December 16, 2002

**International Network on Biofixation of $CO_2$ and Greenhouse Gas Abatement with Microalgae.**

FROM: John R. Benemann, Network Manager,

TO: STEERING COMMITTEE MEMBERS, TECHNICAL ADVISERS
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## RE: DRAFT Minutes - 2nd Network Technical Meeting, October 5, 2002, Kyoto.

This Network Technical Meeting was held after the 6th International Conference on Greenhouse Gas Technologies, at the Kyoto Int. Conf. Center, Saturday October 5, 8:30 AM – 5:30 PM
ATTENDEES: Above listed with a *. Observers: Shin Hirayama, Mitsubishi Heavy Industries, Japan) and Heleen C. de Coninck, Energy Center of the Netherlands, ECN, Amsterdam).

**FINAL AGENDA AND TABLE OF CONTENTS:**

Note: the discussion of the Roadmap was organized around the four processes (waste treatment systems, nutrient recovery, nitrogen fixation and fertilizers, etc.), and the various R&D needs (strain selection/genetics, productivity, harvesting, etc.), each with a discussion leader. Those discussions are summarized in these Minutes, without following a strict order of discussions.

# DRAFT MINUTES OF 2nd TECHNICAL MEETING, October 5, 2002.

## A. INTRODUCTIONS

### A.1. PAOLA PEDRONI, ENITECNOLOGIE: NETWORK STATUS AND ACTIVITIES. OBJECTIVES OF THE MEETING.

Dr. Paola Pedroni welcomed the participants and illustrated the Network status and activities for the year 2002. The Network was first proposed at the Cairns, Australia, meeting of the Executive Committee of the IEA GHG R&D Programme by Drs. Perry Bergman, U.S. Dept. of Energy – NETL, and Dr. Pierpolo Garibaldi, of Enitecnologie, and was formally approved by the Executive Committee at its meeting in April 2002, in Amsterdam. This is the fourth meeting related to the Network, starting with the Workshop held in Monterotondo, near Rome, Italy, in January 2001, followed by the Organizational Meeting in Reston, Virginia, USA, in January 2002 and the 1st Technical Meeting in May, 2002, in Almeria, Spain, just before the Network came officially into being (June 1, 2002). The Monterotondo Workshop provided the technical backing for the establishment of the International Network. The Reston Meeting obtained support for the Network by the potential Participating Organizations (members) and developed the Network Agreement. The Almeria Meeting initiated the discussions of the Roadmap.

The Network is a membership organization drawn from energy companies and other organizations active in greenhouse gas abatement R&D and with an interest in microalgae processes. The objectives of the Network are to advance technology development and applications of microalgae processes for GHG abatement within the next five to ten years. Presently the Network is composed of eight Participating Organizations who are represented in the Steering Committee:

- **Arizona Public Services**, U.S. electric utility
- **EniTecnologie,** Italian oil company
- **ENEL Produzione Ricerca**, R&D arm of the Italian electric utility
- **EPRI**, U.S. R&D organisation serving electric utilities internationally
- **ExxonMobil**, U.S. oil company
- **Gas Technology Institute**, R&D organisation for the natural gas industry
- **Rio Tinto**, international mining company
- **U.S. Department of Energy-National Energy Technology Laboratory**

The Network is assisted by the Network Manager and Technical Advisory Board for technical matters and by the IEA Greenhouse Gas R&D Programme representative for management and budgetary matters:

- **Dr. John R. Benemann,** Consultant, (U.S.), Network Manager
- **Dr. Amha Belay,** Earthrise Farms (U.S.); Technical Adviser
- **Prof. David Brune,** Clemson Univ. (U.S.), Technical Adviser
- **Dr. Gerald Cysewski,** Cyanotech (U.S.), Technical Adviser
- **Dr. John Davison,** IEA GhG R&D Programme (U.K.), IEA Representative
- **Mr. Yoshi Ikuta,** Consultant (Japan), Technical Adviser
- **Prof. Mario Tredici,** Univ. Florence (Italy), Technical Adviser
- **Dr. Joseph Weissman,** SeaAg, Inc.(U.S.), Technical Adviser.

The Poster presented at the GHGT-6 Conference by Dr. Pedroni and colleagues provides a brief discussion of the background to the Network.

Major objectives of this meeting were to review and comment on the draft R&D Roadmap circulated by Dr. Benemann, Network Manager, prior to the meeting, to reach a consensus on recommended R&D pathways, needs and issues and develop coordination among R&D projects carried out by members.

## A.2. DR. JOHN DAVISON, IEA GHG R&D PROGRAMME: OFFICIAL BUSINESS

Dr. Davison reviewed the status of the Network, officially initiated in June of 2002 with four members having joined by that time, with four additional members having joined since then, for a total of eight (see above). The Network governance and objectives are spelled out in the Network Agreement, which calls for participation by the members in Network activities and development of microalgae related greenhouse gas R&D activities.

Participation also involves a contribution of $9,000 per member for support of these meetings and general Network activities. Under the Network Agreement Budgetary matters are to be decided on and approved by the Steering Committee of the member organizations, consisting of designated representatives (and alternates). There being a quorum of Network Steering Committee members present, the budget was presented. A total budget of US$ 72,000 is planned for this present fiscal year, June 1, 2002 to May 31, 2003, based on a membership of eight. Of this budget the following sums were allocated:

$15,000 for the Technical Advisers attending the technical meetings for a honorarium of $1,000 per meeting per Technical Adviser and for the Network Manager for Almeria and Kyoto;

$21,000 is allocated for support of travel and other expenses for the technical meetings.

$28,000 is budgeted for support of the Network Manager, November 1 2002 to May31, 2002, based on a one-week per month consulting work on behalf of the Network.
$ 6,000 is provided for the support of the IEA Greenhouse Gas Programme.
$ 2,000 is reserved for contingencies.
This budget was approved by all the Members present and by email by those not attending.

The Steering Committee Members voted for Dr. Paola Pedroni to be Chairperson of the Network, and to assume the customary duties of such a position.

There was a discussion about the current status of India as a member of the IEA GHG R&D Programme, as India expressed its interest in joining the Network. Dr. Davison reported that at present this matter was still under discussion, but would likely involve some type of reduced membership rate. It was decided to discuss this matter further at the next meeting.

The next meeting of the Executive Committee of the IEA Greenhouse Gas R&D Programme will be held in the San Francisco, California, area at the beginning of May, 2003. It was discussed and agreed to hold the 3rd Technical Meeting of the Network at the end of April 2003 in San Francisco. Some field trips will be planned in conjunction with this meeting. (See end of these Minutes).

### A.3. INTRODUCTIONS AND R&D ACTIVITIES/INTERESTS BY MEMBERS

**A.3.1. Dr. David Barr, Rio Tinto**, Melbourne, Australia.

Rio Tinto is a large, multinational mining company with activities in most continents and a Technology Services group with some 250 staff out of a total work force of 35,000. Through Kennecott Mining Rio Tinto is a major coal producer in the U.S., with some 85 million tons of coals produced. The Company has a number of R&D activities ongoing in biotechnology, including biomining (leaching), phytoremediation and sulfur reducing bacteria. The Company has a commitment to reduce greenhouse gases from its operations and supporting R&D in this field. It has contracted with Maxygen, in Palo Alto, California, to improve the catalytic properties of the RUBISCO enzyme in microalgae. It would now like to explore the potential for applications of such improved enzymes and technology to specific processes of relevance to greenhouse gas abatement. The Network provides a mechanism to leverage such R&D with the breakthrough now possible with biotechnology to accelerate $CO_2$ uptake by plants and microorganisms. They are also interested in techno-economic assessments and issues related to process scale.

**A.3.2. Dr. Evan Hughes, EPRI** (Electric Power Research Institute), Palo Alto, California, USA.

The members of EPRI are electric utility companies that support R&D in areas of specific company interest. The annual budget is some $300–400 million with 800 employees in Palo Alto and other smaller offices. The focus is on the energy industry, with global warming and sustainability are major areas of R&D. The EPRI Biomass Energy Program is part of the renewable energy effort by EPRI, which is looking at options for generating up to 20% of U.S. electricity from renewable sources. Under this scenario biomass will become very important.

One interest of the Biomass Energy Program is in anaerobic digestion and landfill gas, as these are easy fuels to use in  distributed electricity generation.  The interest in microalgae is due to the opportunities of providing additional fuels for such applications and also in overcoming the relatively low productivity levels achieved with trees and annual plants.  EPRI is interested in the Network because they would like to increase biological approaches for energy production. Biomass yield represents the R&D issue of particular interest.

**A.3.3.  Dr. Paola Pedroni, Enitecnologie,** Milan and Monterotondo, Italy.

Dr. Pedroni outlined the process scheme and the work being carried out at EniTecnologie on microalgae for biofixation of $CO_2$. The current effort is to establish a small-scale outdoor facility including ponds and closed systems for testing performance of microalgae in mass cultures using NGCC flue gas $CO_2$ and sunlight as primary inputs. The EniTecnologie research project is still in its start-up phase. Prof. Mario Tredici, Florence University and a Technical Adviser to the Network, is involved in this project and is working with the EniTecnologie team on the design and operation of the experimental system. The experimental system will be completed this year and experimental work initiated next year. The vision of the EniTecnologie project is to develop a process for the production of supplemental, renewable methane for distributed energy (natural gas-fired) power plants.

**A.3.4.  Dr. Roger Prince, ExxonMobil**, Annendale, New Jersey, USA.

Dr. Prince noted that his company is not interested in methane, but, rather, oil and, specifically in the present context, the potential for $CO_2$ and GHG mitigation credits, should those be required in the future and already the case in some countries.  The key issues to be addressed is whether algae ever can or will have a significant scale, in terms of potential GHG reductions. This requires larger scales than swimming pools.  The objective would be to address some large-scale applications even if these are currently not cost-effective in the short term. Such processes should be demonstrated technically.  ExxonMobil is supporting some university research in microalgae R&D, including a project on *Botryococcus braunii* (a hydrocarbon producer) and bioplastics production by cyanobacteria.  One question is whether *B. braunii* could be a source of higher value lubricants – their hydrocarbons are not as linear as desired.  *Phaeodactylum*, a diatom, is another potential source of such products, based on their fatty acids.  There is some but less interest in biopolymers for tertiary oil recovery.

**A.3.5. Dr. Vipul Srivastava, Gas Technology Institute**, Chicago, Illinois, USA.

GTI is a membership organization carrying out R&D for the gas industry. Total staff is some 500 with a budget of some $70 million per year, $90 million including outsourcing, with significant work with the U.S. DOE. GTI is located in Chicago, which has on its agenda to promote green technologies. GTI has many activities in biological processes, including desulfurisation, bioremediation, wastewater treatment, and anaerobic digestion. Microalgae fit into this general area of interest by GTI as a potential additional option for greenhouse gas mitigation and some prior work was carried out. Of particular interest is the yield potential and the use of microalgae biomass as a substrate for fermentations.

## A.4. INTRODUCTIONS AND R&D ACTIVITIES BY TECHNICAL ADVISERS

### A.4.1. **Amha Belay, Earthrise Farms**, Calipatria, California, USA.

Dr. Belay presented an overview of the Earthrise, Inc., facility for the production of *Spirulina*. The plant consists of 15 hectares with some 30 ponds (raceway, paddle wheel-mixed) producing some 500 tons of *Spirulina* powder for the human and animal nutritional market and no discharges. The $CO_2$ source is purchased (fossil) $CO_2$. In this operation, light does not represent a problem, but temperature is the limiting factor, as *Spirulina* likes warmer temperatures and it gets quite cold (though generally not freezing) in the winter, limiting production to 7 month per year. During the shut down period (October –March), they carry out R&D activities. Harvesting by screens is relatively easy for these algae. Dr. Belay has carried out a number of research projects on Spirulina molecular genetics and related topics. (Note: Photographs of the Earthrise facility are included in the Roadmap Report).

### A.4.2. **Gerry Cysewski, Cyanotech, Inc.** Kona, Hawaii.

Cyanotech, Inc., is also growing *Spirulina*, but, in addition, has now established the commercial production of astaxanthin for aquaculture from *Haematococcus pluvialis* in open ponds. This site in Kona allows for year-round cultivation. One of the unique aspect of this plant is the generation of power and $CO_2$ *on site* by a power plant for the production of electricity and $CO_2$ which is captured, with some 90% efficiency, for the culture of the *Spirulina.* (Description of this facility and power plant in the Rome Workshop Proceedings; photographs are also included in the Roadmap and in the Poster presented at the GHGT-6 Conference). An interesting development since last year is that Cyanotech is now using biodiesel made from waste cooking oils in the power plant, purchased from a local producer. This makes this facility completely $CO_2$ neutral, as no fossil fuel or fossil $CO_2$ is used in the operations or cultivation of the microalgae.

### A.4.3. **Mr. Yoshi Ikuta, SeaAg Japan, Inc.,** Tokyo, Japan

SeaAg Japan, Inc., has licensed technology from SeaAg, Inc. (see next introduction), for the mass culture of diatoms for aquacultural production of clams. Diatom strains are maintained in the ponds by management techniques. A facility located in Ei Town in southern Japan is now using this technology with some half dozen ponds with a total area of over 1,000 $m^2$. Mr. Ikuta also briefly discussed prior work he carried out with Mitsubishi Heavy Industries Ltd. and several electric power companies on microalgae $CO_2$ biofixation project launched by MITI during '90s, including one at Sendai Electric Co., on the operation of small ponds using seawater and flue gas $CO_2$. Mr. Ikuta's current interest is to develop a nitrogen-fixation microalgae process in rice systems. (See his presentation at the GHGT-6 Conference for details).

### A.4.4. **Dr. Joseph Weissman, SeaAg, Inc**., Vero Beach, Florida.

Dr. Weissman described briefly the business of SeaAg, Inc., in the aquacultural production of bivalves, specifically small "seed" of the hard clam (*Mercenaria merceneria*). This technology is based on the mass culture of selected diatoms in outdoor cultures, and was derived from the earlier work done by Dr. Weissman for the U.S. DOE Aquatic Species Program. Most recently

Dr. Weissman received a "Phase I" grant under the U.S. DOE SBIR (Small Business Innovative Research) Program to develop technologies for microalgae greenhouse gas abatement. He is working in collaboration with Dr. Huesemann at the U.S. DOE Pacific Northwest National Laboratory who is studying growth rates and productivity in microalgae mass cultures.

### A.5. INTRODUCTIONS AND R&D ACTIVITIES BY OBSERVERS

**A.5.1. Heleene de Coninck, ECN,** Amsterdam, Netherlands.

Ms. Heleene de Coninck attended as an observer from ECN, to report back to Hans Reith, Rene Wijffles, and others from the Netherlands who have attended Network meetings before and are working to set up a Dutch Consortium which, hopefully, may join the Network in the future.

**A.5.2. Shin Hirayama Mitsubishi Heavy Industries**, Yokohama, Japan

Dr. Hirayama attended as a substitute for Dr. Nakajima who has been working on improving photosynthetic efficiencies by microalgae mass cultures under high light intensities, similar to full sunlight, by studying algal strains that are deficient in light harvesting pigments. Recent emphasis in his laboratory has been on the identification of the genetic change resulting in reduction of light harvesting pigments. (See Monterotondo Workshop and Almeria meeting.).

## B. THE ROADMAP

### B.1. JOHN BENEMANN: PRESENTATION OF DRAFT ROADMAP REPORT

The Roadmap Report was prepared under sponsorship of the U.S. Department of Energy - National Energy Technology Laboratory. The Roadmap is to provide a consensus view by experts in this field of the R&D issues that need to be resolved to advance towards practical applications the currently conceptual processes for greenhouse gas abatement with microalgae. The global impact of such microalgae biofixation processes should be in the order of several hundred million tons of $CO_2$ abated for this approach to become a significant greenhouse gas control technology. The need for such a Roadmap was addressed during the Reston Organizational Meeting and the roadmapping effort initiated during the 1$^{st}$ Technical Meeting in Almeria. (See Minutes of those Meetings).

The approach of the Roadmapping effort was to identify and concentrate on processes that had potential for practical development with the following general attributes:

1. Utilization of $CO_2$ from power plant flue-gas, and other concentrated $CO_2$ sources..
2. Potential for individual system scales of 100 ha or above, to allow for economics of scale.
3. Potential for significant contributions to GHG abatement goals, regionally and globally.
4. Possibility of development within 5 years and practical applications with a decade.
5. Cultivation of specific microalgal species and achievement of overall high productivities.
6. Production of renewable biofuels from algal biomass and other GHG abatement credits.
7. Co-products and co-services that improve economics while allowing for high GHG credits.
8. Feasibility for early-stage field projects to allow practical development of such technologies.
9. No requirement for unpredictable R&D breakthroughs or major advances in technology.

10. Potential for developing R&D support from Network Participating Organizations and others.

Although the overriding requirement is for development of economically viable processes, the definition of economically viable in terms of biofuel outputs and GHG credits can be flexible in the long-term. Over the 5 to 10 year horizon for this R&D effort some limitations apply. All the above attributes must be weighed along with costs/benefits in any evaluation of such processes.

Based on such an initial assessment, a number of processes were excluded from consideration under the Roadmap effort. For example, expensive harvesting technologies, such as centrifugation or chemical flocculation, were not considered suitable for the processes selected, with R&D targeted to developing simpler bioflocculation and screening processes. Any process that required closed photobioreactors, except ancillary to inoculum production, was excluded based on simple economic considerations. Similarly, processes for the production of high value co-products were excluded, on the basis that such systems would be too small in both scale and potential to allow for significant greenhouse gas abatement. Finally, wastewater treatment systems serving small communities (e.g. < 50,000 persons) or animal operations would be excluded due to small scales and limitations on integration with energy production and $CO_2$ capture and utilization. Also, such systems generally do not cultivate specific algal strains, considered a major requirement for achieving the performance goals of the proposed processes. The use of attached microalgae cultures (being proposed for nutrient removal) would not be suitable for $CO_2$ capture and were also not further considered in the development of the Roadmap. Neither were schemes considered for promoting phytoplankton blooms in the oceans (ocean fertilization), as any plausible applications would be several decades in the future. Finally, approaches involving $CaCO_3$ precipitation by microalgae were not addressed, as such processes actually produce, rather than reduce, $CO_2$ emissions.

Most importantly, any process that has at its only economic output greenhouse gas abatement credits and the production of renewable biofuels, can at present and for the foreseeable future (< 10 years), not be considered, due to the severe economic constraints on such dedicated renewable bioenergy systems. This is clear from the prior economic analyses that require the achievement of very high productivities (> 200 t/ha/yr) to meet even optimistic economic scenarios (e.g. fossil fuel prices of $35/barrel oil and additional GHG abatement credits of $15/ton $CO_2$). (These studies are reviewed and updated in Benemann and Oswald, 1996).

Although achievement of such productivities is plausible in the long-term, and productivity increases are a central focus of the proposed Roadmap, within the time-scale of the Network only more modest goals for achievable productivity are defensible. A target of 100 t/ha/y is proposed as reasonable for the processes being considered and the Network R&D time horizon.

Four general multipurpose processes are being proposed in the Roadmap that meet the above criteria:

1. Utilization of $CO_2$ in advanced (nutrient removal) municipal wastewater treatment processes for production of $CH_4$, biosolids and clean water.
2. Applications to agricultural (animal) and industrial wastewater treatment processes for production of $CH_4$, agricultural fertilizers, clean water and animal feed co-products.

3. Nutrient recycling and $N_2$-fixation processes for co-production of biofuels ($CH_4$) and agricultural fertilizers.
4. Co-production of biofuels with large volume/higher value biopolymers and other chemicals.

These processes are described in detail in the Draft Roadmap and also discussed further below.

There is a large amount of overlap among these processes, with all using essentially the same approach: large, earthen, raceway ponds, mixed with paddle wheels, harvested by bioflocculation or a similar low-cost process and supplied with exogenous $CO_2$, derived, for example, from fossil-fired power plant flue gas streams. The latter could be a large coal-fired plant, but would in most cases more plausibly be a smaller decentralized power plant (< 50 MW) co-located with the algal facility. The algal biomass could provide a fraction (typically a quarter to a third) of the total fossil fuel used by the power plant as a $CO_2$-neutral, renewable biofuel. In that case, biogas (methane and $CO_2$) would be the preferred fuel product derived from the microalgal biomass.

Alternatively, the microalgae biomass could be fermented to ethanol, hydrocarbons extracted (from *B. braunii*) or the algal oils converted to biodiesel, all of which have a higher value as transportation fuels than as fuel for electricity generation. In any event, a microalgae process cannot live by renewable biofuels and GHG mitigation credits alone, at least not for some time, and other co-products and co-processes must be included to make it economically feasible. It is in this main attribute that the above listed processes differ. In terms of R&D issues and needs they provide a large amount of overlap.

The R&D needs for development of the technology "pathways" proposed by the Draft Roadmap can be categorized into a number of subject areas:

1. Strain selection and development: how to select and maintain strains for algal mass cultures.
2. Genetic studies and applications of molecular biology: is this premature, and if so when?
3. Microalgae physiological responses in algal mass cultures require considerable study.
4. Productivity of even 100 t/ha/yr is a near-term R&D goal, but higher goals could be set.
5. Culture stability is a major issue in mass cultures. An inoculum production process is a must.
6. Algae harvesting has been a major impediment in the past, low cost technologies are needed.
7. Microalgae processes and processing – integrating co-products/co-processes with biofuels.
8. Bioengineering of cultivation systems – hydraulics and mass transfer in large earthen ponds.
9. Multipurpose processes and process economics: integrating multiple goals is a challenge.
10. Overall potential for GHG mitigation. This requires both regional and global assessments.

These R&D needs were briefly addressed in the Roadmap and discussed in what follows.

After completion of the Roadmap the main work of the Network will be to assist the Participating Organizations in developing research projects that meet their own strategic goals and objectives while integrating these into the broad vision of the Roadmap. The Network Agreement calls for Participating Organizations to support R&D efforts and develop research projects in this context after the first organizational year of the Network (2002). The Network, through the technical expertise present in the Technical Advisers and Network Manager, will assist this effort by providing assistance to the members through the Technical Meetings and, on request, by helping develop relevant R&D projects. Other functions of the Network are to advance the techno-economic analyses, most immediately in the assessment of the potential of microalgae systems in GHG abatement.

The latter issue, the potential of microalgae systems to reduce GHG emissions, is at this point one of the most important issues to be addressed by the Network, as also highlighted in the discussions that followed the presentation of the Roadmap (see below). Although waste-treatment or fertilizer production processes would not be likely abate gigatons of $CO_2$, it should be plausible for such microalgae processes to globally abate several hundred megatons of $CO_2$, both directly (with biofuels) and indirectly (other greenhouse gases, etc.) Greater impacts would be possible if this technology is expanded to include higher-value/large volume co-products.

Assuming a 100 t/ha/y of biomass (organic dry weight) productivity, and further that one ton of algal biomass represents one ton of $CO_2$ abated, then 1 gigaton of $CO_2$ abated annually would require some 10 million hectares of pond systems operating world-wide. This compares to orders of magnitude larger area requirements for higher plant biomass fuel processes being considered for renewable energy production. Even larger footprints would be required for long-term C sequestration by terrestrial systems. The limiting factor is, thus, not the land area required, which is very minor on a global, even regional, scale. Even water resource or $CO_2$ availability should not be a major limitations for algal cultivation. Rather, the greatest challenge to achieving such goals will be the integration of microalgae greenhouse gas abatement into multifunctional processes that optimize total social and economic returns on investments in land and other resources. A further assessment of the GHG abatement potential of microalgae systems will be reported on at the next technical meeting of the Network.

## B.2. DISCUSSION OF ROADMAP PROCESSES AND R&D ISSUES/NEEDS

The four processes highlighted in the Roadmap as generic platforms for future process development and the main R&D issues were briefly introduced by the "discussion leaders" (see Final Agenda /Table of Contents, above), with general discussions following. Here, only the discussion highlights are presented, the Roadmap Report provides the background information.

### B.2.1. Microalgae GHG Abatement Processes

The four different processes all rely on essentially the same overall technology, having as basic elements the use of large (typically > 4 ha), paddle wheel mixed, raceway ponds of earthen construction and without plastic liners. All would be based on the use of $CO_2$ emitted from concentrated sources and would grow specific microalgae strains selected for maximizing biomass productivity, harvestability by simple settling or screening, and biofuel outputs. In addition these processes must, to be economically competitive, provide other co-services and co-products to make their economics plausible even with significant greenhouse gas and green energy credits, to justify their applications within the ten year horizon being considered. In the first three cases these co-products are waste treatment and/or fertilizers. Animal feeds are another major potential co-product in some processes, in addition to specialty products such as biopolymers, lubricants and higher value chemicals.

There thus are, as described in the Draft Report, a variety of potentially practical microalgae processes with strong GHG abatement attributes that would allow for broad applications. Still, the scope of these applications was thought by some discussion participants to be too limited, and they felt that the longer-term potential of microalgae needed to be emphasized. The limited nature of the co-products was another concern. The "biorefinery" model currently being developed by the U.S. DOE through its newly reorganized Biomass Program, could also be applied here. The thinking behind this new approach is that stand-alone ("closed loop" or dedicated) biofuel systems cannot succeed economically with crop-grown starch or even lignocellulosics as inputs, and will require some higher value by-products. This is even more the case for microalgae, which are much less developed technologies and higher costs. Application of the biorefinery model to microalgae systems should be discussed further in the future.

The engineering issues related to the microalgae mass culture were pointed out: the hydraulics of such large unlined ponds and the mass transfer of flue gas $CO_2$ and outgasing from the ponds. However, these were not subject to major debate, although the experience in this area is admittedly limited. Harvesting is another major issue in microalgae processes, with either screening or, even better, settling being economically acceptable for present purposes. This however, requires cultivation of defined algal species, perhaps even strains in the case of settling. It is this latter issue, the need for control over algae species, and even which ones to cultivate, that engendered the most discussion from participants, as summarized next.

### B.2.2. Microalgae Strain Selection

A central theme of the discussions was the strategy and R&D needs for the selection, isolation, maintenance and improvement of the microalgae species to be cultivated in any large-scale process. The present technology for microalgae mass cultures is very limited: either to growing ponds of mixed, variable and essentially uncontrolled cultures, or to providing such a selective chemical environment that only a few, even a single, algal species can readily dominate in such cultures. Wastewater treatment ponds are examples of the former approach and *Spirulina* and *Dunaliella salina* cultures examples of the latter.

The latter microalgae can be considered "extremophiles", in that they naturally dominate in high alkalinity and high salinity environments, respectively. Their cultivation is thus simplified: by providing a similar chemical environment these strains can be selectively cultivated, with few problems of contamination. The search for other extremophiles is of interest, species able to exploit similar niches where competition is minimized and a stable culture easily achieved. This compares to the cultivation of *Chlorella* or *Haematococcus*, the other two main algae being mass cultured (all for nutritional products), where the cultivation process involves the elaborate, and costly, building-up using closed photobioreactors of a large started culture that is inoculated into the production ponds. This inoculum is cultivated for as long as possible before contamination sets in or the culture crashes (usually sooner rather than later). It was argued that extremophiles, like *Spirulina* and *D. salina*, are of rather low productivity, as indeed they are in mass cultures. However the correlation between productivity and extreme environment is an open problems, as is the correlation between growth rate and productivity (being investigated with DOE support by Battelle Northwest Laboratory).

The issue of selection of algal species for mass culture was discussed at length. One example was that of the culture collection of the ASP (the 1980 –1995 DOE "Aquatic Species Program"). This program isolated many strains from inland brackish water and similar sources and these were studied in the laboratory and also provided strains for small-scale pond studies. From these, a few strains were selected for the pilot-plant scale studies for microalgae oils production carried out at Roswell, New Mexico, 1988-1990 by Dr. Joseph Weissman. An alternative strategy is to allow the culture system to self-select algal species, as is frequently the case in such systems. As was pointed out, the pond environment, in addition to any chemical conditions, is can also be an extreme environment in terms of $O_2$ build-up, pH fluctuations, and light intensities. Thus the pond environment is a strong selection tool for organisms that are well adapted to it. The still required step is to combine both approaches – to use scaled-down cultures (little ponds) to select for a range of algal species and strains that are competitive in the pond environment and then isolate these strains in the laboratory for study, improvement and re-inoculation into outdoor large-scale cultures. One concern is the strong genetic selection and adaptation that will occur in laboratory cultures, limiting the number of transfers. This could be accomplished with cryopreservation of cultures. It was also pointed out that it would be important from the beginning to select strains able to bioflocculate. It was also suggested that the emphasis on the cultivation of single species may be too narrow. Mixed cultures could provide for greater stability, in using up complementary resources or fluctuating in relative numbers with environmental regimes, overall reducing contamination by unwanted invaders. For example in *Spirulina* culture often several closely related strains co-dominate in the ponds. However, there was strong support for a defined culture approach using specific, isolated, strains, over the un-defined, unconstrained mixed cultures that are the current state-of-the-art in microalgae applications to wastewater treatment. Strain isolation, selection and maintenance was discussed at some length and viewed as high priority R&D for the Network participants.

### B.2.3. Microalgae Biotechnology

The enormous advances of molecular tools available for genetic study and improvement should find some application to this problem. Indeed, there is no lack of proponents of such approaches. In regards to genetically modified organisms (GMOs), the question raised was why use GMOs at all, at least GMOs incorporating foreign genes. The issue of environmental release and public acceptability would of course have to be considered. However, a more immediate and fundamental issue was of the specific gene-protein targets that could be identified for such approaches. One example is the ongoing work on productivity increases through isolation of strains with reduced antenna sizes (see also below). Only spontaneous mutants have been studied up to now, but it would be of interest to construct strains that have targeted mutations leading to specific down regulation of antenna pigment biosynthesis production. Other targets, such as RUBISCO or the respiratory enzymes can also be considered for genetic improvements. However, the feedback from such at present relatively basic studies to applications in outdoor mass cultures will require some time.

Other applications of molecular biology, such as, for example gene chips that can determine gene expression during mass cultures, could find some research application. Overall such technologies are is still at an early stage, and require considerable development in their application to the organisms that would be mass cultured. Indeed, much is still to be learned about the physiological responses of microalgae under conditions of algal mass culture. The consensus view during this discussion was that both approaches, the molecular and physiological, can and should be carried out in parallel, with a meeting of these strands of research as soon as practical.

### B.2.4. Microalgae Productivity and Products

The issue of productivity was discussed relatively briefly. Dr. Benemann stated that 100 t/ha/y for the proposed processes appeared feasible as a general R&D goal for the Network. However, this would need to be reduced for some of the processes (e.g. $N_2$-fixing algae), in marginal climatic zones, and for high oil or hydrocarbon content biomass production. This level of productivity was considered a sufficiently ambitious goal, based on current experience, as to not allow for any higher extrapolations within the timeframe of the Network. However, the application of the techniques of molecular biology to productivity enhancement has the potential to allow for much higher productivities the longer-term. This is a critical issue, as in the future the "footprint" of renewable energy technologies will likely be as important a consideration as greenhouse abatement or sustainability issues are now. It is on this basis that microalgae systems could perhaps best compete with other processes for greenhouse gas abatement.

There was relatively little discussion of the products from microalgae biomass production, the biofuels, animal feeds, biopolymers, etc. The role and potential of microalgae in wastewater treatment, particularly nutrient removal, was viewed as an important focus of the Network. The conversion of microalgae biomass to methane gas was of interest to some participants, and certainly plays a central, though not exclusive, role in the various processes outlined in the Draft Roadmap Report.

## C. CONCLUSIONS AND CONSENSUS DEVELOPMENT

A number of points were made by the participants during the concluding discussions with comments provided by John Benemann:

1. It is too limiting to strictly focus on minimizing costs at this early stage in the R&D.
Comment: This is indeed an important point – economics depend on many factors, most importantly non-technical ones such as regulations, tax (dis)incentives, externalities (price of oil and energy), discount rates, etc. Thus, economics should not be too constraining at present. For example, harvesting by chemical flocculation could be considered for some near-term applications. However, clearly cost prohibitive processes must be excluded. Although the precise point can be argued, some processes are clearly not plausible. For example processes based on closed photobioreactors, having minimum capital costs of about $100/m$^2$ ($1 million per hectare) are not plausible, and cannot be considered in greenhouse gas abatement.

2. On the other hand (or maybe the same), the challenge is to demonstrate some successful applications of this technology in the near-term and some advances in R&D priority areas for longer-term applications.
Comment: Indeed, the focus of the Roadmap is to achieve some early applications through field projects at sites that provide some scale-up potential for an even partially successful process development effort. The trade-off is that early "successful technology" requires favorable economics, implying niche markets. This is the approach to the $N_2$-fixing cyanobacteria for fertilizer production: the initial applications are for relatively small markets in organic agriculture, but these could greatly expand based on the potentially low cost of this technology.

3. The issue of algal species and strains should be a major focus of attention and include extremophiles and a number of diverse approaches.
Comment: This is a fundamental and near-term issue that must be addressed. Small outdoor microalgae ponds and indoor reactors simulating outdoor conditions can select for algal species with desirable properties. These would then be isolated and maintained in the laboratory for inoculum production and potential improvement through biotechnological approaches.

4. The scale and time frame of the proposed processes to be developed are critical. For GHG abatement applications scales must be relatively large, but time frames can be longer.
Comment: This is indeed the central issue in this technology, perhaps even more critical than economics. With a world GHG production, from all sources, already exceeding 30 gigatons (Gt) of $CO_2$ equivalent, technologies that can only mitigate a few megatons (Mt) would find scant interest. For example, it must be recognized that municipal wastewater treatment is only of relatively small potential in member countries, due to land, climatic and economic limitations. The assessment of potential impacts will be a major future objective under the Network.

5. The Roadmap should highlight more clearly what has already been done in a practical sense, for example in the wastewater treatment field, that has applications to GHG mitigation.
Comment: Indeed, some initial applications of microalgae technologies are already used in municipal wastewater treatment, reducing GHG emissions compared to conventional processes. For example, at Sunnyvale California a wastewater treatment plant with several hundred hectares of algae ponds is harvesting the biomass and converting it to methane gas. These provide some case examples of where we are now and how far we still have to go to achieve the potential of this technology. Specific projects that build on such already existing applications and technology will be formulated during the next few months. However, overall, microalgae technology, as it applies to greenhouse gas abatement, is still very much in its early stages.

6. There is a need to prioritize R&D objectives and needs, rather than covering the entire gamut.
Comment: A microalgae production process must integrate all aspects, from strains and productivity, to harvesting and processing, with economics and engineering issues also considered. However, indeed, there must be a focus on critical R&D needs and narrower targets.

7. Technology has advanced in recent years, allowing the revisiting of prior work to overcome the limiting factors, whether they be productivity, harvesting, species control, etc.
Comment: This is a point that can be stressed in the Roadmap Report: new technology creates new opportunities to overcome earlier barriers to process development in this field. Perhaps the clearest example of this is in productivity enhancement using molecular approaches.

8. There is a need to provide targets for GHG mitigation through microalgae technologies, in terms of process goals, economics, demonstrations and timeframe for commercialization. In other words, milestones.
Comment: The Roadmap is too general a document to incorporate discussion of the necessary stages in process development to the level of providing milestones of achievement of particular objectives. However, such milestones are, indeed, important, and should be a focus of future

attention, to provide a guide to the key technology achievements that must be met on the road to commercial development of such processes.

9. The Roadmap should be more positive in what has already been done and be more forward looking at what can be accomplished relatively readily.
Comment: this is a fair comment and the Draft Roadmap was edited with this in mind. Discuss programmatic support from a more forward thinking perspective was suggested by some participants as something requiring more emphasis in the Roadmap Report.

10. The Roadmap should be used to spread the common vision of the Network and positively influence the thinking of decision makers among the Participating Organizations and others.
Comment: Not only developing but also communicating the vision of this enterprise is indeed the main objective and activity of the Network Manager over the next few months.

## D. ANNOUNCEMENT OF THE NEXT TECHNICAL MEETING

The next, 3rd Technical Meeting of the Network will be held in the San Francisco Bay Area, at the end of April 2003 (April 28-29). This meeting will serve as a platform for in-depth discussions of specific already ongoing, planned or proposed R&D projects carried out by the Participating Organizations and to be included in the Network portfolio. Field trips on April 27th and/or 29th are also planned. Announcement of the specific times, venues and planned program will be provided by late December.