Solazyme Integrated Biorefinery (SzIBR)
Final Scientific/Technical Report

Award Number:	DE-EE0002877
Name of Recipient:	Solazyme, Inc.
Project Title:	Solazyme Integrated Biorefinery (SzIBR): Diesel Fuels from Heterotrophic Algae
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Project Partners:	None
Report Date:	December 23, 2014

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Executive Summary

Under Department of Energy Award Number DE-EE0002877 (the "DOE Award"), Solazyme, Inc. ("Solazyme") has built a demonstration scale "Solazyme Integrated Biorefinery (SzIBR)." The SzIBR was built to provide integrated scale-up of Solazyme's novel heterotrophic algal oil biomanufacturing process, validate the projected commercial-scale economics of producing multiple algal oils, and to enable Solazyme to collect the data necessary to complete the design of its first commercial-scale facility.

Solazyme's technology enables it to convert a range of low-cost plant-based sugars into high-value oils. Solazyme's renewable products replace or enhance oils derived from the world's three existing sources—petroleum, plants, and animal fats. Solazyme tailors the composition of its oils to address specific customer requirements, offering superior performance characteristics and value.

Fuels derived from Solazyme's oil are compatible with existing refining and distribution infrastructure, meet industry specifications, and are used with factory-standard engines without modifications. Solazyme's approach to advanced biofuel production can potentially enhance national energy security and help the USA to reach the goals of the Renewable Fuel Standard (RFS) not only by displacing petroleum imports, but also by maintaining full compatibility with today's existing infrastructure. Fuels that Solazyme has produced successfully, include Soladiesel$_{BD}$® an ASTM D6751 biodiesel, a Fatty Acid Methyl Ester (FAME); Soladiesel$_{RD}$®, an ASTM D975 renewable diesel; Solajet™, an ASTM 7566 Aviation Turbine Fuel; and renewable diesel and renewable jet fuel that meet the Navy's HRD76 and HRJ5 specifications, respectively, for advanced drop in biofuels.

Solazyme's platform exploits the prolific oil production capabilities of microalgae as a biocatalyst while leveraging standard fermentation processes and existing industrial equipment to transform renewable biomass such as plant-based sugars into tailored oils. Solazyme has also pioneered methods to recover the algal oil inexpensively with high yields.

The SzIBR was Solazyme's first fully integrated refinery where the company successfully first demonstrated its ability to turn carbohydrate feedstocks into tailored oils at one location. Under this DOE Award, the project objective was to demonstrate integrated scale-up of Solazyme's novel heterotrophic algal oil biomanufacturing process, validate the projected commercial-scale economics of producing multiple algal oils, and enable Solazyme to collect the data necessary to complete design of the first commercial-scale facility through construction, operation, and optimization of a pilot-scale integrated biorefinery, referred to as Solazyme Integrated Biorefinery or the SzIBR. Another objective under the DOE Award was to refine algal oil to an appropriate feedstock for standard liquid transportation fuels.

This report summarizes history and the results of the project.

New Understandings in the Area of Investigation

A key understanding resulting from this work is that an integrated process linking lignocellulosic feedstocks and liquid transportation fuels is practical. Further, the sugar-to-fuel processing equipment necessary for this conversion is well known and common within the bio-manufacturing and oil refining industries.

Technical Effectiveness and Economic Feasibility of the Methods Investigated

From a technical perspective, the underlying technologies are robust and present opportunities for continuing optimization that will, in turn, lead to additional benefits. While not shown within the scope of the current project, the projected performance of an optimized SzIBR provides sufficient insights into commercial-scale operations to support claims of expected economic feasibility.

Public Benefit of Project

There are several key public benefits supported by this project:

1) The project provides one path forward to a degree of independence from fossil fuels and the related geopolitical factors associated with obtaining them.

2) The project provides a practical pathway to the public of an easy to use, renewable, and environmentally friendlier fuel.

1. Actual Accomplishments versus Goals and Objectives

A. Demonstrate integrated scale-up of Solazyme's novel heterotrophic algal oil bio manufacturing process.

Some algae possess internal biochemical pathways that synthesize oil more efficiently than any other known natural or engineered process. Under the right conditions, certain algal species produce so much oil that it constitutes over 75% of the dry weight of the cells. It's not surprising that the world's petroleum deposits consist largely of the fossilized remains of prehistoric algal blooms.

Some strains of algae are heterotrophic: they can grow in the dark by ingesting and metabolizing organic molecules (e.g. domestic, renewable, and environmentally sustainable sources of biomass). Solazyme has identified and isolated strains of heterotrophic algae that achieve high cell densities, high carbon flux (productivity), high carbon yield (utilization), and fast cell doubling times — comparable to standard microbial fermentation systems. These breakthroughs, in conjunction with proven industrial bio-manufacturing technology, are used to produce high quality renewable triglyceride oil.

It's important to distinguish Solazyme's approach from conventional or open pond and photo-bioreactor algal biofuel concepts. A discussion of related technical and economic hurdles is beyond the scope of this report; however, it should be emphasized that the concerns around economic viability and scalability of conventional algal biofuel production concepts do not apply to Solazyme's closed and controlled industrial fermentation approach to producing renewable oils. Further, photosynthesis is part of Solazyme's approach, but it is the biomass feedstocks that employ it, and, in turn, are fed to the heterotrophic algae for oil production. In effect, photosynthesis and oil synthesis are separated leading to an increase in overall production efficiency.

In Solazyme's process, algae grow efficiently in the dark in industrial fermentation vessels at very high cell densities. They ingest and metabolize carbon substrates provided in the growth media and convert them to triglycerides – nearly identical in composition to common vegetable oils – at very high titers. After the fermentation broth is harvested and dried, the resulting oil is extracted and further refined. (See Figures 1 and 2.) The purified algal oil may be transesterified to yield biodiesel, or hydrotreated to yield renewable diesel or jet fuels.

To expeditiously meet project objectives of demonstrating the operation of the SzIBR, domestically-sourced sucrose was utilized as the feedstock for the initial runs in the SzIBR. Subsequently, fermentable cellulosic sugar was successfully utilized in the SzIBR.

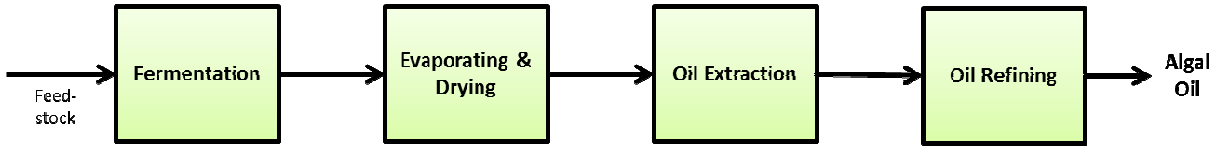

Figure 1. Solazyme Algal Oil Technology Overview

Figure 2. Algal Oil

Following the successful engineering, procurement, construction, and start-up of the integrated biorefinery, nine manufacturing campaigns using sucrose and one manufacturing campaign using sugar from cellulosic feedstock were conducted (See Figures 3.). These campaigns yielded purified algal oil. In the case of the sucrose-derived oil, a portion of the output was sold commercially and converted (with other, separate oil volumes) into biodiesel for commercial use. In the case of the cellulosic sugar-derived oil, the output was converted to renewable diesel as a deliverable under the project. Scale-up of the integrated bio-manufacturing process was wholly demonstrated (See Figure 4.).

Figure 3. Fermentation Vessel – SzIBR

Figure 4. Solazyme Integrated Biorefinery located at Solazyme' s facility in Peoria, IL

B. *Validate the production of algal oil feedstocks at commercial scale for conversion into advanced biofuels.*

Envisioned Commercialization Pathway. The value proposition for Solazyme algal oil feedstock for conversion into advanced biofuels includes:

- Supply the algal oil feedstock for the production of renewable, scalable, environmentally sustainable, drop-in, oil-based fuels — including biodiesel, renewable diesel, and jet fuel — that customers want.
- Solazyme algal oil remains fully compatible with existing petroleum-based infrastructure — including pipelines and other forms of distribution, storage, retailing, and end-use vehicles. Advanced biofuels refined from Solazyme's algal oil can directly replace existing petroleum-based fuels.
- Solazyme algal oils have the potential to create a biodiesel (B100) with a very low cloud point relative to other biodiesels (-5° C) by controlling for oil saturation level.
- Solazyme's renewable diesel directly replaces D975 diesel, and has high Cetane number (73.2), which allows for more complete combustion.

At the project's start, an "ideal" future commercial facility "ComIBR" (i.e., an out-of-scope, post-SzIBR initiative) was considered that would involve at least one company with commercially proven cellulosic conversion technology with which to partner. The front-end or first stage module would implement lignocellulosic processing technology; and the back-end or second stage module would produce purified algal oil (See Figure 5.). Under this ComIBR model, a commercial scale lignocellulosic process that would utilize switchgrass, corn stover, and/or wheat straw as feedstocks would be an essential component.

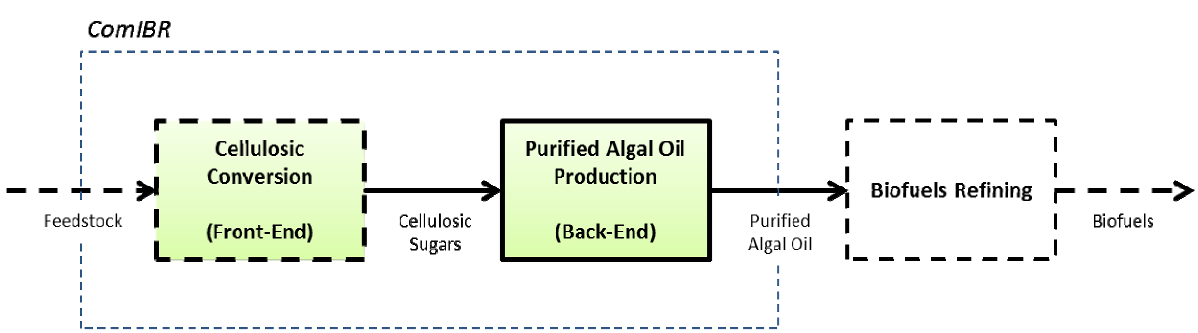

Figure 5. Envisioned possible future commercial integrated feedstock biorefinery

Such a modular process design – front-end (first stage) and back-end (second stage), non-exclusive partnership strategy and likely broad range of cellulosic feedstocks would combine to support a scalable commercialization strategy that could be replicated in most regions of the country. Solazyme's proprietary algal strains would exploit a wide range of non-food carbon feedstocks, including but not limited to switchgrass, miscanthus, bagasse, sugar beet pulp, molasses, corn stover, wheat straw, energy cane, sorghum, poplar, biodiesel glycerol, other industrial byproducts, and municipal green waste. In aggregate, these feedstocks can be found throughout the US and potentially could supply significant amounts of advanced biofuels derived from algal oil. The ability of SzIBR to serve as both a pilot and a demonstration scale facility plays an important role in evaluating the commercialization of cellulosic feedstocks to algal oil.

Currently, Solazyme uses sucrose or corn dextrose as a key input to provide an optimal type and quality of sugar for use in Solazyme's algae oil production process. Sucrose and corn dextrose are widely available and produced at volumes and cost structures that make them suitable feedstocks. However, Solazyme has also successfully produced algae oil with very low fatty acid content from a wide range of cellulosic materials, including switch grass, miscanthus, corn stover, forest residue and green waste. Cellulosic algae fermentations were run at the SzIBR as part of the project objectives. Solazyme is eager to use sugars derived from cellulosic and waste sources as these feedstocks become more readily available and cost-effective. Viability of a ComIBR model as described above will depend on advancements in the production of cellulosic sugars at commercial scale with commodity pricing.

Commercial Fuel Products. Fuels that Solazyme has produced successfully, include Soladiesel$_{BD}$® an ASTM D6751 biodiesel, a Fatty Acid Methyl Ester (FAME); Soladiesel$_{RD}$®, an ASTM D975 renewable diesel; Solajet™, an ASTM 7566 Aviation Turbine Fuel; and renewable diesel and renewable jet fuel that meet the Navy's HRD76 and HRJ5 specifications, respectively, for advanced drop in biofuels.

Under this DOE Award, Solazyme used cellulosic sugars to make an algal oil at the SzIBR that was then converted into renewable diesel (See Table 1).

Under other programs, Solazyme has also endeavored to have engine testing conducted on Solazyme's algal derived fuels in order to confirm their emissions and combustion profiles. (See, for example, Khan, M Yusuf et al, "*Impact of Algae Biofuel on In-Use Gaseous and Particulate Emissions from a Marine Vessel*", Energy Fuels 2012, 26, 6137-6143.)

C. *Enable the collection of data necessary to complete design of the first commercial-scale facility.*

SzIBR Performance Demonstration – Purpose. The SzIBR was constructed at an existing plant facility located in Peoria, Illinois that was purchased by Solazyme (the "Facility Site"). The SzIBR utilized existing available utilities, capacity, and infrastructure of the Facility Site. The SzIBR was installed in existing buildings that were industrial in nature and housed similar equipment to the equipment required for the construction of the SzIBR. The major processes that were constructed at the SzIBR include algae fermentation (using existing Facility fermentation equipment), drying, extraction and purification. The SzIBR was designed and constructed in accordance with recognized codes and standards typical for industrial facilities in the United States using equipment that was new or in good repair and operated in accordance with equipment manufacturers' recommendations.

A primary data collection point in the project was the SzIBR performance demonstration. Data captured during this effort is being used to further strengthen Solazyme's technology platform and to inform the engineering and design of commercial-scale, purpose-built facilities. Another objective of this project was to establish the technical performance of the production of renewable oils from SzIBR when cellulosic sugar is used in lieu of using non-cellulosic sugars.

The primary (product) output of the project demonstration was purified algal oil, which was to be converted to a transportation fuel at a later date by a third party. In turn, the transportation fuel derived from this algal oil was to be compared to ASTM D975 specifications and a certificate of analysis provided to the DOE when fuel conversion (refining) was complete.

Objectives and Limitations. The overall objective of the performance demonstration was to document the current state of Solazyme's technology for conversion of sucrose and cellulosic sugars to algal oil. Process data gathered during the performance demonstration were in the form of on-stream measurements of various control system tags as well as laboratory analytical data obtained from grab samples at key process locations. Log sheets used during operation of the SzIBR were completed during the course of the demonstration similar to normal operation.

Only a limited quantity of cellulosic sugar was available for the project. As such, the demonstration results were limited to the use of the available cellulosic sugar, which was estimated to be sufficient for only two low density fermentation runs, run at partial volume. Because sugars derived from cellulosic and waste sources are not yet readily available and cost-effective, it affected the demonstration results with cellulosic sugar. Although instructive, the cellulosic sugar was not sufficiently available to provide representative runs that fully exploited the current or future operations and capabilities of the SzIBR.

Solazyme's technology platform is extremely feedstock flexible and can use sugars derived from a wide variety of cellulosic materials. Solazyme has successfully produced algae oil with very low fatty acid content from a wide range of cellulosic materials, including switch grass, miscanthus, corn stover, forest residue and green waste. These feedstocks need to be more readily available and cost effective to provide more data to inform commercial scale campaigns.

Demonstration Data. Process data were gathered during the performance demonstration in the form of on-stream measurements of various control system tags as well as laboratory analytical data obtained from grab samples at key process locations.

Key Performance Parameters. Generated data were then used to calculate key performance parameters for the process. These parameters were chosen as to best reflect the overall state of the technology. Of these items, the lipid titer, fermentation age and residual lipid in biomass after extraction were directly measured values, while the remaining ones were calculated.

Linking Process Data to Performance. Relating process data generated by the demonstration to key performance metrics provides a basis for predictive engineering and design as well as focused experimentation for additional development activities. The breadth and depth of these data and the related analyses are sufficient for designing a commercial-scale facility; the goal of collecting data necessary to complete a design was accomplished.

D. Specific Project Objectives

There were several specific project objectives:

- <u>Expeditiously commence construction and operations</u>. The original project plan was to commence construction in month five with its completion by month nineteen; (in-scope) operations were to commence in month fifteen with completion by month thirty nine. Note that operations were planned to continue after month fifteen; however, it was included neither in the project's scope nor its budget. As discussed in Section 2 below, a change in location for the SzIBR affected the construction schedule. Nonetheless, the construction and subsequent operations activities were ultimately successfully completed.

- <u>Integrate all process unit operations successfully into a unified biorefinery</u>. All process unit operations were successfully unified and operated as such in the SzIBR. The project objective was accomplished.

- <u>Validate feasibility of low cost production at commercial scale</u>. To the extent that the demonstration-scale SzIBR operating results are predictive of commercial-scale operations, the validation of the feasibility of low cost production at commercial scale under the right conditions was accomplished.

- <u>Demonstrate refining of the algal oil into fully-compliant liquid transportation fuels</u>. The purified algal oil has been converted to fully-compliant liquid transportation fuel – renewable diesel per ASTM D975 (See Table 1.). A contractor – Southwest Research Institute converted the algal oil to renewable diesel via hydroprocessing incorporating hydrotreatment, isomerization, and testing activities. The project objective was accomplished.

- <u>Processing high-impact lignocellulosic feedstock</u>. By providing a successful process link between cellulosic sugar and purified algal oil which can be reliably converted to multiple liquid transportation fuels, the SzIBR effort contributed to accelerating the development of lignocellulosic feedstocks. The project objective was accomplished.

- <u>Successfully complete the project on schedule</u>. As highlighted above and discussed in Section 2, a change in the SzIBR location among other factors led to a delay in the construction schedule.

Property	Test	Specification	Units	Result	Pass/Fail
Flash Point	D93	52 min	C	58	Pass
Water and Sediment	D2709	0.05 max	% Vol	<0.005	Pass
Distillation Temp	D86	282 min	C 90%, % Vol Recovered	294	Pass
Ash	D482	0.01 max	% Mass	<0.001	Pass
Sulfur	D5453	15 max	PPM	1.5	Pass
Copper Strip Corrosion 3 hours min, control temp 50C	D130	No.3 max	---	No.1a	Pass
Cetane Number	D613	40 min	---	>74.8	Pass
Aromaticity	D1319	35 max	% Vol	7.5	Pass
Cloud Point	D2500	--- (1)	C	-7.7	Pass
Ramsbottom Carbon Residue	D524	0.35 max	% Mass	0.09	Pass
Lubricity	D6079	520 max	Microns	420	Pass
Conductivity	D2624	25 min	pS/m	30	Pass

(1) Specification determined by agreement between buyer and seller.

Table 1: Comparison of Algal Oil-Derived Renewable Diesel Analysis Results with ASTM D975 Specification

2. Summary of Project Activities

The scope of the project encompassed (i) building, operating and optimizing a pilot-scale integrated biorefinery, (ii) cultivating oil-producing algae, (iii) extracting and purifying oil from the algae, (iv) refining the algal oil to standard liquid transportation fuel, (v) optimizing fermentation and oil recovery parameters at both laboratory and pilot scale, and (vi) gathering data to assist in the design of subsequent demonstration and commercial facilities. As part of the project, Solazyme was to produce algal oil derived from lignocellulosic feedstocks as well as other feedstocks (e.g. sucrose). A broader (i.e. beyond the project) aim was to advance the goals of the DOE Biomass Program and to support the advance of the nation's ability to achieve the production targets mandated by the federal Renewable Fuel Standard (RFS).

The specific work tasks that were performed follow. These tasks, were developed to satisfy program/project needs, and represented the work requirements for Solazyme and its partners that were successfully completed during the project.

Activities and Timeline for Budget Period 1 (BP1):

A. BP1: Submission
(Q1 2010)

- Selection kick-off meeting
- Submission of Award 1 application
- Acceptance of Award 1 application
- Release of Award 1 funds

B. Prepare Solazyme Manufacturing Site
(Q1 2010 to Q2 2012)

- Pre-engineering design, engineering design, long lead time procurement
- Engineering, Procurement, Construction, & Management Firm
- Accelerated Equipment Procurement

Activities and Timeline for Budget Period 2 (BP2):

C. BP 2: Application / Submission / Approval
(Q1 2010 to Q3 2011)

- Cherokee facility BP2 application preparation
- Peoria facility BP2 application preparation
- Submission of Award 2 application (DOE Core)
- BP-1 Monthly / Quarterly / Annual reporting
- Other DOE activities

D. Funding Approval and Release Activities
(Q1 2010 to Q4 2011)

- CD-3 Approve Start of Construction (DOE Core)
- Release of Award 2 Funds (DOE Core)
- Financial Closing (DOE Core)

E. Feedstock Sourcing
(Q1 2010 to Q4 2011)

- Finalize sucrose supply agreement
- Lignocellulosic feedstock / supplier go/no decision

F. Create and Qualify Pilot-Scale SzIBR at Manufacturing Site
(Q2 2012 to Q2 2013)

- Remaining equipment procurement
- Construction (P&ID, equipment installation, piping, mechanical, electrical, instrumentation and controls)
- Commissioning (Start of Operation) DOE Core
- Integrated Process Start-up - first crude oil produced
- Shake-down complete (DOE Core)
- Construction substantially complete
- CD-4 Start of Operation Approval
- Define Commissioning Criteria (DOE Core)
- Cellulosic sugar centrifuge commissioned; SzIBR 100% mechanically complete

G. Operate SzIBR to Optimize and Demonstrate Integrated Process
(Q4 2012 to Q2 2013)

- Sucrose (oil production) runs executed

H. Optimize Fermentation Parameters at Laboratory Scale
- Fermentation parameters at laboratory scale optimized: Activities included in this Task were performed as part of other express tasks.

I. Generate concentrated sugars derived from lignocellulosic feedstocks
(Q4 2011 to Q4 2012)

- Cellulosic sugar was procured by Solazyme

J. Integrated Process Campaign on Cellulosic-Derived Sugars
(Q1 2014)

- Cellulosic (oil production) runs executed

K. Refine Algal Oil from SzIBR to Standard Liquid Transportation Fuels
(Q2 to Q4 2014)

- Cellulosic sugar-derived algal oil transported and refined
- Cellulosic sugar-derived oil refined to a standard transportation fuel

L. Complete Commissioning of SzIBR
(Q2 2013 to Q4 2014)

- Performance test facilitated
- Commissioning criteria completed

M. Project Management
(Q1 2010 to Q4 2014)

- Monthly, Quarterly and Annual reporting
- Final reports

Project Summary:

2010 By Q2, the Award Period 1 application was completed and submitted. Funds were released following acceptance of the Special Terms & Conditions related to the DOE funding, and a National Environmental Policy Act (NEPA) categorical exclusion for Award Period 2 was granted. Concurrently, schedule and cost information for the SzIBR project was being refined and revised with input both from an engineering contractor (i.e. the contractor that would become the engineering, procurement, construction, and management (EPCM) contractor for the project), and from ongoing (out of scope) fermentation development activities. The revised schedule and budget was submitted to the DOE as part of the deliverables required for release of Budget Period 2 funding; the DOE Contracting Officer approved the revisions.

By mid-year, the contract negotiations with the EPCM firm were nearly finalized; however, basic- and detailed- process design had commenced earlier under a letter of intent (LOI) with the firm. The basic process design was largely complete, and detailed design was underway. Further, additional contractors were engaged for demolition and drafting services.

Long-lead time equipment including extraction equipment, were specified, tested, and ordered at this point because of their longer procurement period.

Originally, the SzIBR was to be located within a Cherokee Pharmaceuticals site in Riverside, Pennsylvania. However, by mid-year, a change in ownership of the Cherokee facility was announced. Upon discussions with the new owners in the last half of the year, it was determined that relocating to a new site would reduce risk of a decision (by the new owners) to halt the project, or risk of both increased costs for Solazyme and a delayed schedule. To this end, alternative locations were reviewed, and a final selection was made for the (then) idled PMP facility in Peoria, Illinois.

2011 In Q1, a formal proposal was submitted to the DOE for the change in location of the SzIBR; the proposal was approved. An assessment of the new site revealed that many of the physical and permitting advantages and features making the original Cherokee facility attractive were also present with the new facility (e.g., the new site was located within an existing fermentation facility). In addition, the new site would be owned and operated by Solazyme reducing the risks of third-party ownership (e.g. loss of access to the capacity at some future time among other risks). A different EPCM contractor was selected for the project as a result of the change in the site.

In Q2, a revised project plan including schedule, budget, risk management plan, and other elements was under development. Simultaneously, initial discussions with suppliers of lignocellulosic derived sugar were ongoing.

In Q3 and Q4, the DOE approved both an accelerated procurement modification to BP1, as well as the BP2 award. The BP1 modification and BP2 award were acknowledged by Solazyme on September 21st and 30th, respectively. At this time, only limited BP2 construction funds were released; operating funds were to be released following the development and mutual approval of an operations plan. Long-lead equipment deliveries occurred. Demolition work was also initiated during this period.

By the end of the year, a supplier of cellulosic-derived sugar was identified; a supply agreement was negotiated and executed. Delivery was identified for periods throughout 2012.

2012 During the year, procurement, demolition, and construction occurred leading to the start-up of the SzIBR. The first (sucrose) run per the agreed operating plan was successfully completed in December. Fermentation and downstream operations including oil extraction in connection with the sucrose run were successful. Refining operations were started-up and refined oil was recovered. Downstream operations were concluded early to permit optimization of unit operations.

The final shipments of cellulosic-derived sugar were received from the supplier completing the acquisition of the cellulosic feedstock.

2013 In 2013, construction continued leading to mechanical completion in the period; remaining commissioning and start-up activities occurred in parallel. Solazyme conducted nine sucrose-based manufacturing runs by June pursuant to the agreed manufacturing plan. Fermentation and downstream operations including oil extraction in connection with these sucrose runs were successful; refined oil was recovered; downstream operations were concluded and certificates of analysis (CofA) were released.

2014 Integrated process manufacturing runs using cellulosic-derived sugar feedstocks, were substantially completed in January; commissioning was also completed at this time, following the performance test. In Q2, an agreement was entered with a firm that would convert cellulosic sugar-derived purified algal oil to a liquid transportation fuel that meets ASTM D975 specifications. The oil was subsequently delivered and successfully converted (See Figure 5.). All portions of the SzIBR project scope have been completed.

3. Products Developed and Technology Transferred

The primary focus was the integration and scaling-up of existing, proven technology and the production of existing products at a pilot- or demonstration- scale. This was achieved during the project.

4. Computer Modeling

Computer modeling was not integral to accomplishing the project goals and objectives.