Minutes of the 5th Technical Meeting of the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae.

(Organized under the IEA Greenhouse Gas R&D Programme, www.ieagreen.org.uk)

Alexandria, Virginia, Monday, May 3rd, 2004, Hilton Alexandria Mark Center,
(Held in conjunction with the 3rd Annual Conf. on Carbon Capture & Sequestration)

Membership: The following organization are members of the Network: **Arizona Public Services** (USA), **ENEL Produzione** (Italy); **EniTecnologie** (Italy); **EPRI** (formerly Electric Power Research Institute, USA), **Gas Technology Institute** (USA); **Pacific Northwest National Laboratory** (USA), Rio Tinto (Australia), **TERI** (formerly Tata Energy Research Institute, India) and **U.S. Department of Energy** (USA).

SUMMARY: This meeting reviewed ongoing R&D activities by Participating Member Organizations and discussed future plans and R&D required to achieve significant greenhouse gas abatement by microalgae technologies. The development of a "Business Case" was discussed for how microalgae biofixation technology and the Network can help member organizations meet their strategic goals in GHG abatement.

AGENDA AND TABLE OF CONTENTS

8:15 AM. Assembly, Coffee, Continental Breakfast (Time moved up 15 minutes).

A. 8:45 AM- 9:45 AM. Welcomes and Introductions
- a. Paola Pedroni (Chair, EniTecnologie). Welcome and Introduction to Network
- b. Angela Manancourt (IEA GHG R&D Programme). Web site, budget, other matters
- c. John Benemann (Network Manager). Update and Biohydrogen Developments.
- d. Introductions by Steering Committee Members, Technical Advisers, Observers.

B. 9:45 AM -12:30 PM. Brief updates on research projects by Network Members and Technical Advisors and other participants (Break at 10:30 – 10:45 AM).
- a. Paola Pedroni and Mario Tredici. EniTecnologie - U. Florence Project
- b. Vito Marraffa. ENEL Project
- c. Juergen Polle and Joe Weissman. DOE SBIR Project.
- d. Michael Huesemann. DOE NETL Project).
- e. Qiang Hu. Arizona Public Services Project.
- f. Dave Brune and Bailey Green Wastewater Treatment Applications
- g. Other ongoing microalgae R&D projects (e.g. Mulbry, USDA, etc.)

12:30 PM - 13:30 PM. Lunch in Hotel

C. 13:30 PM - 15:00 PM. Further discussions on presentations and ongoing projects technical objectives for next two years. Issues.

D. 15:00 PM - 15:30 PM Presentations of work on System and Life Cycle Analysis and "Business Case" of benefits of Network to Members. BioH2. Q&A. (J. Benemann).

Break 15:30 PM – 16.:00 PM

E. \16:00 PM–17:00 PM. Discussions of above, potential for GHG abatement, Expanding membership. Other matters pending. Final discussions.

17:00 Adjourn. (Reception by the 3rd Annual Conf. on Carbon Capture & Sequestration)

5th NETWORK TECHNICAL MEETING PARTICIPANTS

John Benemann, Network Manager, Walnut Creek USA jbenemann@aol.com

David Brune, Adviser, Clemson University, USA, debrune@clemson.edu

Ed Frank, Argonne National Laboratory, USA efrank@mcs.anl.gov

Bailey Green, Adviser, Lawrence Berkeley Laboratory, USA fbgreen@lbl.gov
oswaldgreen@attglobal.net

Qiang Hu, Observer, Arizona State University, USA huqiang@asu.edu

Michael Huesemann, Member, Pacific Northwest National Laboratory, USA
michael.huesemann@pnl.go

Evan Hughes, Member, Consultant to EPRI, USA EHughes@EPRI.com

Michael Jawson, Observer, U.S. Dept. of Agriculture, USA mdj@ars.usda.gov

Angela Manancourt, IEA GHG R&D Programme, UK Angela@ieagreen.demon.co.uk

Vito Maraffa, Member, ENEL, Italy marraffa@crr.enel.it

Blaine Metting, Member, Pacific Northwest National Laboratory, USA blaine.metting@pnl.gov

Walter Mulbry, Observer, US Dept. of Agriculture, USA mulbryw@ba.ars.usda.gov

Robert Paterek, Member, Gas Technology Institute, USA robert.paterek@gastechnology.org

Paola Pedroni, Member/Chair EniTecnologie, Italy ppedroni@mail.enitecnologie.eni.it

Roy Ramani, Observer, Water Environment Research Foundation. Alexandria, Virginia, USA
rramani@werf.or

Mario Tredici, Adviser, University Florence, Adviser, Italy mario.tredici@unifi.it

Mr. Gary Walling, Observer, Alliant Energy garywalling@alliantenergy.com

Joseph Weissman, Adviser, SeaAg, Inc., Adviser, USA weissm_j@bellsouth.net

Qing Xu, Observer, Institute for Biological Energy Alternatives, USA qxu@tcag.org

A. WELCOMES AND INTRODUCTIONS

a. Dr. Paola Pedroni, EniTecnologie, Chair, Welcome to the 5th Technical Meeting. "Network Status, Goals and Activities, Objectives of the Meeting"

Dr. Pedroni welcomed the members, technical advisers and observers. Dr. Pedroni briefly reviewed the history, organization, status and activities of the Network for the observers and participants attending for the first time:

Network Objectives. The Network provides a forum for information exchange, sharing of expertise, promotion of research cooperation and collaborations. It also provides technical assistance to Member organizations in developing practical microalgae-based processes for greenhouse gas (GHG) abatement that meet their strategic goals. Finally, the Network assesses the resource and economic potential of microalgae technologies in GHG abatement.

Network History. The Network was initially proposed by the U.S. Dept. of Energy and EniTecnologie in the summer of 2000, following which a Workshop was held in January 2001 in Monterotondo, Italy, at EniTecnologie, where over 30 experts discussed the technology and potential of microalgae in greenhouse gas abatement, and supported the formation of the Network. In January 2002 a pre-organizational meeting was held in Reston Virginia of potential members and the Network was officially started in June of that year. Four technical meetings have been held prior to the present one, in Almeria, Spain (May, 2002), in Kyoto, Japan (October 2002), Berkeley, California, USA (April, 2003), and in Paris, France (September 2003. (Minutes for all the meetings are available to Members from the Network Manager).

Network Organization and Status. The Network governance is by a steering committee made up of representatives of the member organizations, who determine the budget and direction of the Network. Five member organizations were represented at this meeting: EniTecnologie (Dr. Paola Pedroni, Chairperson of Network), PNNL (Dr. Blaine Metting), EPRI (Dr. Evan Hughes), GTI (Dr. Robert Paterek) and ENEL (Dr. Vito Marraffa). (Absent: U.S. Department of Energy, USA; TERI, India; Rio Tinto, Australia; and Arizona Public Services, USA). The Network is supported by Technical Advisers, of which four attended this meeting: Dr. David Brune (Clemson U.), Dr. Bailey Green (Lawrence Berkeley National Laboratory), Dr. Mario Tredici (U. Florence) and Dr. Joseph C. Weissman (SeaAg, Inc.). Dr. John Benemann is the Network Manger for technical matters, and Ms. Angela Manancourt represents the IEA Greenhouse Gas R&D Programme, supports the web site and administers financial matters of the Network and the web site. The Network Manager and some Technical Advisers play a direct role in the Network through development of research projects with member organizations. Network membership is open to organization interested in the development of microalgae biofixation technologies.

Strategic Goals of the Network: Demonstrate the technical and economic feasibility of microalgae biofixation processes for GHG abatement within five years and some practical applications within ten years. One specific goal of the research carried out by Network Members is to demonstrate the production of microalgae biomass using power plant flue gases at about twice the rate than is currently achieved. The Network has developed a Technology Roadmap that outlines the most promising areas for R&D over the next few years, discussed below.

Network Activities and Objectives of Meeting. This meeting updates the R&D projects being carried out and planned by the Network Members, reviews the first two years of activities and accomplishments of the Network and discusses plans for the upcoming two years, an discusses ongoing technical assessments, including a "Systems and Life Cycle Analysis" and a "Business Case" for the Network. It also discusses the budget for the current and next Fiscal Year.

b. Ms. Angela Manancourt, GHG R&D Programme, Budget and Organization

The GHG R&D Programme. This technical organization was set up in 1991 under the auspices of the International Energy Agency (IEA), it is one of about 40 R&D "Implementing Agreements" of the IEA. It aims to evaluate technologies for abatement of greenhouse gas emissions, disseminate results of such assessments, promote research, development and demonstration projects, and support member organizations (countries and major energy companies) in their efforts to advance and apply such technologies. It supports other R&D networks, in areas such as in CO_2 capture. Set up the network agreement

Role of the GHG R&D Programme in the Network. The IEA GHG R&D Programme provides a formal basis for the network, including the Agreements for organizations to join the Network, administration of finances for the Network, providing logistical assistance to the network manager, and development and maintenance of the website to disseminate information.

Network Website. The website was set up during the past period to help disseminate information about the Microalgae Network. (See **www.ieagreen.org.uk,** go to "Networks". The Website contains all the reports from the Network, starting with the initial Workshop Report from the Monterotondo (Rome) Workshop in January 2001 and the publications related to the Network. The reports of the Network technical meetings are also on the web, but accessible only of Members. A copy of the Network Agreement is also posted on the open part of the Website.

Network Budget. The budget for the first year of the Network June 2002 to May 2003 was $72,000 (eight members, @$9,000/each) and was completely spent without any carry over. The 2003-2004 budget was $72,500 (eight members @ $9,000, with $500 for TERI), of which $48,000 was designated for support of the Network Manager, $6,000 for the IEA Greenhouse Gas R&D Programme, and the remainder budgeted for meetings. The first meeting in Paris cost $10,000 and the present meeting approximately $6,000, leaving a small amount of carry over for next year. It is assumed that the next year (starting June 1) will have approximately the same budget, but could be adjusted up or down somewhat, depending on the number of members.

c. Dr. John R. Benemann, Network Manager: News, Current Activities and Status.

Recent Developments Related to Microalgae Greenhouse Gas Abatement. There have been a few developments in this field. In the U.S., two ongoing projects funded (for a three year period) by the US DOE NETL (National Energy Technology Laboratory) were concluded earlier this year. These projects involved the use of tubular bag-type photobioreactors for biofixation of CO_2 (Aquasearch Corp., recently renamed Mera Pharmaceuticals, Inc., Dr. Miguel Olaziola, P.I.) and concentrating mirrors coupled to optical fibers for illumination of closed bioreactors (Prof. D. Bayless, U. of Ohio). These projects were funded by US DOE prior to the initiation of the Network, indeed, they contributed to its formation. As these approaches are inherently too expensive for significant greenhouse gas abatement they were not included in the Technology Roadmap. Based on a recent program review (March 2004) it is not likely that US DOE–NETL will fund new microalgae projects in the near future through such a solicitation mechanism. However, the DOE SBIR (Small Business Innovative Research Program) has been soliciting proposals in this general area and several such projects were recently awarded to Network participants by US DOE. (See further discussions below). There were few news related to microalgae biofixation of CO_2 and greenhouse gas abatement outside the U.S.

Microalgae for Hydrogen Production. Photobiological hydrogen production has become a focus of R&D efforts by the U.S. DOE & others, both in the U.S. (for example, at Stanford University) and abroad (several projects ongoing in Europe and elsewhere). The U.S. DOE is sponsoring R&D in this area mainly focusing on direct biophotolysis, that is, a direct splitting of water without CO_2 fixation. Projects are ongoing at several National Laboratories and one major project is being carried out by Dr. Craig Venter (of human genome fame) who is searching the oceans of the world for new algal species of promise in direct biophotolysis and biofixation of CO_2. Indirect biophotolysis processes that involve CO_2 biofixation, and thus are of interest to the Network, have also been proposed. A process that uses large-scale algal ponds for production of high starch (for green algae; glycogen for cyanobacteria), followed by dark fermentations has been proposed by the Network Manager and will be pursued as part of the Network in the future as a long-term option for use of microalgae in greenhouse gas abatement.

Technology Roadmap and Techno-Economic Analysis. The Technology Roadmap published last year identified four general applications of microalgae technologies with significant potential for greenhouse gas abatement (with the main mechanisms for such reduction in parenthesis):

- Municipal wastewater treatment using power plant CO_2 (energy production and conservation);
- Agricultural / aquacultural / industrial wastewater with power plant CO_2 utilization (Ibid);
- Nitrogen fixation by cyanobacterial cultures for agricultural fertilizer applications (Ibid);
- Co-production of biofuels and large volume/higher value byproducts (biopolymers, feeds, etc.)

The Technology Roadmap, however, lacked a definition of either the costs (economics) or of the potential resource (e.g. likely global greenhouse gas abatement impacts, assuming successful R&D. The productivity goal for the Network is 100 metric tons of ash-free dry biomass per hectare-year (100 t/ha/y), corresponding to about twice as much CO_2 fixed. Thus, world-wide, a relatively modest 5 million hectares of algal ponds would capture 1 Gigaton of CO_2. However, biofixation is not identical with GHG abatement of CO_2, which is in large part based on substituting fossil fuels with renewable fuels. Typically half as much CO_2 is abated as is fixed in the biomass (a factor that is relatively independent of the biofuel produced - methane, ethanol, biodiesel, etc.). However, abatement of secondary greenhouse gases (methane, nitrous oxides) and energy conservation in environmental applications, specifically in waste treatment, can be significant and in some cases even exceeds the GHG abatement resulting from renewable energy production. Due to high variability, resource limitations (climatic, land use, water, etc.) and economic factors, it is difficult to arrive at a better estimate of the potential for GHG abatement with microalgae. The major advantages of microalgae are their potentially much higher productivities than conventional plants, as well as their utility in waste treatment, ability to use saline or brackish waters and power plant CO_2 sources. These issues are being addressed by the "Business Case" analysis being undertaken by the Network Manager (see further below).

d. Introductions by Other Participants .

Prof. David Brune, Technical Adviser, Dept. of Agricultural Engineering, Clemson University, Clemson, South Carolina, USA. Dr. Brune has been working on algal mass cultures for wastewater treatment for aquaculture applications and is currently carrying out a project on nutrient recovery from the Salton Sea, a potentially large-scale application for microalgae systems. (See prior Minutes of meetings and also below).

Dr. Ed Frank, Observer, Division of Math & Computer Science, Argonne National Laboratory, Argonne, Illinois, USA. Dr. Frank is working on the development of systems biology modeling tools, and is interested in modeling microalgae growth and metabolism for energy production and greenhouse gas abatement. At this time the effort is at an early exploratory stage. The plan is to focus on sequenced organisms so that genomic analysis can guide the metabolic network construction.

Dr. Bailey Green, Technical Adviser, Lawrence Berkeley Laboratory and OswaldGreen LLC, Berkeley and Concord, California, USA. Dr. Green has been working for many years with Prof. William J. Oswald at UC Berkeley on the development of microalgae municipal wastewater treatment systems and related technologies. Dr. Green presented an overview of wastewater treatment ponds using microalgae, including harvesting of the algal biomass and methane capture from anaerobic waste treatment ponds (See Minutes of the 3rd Meeting, in Berkeley, California, for a review).

Dr. Qiang Hu, Observer, School of Life Sciences, Arizona State University, Tempe, Arizona, USA. Dr. Hu has worked in the field of microalgae production for higher value products for a number of years and is working with funding from the Arizona Public Services Co. (a member) to address issues of animal wastewater treatment and nitrogen fertilizer recycling. (See Minutes of the 3rd Meeting, in Berkeley, California for a report). In the past year one focus of the work in this area was to select for microalgae suitable for N removal from wastewaters (see below).

Dr. Michael Huesemann, Member, Battelle Marine Sciences Laboratory, Pacific Northwest National Laboratory, Sequim, Washington, USA. Dr. Huesemann is carrying out DOE NETL funded work on the cultivation of microalgae to determine the correlation between growth rates and productivity, if any (See Minutes of the 3rd Meeting, Berkeley, California, and also below).

Dr. Evan Hughes, Member, Consultant and representative of EPRI, Palo Alto, California, USA. EPRI was a founding member of the Network and is interested in technologies that can integrate into power generation and reduce greenhouse gas emissions from power plants. EPRI works for member utilities that express interest in and support R&D in specific technologies and projects.

Dr. Michael Jawson, Observer, U.S. Dept. of Agriculture, Agricultural Research Service, Beltsville Maryland, USA. The USDA has an interest in technologies that can treat agricultural wastes, produce bioenergy, and abate greenhouse gases. Microalgae technologies are of interest in these applications.

Dr. Vito Maraffa, Member, ENEL, Divisione Generazione ed Energy Management, Area Tecnica Ricerca, Tuturano, Brindice, Italy. ENEL, the major Italian electricity company, produces about 55 Mt/y of CO_2 in thermoelectric plants and reduction of this CO_2 is a strategic target is carrying out two projects related to CO_2 abatement, one dealing with CO_2 absorption by serpentine rocks and a microalgae R&D project using actual power plant flue gases and photobioreactors as cultivation systems (see prior Meeting Minutes and also below).

Dr. Blaine Metting, Member, Pacific Northwest National Laboratory, Richland, Washington, USA. Dr. Metting has worked on microalgae R&D for over 25 years, and has started a small microalgae company that still functions. PNNL, a Dept. of Energy Laboratory, is carrying out a wide range of R&D activities related to greenhouse gas abatement and the Network focus fits with these goals.

Dr. Walter Mulbry, Observer, US Dept. of Agriculture, Agricultural Research Service, Animal Manures By-Products Laboratory, Beltsville, Maryland, USA. The ARS-AMBL deals with the management of animal wastes (manures) and the recovery of nutrients, energy and other values (See below).

Dr. Robert Paterek, Member, Gas Technology Institute, Chicago, Illinois, USA. GTI is the R&D arm for and supported by the natural gas industry. It carries out a wide range of research activities, including in waste treatment and greenhouse gas abatement. Microalgae have been studied in the past by GTI and are of interest because they are a potential source of methane fuel.

Dr. Roy Ramani, Observer, Water Environment Research Foundation, Alexandria, Virginia., USA. Dr. Ramani received his Ph.D. with Prof. William Oswald in Berkeley working on algal ponds for wastewater treatment. He has worked since at the World Bank and most recently at WERF, where he is a program manager with an interest in wastewater treatment processes.

Prof. Mario Tredici, Technical Adviser, Dipartimento di Scienze e Tecnologie Alimentari e Microbiologiche, Universita' degli Studi di Firenze Deptarment of Agricultura, Florence, Italy. Prof. Tredici is an expert in microalgae mass cultures and is assisting EniTecnologie in their project (see below).

Mr. Gary Walling, Oberver, Alliant Energy, Cedar Rapids, Iowa, USA. Alliant Energy is a major U.S. electric utility and interested in innovative greenhouse gas abatement technologies, including biomass systems, which can include microalgae.

Dr. Joseph Weissman, Adviser, SeaAg, Inc., Vero Beach, Florida, USA. Dr. Weissman has been working for many years on algal mass cultures and is currently working on a DOE-supported project on microalgae productivity (see below).

Dr. Qing Xu, Observer, Institute for Biological Energy Alternatives, Rockville, Maryland, USA. The Institute for Biological Energy Alternatives was founded by Drs. Craig Venter (of human genome fame) and Ham Smith (Nobel Prize for biochemistry) to exploit genomic technologies for the search and development of microalgae that can produce hydrogen and fix CO_2, among other attributes. Dr. Xu is working on hydrogen production by microalgae.

B. Updates on research projects by Network Members and other Participants.

a. Paola Pedroni and Mario Tredici. EniTecnologie R&D Project on Microalgae Biofixation of CO_2.

Prof. Tredici has been working this past year with the EniTecnologie team headed by Dr. Pedroni, providing technical support, design and fabrication of the ponds and photobioreactors, strains for the reactors and training and related assistance to that project. Prof. Tredici discussed the alternative photobioreactors that can be used in algal mass culture and factors affecting productivity in both photobioreactors and open ponds (see also prior Minutes of Meetings of the Network).

Dr. Paola Pedroni presented an overview of the EniTecnologie project. The project is a feasibility evaluation, at a small pilot scale and under outdoor conditions, of a process for the direct biofixation of fossil CO_2 from concentrated sources using microalgae mass cultures. The process would also involve the conversion of the biomass in biofuels (specifically methane, CH_4) to replace fossil fuels and thereby achieving GHG abatement. This process does not consider, at least at this stage, the treatment of wastes as a part of the process.

The central focus of the R&D activities are on aachievable algal biomass productivity under operating conditions (outdoors, using a NGCC-simulating flue gas as a CO_2 supply). The goal of the project is to demonstrate an increase in productivity to a currently projected 30 g/m2/day (dry matter) to a near-theoretical 60 g/m^2/day in the long-term. This would maximise CO_2 utilization of CO_2, reduce land area requirements (“footprint”), and lower the costs of biomass production.

The first experimental study, carried out April-October, 2003, was to compare productivity performance of different microalgal strains (marine) in small open ponds and closed photobioreactors. A second objective was to select strain(s) optimized for sustained outdoor mass cultivation as monoculture(s). The experiments were carried out with two open ponds and two small tubular reactors at the Moterotondo R&D facility of EniTecnologie. .

The two open ponds and two closed, tubular reactors, were operated side-by-side at different dilution rates with the marine microalgae, *Tetraselmis suecica*. A number of variables were monitored to allow for comparable results between the reactors. In brief, the results demonstrated that the open ponds were essentially as productive as the closed photobioreactors,. Indeed, for the best dilution rate (50% per day), the open ponds were actually slightly (about 10%) more productive (at 25 g/m2/day) than the closed photobioreactors. This was an important finding as it argues that ponds would be suitable for large-scale high productivity mass culture of microalgae.

In the second year of this study, three open ponds and one closed photobioreactor will be operated, to obtain further data with additional algal strains. Eventually, this project aims at demonstrating greatly improved productivities using mutants such as those being developed
By Prof. Juergen Polle at Brooklyn College and being tested at SeaAg, Inc. (see below). The application of this technology is for natural gas fired power plants, to generate methane gas for use in the power plant.

b. **Vito Marraffa: ENEL Research Activity in CO_2 Biofixation**

.

Biological R&D activities for GHG abatement are focused on studies on utilization of microalgae for biofixation of CO_2 produced at power plants in order to produce renewable fuels and high value products. The research includes an evaluation of mineralization of CO_2 by coccolithophores.

Previous tests and results with *Phaedactylum tricornutum* cultivation in bubbling closed devices (see below) with air/CO2 mixtures showed that there was no difference in growth due to CO_2 concentrations and no effects of low concentrations of NO (25 ppm) and SO_2 (50 ppm) on algal physiology. Daily productivity of 0.25 g/l (AFDW) and final density of 4 g/l were achieved during the experiments. (See also previous 4th Technial Meeting Minutes, Paris, 2003).

Latest tests with *Phaedactylum tricornutum* and indoor cultivation in closed systems were carried out with gas mixtures $N_2/CO_2/O_2$ (90:4:6 v/v/v) similar to gas-fired power plants flue gases. Tests conditions: artificial illumination (3000 lux), light/dark cycle 12:12, test period 25 days, working volume 8 l, bubbling mixture flow rate of 0.2 l/min. Results: algal growth values were lower than data of previous trials. This is being investigated. Planned Activities: outdoor microalgal cultivation and evaluation of power plant waste-waters reclamation potential.

c. Dr. Joeseph Weissman, SeaAg, Inc. "Comparison of Marine Micro Algae Culture Systems for Fuels Production and Carbon Sequestration". (DOE SBIR Grant).

This project is a collaboration with Prof. Juergen Polle of Brooklyn College, who is developing mutant strains of microalgae with reduced antenna size and potential for increased productivity. During the first year of the project (Phase I) the effects of intermittent illumination were investigated (see prior Minutes of Technical Meetings). During the present Phase II, the focus is on testing of the reduced antenna size mutants. Initial experiments were carried out to, among others, establish growth characteristics of the wild type strains to compare these to the mutants. All experiments were carried out in 2.8 m^2 ponds using a *Cyclotella* sp. and a *Tetraselmis* sp. The wild types were compared in heated and unheated ponds, level of silicate feeding (for *Cyclotella*), and other parameters. With *Tetraselmis.* experiments compared ponds vs. small, 0.8 m^2, vertical photobioreactors (supplied by Prof. Tredici) (see Prior Minutes). Overall the results were that no significant differences in productivity were noted in most of the treatments. The differences in the vertical photobioreactors and ponds can be explained based on the P.vs. I curve and actual light intensities at the surfaces. Productivities were somewhat lower than expected based on prior data. The reasons for this (strains used?) are being determined.

Three initial mutant strains of *Cyclotella* tested did not achieve significant productivity increases tested, rather a small decrease in productivity compared to the wild type was noted. The screening and development of mutants to increase productivity continues, and remains the most plausible approach to increasing mass culture productivity significantly. However, prior work already suggested that without a stronger pre-screening effort and more directed mutant development process, it would be difficult to identify promising mutants. Dr. Weissman discussed the factors affecting productivity, in particular light and temperature.

d. **Dr. Michael Huesemann, PNNL. Selection of Microalgal Species that Maximize Biofixation of CO_2 from Power Plant Flue Gases (DOE NETL funded Project).**

(See also prior presentation in the Minutes of the 3rd Technical Meeting, in Berkeley California). This project has for its long-term research objective to screen and select marine microalgae that exhibit maximum CO_2 biofixation potential in outdoor mass culture. The hypothesis that is being tested is that the maximum specific growth rate in batch cultures is a good predictor of maximum biomass productivity in semi-continuous culture. The objective is to select algal strains with increased CO_2 biofixation potential in outdoor mass cultures. Experimentally, easily measurable parameters, such as photosynthesis vs. light intensity (P-I Curve) and other parameters are correlated to maximum biomass productivities. With three strains, there was no clear-cut correlation, positive or negative, in the growth rate vs. productivity parameters. However, the sample size is still too small to allow any final conclusions. Future work is to obtain complete data sets for at least five different microalgal species and to compare indoor and outdoor results with the same algal strain. The objective is to advance both the fundamental and applied aspects of algal mass cultures and productivity. Future work will also incorporate promising mutants being developed by Prof. Polle and tested by Dr. Weissman a SeaAg, Inc.

e. Qiang Hu, Arizona State University (ASU): Strain Selection / Improvement for Microalgal Carbon Sequestration. Project supported by Arizona Public Services (APS) and Universal Entech LLC (UE)

Strain selection is critical for higher photosynthetic efficiency and CO2 fixation rates. For better temperature and light tolerances and overall better competitiveness in mass cultures. The objective is to select strains that allow for a sustainable and predictable management of the algal cultures. A most important consideration is for the algal biomass to contain high value –added compounds. Finally, high extraction efficiency/bioavailability must be considered for bioactive products. The example used in this research is the isolation of mutants of Haematococcus pluvialis for high astaxanthin production . The picture below shows a mutant of Haematococcus (right) which contains a higher content of Astaxanthin then the wild type (left). The production of astaxanthin, including cell breakage and extraction was discussed as an example of algal mass culture processes. Dr. Hu also discussed the use of microalgae in N removal from wastewaters.

f. Prof. David Brune, Clemson University: "The Controlled Eutrophication Process; Microalgae for Biofuels Production and Fertilizer Recycling at the Salton Sea, California". (With Kent SeaTech, Inc., Supported by DOE-SBIR Program).

The "Controlled Eutrophication Process" (CEP) is a high rate pond ecosystem designed for recovery of excess nutrients as aquatic products and biofertilizers. The immediate and specific application of the CEP is at the Salton Sea, California, where a 950 km^2 saline evaporative lake is seriously polluted with agricultural drainage waters, resulting in hypereutrophication. As discussed in prior Minutes of Network Technical Meetings, removing the offending phosphates (and nitrates) from the agricultural drainage waters entering the Salton Sea has a potential for supporting over 1,000 hectares of highly productive algal ponds. The present project is designed to develop and demonstrate this process at the pilot scale using two 0. 3 hectare high rate ponds (see figure below). This past year the emphasis was on demonstrating the effect of fish co-culture on algal cells harvesting by sedimentation – with very good results, and installing a harvesting belt for the settled biomass. This process is an example of a microalgal "total environment" solution, in that it combines wastewater treatment, nutrient recycling, fish production water conservation and energy production together with greenhouse gas abatement.

g. Dr. Walter Mulbry, USDA ARS. Nutrient removal with Microalgae Cultures.

A major driver in the management of animal wastes is preventing the release of N to the soil (groundwater) and air. A potential alternative to land application of livestock manures for crop production, which is often limiting, is the production of algae to recover the nitrogen (N) and phosphorus (P) present in the manure. This project has studied an "algal turf scrubber" for such purposes. In this the algae are present not as a planktonic culture but as an attached mat over which the wastewater flows. There are several advantages to this, in particular the ability to remove lower concentrations of nutrients than would be possible with suspended growth. In the experimental studies, the algal turfs contained mixed indigenous assemblages of benthic algae, most abundantly the genera *Ulothrix*, *Oedogonium*, and *Rhizoclonium*. However, the turf scrubber is not a panacea, and significant technical problems remain with this process, in particular the stability of the turf. Also it does not appear that that system will be able to achieve the highest productivities. For this reason the use of high rate ponds, with CO2 fertilization, is being explored as an alternative. This project is starting to develop a process for using CO2 from flue gases for the mass culture of microalgae on animal wastes for the purpose of nutrient recycling and energy production.

C. Discussions of Ongoing R&D Projects.

The following summarizes the ongoing R&D projects carried out or supported by the Members:
1. Arizona Public Services (USA) supports R&D on microalgae animal waste treatment;
2. ENEL (Italy) has continued indoor photobioreactor studies of algal culture on flue gases;
3. EniTecnologie (Italy) is comparing outdoor productivities in ponds and photobioreactors;
4. Rio Tinto, continues its sponsored R&D on the algal CO2 fixation enzyme rubisco;
5. PNNL, a DOE facility, carries out research on algal growth rates and productivity.

In addition, DOE, through its SBIR Program, funded three new projects this year being carried out by the Network Technical Advisers with assistance of the Network Manager:
6. Maximizing productivities with antenna mutants (Phase II, SeaAg, Inc. & Brooklyn College);
7. Fertilizer production by nitrogen-fixing cyanobacteria (Phase I, SeaAg, Inc. and Clemson U.)
8. Large-scale algae culture on drainage waters (Phase I, Kent SeaTech, Inc., and Clemson U.)
(The last two were announced in May of 2004, after the present Network Meeting)

The budgets of these projects were not disclosed, but a reasonable estimate would be about $2 million per year for the first five listed above, and about $0.5 million per year for the last three. Overall, the R&D being carried out and represented by the Network is a significant effort. However, for maximum utility a greater degree of cooperation and collaboration between projects would still be desirable. Five of the eight projects listed above (#3, #5-8) are already well integrated in terms of sharing strains, experimental methods, data and technical advisers. The three other projects are also benefiting from membership in the Network and the information developed. Four of the eight projects (#5-#8) were initiated during and a result of the Network with the active participation of the Network Manager and Technical Advisers. Additional projects are under development, including a biohydrogen project (indirect biophotolysis) ad a project being developed by TERI, with some assistance from the network Manager.

D. Discussions of “Business Case”.

The original plan was to initiate this year the development of a “techno-economic” and a “life cycle” analysis (TCA and LCA) of microalgae biofixation and greenhouse gas abatement. The former is an engineering feasibility study of the process to allow projections of costs, the latter provides information on environmental impacts by accounting for all pollutant emissions from the process, and how these compare to the alternative technologies in specific applications. Included in such analyses would be the overall energy efficiency of the processes (solar, parasitic, fossil), their sustainability (e.g. use of non-renewable resources), use of renewable resources (e.g. water), “footprint” (land use per unit output), and human health impacts, in addition to environmental impacts. The difficulty is that there are several quite different and distinct processes under consideration by the Network and its members, from municipal wastewater treatment to stand-alone algal biofuels production (including biohydrogen). Each requires unique and fundamentally different TCAs and LCAs. Thus, each process and project requires a separate analysis, based on distinct process characteristics, scales, even locations. Therefore, the better approach is to carry out such analyses specifically for, and by, each project, with assistance of the Network Manager. The Salton Sea Project, by Kent SeaTech Corp. and Clemson U. (now funded by DOE-SBIR) will be the first project subjected to such analyses.

The important points raised in the concluding discussions were that the Network lacked a clear definition of the importance of the microalgae technology being developed by the Network within the business context of the member organizations. Of course, all members are most interested in greenhouse gas abatement, and the case for this must be clearly made. For example, what are the benefits of microalgae technologies compared to alternative technologies, such as indirect biofixation of CO_2 by higher plants (crop plants, trees) or CO_2 capture technologies. As mentioned in the introduction, microalgae have the potential for very high solar conversion efficiencies, thus maximizing outputs and minimizing footprint. Counter-intuitively, microalgae ponds use water much more efficiently than higher plants, 200 tons of water per ton of biomass output, a factor of about 10-20 fold lower than for conventional plants. Microalgae also use saline or brackish or wastewaters, generally unsuitable for agriculture. Thus, the fundamentals are strong for justifying such systems in the context of scarce resource utilization. Of course on the practical side the costs of microalgae systems are higher than for crop plants, even assuming high productivities. This requires that such systems provide services and benefits in addition to just renewable energy and greenhouse gas abatement. The Technology Roadmap addressed this issue by integrating microalgae for greenhouse gas abatement into other functions and outputs.

Compared to physical-chemical CO_2 capture and sequestration processes, microalgae combine both functions into one process, a great advantage, particularly in light of the many problems faced by CO_2 sequestration. The major drawback, aside from land use issues, is the fact that such systems capture only a fraction, at most of about 30 %, of fossil CO_2 emission from a power plant due to diurnal and seasonal factors, among others. However, in many cases such a decrease in CO_2 emissions is quite sufficient for most industrial greenhouse gas abatement goals. These will be driven by legislative and voluntary abatement programs that are specific to industries and locations. The reuse of the CO_2 and production of renewable energy by microalgae processes would be preferred to the once-through technologies of fossil CO_2 capture and sequestration.

Ultimately, the case for microalgae must be made based on economic, resource and sustainability arguments. Rapid growth in fossil fuel consumption requires rapid development of technologies that can have significant impacts at a global scale in reducing CO_2 and other greenhouse gas emissions. Microalgae can be developed faster than other plant systems because of their inherently very short generation times. However, they certainly have a much more limited potential than other higher plant systems, because of the many constraints on their application, from economics to land and water availability. However, fundamentally, it will be economics, the cost of ponds, CO_2 supply systems, harvesting, processing, etc., that will most influence the adoption of such microalgae technologies. And economics depends on technological advances.

It was remarked by several attendees, that microalgae processes are multipurpose – they provide, in addition to greenhouse gas abatement, a number of other environmental and economic services, from wastewater treatment and purification to fertilizer and chemicals production, all more important than greenhouse gas abatement. This is a message that must be more clearly conveyed to existing as well as to potential new members. A “Business Case” must be developed that clearly demonstrates how member organizations benefit from participation in the Network and how microalgae processes can contribute to their business goals. Such a “Business Case” will be developed by the Network Manager, with assistance from the Technical Advisers and members, to be presented at the next Technical meeting (Vancouver, September 5th, see below).

DRAFT AGENDA - 6th TECHNICAL MEETING OF THE

INTERNATIONAL NETWORK ON BIOFIXATION OF CO_2 AND GREENHOUSE GAS ABATEMENT WITH MICROALGAE

Vancouver, British Columbia, Canada, Sunday September 5, 2004,
Burrard Room, Fairmont Waterfront Hotel (604 691 1991)
Held in conjunction with GHGT -7 (see www.ghgt7.ca or www.ieagreen.org.uk)
(NOTE:The Network dinner on September 4th, Place tba)This Draft Agenda: Aug 4, 2004

OBJECTIVES: Review current R&D activities and accomplishments by participating organizations and the network as a whole and plan for the next three years. Identify R&D required to achieve significant greenhouse gas (GHG) abatement by microalgae technologies, in particular breakthroughs in productivity. Discuss "Systems and Techno-economic" analysis initiated for the processes identified in the Technology Roadmap. Review the "Business Case" for microalgae biofixation technology and how the Network can help member organizations meet their strategic goals in GHG abatement. Discuss web site, future meetings, expansion of membership, budgets and other matters arising.

8:30 AM. Assembly, Coffee
A. 9:00 AM- 10:00AM. Welcomes and Introductions
   a. Paola Pedroni (Chair, EniTecnologie). Welcome and Introduction to Network
   b. Angela Manancourt (IEA GHG R&D Programme). Web site, budget, membership
   c. John Benemann (Network Manager). Update on Network activities and projects.
   d. Introductions by Steering Committee Members, Technical Advisers, Observers.
B. 10:00 AM -12:20 PM. Brief research updates by Network Members, Technical Advisors and participants (Enitecnologie, Rio Tinto, PNNL, TERI, Kent SeaTech -Clemson U., SeaAg, Inc.-Brooklyn College, invited presenters). Discuss of R&D issues and needs, research collaborations (strains, etc.)
Break at 10:40 – 11 AM). 12:00 PM - 13:30 PM. Lunch informal discussion (in Hotel)
D. 13:30 PM - 14:30 PM. Discussion of "Business Case" for Microalgae Biofixation. Member feedback to Network. Planning future projects and course of action.
E. 14.30 – 15:00 Discussion of microalgae systems for greenhouse gas abatement: techno-economic and resource analysis, resource potential, productivity effects, etc.
D. Break 15:00 PM - 15:20 PM
F. 15:20 –16:0). Life Cycle Analysis for greenhouse gas abatement (John Benemann).
F. 16:00 PM–17:00 . General discussions, matters pending, next meeting, conclusions.
17:00 Adjourn. GHGT-7 Reception (for registered participants).
19:30 Dinner. (on own, informal, tba)
NOTE: Hosted dinner, Saturday night, September 4, tba (assembly at Renaissance Hotel).
CONTACT John Benemann at jbenemann@aol.com or 925 352 3352 for any questions.