Technology Transition Approach

Critical to the successful completion of this project is the proper management of intellectual property issues. NMSU has a long and successful history of managing these issues and creating appropriate structures for the diffusion and adoption of technology developed by our faculty and staff. NMSU has created Arrowhead, Inc. to manage these issues and create a streamlined process for faculty and industry to create mutually beneficial arrangements and spur the commercialization of technology developed by NMSU and her partners.

NMSU is the primary submitting entity for this project and as such all intellectual property will flow to NMSU. As technologies are developed, the licensing, royalty, equity, and other rights issues will be coordinated through Arrowhead , Inc. and will provide a systematic and well established way for the partners in this project to commercialize the processes and technologies that will stem from the research herein; this assures DoD of the commercialization of the technologies developed in this project.

Utilizing algae for JP8 or, more generally, as a substitute for petroleum crude will require research into wide-scale and rapid commercialization of the algae based lipid products. This project proposes through a series of partnerships and specific steps to provide for this commercialization. The team has already developed an in depth production cost model which draws information from a broad literature review enhanced with our experimental experience with *Nannochloropsis*. Our analysis provides guidance on the estimated production costs of the crude oil, as well as estimates regarding the ancillary products, marketing, distribution, and others factors relating to the cost to bring algal oil based products to market.

The research proposed herein utilizes microalgae to generate a replacement for petroleum crude. The team proposes this ‘biocrude’ can be refined in a variety ways to generate products traditionally supplied by petroleum. In our estimation it is critical to fully utilize all the products and byproducts of the algae in order to achieve commercial success.

The biocrude generated from microalgae can be used to generate the following raw oil materials:

- Fatty acid chains of varying lengths and structure;
- Protein;
- Carbohydrate; and
- Glycerides.

Each of these components of the raw algal biomass can be utilized for a variety of commercial purposes. The development of these valuable co-products may be more profitable then the commodity value of the oil derived from algae. Most researchers studying microalgae for pharmaceutical, nutraceutical, or biofuel purposes realize the value of these co-products and propose using vertically integrated processes to generate 'biorefinery' industries. These biorefineries differ from petroleum refineries in significant ways. The typical petroleum refinery takes the raw commodity that has been shipped to the facility from its production sources (typically thousands of miles away and sourced from areas all around the world) and converts them into transportation fuels, heating fuels, naptha, and other products. These refined products are then shipped to other facilities where they are converted into a diverse array of products (such as plastics). The petroleum extraction and refining processes are largely separate. In the vertically integrated biorefinery the raw commodity is produced in the same area as the refining and as many of the processing and utilization facilities are sited close to the areas where the biomass is produced. Ideally, much of the technology used in the refining and utilization of petroleum can be modified for use with the biocrude. Additionally, technology and basic science from the oleochemical processing industries can be directly transferred to the biocrude refining processes. One of the more attractive aspects of algal based biocrude is the potential ability to transfer science and technology from an already mature industry (the oleochemical industry and to a large extent the petroleum processing industry) to this new, undeveloped industry. This has a direct and positive impact on the potential economic viability and commercialization of algal oils into a biocrude substitute for petroleum crude.

There is significant basic science that needs to be completed, and a large host of technical issues that need to be solved in order to achieve the commercialization of algal biocrude, but the basic chemical structure of the algal fatty acids and the potential ability to derive large quantities of the raw substances has generated wide-spread commercial, military, and government interest in solving these issues. The benefits to successfully commercializing the algal biorefinery industry are large and will have impacts on all aspects of American life. A successful biorefinery industry will provide low-cost, reliable energy to run the country, while providing a competitive advantage in technology, chemistry, and industry vital to future economic well-being, as well as rural economic development, and potentially an improved profile of environmental impacts relative to petroleum products.

The major questions that need to be addressed to commercialize this theoretical biorefinery concept:

- Mass production of optimized strains of algae;
- Reducing the per unit production costs of the biomass;
- Adopting/developing processing and utilization technology to fully utilize the biomass;
- Stability of the oil products and finished fuel products;
- Co-product development; and
- Utilization of the glycerides.

The research our team proposes will address each of these major concepts and seek to identify the key roadblocks and then focus research on solving the issues preventing commercialization. The economic viability and commercialization aspects will be explicitly considered at each stage of the research, no matter how 'basic' the science question being addressed. Deriving solutions to the commercialization roadblocks will guide our allocation of research. NMSU and her industrial partners will work closely to apply the laboratory results to the field and develop commercial processes.

Mass Production of Optimized Strains of Algae

Research over the past 20+ years has been investigating ways to mass produce a high quality algal biomass stock. The two main methods that have been investigated are open raceway ponds and closed photobioreactors. Many researchers have proposed that the open raceway ponds are lower cost than photobioreactors; but they also have lower biomass concentrations are more difficult to harvest biomass, and have significant quality control and strain optimization limitations. Researchers have thus focused on creating low-cost photobioreactors which address the problems associated with open raceway ponds. Closed photobioreactors are considered superior to open raceway ponds because the strain of algae and the growing conditions can be optimized for the desired biomass characteristics. However, the bioreactors are thought to be more expensive to build, operate, and maintain relative to raceway ponds. Additionally, experience in the field has shown significant issues with contamination and maintaining the desired cultures.

Our team proposes a three stage system that combines the lower cost open raceway ponds for the initial and final phases of biomass production with a continuous batch closed photobioreactor to generate a concentrated mass of optimized strain to feed to the other components of the system. This system is designed to address the major flaws of each separate technology; and should reduce the quantity of water required to produce the biomass. This research will build and optimize this proposed system with the clear goal of creating commercial, scalable facilities.

Biomass Production Cost Reduction

The research done to date indicates that the primary obstacle to the use of biomass to replace petroleum is the production cost of the biomass. The economic viability of any algal based biocrude is dependent upon dramatic reductions in the cost of producing the biostock. The most significant cost factors in biomass production relate to the capital cost of the production facilities, as well as operating and maintenance costs—including labor expenses. To optimize the production of high-lipid bearing algal stock, significant quantities of carbon dioxide, nitrogen, and phosphorous must be used. There are costs related to energy for circulating the water as well as the gassing and degassing phases of growth. Additional energy will be consumed in the harvesting and extracting phases of production. Creating a fully integrated production and refining facility that can fully utilize all of the algal products as well as minimize the energy and resources needed to grow and process the biostock will be necessary to create an economically viable algal biocrude industry.

While capital costs are important in the feasibility of biomass production, because these costs can be amortized over a long period of time (the expected lifetime of the facility) they are not the most significant component of the production costs; indeed, the most significant factor is the maintenance and labor components of production. Facilities need to be designed with labor-saving features wherever possible.

Preliminary Economic Analysis: 50 Million Gallon Facility

The NMSU-Western Refining Team has conducted an economic analysis to help guide and direct this proposal project and to identify the key issues in creating an economic feasible commercial scale algal oil facility for the production of JP8 for the Department of Defense and for retail customers. Our analysis is drawn from the literature as well as the experimental results of the team members. This analysis and model will be continually refined and updated with information from the project as work proceeds.

The analysis uses an existing design for a closed photobioreactor as described by Tapie and Bernard (1988) and a similar model analyzed by Christi (2007). The prototypical reactor is a 1 hectare scale facility that contains 500 cubic meters of algal broth in closed tubes. For the initial model presented in this proposal, the tubes lie on the ground, with furrows lined with PVC. Using this generic system, the cost of producing 50 million gallons of oil is analyzed. This analysis uses this system as a base case from which to build a more sophisticated model as experimental data becomes available. Table 1 presents the preliminary results.

Table 1

_Tubular Passive Photobioreactor On Ground_*

	Current Retail Cost (USD2007)	**40% Economies of Scale applied to Materials Cost (USD2007)**
UV Film Needed		
Area of 6mil UV LDPE film (100'x12' sheet) in m2 per Module (750 m of tube x .0666 diameter)	108.00	43.20
Cost per m2 of film	0.99	0.40
Area of film needed (25 modules at 108 m2 each) m2 for 1 ha PBR	2,700.00	1,080.00
Cost of film for 1 ha bioreactor	2,683.00	1,073.20
Connectors, Valves, Pumps Needed		
connectors (4 connectors/tube)*(6 tubes/unit)*(4 units)=1 module*25 modules	2,400.00	960.00
connectors cost approx. $7/connector	16,800.00	6,720.00
valves (2 valves/module)*25 modules cost approx. $50/valve	2,500.00	1,000.00
pumps for circulation (2/module)*25 modules @ approx. $1,000/pump @50,000 gph @ 5 hp	50,000.00	20,000.00
cooling costs (1/module)*25 modules at approx. $150/pump (1hp pump each)+$50/module	5,000.00	2,000.00

Ground Preparation		
PVC Liner (dig furrows to keep tubes in place) at .35/ft in m2 (10,000m2-3,125 m2 in between)	26,736.11	10,694.44
Digging Furrows and other preparation	20,000.00	20,000.00
Total Basic Materials Cost (1ha system)	**128,928.10**	**63,571.24**
Land		
Land (10 ha) [Note: this uses 2007 USD for land in S. NM at $150/acre current market value+10% commission and fees; T & P use $18,661.23/acre for land] for a 25,000 acre purchase	7,780.50	7,780.50
Construction, Engineering, and Infrastructure Costs		
Construction 75% of Basic Materials Cost (includes labor charges)	96,696.08	47,678.43
Engineering 30% of Basic Materials Cost (excludes basic science research charges)	38,678.43	19,071.37
Infrastructure Costs 30% of Basic Materials Cost	38,678.43	19,071.37
Total Basic Costs	**439,689.65**	**220,744.16**
CO2 Gassing and O2 Degassing Equipment		
20% of basic materials cost (C02 I)	25,785.62	12,714.25
50% of basic materials cost (C02 II)	64,464.05	31,785.62
150% basic materials cost (C02 III)	193,392.16	95,356.86
Total Estimated Basic Costs		
CO2 I	**465,475.27**	**233,458.41**
CO2II	**504,153.70**	**252,529.78**
CO2 III	**633,081.81**	**316,101.02**
Costs of Capital (5 year loan at 10% APR)		
Total Cost of Capital CO2 I	767,438.98	745,887.93
Total Cost of Capital CO2 II	831,208.93	777,331.31
Total Cost of Capital CO2 III	1,043,775.44	882,142.57
Maintenance Costs (20 year facility life)		
LDPE tubes every 4 years	13,415.00	5,366.00
Valves, Connections, and Other Materials	86,800.00	34,720.00
Maintenance Factor (15% of Total Basic Cost)	64,786.37	31,944.55
Annualized Maintenance Cost	**8,250.07**	**3,601.53**
Water Cost (water commodity price=0)		
Cost of Water (First Year)	7.66	7.66
Cost of Water Annual Operating Estimate	1.28	1.28
Cost of Pumping Cooling Spray (volume of water in PBR*5mos*30days)	1,149.04	1,149.04
Operating Costs (Annualized Basis) [excluding water pumping costs]		
Energy for broth circulation (.08/kWh)	2,718.33	2,718.33
Nutrients (300 kg per year) @ 4.4 2007USD/kg	1,320.00	1,320.00
.002 staff @ $35,000/yr salary	700.00	700.00
.002 supervisor @70,000/yr salary	1,400.00	1,400.00
Miscellaneous expenses	61.38	61.38
Annualized Expenses for Operating 1ha (500m3) facility		
operations and maintenance (includes water cost)	15,600.10	10,951.56
annualized capital cost (C02 I)	38,371.95	37,294.40
annualized capital cost (C02 II)	41,560.45	38,866.57

annualized capital cost (C02 III)	52,188.77	44,107.13
Total per 1ha per year production costs (C02 I)	53,972.05	48,245.95
Total per 1ha per year production costs (C02 II)	57,160.54	49,818.12
Total per 1ha per year production costs (C02 III)	67,788.87	55,058.69

**1-hectare photobioreactor contains 25 modules; with each module having 4 units containing 750 meters of tube and 500 cubic meters of surface area*

An attempt was made to include all significant costs in the facilities construction and production of the algal biomass. Data is derived from a large variety of sources. An emphasis was placed on using the conservative estimates and for using costs from current vendors and contractors where possible. The areas of largest uncertainty in this initial analysis are in the gassing and degassing component and the labor expenses. Three estimates for the carbonation (gassing/degassing) use 20% (CO2 I), 50% (CO2 II), and 150% (CO2 III) of the capital cost are used in this model around this uncertainty. If facilities are placed near an animal feedlot, power plant, or wastewater treatment plant where CO2 can be captured cost-effectively these costs may declined. Additionally, scenarios where carbon credits, or tax incentives are applied will further reduce these costs; but in attempt to derive a conservative first-pass estimate of the basic costs to produce large scale biomass from algae these types of offsets were excluded. The two columns in Table 1 reflect the best estimate retail cost and then assume that in the commercial (50 million gallon) production-scale the costs of materials would decline by 40% due to the large quantities required, capturing significant economies of scale.

Labor is another component with large uncertainties inherent in the cost. In this first model a large scale facility is assumed so that economies of scale can be captured in the labor component; hence, each 1-ha unit only utilizes 2% of the total facility labor. This allows us to later scale up these costs for the commercial scale. Clearly, if only a single 1-ha facility were built the full labor cost would accrue to that single unit—which would dramatically increase the per unit cost of the biomass.

Other significant uncertainties that dramatically affect the per unit costs relate to the concentration of biomass, the nutrient costs, and importantly the yield of oil per unit of broth. This is one of the most critical areas of research, and is the lynchpin to the viability of algae as a fuel source. At this point, no large scale facilities with reliable data on concentration, yields, and quality/composition are publicly available. In this analysis a range of possible yields are provided and a breakdown of the resulting per unit costs for the biocrude are presented. Table 1 uses the 1-ha 500 cubic meter culture volume scale to derive a per hectare value that is then scaled up to estimate the per liter cost for the biocrude and the finished products.

Table 2 provides a series of scenarios and the resulting per hectare yield of oil under differing assumptions regarding the yield of oil per liter of broth. Four assumptions regarding yield are used: (1) the near-term feasible yield; (2) the standard value cited in the literature; (3) a value based on the photosynthetic efficiency of algae; and (4) the absolute physical theoretical photosynthetic yield.

Table 2: Yields of Oil for a 1-ha system Under Differing Yield-Rates

Improving Efficiency over time	liters oil yield/ha/year	gallons oil yield/acre/year
1 ml oil/liter of broth (near-term feasible)	50,000.00	5,346.03
2 ml oil/liter of broth	100,000.00	10,692.06
4.019294118 ml oil/liter of broth (Approx. Theoretical Max at 8% PAR)	200,964.71	21,487.27
13.56511176 ml oil/liter of broth (Approx. Theoretical Max at 27% PAR)	678,255.59	72,519.49

It is expected that NMSU and her team can obtain 1 ml oil/liter of broth in the first phases of this project. Much of the literature associated with algal production provides for a yield of 2 grams oil/liter of biomass at between 30-70% oil by dry-weight. This is consistent with our 2 ml oil/liter of broth value above. To provide a basis for comparison the photosynthetic maximums per hectare are provided. Algae are more efficient at converting sunlight into biomass, the maximum photosynthetic efficiency based on physical limits and a realistic photosynthetic efficiency value of 8% of the total solar irradiation (6.5 kWh/square meter/day in southern New Mexico) value provides a good estimate of the maximum yield per hectare that is achievable if the major significant technical hurdles are solved. A photosynthetic efficiency of 27% is provided to show the total amount that would be theoretical limit that could be produced, based on the physical limit of photosynthesis. Both the 8% and 27% efficiency levels assume that 100% of the photosynthesis process is converted into oil. These values provide the absolute upper bound on the production of oil from algae.

Table 3 provides an estimate for the total land area needed to produce 50 million gallons of oil per year under the differing yield efficiencies described above.

Table 3: Land Area Needed to Produce 50 million gallons of Liquid Fuel

Improving Efficiency Over Time: Land Area Needed	Hectares Needed	Acres Needed	Square Miles Needed
1 ml oil/liter of broth (near-term feasible)	1,200.00	2,965.20	4.63
2 ml oil/liter of broth	600.00	1,482.60	2.31
4.019294118 ml oil/liter of broth (Approx. Theoretical Max at 8% PAR)	298.55	737.74	1.15
13.56511176 ml oil/liter of broth (Approx. Theoretical Max at 27% PAR)	88.46	218.59	0.34

Table 3 illustrates that under the conservative assumption of 1 ml oil/liter of broth only 4.63 square miles are needed to produce the Department of Defense requirement of 50 million gallons per year. Land in southern New Mexico can be purchased for as little as $125/acre for a 25,000 acre ranch. This ranch land is arid, receives lots of solar irradiation, and contains significant quantities of brackish waters in extensive shallow aquifers. Currently, this land is lightly grazed or vacant and could be utilized for algae production without conflicts for competing purposes. The conditions for producing algae on a large scale in southern New Mexico are ideal, and as Table 3 shows, it is feasible to produce the quantities needed by the Department of Defense in a small area.

Tables 4 and 5 provide some cost projections based on the 50% of capital cost carbonation system scenario and the four yield rates discussed above. The values are given in liters and gallons. The first two rows illustrate the raw cost of the biomass production. The next two rows provide the wholesale cost of the oil which includes an initial estimate of the refining and processing costs of the biomass into a transportation fuel. The charge for processing and refining is $.33/liter and is based on published refining costs for crude petroleum in transportation fuels as published by the EIA (cite). The retail costs provided in the next two columns includes additional charges for distribution and marketing, and again are estimates based on petroleum based transportation fuels.

The generation of fuel from the algal oil generates 1 mol of glycerol for every 3 mol of methyl esters; this glycerol can be utilized in numerous other manufacturing processes and is an important co-product in the production of the algal fuel. A very low-end offset price of $.30/gallon for glycerol was subtracted from the refining cost. The glycerol is potentially as valuable as the methyl ester fuels and in the vertically integrated biorefinery concept is further used to create plastics, soaps, cosmetics, and other products that are currently derived from petroleum derivatives. Research into should be joint with the research into the fuel production, as it is a critical aspect to the commercialization of algal ‘biocrude’. For purposes of this analysis a small resale value for glycerol was used, as the intent is to generate a conservative estimate. However, the net feasibility of the fuel is sensitive to the value of the glycerol byproduct, and the numbers presented herein could be significantly improved by finding valuable uses for the glycerol in a fully integrated process.

Table 4: Per Unit Cost of Fuel (CO2 II and No Economies of Scale)

	1 ml oil/liter of broth	**2 ml oil/liter of broth**	**4.019 ml oil/liter of broth**	**13.565 ml oil/liter of broth**
USD2007/liter lipid production base cost	1.14321	0.57161	0.28443	0.08428
USD2007/gallon lipid production base cost	4.32705	2.16353	1.07657	0.31898
USD2007/liter wholesale cost includes refining/processing	1.47462	0.90302	0.61584	0.41569
USD2007/gallon wholesale cost includes refining/processing	5.58145	3.41792	2.33097	1.57338
USD2007/liter retail cost includes marketing/distribution	1.67462	1.10302	0.81584	0.61569
USD2007/gallon retail cost includes marketing/distribution	6.33845	4.17492	3.08797	2.33038

Using the 1 ml oil/liter of broth value, $4.32/gallon for the production of the biomass is estimated. After adding in refining and processing costs, and providing an offset for glycerol sales, an estimate of $5.58/gallon is returned; and finally once marketing and distribution costs are added, an estimate of $6.33/gallon is calculated. If yields are increased to 2 ml oil/liter of broth the costs for the finished product are projected to be $4.17/gallon. This is the cost per gallon that could be expected if the costs per hectare are at the upper end of the estimates; i.e., no economies of scale are found and no significant improvements in the production of the biomass are achieved in the first round of commercialization. It also assumes that no offsets for carbon-credits and no low cost carbonation scheme are utilized.

The production of fuel from algae is in its infancy, and there is significant reason to believe that the values used to derive the cost estimates in Table 4 can be substantially improved by experience. By adding in a 40% reduction in capital cost resulting from economies of scale achieved by building a commercial scale project, the per gallon costs are further refined in Table 5.

Using the economies of scale, the per gallon cost (retail) of fuel drops from $6.33 to $5.78 at the 1 ml oil/liter of broth yield. If the often cited 2 ml oil/liter of broth yield is used then the cost per gallon (retail) falls to $3.89.

In examining the cost of biomass production alone, it is estimated that at 1 ml oil/liter of broth that it will cost $3.77 gallon of biomass; at 2 ml oil/liter of broth that cost declines to $1.88 gallon. This puts the estimated cost of feedstock production within the range required by the Department of Defense for this proposal. It should be noted, that these estimates are simply an indication of the production costs, and will need to be updated as better data is derived from the large-scale experiments that will be completed during this project.

Table 5: Per Unit Cost of Fuel (CO2II and 40% Economies of Scale on Capital Costs)

	1 ml oil/liter of broth	**2 ml oil/liter of broth**	**4.019 ml oil/liter of broth**	**13.565 ml oil/liter of broth**
USD2007/liter lipid production base cost	0.99636	0.49818	0.24789	0.07345
USD2007/gallon lipid production base cost	3.77123	1.88562	0.93828	0.27801
USD2007/liter wholesale cost (includes refining/processing)	1.32777	0.82959	0.57931	0.40486
USD2007/gallon wholesale cost includes refining/processing	5.02563	3.14001	2.19268	1.53241
USD2007/liter retail cost (includes marketing/distribution)	1.52777	1.02959	0.77931	0.60486
USD2007/gallon retail cost (includes marketing/distribution)	5.78263	3.89701	2.94968	2.28941

Reducing the uncertainty in the labor, oil yield, biomass harvesting, and gassing/degassing areas, as well as more refined information on the capital needs of the systems will significantly affect these numbers. It should also be noted, that if NMSU and her partners are awarded this project this economic analysis develop detailed values for all the system components and specifically provide estimates of commercial viability and the cost to the Department of Defense for the finished fuel product as the experimental data and biomass/refining production systems are developed by the engineers and physical scientists. This analysis merely provides a baseline indicating the potential economic viability of large scale algal production.

Based on the estimates presented in Table 5, NMSU and her partners feel confident that we can supply the Department of Defense with algal based JP8 within the range of values specified in the proposal; and that the numbers derived based on the existing small-scale, experimental values (as presented in Table 1-5) can be improved, and a commercially viable product can be brought to market.