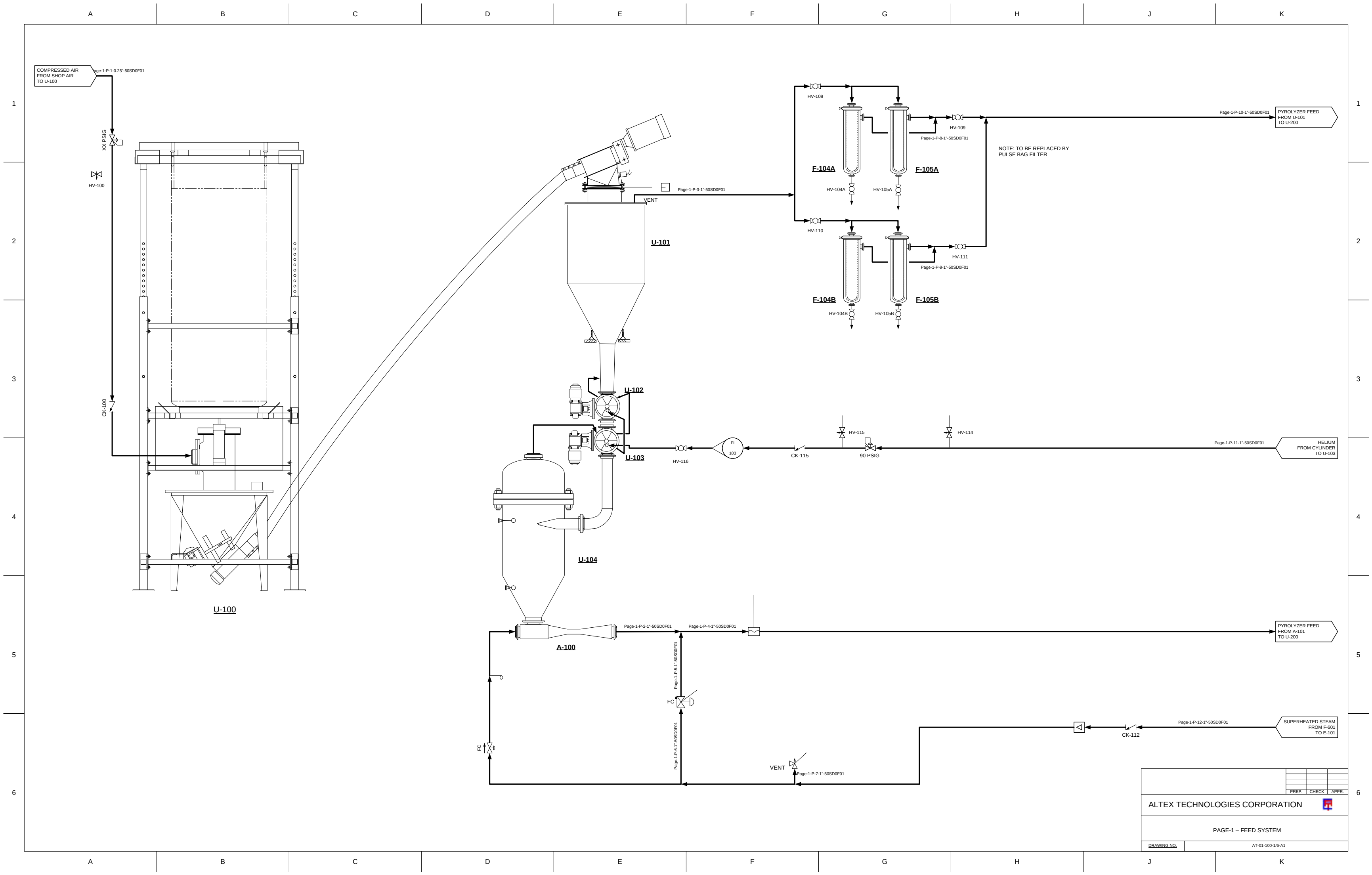
In order to identify modifications to U-101, U-104, and A-100 that are listed in Table 9, we performed feed tests utilizing biomass as the feed material. To evaluate the design of the U-101 and U-104, the flow rate and flow patterns of biomass were examined for cones made of different materials, having different cone angles and different discharge-port sizes and active measure to break potential rat-holing.

Figure 17 shows examples of test of the biomass followability using hoppers with different cone angles. To make prototypes rapidly, sheet metal was used. The original design of the hopper asked for a 45-degree angle cone with horizontal. Tests showed that coal/biomass mixtures easily flow through this angle hopper, but the biomass flow stopped regularly during testing due to bridging. The frequency of the bridging reduced drastically using a 60-degree (measured against horizontal) cone angle. This steeper wall, combined with a two-inch opening at the bottom, stopped the material bridging. However, occasional rat-holing was observed. Active measures such as air injection and mechanical agitators were tested that all were successful. Figure 19 shows a commercial bin aerator that was installed and was successful in breaking the rat-holes and resulting in a continuous flow. These test results provided the basis to select the appropriate cone angles and discharge-port sizes for U-101 and U-104. The combination of a steeper cone angle and a larger discharge port were selected for BCSGS feed-system design. Figure 18 shows the PFD of the GHGR feed test system.

Figure 17: Test of Biomass Followability with 45-degree (Left) and 60-degree (Right) Cones

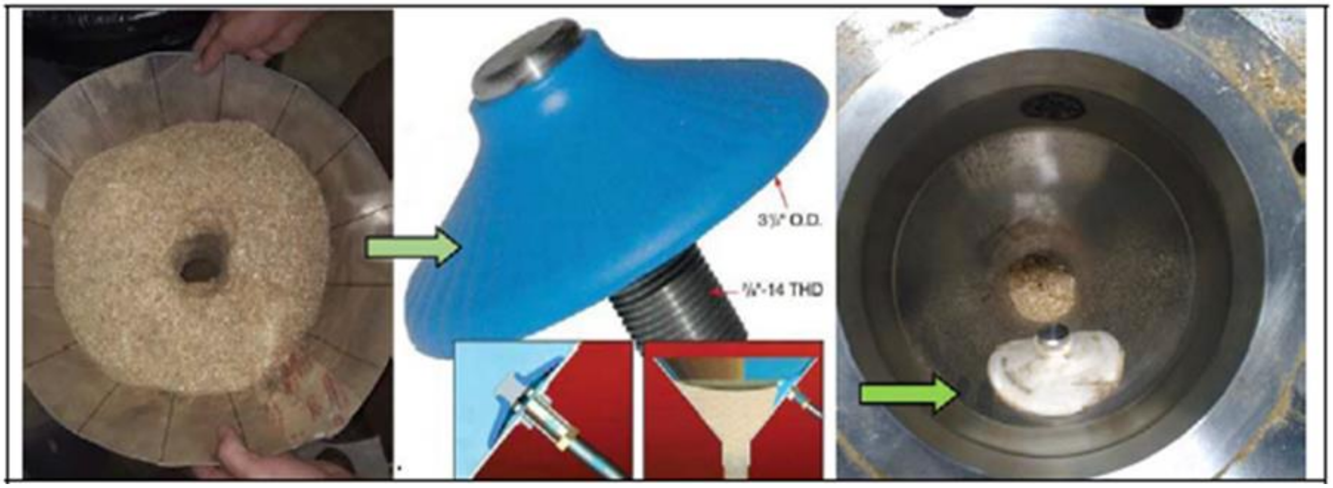
Source: Altex Technologies Corporations

Figure 18: PFD of the GHGR Feed Test System



Source: Altex Technologies Corporation

Figure 19: Active Measures to Prevent Rat-Holing in the Hopper



Source: Altex Technologies Corporation

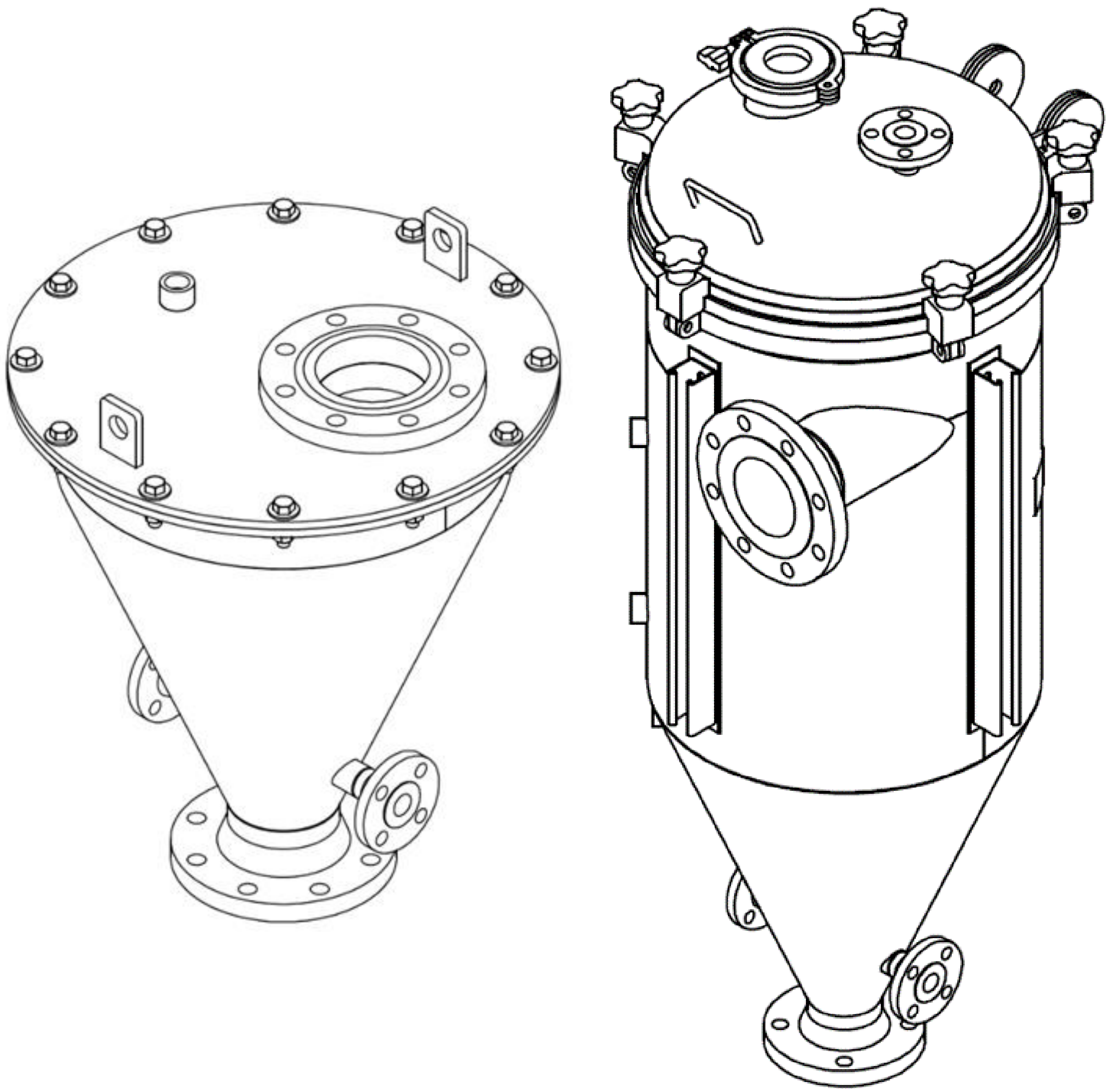
As shown in Figure 19, after the materials flow through two hoppers, steam inducts the material. Therefore, in addition to testing hopper designs, the flow rate through an existing eductor also finalized the design of the eductor. The test set-up is presented in Figure 20. For these tests, the research team used compressed air to educt the materials. The eductor manufacturer reviewed these results and also examined the materials before recommending the final eductor.

Figure 20: Feed Tests of Biomass for BCSGS Using a Test Set-up Consisting of Educator and Feed Purge Separator from Cost-Shared U.S. DOE Project

Source: Altex Technologies Corporation

Figure 21 shows the upper and lower hopper final designs. The major modifications were a steeper angle (67.5-degree with horizontal) or 45-degree cone angle, polished surface, and 3-to-4-inch exit diameter. Note that this cone angle is much steeper than the original GHGR design that had a 45-degree hopper design with horizontal (90-degree cone). In addition, as shown, the research team included flanged ports near the outlet in case active measures were required to break the rat-holing.

Figure 21: Design of the Upper Hopper 101 (Left) and Lower Hopper 104 (Right)



Source: Altex Technologies Corporation

The team based the feed system design modifications on the followability of the courser and non-uniform ground biomass. After receiving the final, ground feedstock from Andritz, the research team tested it with the 60-degree hopper with horizontal (Figure 21 test setup). The material flew through the hopper with no rat-holing or blockage and there was no need for any active measure. This contrasts with the original test that required the bin aerator pulse to break the rat-holing. This is due to the fact the new material was better sieved to remove long straws that would result on interlocking of the material at the exit. In fact, the material was visually finer than previously ground biomass.

Note that this test included a cone angle of 60 degrees with horizontal (60-degree cone) and a 1.6-inch discharge hole (Figure 18 test setup). The successes of this test indicates that the final design (Figure 21) that has even steeper angle (67.7 degrees with horizontal-i.e. 45-degree cone) and larger exit ports (3 inch upper hopper and 4 inch lower hopper) have been designed conservatively and will operate successfully with the finer material. Also note that the rotary valves positioned under these hoppers (see Figure 29) will further help the material followability through the feed system.

2.3.2 Fuel-Production-System Modifications

The fuel-production system consists of two reactors for continuous operation. While one reactor produces the gasoline, the second reactor undergoes regeneration of the catalyst. For GHGR, the fuel-production system was designed to perform over a wide range of temperatures, pressures, WHSVs, and feed-concentrations. Based on detailed bench-scale testing of this portion of the system for BCSGS, the research team determined that the mechanical design of these two reactors for GHGR will work for BCSGS without significant modification. However, the process conditions selected for GHGR have been modified to optimize gasoline production. Some of the results of this optimization work are presented in Table 11.

Table 11: BCSGS Catalysts Being Optimized for Oligomerization Process

Catalyst	Pressure	Temperature	Gasoline Fraction	Liquid Yield
1	High	Low to high	60% to 75%	50% to 80%
2	High	Low to high	90% to 98%	30% to 50%
3	Low	High	92% to 100%	27% to 36%

Source: Altex Technologies Corporation

The research team based the reactor design on lab scale testing reactors that were used to test the catalysts. The lab scale reactors were simple tubes with different diameters and lift-to-drag ratios. The test reactor design consisted of multiple tubes in the form of a shell and tube heat exchanger. Excel-based models of heat transfer were used to finalize the design. These models ensured that the desired temperature profiles are obtainable with reasonable cooling and heating flow rates around the tubes. These simulations provided qualitative verification of the reactor design and showed that the reactor design selected should provide good performance.

2.3.3 Conclusion

The modifications to the GHGR system needed for BCSGS have been identified and are being implemented. These modifications impacted only two sections of the system: Section 1 (the feed system) and Section 6 (the fuel-production system).

The modifications to the feed system include steeper cone angles and discharge ports for the feed hopper and feed-purge separator along with a larger suction inlet for the eductor. The research team developed these feed-system modifications by biomass feed tests with cones of different neck-size, and different discharge-port sizes, and with an existing eductor.

The modifications to the fuel-production system to optimize gasoline production over jet-fuel production include changing the targeted operating conditions and modifying the catalyst pore size, pore volume, and surface functionality. This avoids the need for modifying the mechanical design of the reactors used in GHGR for use in BCSGS.

2.4 Catalyst Upgrade

The goal of this activity was to identify available commercial catalysts and to improve the in-house catalysts for gasoline production for BCSGS. To accomplish this task, the cost-shared GHGR-CBTL downstream process was implemented with a set of new process-conditions and catalyst modifications to optimize gasoline production. The downstream conditions were modified and optimized to increase C5 through C12 hydrocarbon range (gasoline) in the liquid-fuel for BCSGS while the GHGR process was optimized for C9 through C18 hydrocarbon (JP-8) range. To achieve gasoline-range hydrocarbons a comprehensive test matrix was designed and completed to optimize gasoline production for BCSGS. The properties of the resulting hydrocarbons were determined through ASTM D2887 Simulated Distillation testing.

The data from the benchmarking and Primary Sampling Unit (PSU) catalyst-development activities under the cost-shared GHGR project were used as a baseline to identify the downstream catalysts and their operating conditions for BCSGS. Summary of the catalyst-improvement results are discussed below.

2.4.1 Catalyst Improvement and Supply

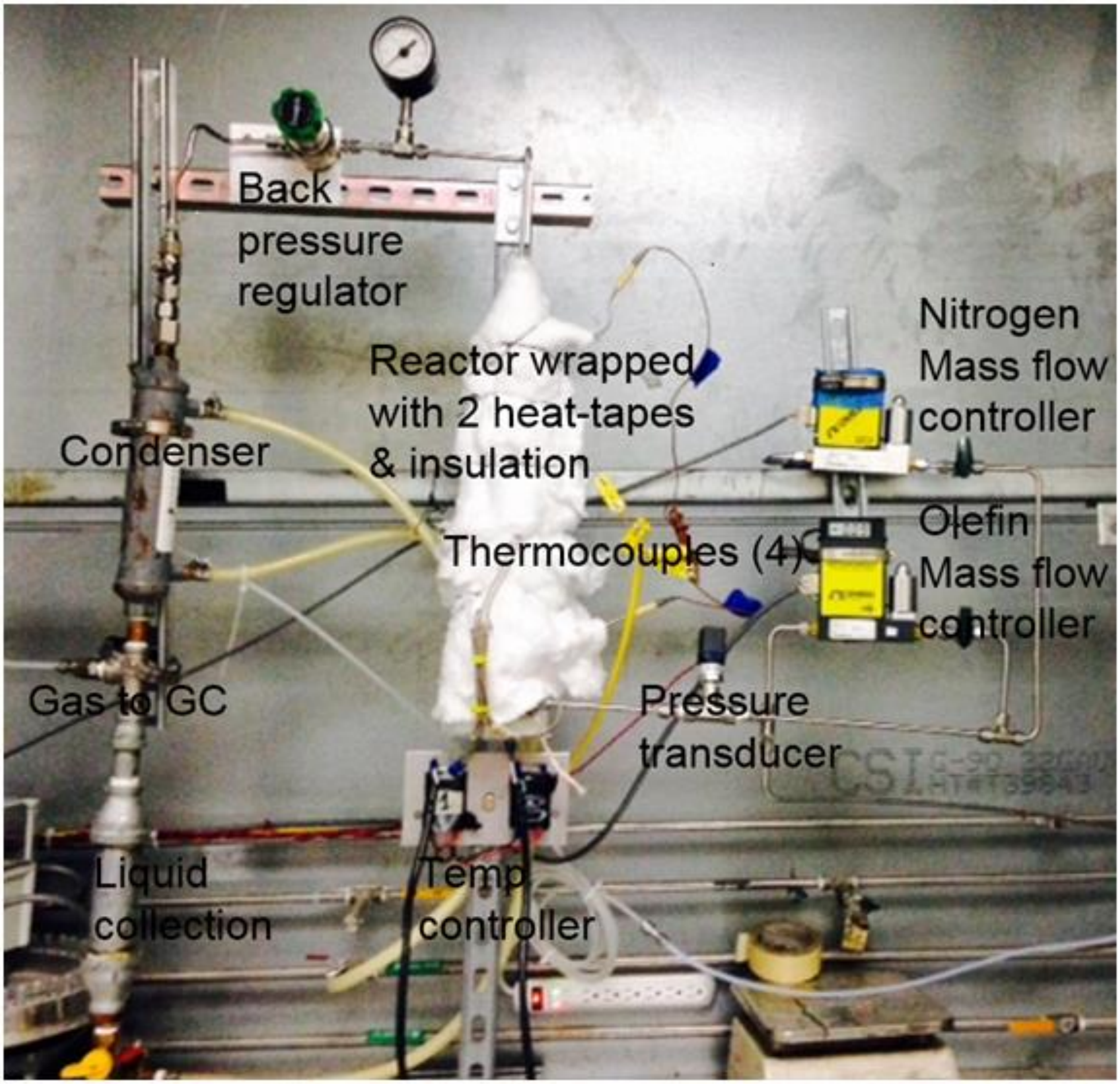
Catalyst-improvement and supply activities include: benchmarking commercial catalysts at Altex; synthesizing gasoline-specific-catalyst for improved catalyst durability and reduction of coke formation by PSU; and optimization of downstream operating conditions for gasoline production for all catalysts and Altex-designed downstream unit operations.

A comprehensive set of tests was performed at Altex and PSU with variable temperature, pressure, WHSV, and feed concentrations to identify the optimum catalyst and optimize gasoline production.

2.4.2 Benchmarking Commercial Catalysts

Catalysts were tested using the test setup shown in Figure 22. It includes two heat tapes for heating the reactor; two proportional relays to control the heating rate of heat tapes; four thermocouples to measure reactor bottom and top temperatures as well as surface temperature beneath each heat tape; a back pressure regulator to adjust the reactor pressure, and two mass flow controllers to control the flow of gases. Reactor’s bottom and top temperatures are used to control the heating rates of the heat-tapes on the lower and upper sections of the reactor respectively. A programmable logic controller) controls the temperature. For user interface a LabVIEW program was used. The operator sets the desired flow rates and temperature set point for the reactor through user interface. The pressure setting is done manually by adjusting the backpressure regulator valve. The catalysts were loaded in the reactor and tested.

Figure 22: Catalyst Test Setup



Source: Altex Technologies Corporation

Table 12 compares the test results between the commercial and the Altex-in-house catalysts. The in house catalyst was developed in collaboration with PSU, a subcontractor under the project. Three commercial catalyst were acquired. Commercial Catalyst 1 and Catalyst 2 did not perform at low pressures resulting in no liquid-fuel production. Catalyst 3 gave 10-25 percent liquid yield and >20 percent conversion at low pressures, while up to 45-70 percent liquid yield and 60 percent conversion at high pressures. As shown in Table 12, the In-house catalysts gave up to 100 percent conversion and liquid yield >20 percent at low pressures. With an increase in pressure, the commercial catalyst, Catalyst 2 gave 52 percent liquid yield and 84 percent conversion. In comparison, liquid yield of 65 percent and conversion of 100 percent was obtained with the pressure increase within house catalyst. Similarly shown in Table 12, the commercial Catalyst 3 gave 66 percent conversion and 50 percent liquid yield for higher pressures of 120 to 170 pounds per square inch (PSI). In comparison, In-house catalyst gave 100 percent conversion and >20 percent liquid yield at atmospheric pressure at sea level (ATM). These tests show that the In-house catalyst is superior to the commercial catalysts, because it operates at lower pressure, eliminating the need for any compressor.

Figures 23 and 24 and show the effect of WHSV and pressure on fuel distribution respectively. These set of tests were performed on Catalyst 3, which is the base of PSU catalyst. With increasing WHSV, the gasoline fraction in the liquid-product increased from 43 percent to 60 percent. Therefore, higher WHSV favored gasoline production with Catalyst 3 as the olefins have higher selectivity to the catalyst at higher WHSV producing lighter hydrocarbon range fuel, gasoline versus JP-8 at lower WHSV.

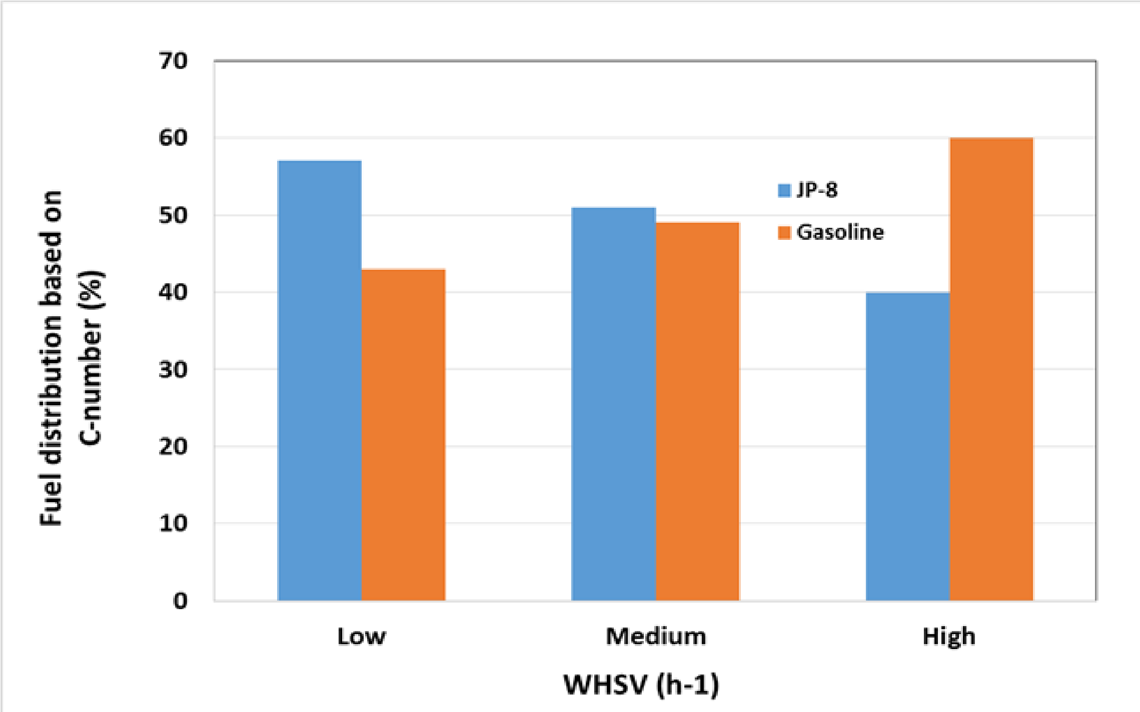
As shown in Figure 24, with decreasing pressure to atmospheric condition (low), gasoline composition increased from 36 percent to 55 percent. Therefore, lower pressure was favored for gasoline production with Catalyst 3 as the olefins have higher selectivity to the catalyst at lower pressure producing lighter hydrocarbon range fuel, gasoline versus JP-8 at higher pressure.

Table 12: Comparison between Commercial and In-House Catalysts

Catalyst	Pressure (PSIG)	WHSV (h^{-1})	Liquid Yield (%)	Conversion (%)
Catalyst 1	ATM to high	Low to high	10-70	17-97
Catalyst 1	ATM to high	Low to high	15-28	30-60
Catalyst 2	ATM to high	Low	0-52	84
Catalyst 3	ATM to medium	Low	0-50	66
In House Catalyst	ATM to medium	Low to high	20-65	50-100
In House Catalyst	ATM to medium	High	20-45	97-100

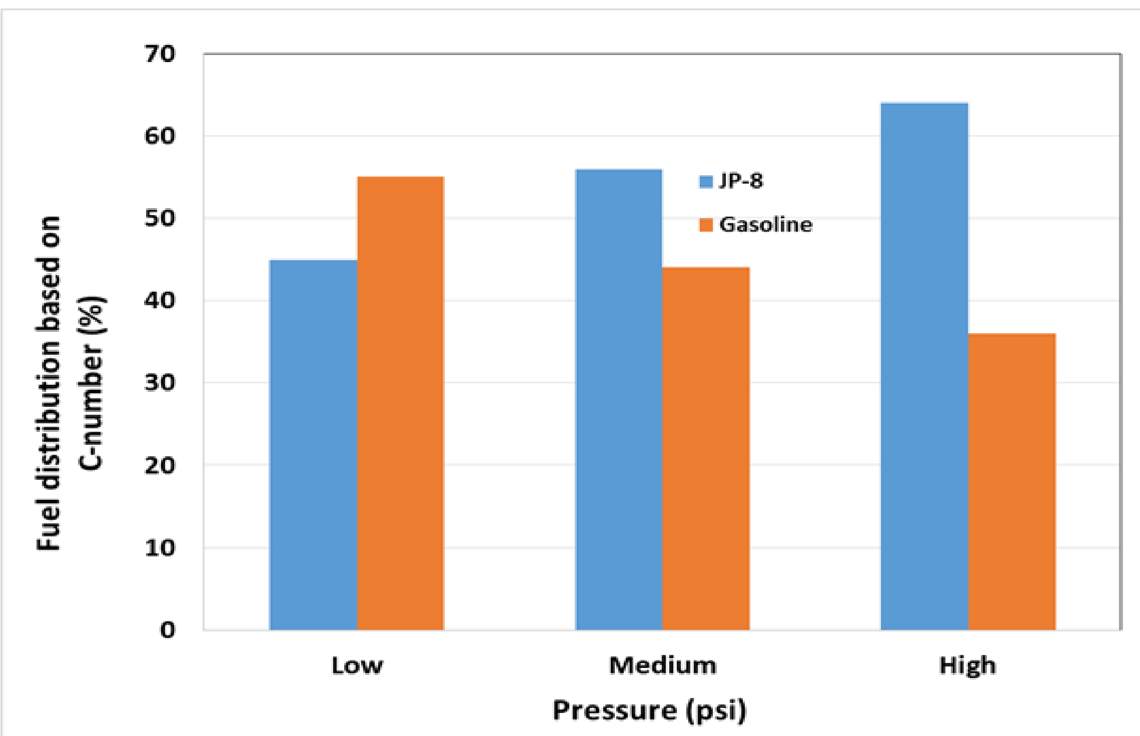
Source: Altex Technologies Corporation

Figure 23: Effect of WHSV on Gasoline Fraction in the Fuel



Source: Altex Technologies Corporation

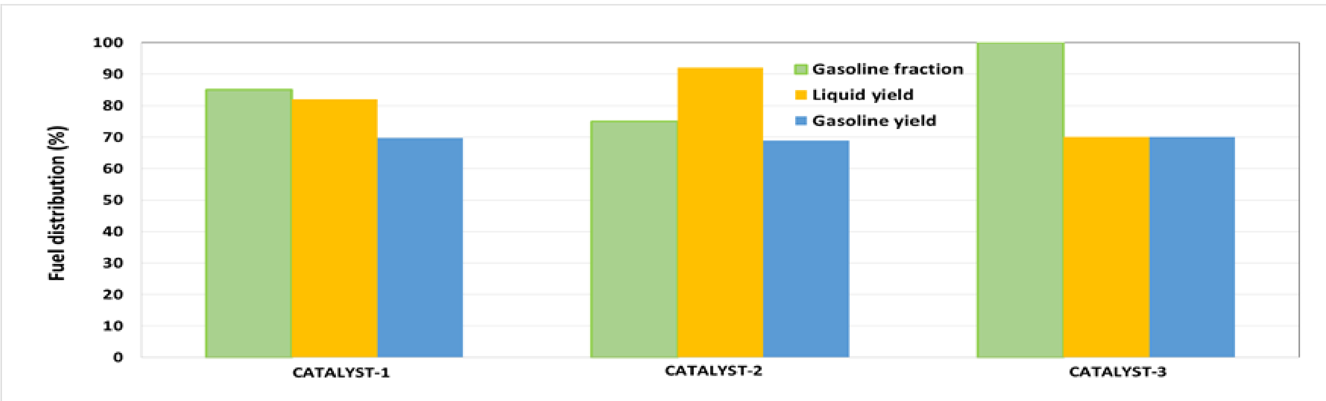
Figure 24: Effect of Pressure on Gasoline Fraction in the Fuel



Source: Altex Technologies Corporation

The set of comprehensive testing under BCSGS defined the optimum conditions for each catalyst. These included temperature, pressure, WHSV, and feed concentration. A summary of the optimized performance of the three different commercial catalysts are presented in Figure 25. Through a broad range of optimization tests, conditions for each of the catalysts were identified where it is possible to maintain a constant gasoline yield of 70 percent with liquid yields ranging from 70 percent to 92 percent and gasoline fractions ranging from 70 percent to 100 percent. Effect of Process-Conditions Optimization on Commercial Catalysts 1, 2, and 3 achieved 100 Percent Gasoline Fraction, 70 Percent Liquid Yield, and 70 Percent Gasoline Yield.

Figure 25: Altex Tests for Gasoline Optimization



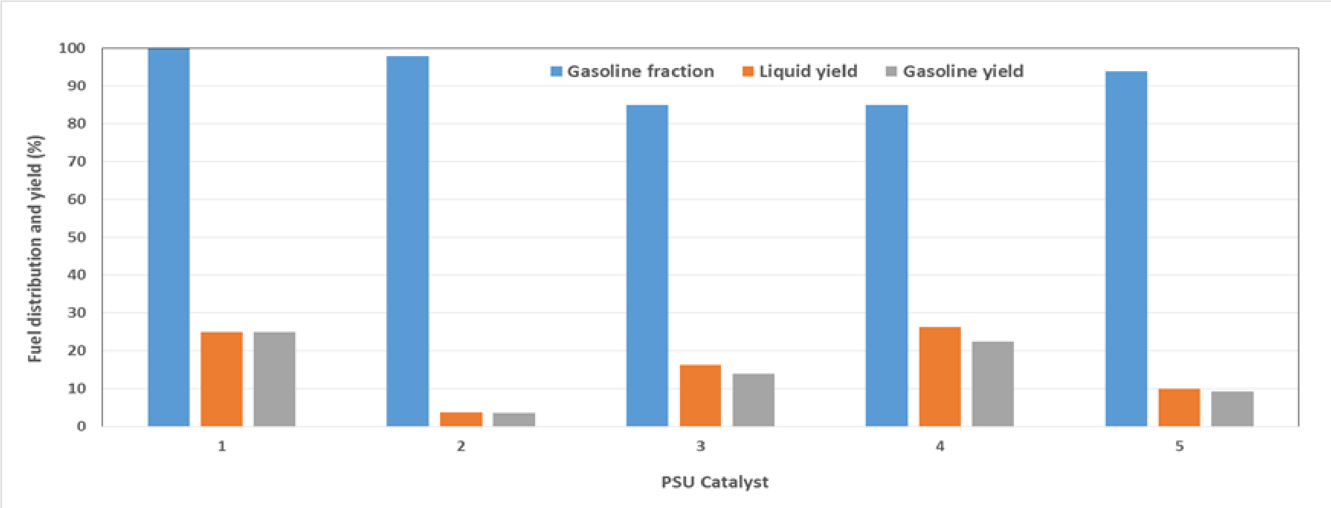
Source: Altex Technologies Corporation

2.4.3 Altex In-house Catalyst Performance

Under BCSGS, PSU's catalyst-improvement activity involved optimizing gasoline production, liquid yield, catalyst durability, and reducing coke formation. This activity was concentrated in producing a catalyst that operates under milder conditions than the commercial catalysts discussed above, thus reducing the process complexity and cost.

For BCSGS, PSU has synthesized five different catalysts. Catalyst-1 serves as the baseline for all of the PSU-developed catalysts, whereas Catalyst-2, Catalyst-3, Catalyst-4 and Catalyst-5 are versions of Catalyst-1 that has been modified by PSU to change catalyst properties. All PSU catalysts were optimized for gasoline production over their designed range of optimized conditions. Through a broad range of catalyst synthesis and optimization tests, the achieved gasoline fraction, liquid yield, and gasoline yield are 100 percent, 28 percent, and 28 percent, respectively, as shown in Figure 26. While the gasoline yields are lower than the commercial catalysts, the PSU catalysts operate at lower pressure and are more resistant to coke formation resulting in a longer lifetime between regeneration cycles than the commercial catalysts.

Figure 26: PSU Tests for Gasoline Optimization



Source: Altex Technologies Corporation

2.4.4 Catalyst Summary

The catalysts for BCSGS were identified, improved, and optimized for gasoline production. Under the benchmarking-commercial-catalysts activity, a gasoline yield of 70 percent was achieved and under the PSU-synthesized-catalyst activity, a gasoline yield of 28 percent was achieved. All selected catalysts for BCSGS are designed to operate over a wide range of pressures, temperatures, WHSVs, and feed concentrations. Catalyst improvement activities also contributed to reduced coke formation, improved catalyst-life-time, and use of mild operating conditions in comparison to existing industrial conditions resulting in savings. After testing the catalyst candidates, the catalysts for BCSGS have been selected based on the catalysts being readily available in the quantities required. Furthermore, the required quantities have been received at Altex. With these activities, the catalyst-improvement and supply task and its associated milestone on the project schedule have been completed.

2.5 BCSGS Test System Upgrade and Verification

The BCSGS test system was planned to be an upgrade of the cost shred GHGR test system by upgrading the feed and fuel production components. Under the U.S. DOE cost shared project a 1-BPD system was designed to be built in a new building adjacent to the Altex existing facility in Sunnyvale California. The new test set up required a new permit that was handled under the U.S. DOE cost shared project. The permitting process required detailed mechanical, ventilation and electrical layouts and seismic, fire, hazmat and process safety and hazard assessment. While some of these activities were planned under the U.S. DOE cost shared project, after interaction with the city the activities kept expanding. As a result, it was decided to abandon the new facility expansion and upgrade an existing 0.3-BPD test facility. These activities are described below.

2.5.1 Feed-System-Component Procurement

After preparing the piping and instrumentation diagram, bill of materials, and spec sheets, equipment was procured. This process included issuing purchase orders, approving equipment drawings (where necessary), and receiving the equipment. The feed system components, consistent with the Figure 18 PFD, were procured.

Figure 27 shows a photograph of the bulk-bag unloader. This unit allows feeding the biomass from the super sacks cleanly. The equipment consists of a bulk bag discharger, designed for loading of bulk bags via a cantilevered I-beam, with electrically operated 2-ton capacity hoist and trolley. This unit can accommodate bulk bags and super sacks ranging in height from 36 inches to 72 inches high, with a maximum width of 48 inches at the widest point when full. The unit also includes bag dump hood, with interface chute. The chute has a dust-tight snap-action door, for easy access to the dump-bag spout, and the external dust hood has a gas-spring-assisted access door, with quick-release clamps, and includes a gasket connection to the hopper. This allows flowing the biomass to the unit hopper with no dust generated. A long inclined screw feeder (a portion of it is visible in Figure 28) transports the biomass to the feed system upper hopper or feed bin, which is shown on the left side of Figure 28) according to the feed system design PFD of Figure . The biomass is then fed to the lower hopper (Figure 28, right picture) through the rotary vales shown in Figure 29. The valves control the flow of the biomass to the lower hopper that is also a purge separator. The combination of these two hoppers and the two vales in-between will stop air from entering the upstream components.

Figure 27: Photograph of the Bulk-Bag Unloader During Assembly at Altex (Left) and During Testing at Supplier's Facility (Right)

Source: Altex Technologies Corporation

Figure 28: Upper (Left) and Lower (Right) Hoppers

Source: Altex Technologies Corporation

Figure 29: Rotary Valves

Source: Altex Technologies Corporation

2.5.2 Fuel-Production-Component Procurement

The fuel production was fabricated based on the design that was discussed in Section 2.3.2. The fabricated unit is shown in Figure 30. The reactor is a shell and tube design with the reactor tubes centrally located and are surrounded with the pump of coolant that is flown to control the temperature through the fuel production and subsequent regeneration cycles.

Figure 30: Fuel Production Reactor

Source: Altex Technologies Corporation

2.5.3 Test System Build

The test system upgrade and buildup was initiated when erecting the feed system. The completed feed system including the bulk-bag unloader is shown in Figure 31. The process of erecting this system is shown in Figure 32, Figure 33, Figure 34, and Figure 35. As shown the feed system frame is split between lower and upper frames upon which, respectively, the lower and upper hoppers and associated valves were installed. Then as shown in Figure 34, the lower and upper frames were welded together to complete the feed system installation. As shown in Figure 34, the feed system is joined to the bulk bag unloader through the inclined screw feed. This screw is rotated by the motor that is located on top of the feed frame and carries the biomass from the hopper for the bulk-bag unloader to the upper hopper of the feed system. The biomass is then fed to the lower hopper through the rotary vales shown in Figure 29. The valves provide an airlock and control the flow of the biomass to the lower hopper from which the biomass is educted into the pyrolyzer by steam.

Figure 31: Completed Feed System Setup with Bulk-Bag Unloader

Source: Altex Technologies Corporation

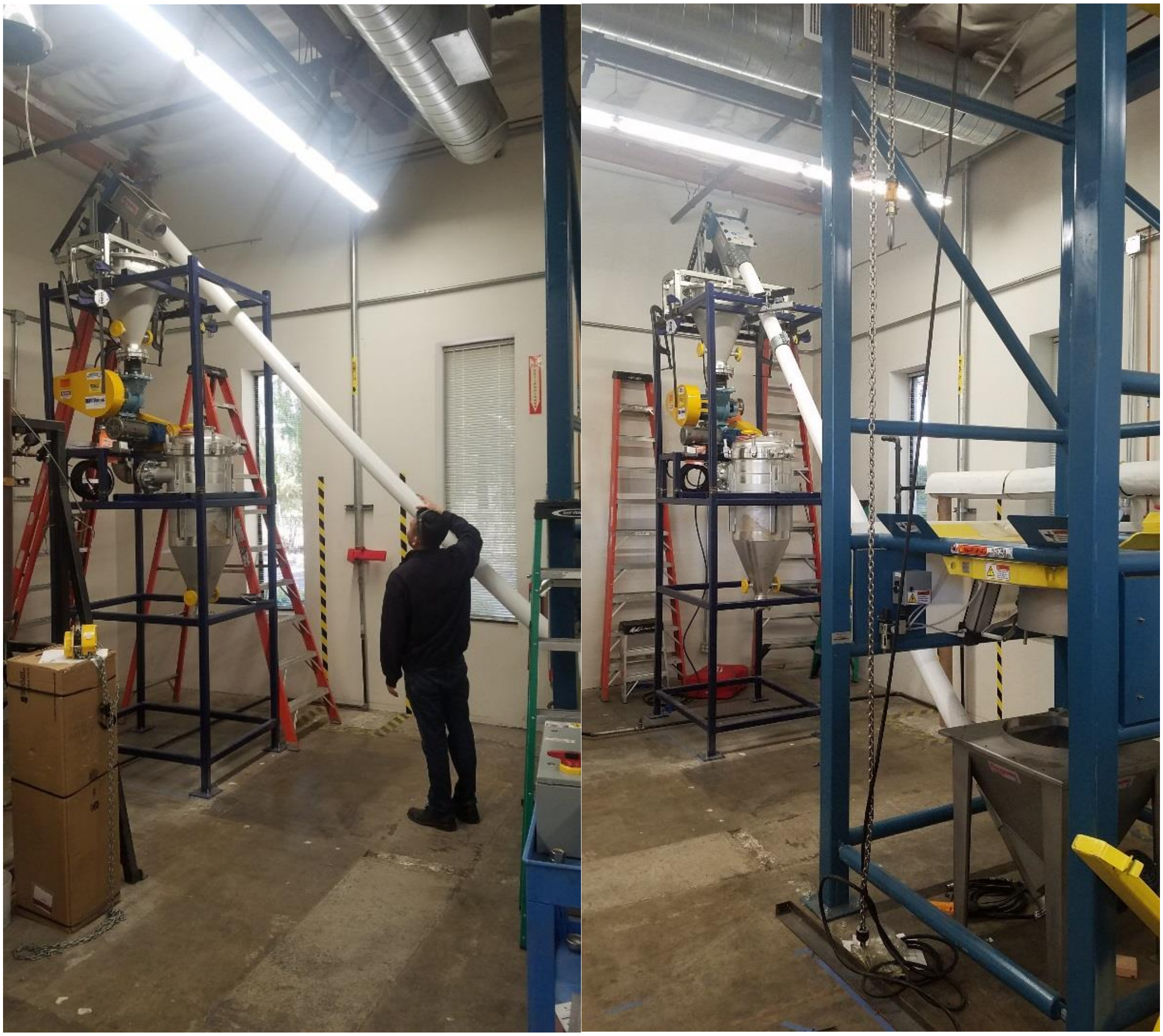
Figure 32: Lower Hopper and Valves Installation Process

Source: Altex Technologies Corporation

Figure 33: Installed Upper Hopper (Left) and Completed Feed System (Right)

Source: Altex Technologies Corporation

Figure 34: Connection of Bulk-Bag Unloader to the Feed System with a Screw Feed Line



Source: Altex Technologies Corporation

Figure 35 shows the installation of the fuel-production reactor. The reactor was setup after it was loaded with the catalyst. The catalyst was loaded from the top into multiple tubes after the particles were sized for a uniform loading. The loading procedure involved sizing the catalyst, measuring its weight and loading them into each tube. By measuring the weight, it was assured that each reactor tube contains the same amount of catalyst. To control cost it was decided to load only 1/5 length of the reactor. The process is scalable and a successful testing with this partially loaded reactor volume will prove the system.

The picture of the right side of Figure 35 shows the installed reactor. The setup includes a burner on the top and an exhaust at the bottom. The burner provides the needed heat to bring the reactor to the preset temperature for optimum fuel production. These conditions were defined during the catalyst development and selection. The amount of required heat is low, and, as shown, a natural gas pilot burner is installed that fires horizontally into the horizontal pipe that is flanged to the top of the reactor. This pipe has a tee for connecting an air dilution blower (not shown) to control the reactor temperature. The products of combustion exit the reactor from the bottom through the exhaust line that, as shown, is connected to a vertical exhaust pipe through a flange.

Figure 35: Fuel Production Reactor Installation (Left) and the Installed Unit (Right)

Source: Altex Technologies Corporation

Figure 36 shows the insulated fuel-production reactor that is connected to two water-cooled condensers that operate in parallel (the left condenser is better visible with the water line connection). These condense the gasoline vapors and discharge the fuel into the gray tank. This tank includes a valve at the bottom for occasional discharge of the fuel. When the valve is closed the reactor remains under the preset pressure for optimum gasoline production.

Tests were carried out to ascertain the performance of the fuel-production reactor on process gas that had similar olefins as the end-to-end system operation. For this purpose, ethylene was mixed with nitrogen matching the expected ethylene concentration from biomass. The results are described below.

Figure 36: Installed Fuel Production Unit with Gasoline Condensers

Source: Altex Technologies Corporation

2.6 Data Collection and Analysis

Figure 37 shows the typical gasoline fuel that was produced during testing. The reactor produced around one quart of fuel per hour. As discussed above to save time and cost only 1/5 of the fuel production reactor was loaded with catalyst. Therefore, the reactor is capable of producing 30 gallons of fuel per day or 0.7-BPD. This is achieved at lower range of WHSVs. At higher WHSVs the reactor will produce 1-BPD, as per design.

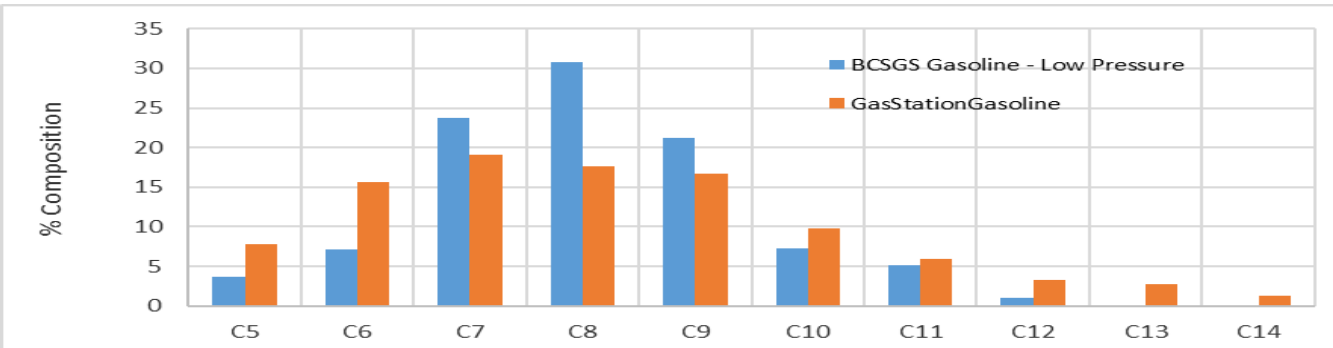
Figure 37: Fuel Production Testing

Source: Altex Technologies Corporation

Initially during the test, the temperature and WHSV were set based on the lab scale data and the pressure was mildly varied to collect fuel samples. The liquid-fuel produced from the downstream system was analyzed for its carbon-number distribution using the ASTM D2887 Simulated Distillation method and compared to commercial gasoline procured from a local gas station.

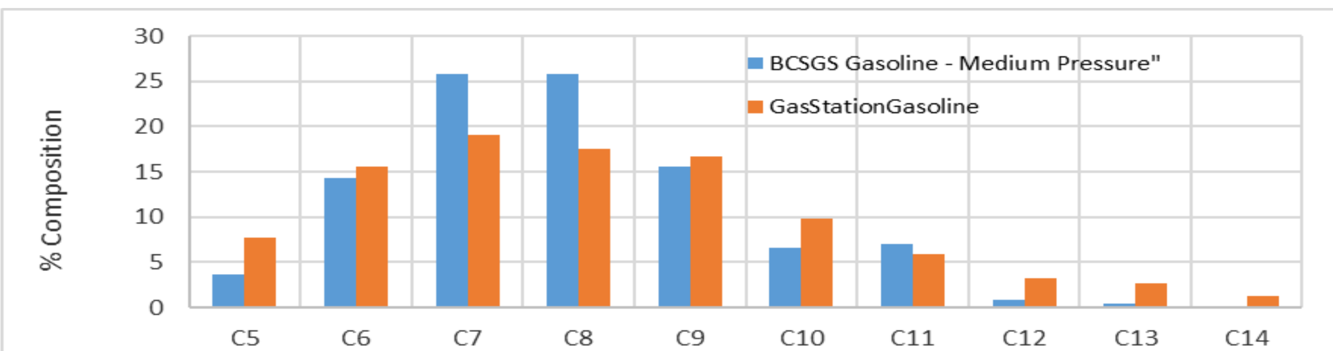
Figure 38, Figure 39, and Figure 40 show comparisons of the C-number distribution between the liquid-products obtained from C2, and commercial-gasoline sample from a gas station at low, medium, and high pressures respectively. All liquid fuel collected follow similar branch-like distribution as gasoline with a carbon range between C5 and C14, peaking at C8 for C2-feed-processing. In comparison, gasoline shows similar C-number distribution. These C-number distributions co-relates to ≥97 percent gasoline in the liquid-product from C2-olefin processing.

Figure 38: BCSGS-Fuel Produced at Atmospheric Pressure Compared to a Commercial Gasoline Sample



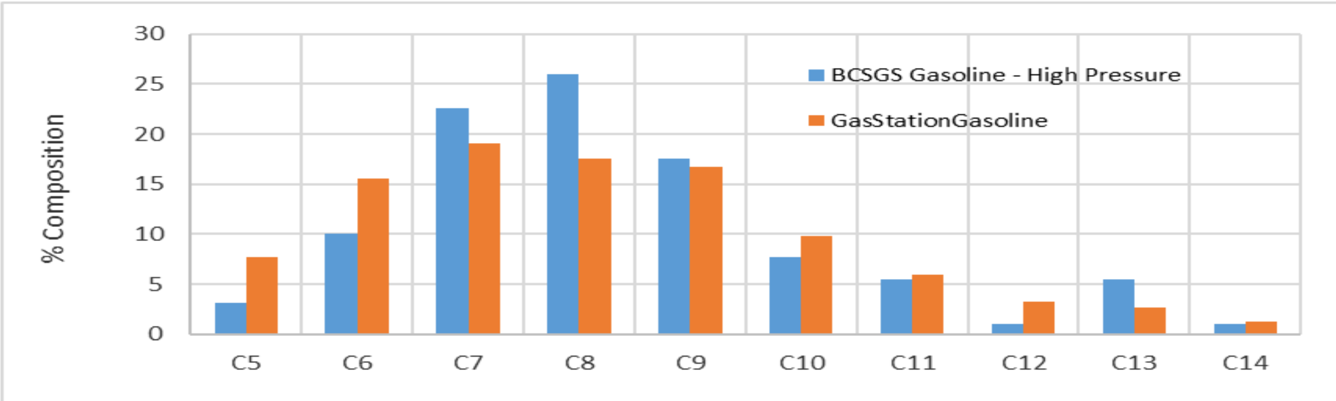
Source: Altex Technologies Corporation

Figure 39: BCSGS-Fuel Produced at 25 PSIG Pressure Compared to a Commercial Gasoline Sample



Source: Altex Technologies Corporation

Figure 40: BCSGS-Fuel Produced at 50 PSIG Compared to a Commercial Gasoline Sample

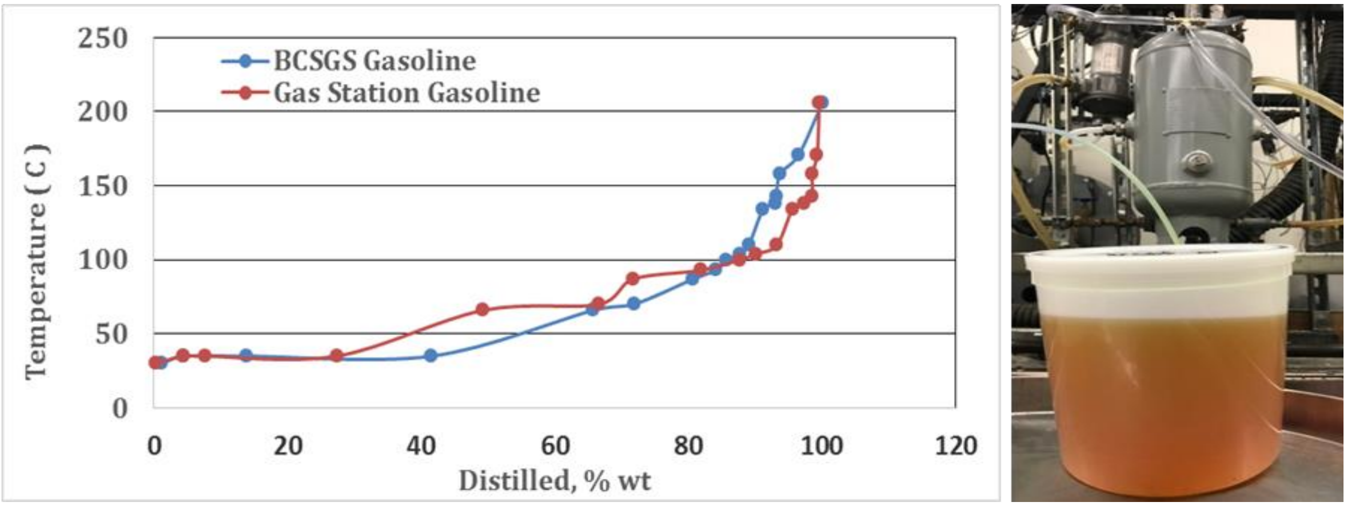


Source: Altex Technologies Corporation

As shown in Figure 38, Figure 39, and Figure 40, with increase in pressure, C5 through C10 decreases while C11 through C14 increases. Previously performed comprehensive testing showed that downstream conditions, pressure, temperature, WHSV, and feed concentration of the olefins can be varied to alter this distribution towards gasoline versus JP-8 or diesel compositions. However, during this testing period, operational conditions were maintained for BCSGS gasoline production. As shown, all simulated distillation results follow gasoline C-number distribution. Based on these results and the fact that operation at lower pressures results in less capital and operating costs for pumping, the low pressure operation is recommended.

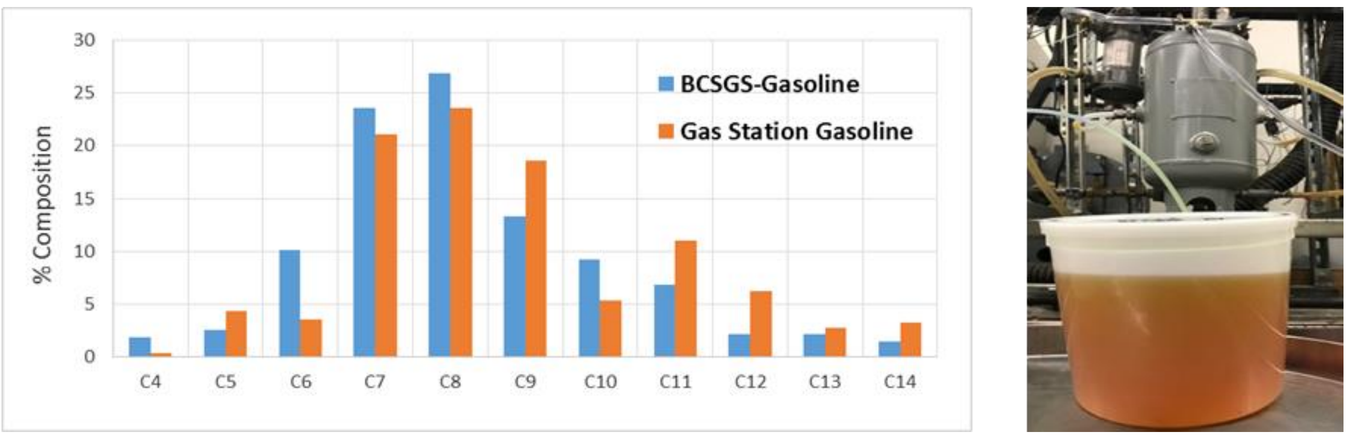
Further, three gallons of gasoline was produced from the BCSGS downstream system by maintaining a slightly higher WHSV, high pressure, and low temperature. Distillation curve was generated for the BCSGS gasoline and a sample of commercial gasoline for comparison, as shown in Figure 41. An equivalent C-number distribution profile was generated for these samples, as shown in Figure 42.

Figure 41: Distillation Curve Comparison between BCSGS and Commercial Gasoline



Source: Altex Technologies Corporation

Figure 42: BCSGS C-Number Distribution Comparison with a Gasoline Sample



Source: Altex Technologies Corporation

These results show that Altex has successfully selected a gasoline-specific-catalyst based on their performance and scale-up availability for BCSGS. The Altex system design allows a wide range of P, T, WHSV, and olefin concentration for gasoline production. There are also multiple catalyst-packing options available to optimize gasoline production at certain operational conditions. With both C2 and C3-olefins, Altex has achieved to date a gasoline yield of 70 percent. Further, all the fuel production-optimization test conditions follow the Altex downstream-reactor design. Availability of the Altex-selected-and-developed catalysts for the BCSGS system at commercial scale, combined with significantly better gasoline yield at mild conditions as compared to existing industrial olefin processing catalysts makes the Altex downstream fuel production approach for the BCSGS system both low-risk for gasoline production and energy-efficient.

2.7 Conclusions, Lessons Learned, and Recommendations

2.7.1 Conclusions

This Final Technical Report describes the work and accomplishments of the project entitled, "Biomass Conversion to Synthetic Gasoline System". The main goal of the project was to develop a technically and economically feasible BCSGS system that will produce gasoline from cellulosic biomass at less than $2 per gallon with carbon intensity of less than 30 g-CO_2e/MJ. This goal was achieved with the projected gasoline production cost of $1.80/gallon of biofuel. The BCSGS process is projected to have a carbon footprint of -77 g-CO_2e/MJ using wheat straw as the feedstock. This has the potential to eliminate the entire GHG emissions related to the use of gasoline use in California.

The economic advantage of BCSGS is due its lower cost process as compared to alternative approaches, such as those using gasification and FT synthesis or fast pyrolysis and hydrotreating. BCSGS is a transformative patented technology that overcomes the technical and economic barriers that exist in converting biomass and other carbon-containing feedstocks into a drop-in fuel like gasoline. The BCSGS process removes the oxygen in the feed as carbon monoxide and CO_2 that can be removed or slipped through the reactors that produce the fuel from other highly reactive intermediates. This eliminates the need for hydrotreating the liquid fuel in order to obtain a drop-in fuel, which eliminates the need for producing high-pressure hydrogen. This is in contrast to traditional approaches that require hydrotreating that requires the production of high-pressure hydrogen with the added costs and GHG emissions. Like the proven FT, the process uses gaseous intermediates to build the synthetic fuel, with the required properties to produce the desired synthetic fuel. These attributes increase the BCSGS productivity and reduce the capital and operating costs when compared to classical gasification-FT or pyrolysis-bio-oil-hydrotreating.

A key development under the project was a gasoline specific catalyst that was scaled to large quantities. The catalyst does not contain any precious metal and operates well at atmospheric and below 50 PSI, thus contributing to the low fuel cost. This catalyst was tested in a 1-BPD reactor and proved to produce a fuel that without fractionation has a distillation curve and carbon-number distribution similar to those of petroleum-based gasoline.

The process heat and mass balance data for a 2,000-ton-per-day plant were used in an LCA to estimate the well-to-wake life-cycle GHG emissions. The LCA framework was prepared and performed by Argonne National Laboratory under the U.S. DOE GHGR cost-share project. This framework included adding a module for these processes to the GREET® model.

The GREET® model shows that while the well-to-plant emissions per dry ton varied with feedstock, these differences were overwhelmed by the negative plant-to-wake emissions of fuel produced by the BCSGS process. The higher carbon contents in the switchgrass and corn-stover feedstocks more than offset their higher well-to-plant GHG emissions.

In addition, the final use of the char produced by the process has a large effect on the well-to-wake GHG emissions. Three char-use scenarios were examined: burying the char in a landfill, burning the char to produce electricity while discarding the waste heat, and burning the char to produce electricity in a combined-heat-and-power system. For all of the feedstocks and char-use scenarios, the well-to-wake GHG emissions were negative and ranged from -3.7 to -114 gCO_2e/MJ. To be conservative, the result with the largest well-to-wake GHG emissions for the scenario where the char is used for combined-heat-and-power was selected as the final estimate. This was for the use of wheat straw and resulted in well-to-wake GHG emissions of -77 gCO_2e/MJ. This value should be compared with the carbon footprint of the petroleum gasoline that is +93 gCO_2e/MJ.

It is important to note that the BCSGS process uses many unit operations that have already been proven and have been put into commercial operation. In particular, ethylene production from the steam cracking of hydrocarbon feedstocks, including heavy feedstocks, is one of the largest chemical industries in the world. Certain equipment from this industry can be adapted to BCSGS plant. This demonstrates that the process and the equipment associated with the process are readily available at the large scales needed for significant fuel production. Also, fuel-production reactors are well known and has been commercialized for utilization with both heterogeneous and homogeneous catalysts (*e.g.*, Phosphoric Acid process, Shell Higher Olefin Process, Dimersol processes), although these operate at higher pressures (>550 PSIG) than the BCSGS catalysts. This means that there are drop-in replacements for the BCSGS fuel-production reactor that are commercially available. Utilizing two processes that are so well developed and commercialized greatly reduces the risk of the BCSGS process.

While the lab-scale system was not run end-to-end, major efforts were expended to design the lab-scale system and a full-scale plant. No technical barriers were identified. The techno-economic analysis was applied to the full-scale plant following U.S. DOE guidelines for economic analyses. BCSGS produced drop-in gasoline at a lower cost than Gasification/FT, which is consistent with the advantages of the BCSGS process (e.g., its lower temperatures, lack of hydrotreating/hydrocracking). These lower costs and the detailed design that was performed under this project are being used by Altex to attract funding partners to move the BCSGS development forward.

2.7.2 Lessons Learned

The major lesson learned was that at this intermediate scale, the cost of process equipment can be significantly more than expected. This is due mainly to the fact that at this scale, equipment is larger than readily available off-the-shelf, but significantly smaller than typical small petrochemical facilities. This leads to a significant amount of the process equipment needing to be custom fabricated. This involves not only custom materials and fabrication, but also the engineering effort needed to design the custom equipment.

Additionally, because the size of this system is significantly larger than many other systems, Altex has produced and tested in the past, the City of Sunnyvale required significant permitting. The time and effort required to learn and to conduct the permitting process required by the city added additional costs. This process required conducting additional analyses of the facilities, process, and system as well as coordinating with subcontractors that are authorized to sign off on component drawings, system drawings, facility drawings, fire-safety plans, hazmat plans. While many of these activities were covered by Altex and under cost share efforts, formalizing these plans in the format the city required resulted in additional effort. On the positive side, this process has allowed us to better understand the city requirements and processes for future projects.

2.7.3 Recommendations

The BCSGS process has the potential to drastically undercut both the capital investment and the fuel price of competing biomass to biofuel technologies (i.e., gasification plus FT synthesis). This was shown by a detailed techno-economic analysis for both BCSGS and the U.S. DOE cost-shared system (coal-and-biomass mixed feed to jet fuel), which uses realistic economic assumptions coupled with estimates of feedstock costs, operating costs, and a Class 4 capital cost estimate. To further show the potential of the BCSGS it is recommended that Altex secures funding for further demonstrating the current end-to-end system and scaling up the process for securing commercial investment.

GLOSSARY

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) – An international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.[22]

ATMOSPHERIC PRESSURE AT SEA LEVEL (ATM) – A unit of pressure defined as 1013.25 mbar (101325 Pa), equivalent to 760 million Hg (torr), 29.9212 inches Hg, or 14.696 PSI. The ATM unit is roughly equivalent to the mean sea-level atmospheric pressure on Earth, that is, the Earth's atmospheric pressure at sea level is approximately 1 atm.[23]

BARRELS PER DAY (BPD) – A measure of oil or gas output, represented by the number of barrels of oil produced in a single day.

BIOMASS CONVERSION TO SYNTHETIC GASOLINE SYSTEM (BCSGS) – A system by which biomass feedstocks undergo chemical conversion into synthetic fuel products.[23]

CALIFORNIA ENERGY COMMISSION (CEC) – The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The CEC's five major areas of responsibility are:

- Forecasting future statewide energy needs
- Licensing power plants sufficient to meet those needs
- Promoting energy conservation and efficiency measures
- Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
- Planning for and directing state response to energy emergencies

CHAR: The remains of solid biomass that have been incompletely combusted (e.g., charcoal, if wood is incompletely burned).[24]

CARBON DIOXIDE (CO_2) – A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA) – An agency of the United States Department of Defense created in 1958 by Dwight D. Eisenhower for the development

22 American Society for Testing and Materials (https://www.astm.org/)

23 Wikipedia (https://www.wikipedia.org/)

24 U.S. Department of Energy (https://www.energy.gov/)

of emerging technologies for use by the military.[25]

FISCHER-TROPSCH (FT) – A catalyzed chemical reaction in which synthesis gas, a mixture of carbon monoxide and hydrogen, is converted into liquid hydrocarbons of various forms.[26]

FRACTIONATION – A separation process in which a certain quantity of a mixture (gas, solid, liquid, enzymes, suspension, or isotope) is divided during a phase transition, into a number of smaller quantities (fractions) in which the composition varies according to a gradient.[23]

GREENHOUSE GASES (GHG) – Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TRANSPORTATION (GREET®) – A full life-cycle model sponsored by the Argonne National Laboratory (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy). It fully evaluates energy and emission impacts of advanced and new transportation fuels, the fuel cycle from well to wheel and the vehicle cycle through material recovery and vehicle disposal need to be considered. It allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.[27]

GREENHOUSE-GAS-REDUCED (GHGR) – Pertains to engines and machinery that are designed to limit the output and spread of greenhouse gases including water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GREEN-HOUSE-GAS-REDUCED COAL-AND-BIOMASS-TO-LIQUID-BASED JET FUEL (GHGR-CBTL) – Jet fuels manufactured by processing coal into liquid fuels like gasoline, diesel and jet fuel, with biomass to reduce carbon dioxide emissions.[28]

HYDROTREATING – Refinery catalytic process in which hydrogen is contacted with petroleum intermediate or product streams to remove impurities, such as oxygen, sulfur, or unsaturated hydrocarbons.[24]

INTERNAL RATE OF RETURN ON EQUITY (IRROE) – One of the two discounted cash flow techniques used in comparative appraisal of investment proposals where the flow of income varies over time. IRROE is the average annual return earned through the life of an

25 Defense Advanced Research Projects Agency (https://www.darpa.mil/)

26 California Air Resources Board (https://www.arb.ca.gov)

27 Argonne National Laboratory (https://greet.es.anl.gov/)

28 National Energy Technology Laboratory (https://www.netl.doe.gov/)

investment.[29]

LIFE-CYCLE ANALYSIS (LCA) – An account for all the inputs and outputs throughout the life cycle of a product, from its birth, including design, raw material extraction, material production, part production, and assembly, through its use, and final disposal.[30]

MEGAJOULE (MJ) – A Joule is a unit of work or energy equal to the amount of work done when the point of application of force of 1 newton is displaced 1 meter in the direction of the force. It takes 1,055 joules to equal a British thermal unit. It takes about 1 million joules to make a pot of coffee. A megajoule itself totals 1 million Joules.

OLEFIN – A class of unsaturated hydrocarbons having the general formula C_nH_{2n}. Olefins in gasoline are responsible for the formation of deposits in storage tanks, fuel ducts and injectors. Therefore, their volume is limited by the reformulated gasoline regulation.[26]

POUNDS PER SQUARE INCH (PSI) – A unit of pressure or of stress based on avoirdupois units. It is the pressure resulting from a force of one pound-force applied to an area of one square inch.[31]

POUNDS PER SQUARE INCH GUAGE (PSIG) – The pressure relative to atmosphere.[31]

PROCESS FLOW DIAGRAM (PFD) – A diagram commonly used in chemical and process engineering to indicate the general flow of plant processes and equipment. The PFD displays the relationship between major equipment of a plant facility and does not show minor details such as piping details and designations. Another commonly used term for a PFD is a flowsheet.[23]

PYROLYSIS – The breaking apart of complex molecules by heating in the absence of oxygen, producing solid, liquid, and gaseous fuels.[24]

UNITED STATES DEPARTMENT OF ENERGY (U.S. DOE) – The federal department established by the Department of Energy Organization Act to consolidate the major federal energy functions into one cabinet-level department that would formulate a comprehensive, balanced national energy policy. DOE's main headquarters are in Washington, D.C.

UNIVERSITY OF CALIFORNIA, DAVIS (UC Davis) – A public research university located in Davis, California. It is one of the 10 campuses in the University of California (UC) system.[23]

WEIGHT HOURLY SPACE VELOCITY (WHSV) – The time necessary to process one reactor volume of fluid, given a particular set of entrance conditions.[23]

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29 Business Dictionary (http://www.businessdictionary.com)

30 The Environmental Literary Council (https://enviroliteracy.org/)

31 Parker Hannifin Corporation (https://promo.parker.com/promotionsite/smoghog-dusthog/us/en/home)