**RECOVERY AND SEQUESTRATION OF CO₂ FROM STATIONARY COMBUSTION
SYSTEMS BY PHOTOSYNTHESIS OF MICROALGAE**

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ABSTRACT

Most of the anthropogenic emissions of carbon dioxide result from the combustion of fossil fuels for energy production. Photosynthesis has long been recognized as a means, at least in theory, to sequester anthropogenic carbon dioxide. Aquatic microalgae have been identified as fast growing species whose carbon fixing rates are higher than those of land-based plants by one order of magnitude. Physical Sciences Inc. (PSI), Aquasearch, and the Hawaii Natural Energy Institute at the University of Hawaii are jointly developing technologies for recovery and sequestration of CO₂ from stationary combustion systems by photosynthesis of microalgae. The research is aimed primarily at demonstrating the ability of selected species of microalgae to effectively fix carbon from typical power plant exhaust gases. This report covers the reporting period 1 October to 31 December 2001 in which PSI, Aquasearch and University of Hawaii conducted their tasks. Based on the work conducted during the previous reporting period, PSI initiated work on the component optimization work. Aquasearch continued their effort on selection of microalgae suitable for CO₂ sequestration. University of Hawaii initiated effort on system optimization of the CO₂ sequestration system.

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1. INTRODUCTION

Emissions of carbon dioxide are predicted to increase in this century¹ leading to increased concentrations of carbon dioxide in the atmosphere. While there is still much debate on the effects of increased CO₂ levels on global climate, many scientists agree that the projected increases could have a profound effect on the environment. Most of the anthropogenic emissions of carbon dioxide result from the combustion of fossil fuels for energy production. It is the increased demand for energy, particularly in the developing world, which underlies the projected increase in CO₂ emissions. Meeting this demand without huge increases in CO₂ emissions requires more than merely increasing the efficiency of energy production. Carbon sequestration, capturing and storing carbon emitted from the global energy system, could be a major tool for reducing atmospheric CO₂ emissions from fossil fuel usage.

The costs of removing CO₂ from a conventional coal-fired power plant with flue gas desulfurization were estimated to be in the range of \$35 to \$264 per ton of CO₂.² The cost of power was projected to increase by anywhere from 25 to 130 mills/kWh. DOE's goal is to reduce the cost of carbon sequestration to below \$10/ton of avoided net cost.

Photosynthesis has long been recognized as a means, at least in theory, to sequester anthropogenic carbon dioxide. There has been relatively little research aimed at developing the technology to produce a gaseous combustion effluent that can be used for photosynthetic carbon sequestration. However, the photosynthetic reaction process by plants is too slow to significantly offset the point source emissions of CO₂ within a localized area. Aquatic microalgae have been identified as fast growing species whose carbon fixing rates are higher than those of land-based plants by one order of magnitude.

The Department of Energy has been sponsoring development of large-scale photovoltaic power systems for electricity generation. By this analogy, a large-scale microalgae plantation may be viewed as one form of renewable energy utilization. While the PV array converts solar energy to electricity, the microalgae plant converts CO₂ from fossil combustion systems to stable carbon compounds for sequestration and high commercial value products to offset the carbon sequestration cost. The solar utilization efficiency of some microalgae is ~ 5%, as compared to ~ 0.2% for typical land based plants. Furthermore, a dedicated photobioreactor for growth of microalgae may be optimized for high efficiency utilization of solar energy, comparable to those of some photovoltaic cells. It is logical, therefore, that photosynthetic reaction of microalgae be considered as a mean for recovery and sequestration of CO₂ emitted from fossil fuel combustion systems.

Stationary combustion sources, particularly electric utility plants, represent 35% of the carbon dioxide emissions from end-use of energy in the United States.¹ The proposed process addresses this goal through the production of high value products from carbon dioxide emissions. Microalgae can produce high-value pharmaceuticals, fine chemicals, and commodities. In these markets, microalgal carbon can produce revenues of order \$100,000 per kg C. These markets are currently estimated at >\$5 billion per year, and projected to grow to >\$50 billion per year within the next 10 to 15 years. Revenues can offset carbon sequestration costs.

An ideal methodology for photosynthetic sequestration of anthropogenic carbon dioxide has the following attributes:

1. Highest possible rates of CO₂ uptake
2. Mineralization of CO₂, resulting in permanently sequestered carbon
3. Revenues from substances of high economic value
4. Use of concentrated, anthropogenic CO₂ before it is allowed to enter the atmosphere.

In this research program, Physical Sciences Inc. (PSI), Aquasearch, and the Hawaii Natural Energy Institute at the University of Hawaii are jointly developing technologies for recovery and sequestration of CO₂ from stationary combustion systems by photosynthesis of microalgae. The research we propose is aimed primarily at quantifying the efficacy of microalgae-based carbon sequestration at industrial scale. Our principal research activities will be focused on demonstrating the ability of selected species of microalgae to effectively fix carbon from typical power plant exhaust gases. Our final results will be used as the basis to evaluate the technical efficacy and associated economic performance of large-scale carbon sequestration facilities.

Our vision of a viable strategy for carbon sequestration based on photosynthetic microalgae is shown conceptually in Figure 1. In this figure, CO₂ from the fossil fuel combustion system and nutrients are added to a photobioreactor where microalgae photosynthetically convert the CO₂ into compounds for high commercial values or mineralized carbon for sequestration. The advantages of the proposed process include the following.

1. High purity CO₂ gas is not required for algae culture. It is possible that flue gas containing 2~5% CO₂ can be fed directly to the photobioreactor. This will simplify CO₂ separation from flue gas significantly.
2. Some combustion products such as NO_x or SO_x can be effectively used as nutrients for microalgae. This could simplify flue gas scrubbing for the combustion system.
3. Microalgae culturing yields high value commercial products that could offset the capital and the operation costs of the process. Products of the proposed process are: (a) mineralized carbon for stable sequestration; and (b) compounds of high commercial value. By selecting algae species, either one or combination or two can be produced.
4. The proposed process is a renewable cycle with minimal negative impacts on environment.

The research and experimentation we propose will examine and quantify the critical underlying processes. To our knowledge, the research we propose represents a radical departure from the large body of science and engineering in the area of gas separation. We believe the proposed research has significant potential to create scientific and engineering breakthroughs in controlled, high-throughput, photosynthetic carbon sequestration systems.

Figure 1. Recovery and sequestration of CO₂ from stationary combustion systems by photosynthesis of microalgae.

2. EXECUTIVE SUMMARY

The proposed program calls for development of key technologies pertaining to: (1) treatment of effluent gases from the fossil fuel combustion systems; (2) transferring the recovered CO₂ into aquatic media; and (3) converting CO₂ efficiently by photosynthetic reactions to materials to be re-used or sequestered.

The work discussed in this report covers the reporting period from 1 October to 31 December 2001. Up to this point in time we have

- Characterized power plant exhaust gas
- Identified suitable CO₂ separation method and clean-up technologies
- Conducted analysis of carbon dissolution methods
- Tested 41 different species of microalgae for growth at three different temperatures (15, 20, and 25 °C)
- Analyzed 15 different species for high-value pigments
- Started testing 4 strains (3 species) for pH shift tolerance in chemostat culture
- Started testing six species at the chemostat level for carbon uptake rate
- Started testing three different species for carbon sequestration potential into carbonates for long-term storage of carbon
- Designed and purchased the components necessary for carbon sequestration potential experiments utilizing five different simulated flue gases
- Completed subcontract agreement between PSI and University of Hawaii for system analysis work.

3. WORK ACCOMPLISHED

3.1 Task 1: Supply of CO₂ from Power Plant Gas to Photobioreactor

Much of the work within the two subtasks (Task 1.1: Power Plant Exhaust Characterization and Task 1.2: Selection of CO₂ Separation and Cleanup Technologies) has been conducted during the last reporting period. No significant activities were made during the present reporting period.

3.2 Task 2: Selection of Microalgae

As part of Task 2 we have continued to scale up cultures of microalgae to the 3.3 l chemostat scale to determine their tolerance to changes in pH and simulated flue gas streams following the methods indicated below and in previous reports. Table 1 lists the experiments already carried out.

3.2.1 Task 2.1: Characterization of Physiology, Metabolism and Requirements of Microalgae

Chemostat cultures, as opposed to batch cultures, receive a continuous supply of nutrient medium. Our cultures are grown under light limitation. As the cells are diluted by the continuous medium addition more light/cell is available, permitting cell growth. Thus, the growth rate is dependent on the rate of medium addition. At steady state (no change in cell concentration in the chemostat culture) the growth rate is equivalent to the dilution rate. Also at steady state, the growth conditions stay constant, allowing for better characterization of the physiological state of the cells. The physiological state of the cells was determined daily using fluorescence techniques based on the techniques developed by Schreiber et al. (1986). Briefly, fluorescence measurements were carried out on the experimental cultures using the MiniPAM system (Walz, Germany). The MiniPAM can be used to estimate the so-called F_v/F_m , an estimate of the fraction of open reaction centers in photosystem II of photosynthetic organisms. The fraction of open reaction centers is directly proportional to the probability that the energy of an absorbed photon will participate in photosynthesis. Thus, it is a measure of the photosynthetic efficiency of the cells and of their physiological state.

While at steady state the dilution rate (or rate of nutrient addition to the culture) determines the growth rate, during the initial ramp up phase the chemostat culture is managed as a batch culture. A 3.3 liter chemostat vessel is inoculated with a starter culture and allowed to grow. Once the culture reaches a sufficiently high biomass (the culture starts to reach light limitation), nutrients are continuously added using a pump. Over the first few days, then, we can estimate a maximal growth rate from changes in daily biomass estimated from fluorescence measurements (Figure 2). This estimated growth rate is considered 'maximal' since during that period in the cultures life light is not yet limiting (i.e., the culture is sufficiently dilute still). The pH tolerance experiments were conducted on cultures grown in chemostats.

Table 1. List of Strains and Experiments Carried Out

AQ strain	Temperature Tolerance					pH Tolerance			Flue gas tolerance				
	15C	20C	25C	30C	35C	6.5 pH	7.5 pH	8.5 pH	A	B	C	D	E
AQ0001	X	X	X										
AQ0002	X	X	X										
AQ0003	X	X	X										
AQ0008	X	X	X						X	X	X	X	X
AQ0009	X	X	X	X	X								
AQ0011	X	X	X	X	X	X	X	X					
AQ0012	X	X	X	X	X	X	X	X	X	X	X	X	X
AQ0013	X	X	X	X	X	X	X	X					
AQ0016	X	X	X	X	X								
AQ0017	X	X	X	X	X								
AQ0018	X	X	X	X	X								
AQ0019	X	X	X	X	X								
AQ0020	X	X	X	X	X								
AQ0021	X	X	X	X	X								
AQ0022	X	X	X	X	X	X	X	X					
AQ0023	X	X	X	X	X								
AQ0024	X	X	X	X	X	X	X	X					
AQ0025	X	X	X	X	X	X	X	X	X	X		X	X
AQ0027	X	X	X	X	X								
AQ0028	X	X	X	X	X	X	X	X					
AQ0029	X	X	X	X	X	X	X	X					
AQ0030	X	X	X	X	X								
AQ0031	X	X	X	X	X								
AQ0032	X	X	X	X	X								
AQ0033	X	X	X	X	X	X	X	X					
AQ0034	X	X	X	X	X								
AQ0035	X	X	X	X	X								
AQ0036	X	X	X	X	X	X	X	X					
AQ0037	X	X	X	X	X								
AQ0038	X	X	X	X	X	X	X	X	X	X	X	X	X
AQ0039	X	X	X	X	X								
AQ0040	X	X	X	X	X	X	X	X	X	X			
AQ0041	X	X	X	X	X	X	X	X					
AQ0042	X	X	X	X	X	X	X	X					
AQ0043	X	X	X	X	X								
AQ0044	X	X	X	X	X	X	X	X					
AQ0045	X	X	X	X	X								
AQ0046	X	X	X	X	X								
AQ0048	X	X	X	X	X								
AQ0050	X	X	X	X	X								
AQ0051	X	X	X	X	X								
AQ0052	X	X	X	X	X	X	X	X					
AQ0053	X	X	X	X	X	X	X	X					
AQ0054	X	X	X	X	X								

Table 1. List of Strains and Experiments Carried Out (Continued)

AQ strain	Temperature Tolerance					pH Tolerance			Flue Gas Tolerance				
	15C	20C	25C	30C	35C	6.5 pH	7.5 pH	8.5 pH	A	B	C	D	E
AQ0055	X	X	X	X	X								
AQ0056	X	X	X	X	X								
AQ0058	X	X	X	X	X								
AQ0059	X	X	X	X	X								
AQ0062	X	X	X	X	X								
AQ0064	X	X	X	X	X								
AQ0073	X	X	X	X	X								
AQ0074	X	X	X	X	X								
AQ0077	X	X	X	X	X								
AQ0079	X	X	X	X	X

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Figure 2. Example of fluorescence-based biomass estimates during the initial growth phase of a chemostat cultures (i.e., before nutrient additions were started and steady state was reached) used to estimate a maximal growth rate of the culture.

3.2.1.1 pH Tolerance Experiments

To test the pH tolerance of the different microalgal strains, the cultures were grown in chemostats and exposed to different pH conditions. Initially, the cultures were grown in chemostats at a pH range of 7.4 to 7.6. The pH of the cultures was automatically controlled by CO₂ injections into the growth medium in response to raises in pH. Fluorescence-based biomass estimates during the initial growth phase of the chemostat cultures (i.e., before nutrient additions were started and steady state was reached) were used to estimate a maximal growth rate of the culture. These growth rates represent a near-maximum attainable since both nutrients and light are not limiting during this period of culture growth (see Figure 2).

Once the chemostats were at steady state (no change in biomass from day to day) the pH set points were changed to either 6.4-6.5 or 8.4-8.6. A decrease in biomass in response to the pH manipulations would indicate that the culture was being washed out, that the growth rate did not keep up with the dilution rate. An increase in biomass in response to pH manipulations would indicate the growth rate of the culture was higher following changes in pH.

We have attempted to grow 20 different strains at the chemostat scale. The biomass data obtained during the ramp up phase of the culture was used to estimate the cultures maximum growth potential. The results are shown in Figure 3 and indicate growth rates ranging from as low as 0.39 d^{-1} to as high as 0.87 d^{-1} depending on the strain.

Figure 3. Growth rate of different microalgal strains during the initial phase (the ramp-up phase) of the chemostat cultures.

Of the 20 strains tested so far, three strains (AQ0025, AQ0052 and AQ0053) were not successfully grown for a long enough period of time to test the different pH levels. The data for four more strains has yet to be analyzed. We report here results obtained from the response of other thirteen strains to pH changes.

Figure 4 summarizes the results of the pH experiments. The figure shows the fluorescence-based biomass values measured in the chemostats following adjustments in the pH set points. A lower biomass level versus that at pH 7.5 indicates that the culture's growth is not keeping up with the chemostat's dilution rate and, thus, the growth rate is lower than under the standard condition (pH = 7.5). Lower biomass levels at high pH (8.5) could be interpreted as CO_2 limitation of the cultures. Lower biomass levels at low pH (7.5) could be interpreted as a detrimental effect on the cells due to the acidity of the medium.

Figure 4. Average fluorescence based estimate of biomass measured at steady-state in chemostat cultures at different pH.

Of the 13 strains so far characterized 5 maintained a higher biomass level at pH 6.5 than 7.5 possibly indicating carbon limitation at 7.5 pH. Similarly, 10 strains maintained higher biomass level at pH 7.5 than 8.5 indicating carbon limitation at 8.5 pH. This will become important in the final phase of this project, during the design of a microalgal facility to sequester smoke stack CO₂. An oversized facility would translate into lower CO₂ available for the cultures, decreasing its efficiency.

Figure 5 shows the results of the fluorescence measurements, averaged over several days, for the chemostat cultures grown at different pH. The highest F_v/F_m values are those of **AQ0011, AQ0022, AQ0024, AQ0040, AQ0042, and AQ0044**. These strains belong to the Chlorophyceae or green algae. AQ0033 and AQ0036 belong to the Rhodophyceae, or red algae. These strains show a lower F_v/F_m than the green algae due to the difference in photosystem architecture. However, note that there are no discernible changes in F_v/F_m among all these strains in response to changes in culture pH. AQ0012 and AQ0028 are representatives of the Cyanophyceae, or blue-green algae. In this case there appears to be a reduction in photosystem efficiency at the higher pH values (equivalent to lower levels of dissolved CO₂ in the culture medium).

Figure 5. The average F_v/F_m value (a measure of the photosynthetic efficiency) measured in steady-state chemostat cultures grown at different pH.

3.2.1.2 Flue Gas Tolerance Experiments

To test the flue gas tolerance of the different microalgal strains, the cultures are grown in chemostats and exposed to different gas mixtures selected to mimic the flue gas from power plants utilizing different fuels (Table 2). Initially, the cultures are grown in chemostats at a pH range of 7.4-7.6. The pH of the cultures is automatically controlled by pure CO_2 injections into the growth medium in response to raises in pH. Once the cultures have reached steady state, the stream of pure CO_2 for pH control is substituted for the mixtures of gases specific to mimic different flue gas compositions. As in the pH tolerance experiments (above) changes in the fluorescence-based estimates of biomass and photosynthetic efficiency in response to exposure to different gas mixtures will indicate whether the cells are negatively affected.

Table 2. Typical Composition of Industrial Flue Gases as per the Type of Fuel Combusted

	Utility Boilers Bituminous Coal	Utility Boilers Sub-Bituminous Coal	Utility Boilers Natural Gas	GTCC Natural Gas	Diesel Fuel Oil
	A	B	C	D	E
CO_2	12	15	7.5	3.5	4
H_2O	7	12	15	7	3.5
O_2	6	6	6	13.5	15
N_2	74.8	66.94	71.49	76	77.475
SO_2	0.16	0.04	0	0	0.005
NO	0.036	0.018	0.009	0.00225	0.018
NO_2	0.004	0.002	0.001	0.00025	0.002

The fluorescence-based biomass indicates that none of the strains have responded negatively to flue gas exposure (Figure 6).

Figure 6. Average fluorescence based estimate of biomass measured at steady-state in chemostat cultures under different simulated flue gases.

Similarly, the estimates of photosynthetic efficiency indicate no deleterious effect caused by the exposure to flue gases (Figure 7).

Figure 7. The average F_v/F_m value (a measure of the photosynthetic efficiency) measured in steady-state chemostat cultures grown under different simulated flue gases.

3.2.2 Task 2.2: Achievable Photosynthetic Rates, High Value Product Potential and Sequestration of Carbon into Carbonates

3.2.2.1 CO₂ Utilization Capacity

The automated pH monitoring and control system allows us to closely follow changes in pH in all the chemostat cultures. As an example, Figure 8 shows the changes in pH over the life history of a chemostat culture of strain AQ0022. Changes in pH reflect changes in the concentration of dissolved CO₂ and the total dissolved inorganic carbon ($\text{DIC} = \text{CO}_2 + \text{HCO}_3^- + \text{CO}_3^{2-}$). We make the assumption that increases in DIC in the medium are produced either by respiration by the algae or by the injection of CO₂. We also make the assumption that decreases in DIC are produced by photosynthetic uptake of carbon and degassing from the culture medium. Figure 9 shows an example of such changes. The figure shows two traces. The first trace is the pH of the culture medium over 4 days and nights for a culture of strain AQ0036. Decreases in pH correspond to increases in DIC produced by CO₂ injections and algal respiration. Increases in pH correspond to decreases in DIC caused by photosynthetic uptake of CO₂ by the algae or degassing.

Using the changing concentrations of DIC over time we can calculate the net rate of carbon uptake ($\text{mg CO}_2 \text{ l}^{-1} \text{ min}^{-1}$). The results of this calculation, with a resolution of 5 min, are shown in Figure 10. Positive values indicate net uptake of CO₂ by the culture and degassing of CO₂ from the culture medium while negative values indicate injection of CO₂ into the medium and cellular respiration. Note that, in this case, degassing during the night periods (which would be evidenced by a rise in pH) is negligible. If we calculate an average net CO₂ uptake rate, using the values when no CO₂ is being injected, we obtain an average net rate of $0.094 \text{ mg CO}_2 \text{ l}^{-1} \text{ min}^{-1}$. For a 14-hr day this is equivalent to $79 \text{ mg CO}_2 \text{ l}^{-1} \text{ d}^{-1}$ or $21.5 \text{ mg C l}^{-1} \text{ d}^{-1}$.

Figure 8. Computer generated trace of culture pH in a chemostat culture (strain AQ0022). Showing the periods of time during which the culture's pH was maintained at 6.5, 7.5, and 8.5.

Figure 9. Changes in pH and total DIC over a 4-day period for a chemostat culture of strain AQ0036.

Figure 10. Changes in carbon uptake rate over a 4-day period for a chemostat culture.

We have now started to analyze the data obtained in these experiments to understand not only how the physiology and the growth of the microalgal cells may change when grown at different pH but also how the different medium pH affects the degassing of CO_2 from the medium and the uptake of CO_2 by the microalgae. For example, if we consider the changes in pH during the light and dark period (i.e., no photosynthetic carbon uptake) for the AQ0011 grown at different pH, both the rate of uptake and the rate of degassing are inversely proportional to the medium pH (Figure 11). At lower pH the concentration of CO_2 is higher in the medium so diffusion of CO_2 out of the medium is expected to be faster (Figure 11). If we compare the

Figure 11. Rates of CO₂ uptake and/or degassing for a chemostat culture.

calculated rates between the light and dark periods the difference should be that due to photosynthetic uptake of CO₂. The result indicates that the photosynthetic uptake of CO₂ is also pH dependent.

The photosynthetic carbon uptake estimates thus calculated are summarized in Figure 12. As for strain AQ0011, the results indicate a pH dependency on the uptake/degassing rates calculated. This is expected since at lower pH the degassing of CO₂ from the liquid medium is expected to be faster due to the larger partial pressure of CO₂ in the medium.

Figure 12. Difference between rates of CO₂ uptake and degassing light and dark periods.

3.2.2.2 Production of High Value Products from Microalgae to Offset the Cost of Carbon Sequestration

We are in the process of analyzing samples from several more microalgal strains but have no new data to report at this time. As the data become available the potential for commercial production and carbon sequestration cost mitigation will be analyzed.

3.2.2.3 Carbon Sequestration Into Carbonate Minerals Utilizing Microalgae

We have not conducted further experiments related to microalgal mediated carbonate mineral production during this quarter.

3.3 Task 3: Optimization and Demonstration of Industrial Scale Photobioreactor

The goal of years 2 and 3 of this research program is to optimize carbon sequestration, high value component production and CO₂ carbonation utilizing microalgal cultures at a commercially significant scale. This will be done in two phases. During year 2 we will conduct a pilot evaluation and during year 3 we will conduct full scale production runs (below).

3.3.1 Task 3.1: Pilot Evaluation

During this quarter we have ordered the equipment necessary to carry out scale up of microalgal cultivation to 3,000 l photobioreactors outdoors. As we move into the 6th quarter of the project the culture systems will be put into operation. At that time we will be able to report the results of our first experiments.

3.3.2 Task 3.2: Full Scale Production Runs

This task will be taken up during year 3 of the project. Species determined to be outstanding performers will be selected and scaled up to 25,000 l outdoor photobioreactors.

3.3.3 Task 3.3: Algae Separation and Final Product

We expect to carry out some preliminary work on this task during year 2 as biomass produced during the pilot evaluations becomes available.

3.4 Task 4: Carbon Sequestration System Design

To evaluate the potential for application of photosynthetic sequestration of CO₂ to industrial-scale combustion systems, we will conduct a system-level design study. The purposes of this study are as follows:

- (1) Identify design concepts for components and the integrated system of the proposed concept
- (2) Optimize and evaluate performance of the components and the system

- (3) Develop deployment methodologies
- (4) Identify key technology issues for further development.

This task consists of two sub-tasks: Task 4.1-Component Design and Development; and Task 4.2-System Integration. Process simulations will be performed for conventional coal-fired and gas turbine power stations and natural gas boilers.

3.4.1 Task 4.1: Component Design and Development

The purpose of this subtask is to develop design concepts for each of the key components of the industrial scale photosynthetic sequestration of CO₂. Key components to be designed include: CO₂ removal process; CO₂ injection device; photobioreactor; product algae separation process; and process control devices. As the proposed system depends on the solar energy to photosynthetically convert CO₂ to products compounds, optimization of the photobioreactor is an important part of this task.

In the reporting period, Task 4.1 has progressed. As reported in the last progress report, PSI believes that a key to successful CO₂ sequestration is efficient use of solar energy. The area required for photosynthetic process by microalgae is a key cost driving factor. Therefore, we need to develop a photobioreactor design which makes efficient use of solar light.

3.4.1.1 Photobioreactor Design Concept

In the last quarterly progress report, we reported that microalgae utilize solar radiation to convert CO₂ into organic substances and oxygen by utilizing the spectra typically between 400 nm and 700 nm called photosynthetically active radiation (PAR). Figure 13 shows solar spectral data for AM1.5, a typical terrestrial condition in the United States. The portion of the spectra used by microalgae between 400 and 700 nm is 424 W/m², which is 44% of the total solar spectral energy of 962 W/m².

We are investigating possibilities for developing an efficient photobioreactor which:
(a) maximizes availability of the PAR spectra for microalgae; and (b) utilizes the solar radiation outside of PAR spectra for generating products that potentially offset the sequestration cost.

We have been looking into possibilities of implementing method (b). As we briefly discussed in the last quarterly report, PSI has been working on this issue for a program supported by NASA/KSC (Nakamura, 2001). In this program we have demonstrated separation of PAR from the solar spectra and directed it to a location 10 m away from the solar collector, while the longer wavelength spectra outside of the PAR was converted to electrical power by low-bandgap Photovoltaic cells. PSI has developed several design concepts for microalgae growth and photovoltaic power generation. Figure 14 shows a schematic of the concept. In this concept, the solar radiation is directed to a selective spectral reflector which reflects only the non-PAR spectra to the PV cells while the PAR components are transmitted to the photobioreactor.

Figure 13. Solar spectral irradiance with PAR highlighted in gray.

Figure 14. Concept for utilizing solar spectra not used for photosynthetic process.

We are also analyzing data obtained during NASA tests to evaluate the “by-product credit” to CO₂ remediation. The experimental results reviewed above indicated that electric power generation is possible at the photobioreactor without negative effects, namely the electric power is generated at no penalty to photosynthesis of microalgae. During the reporting period we have begun our study to assess feasibility of implementing the concept of simultaneous production of sequestered carbon and electric power. We plan to keep working on the design concept the next reporting period.

3.4.2 Task 4.2: System Integration

3.4.2.1 Carbon Dioxide Supply, Separation, and Biological Uptake System

The process model for CO₂ supply, separation, and biological uptake using microalgae which had been developed during the last reporting period was used to identify critical experimental and other data that need to be collected, and to evaluate alternative photobioreactor designs and carbon sequestration options. Figure 15 presents the ASPEN flowsheet for the preliminary model presently being simulation tested. This figure is identical to the figure presented in the last quarterly report as no change has been implemented yet.

Figure 15. ASPEN flowsheet of CO₂ supply, separation, and biological uptake system.

An explanation of the flowsheet was given in the last quarterly report and will not be repeated here. Details on the bioreactor and downstream processing subsystems are currently being provided by Aquasearch. The preliminary model described in Figure 15 has been shared with PSI and Aquasearch for review and discussion on the modeling is ongoing.

4. SUMMARY AND FUTURE PLANS

4.1 Task 2: Selection of Microalgae

Up to this point in time we have

- Tested 50 different strains of microalgae for growth at five different temperatures (15, 20, 25, 30 and 35°C) and 4 strains at three temperatures (15, 20, and 25°C),
- Tested 13 different strains for pH shift tolerance in chemostat cultures,
- Analyzed 34 different strains for high value pigments,
- Tested 17 strains at the chemostat level for growth and carbon uptake rate,
- Started testing the tolerance of microalgae to simulated flue gases, and
- Tested 3 different strains for carbon sequestration potential into carbonates for long-term storage of carbon.

Our preliminary results indicate that

- Out of 54 strains tested two did not grow at 15°C, 1 did not grow at 15 and 20°C, 9e did not grow at 35°C, and 1 did not grow at 30 and 35°C,
- Out of 13 strains tested so far for pH tolerance only 2 strains, both Cyanobacteria, appear to lower their ability to photosynthesize as the pH increases,
- Out of 13 strains tested at chemostat scale, 5 maintained a higher biomass level at 6.5 pH than 7.5 pH but 10 strains maintained lower biomass at 8.5 pH than 7.5 pH,
- Out of 34 strains analyzed for high value pigment content we have identified possible good sources of zeaxanthin, lutein, fucoxanthin, phycocyanin, and phycoerythrin, and
- Changes in culture pH caused by microalgal photosynthesis appear to be conducive to the precipitation of CaCO_3 from the growth medium.

Within the next quarter we expect to

- Continue to carry out carbon sequestration experiments in chemostat cultures,
- Continue to carry out simulated flue gas experiments in chemostats, and
- Scale up of promising strains to the 3000 L outdoor photobioreactor scale.

4.2 Task 4: Carbon Sequestration System Design

In the reporting period, work on Task 4 continued. Summary of the results in this task is as follows:

- ☐ We have conducted work on designing key components including: CO₂ removal process; CO₂ injection device; photobioreactor; product algae separation process; and process control devices.
- ☐ The test results obtained during PSI experiments showed that full utilizations of solar spectra is possible for two distinct purposes: CO₂ sequestration; and electric power generation.
- ☐ We are working on design concept for photobioreactor incorporating the method for full utilization of solar energy.
- ☐ The process model for CO₂ supply, separation, and biological uptake using microalgae has been studied. A skeleton ASPEN flowsheet for the preliminary model is presently being simulation tested.
- ☐ The ASPEN model incorporates:
 - the CO₂ separation subsystems including an alkaline salt solution CO₂ separation process
 - the algae production subsystem utilizing closed, open, or both types of photobioreactors
 - the product processing subsystems.
- ☐ The model has the ability to perform parametric studies to identify critical experimental and other data that need to be collected, and to evaluate alternative photobioreactor designs and carbon sequestration options.
- ☐ The ASPEN model has been shared with PSI and Aquasearch for their review and discussion.