DRAFT DATE: July 3, 2002
From: John R. Benemann (jbenemann@aol.com), Network Manager
Subject: International Network on Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae – DRAFT **Minutes of the Almeria Meeting, Request for Comments/Inputs.**
To: Current/Prospective Members and Advisers of the Network Attending Meeting.
ppedroni@mail.enitecnologie.eni.it (Paola Pedroni, EniTecnologie, Italy),
David.Barr@riotinto.com (David Barr, Rio Tinto, Australia),
marraffa@crr.enel.it (Vito Marraffa, Enel Produzione Ricerca, Italy)
nakajima@atrc.mhi.co.jp (Yuji Nakajima, Mitsubishi Heavy Industries, Japan)
reith@ecn.nl (Hans Reith, ECN, Netherlands)
rene.wijffels@algemeen.pk.wau.nl (Rene Wijffels, Wageningen Univ. Netherlands),
yikuta@jb3.so-net.ne.jp (Yoshi Ikuta, Consultant, Japan, Technical Adviser),
Mario.Tredici@unifi.it (Mario Tredici, Univ. Florence, Technical Adviser),
debrune@Clemson.edu (Dave Brune, Clemson Univ., USA, Technical Adviser),
cc. John@ieagreen.demon.co.uk (John Davison, IEA GhG Programme),
Heino.Beckert@netl.doe.gov (Heino Beckert, U.S. Dept. of Energy)
VPILCHER@apsc.com (Vernon Pilcher, Arizona Public Services, USA)
rprinc@erenj.com (Roger Prince, ExxonMobil, USA)
quattroni@pte.enel.it (Giuseppe Quattroni, Enel, Italy),
EHUGHES@epri.com (Evan Hughes, EPRI, USA)
Joseph_Weissman@hotmail.com (Joseph Weissman, SeaAg, Inc., USA, Technical Adviser)
grc@kona.net (Gerald Cysewski, Cyanotech Co., USA, Technical Adviser)
abelay@cts.com (Amha Belay, Earthrise Farms, USA, Technical Adviser)

The good news is that the Network is now officially operating (as of June 1, 2002). Four participants had signed the Agreement by the time of the Almeria meeting, the minimum necessary to start, and one more has joined since. The initial members are (in order of joining): Arizona Public Services, EniTecnologie, Rio Tinto, Enel and GTI. Several others have indicated that they will join, some may need more time. In any event, the Network is open for business and, as Network Manager, I want to thank all who participated in this effort, starting with the Rome meeting last January, and most particularly Dr. Paola Pedroni, who has guided this process from the beginning.

The objective of this meeting was to discuss technical issues related to microalgae biofixation of CO_2 and greenhouse gas abatement. These discussions were a key step in the process of developing a technical consensus for the "Roadmap" which I am starting to develop, with support from the U.S. DOE. The Roadmap will outline the R&D "pathways" to the development of microalgae technologies for greenhouse gas abatement. The Roadmap will be developed through interactions with the technical advisors and networks members, current and prospective, as well as others, to achieve a broad and strong consensus on key technical issues. The Roadmap will provide the basis for the future activities of the Network and assist Network members in developing their own R&D plans. **Please review the attached Draft Minutes and comment on these, as well as what areas of discussions you think are neglected, additional issues and points that need to be raised**. I will then make any changes, for the record, and let you know anything substantial. However, the main reason I ask for your comments and inputs is to help develop the Roadmap.

The background to the Roadmap development process and methodology was outlined in the overheads I discussed at the Almeria meeting, which were originally presented at the Reston Meeting (Reston, Virginia, Network Organizational Meeting, January 29, 2002). These are included in these Minutes as APPENDIX I. These overheads were an initial attempt to capture the Roadmap process and apply it to microalgae biofixation.

I also attach to these Minutes an expanded discussion of some of the points I discussed during my presentation - "Issues Related to the Microalgae Biofixation Roadmap (ATTACHMENT I). This is a starting point for the roadmapping effort, an effort I am carrying out this summer, and for which I, again, ask for your inputs and help. The Roadmap document will focus on the technology "pathways" which could lead to practical processes for greenhouse gas mitigation using microalgae within the context of the Network. The Network is planned as a ten-year effort and thus the Roadmap focuses on processes that could be developed to a practical stage within that time period. The Roadmap Report will discuss attributes and parameters of such processes, including underlying scientific and technical issues that need to be addressed through R&D.

The Roadmap document, will be discussed at **the next Meeting of the Network, October 4 (late afternoon, evening) and 5 (all day) in Kyoto Japan.** This meeting is being held in conjunction with the IEA-sponsored greenhouse gas meeting of September 30 - October 4. The website is **www.rite.or.jp/ghgt6 or www.ieagreen.org.uk, e.mail ghgt@rite.or.jp**. **I urge you all to prepare for attending this meeting**. More details will be forthcoming

Minutes of the Technical Meeting of the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae Almeria, Spain, May 26, 2002

Table of Contents:

DRAFT July 3, , 2002

Minutes
of the Technical Meeting of the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae Almeria, Spain, May 26, 2002

1. BACKGROUND, OBJECTIVES, ATTENDEES AND AGENDA

This meeting was called to be held in conjunction with the 1st International Congress of Applied Phycology, May 26-30. It was decided that this would be an informal Technical Meeting, with the objective of discussing and receiving inputs from Technical Advisers and Network Members for the "Roadmapping" effort to be carried out during the May-October 2002 period by Dr. John Benemann, Network Manager. At the time of the meeting, the fourth signed agreement had just been received by Dr. John Davison of the IEA Greenhouse Gas R&D Programme, the minimum number of initial participants. Currently (July 1st, 2002) five members have joined. The official start of the Network was June 1, 2002..

In addition to the Network Manager, attendees included representatives of three of the four official (at that point) participants in the Network (Dr. Paola Pedroni, EniTecnologie; Dr. David Barr, Rio Tinto; Dr. Vito Marraffa, ENEL Produzione Ricerca) and three the Technical Advisers to the Network (Prof. Mario Tredici, Prof. David Brune, and Mr. Yoshi Ikuta). In addition three representatives of potential members attended (Dr. Hans Reith, ECN, Prof. Rene Wijffels, Wageningen U., The Netherlands, and Yuji Nakajima, Mitsubishi Heavy Industries). Three observers were also invited to the meeting (Dr. Bailey Green, Oswald Green LLC; Dr. Eugenia McNaughton, U.S EPA; and Dr. Adelina de Benito Abad, ENDESA, Spain). The original agenda was modified to focus mainly on discussions by the various participants, with a more in depth discussion of the Roadmap effort presented by Dr. John Benemann. The present write-up of the minutes expands on his oral presentation as Attachment I, to elicit further comment and inputs in the development of the Roadmap.

2. INTRODUCTORY REMARKS ON THE NETWORK AND THIS TECHNICAL MEETING by Dr. Paola Pedroni, EniTecnologie

After the Monterotondo Workshop in January 2001 (see "**Monterotondo 2001 Workshop Report**"), the initial proponents of the Network, EniTecnologie and U.S. Department of Energy (DOE), with assistance of John Benemann, consultant, and John Davison, Project Manager of the IEA GHG R&D Programme, continued the effort to develop the Network. At two Executive Committee (ExCo) meetings of the IEA Greenhouse Gas R&D Programme, in Regina, Canada (March 2001), and in London, England (August 2001), the Network was discussed and its continuing development supported. The proposed Network was also featured at the DOE Carbon Sequestration meeting held in May 2001 in Washington D.C. (see Pedroni et al., 2001, see www.netl.doe.gov). By the end of the year, some ten organizations had indicated interest in participation in the Network.

These activities led to a 1st Organizational Meeting held on January 29th 2002 in Reston ,USA, with participants from most of the prospective organizations present (see Minutes of "Reston January 29th 2002 Meeting"). An Agreement was drafted and after discussions and amendments adopted, setting forth the vision, objectives, governance and budget of the Network (See "Network Agreement"). It was fixed that the Agreement comes into force as soon as four Participating Organizations return it signed to John Davison of the IEA GhG R&D Programme. During this meeting John Benemann was asked to assume the role of Network Manager, and he nominated six Technical Advisers to the Network (D. Brune, G. Cyesewski, A. Belay, Y. Ikuta, M. Tredici, and J. Weissman) of which three attended this meeting (Brune, Ikuta and Tredici).

During the ExCo meeting in Amsterdam, April of 2002, several organizations indicated their intent to joining the Network, including EniTecnologie, Exxon, DOE, and EPRI. Several others (GTI, Arizona Public Services, ENEL, Rio Tinto) had communicated their interest prior to this meeting. The ExCo members officially approved the Network Agreement and the start of the initiative.. Due to the short time and uncertain start date for the Network, it was decided to make this an informal Technical Meeting, rather than a formal one. The major immediate objective of the Network is to develop the Roadmap, a tool for helping guide future R&D efforts by Network Members, integrating in its broad visions of general "pathways" a plethora of applicable research projects. The Roadmap would outline the main potential processes or "pathways" which could be plausibly developed within the time-frame of the Network (a ten year horizon) and identify the key R&D issues that need to be addressed to advance their technical development.

To help in the development of the Roadmap, six Technical Advisers agreed to support the Network in this effort, and in future R&D activities carried out by the members. These are individuals with practical and scientific expertise in large-scale microalgae mass culture, as well as related disciplines (photobioreactors, algal physiology, etc.). They will provide a first level of inputs and review to the Roadmap being developed. (The Technical Advisers are Amha Belay, David Brune, Gerald Cysewski, Yoshi Ikuta, Mario Tredici, and Joseph Weissman).

3. INTRODUCTIONS BY PARTICIPANTS (in order)

3.1. Dr. Bailey Green, Lawrence Berkeley Laboratory and OswaldGreen LLC, Calif., USA

Dr. Green has worked in association with Prof. Oswald for many years. His main interests are in improved wastewater treatment processes using microalgae and methane recovery. This technology, called AIWPS® (Advanced Integrated Wastewater Pond Systems®), is based on a series of ponds, including anaerobic deep fermentation pits for methane recovery and subsequent algal growth ponds. This technology has considerable potential for greenhouse gas mitigation.

3.2. Dr. Eugenia McNaughton, EPA, California, USA

Dr. McNaughton, with the U.S. EPA, is interested in algal systems for pollution control, such as described by Dr. Green and applicable to the Salton Sea. (The Salton Sea in S. California is an appx. 700 km^2 lake polluted with agricultural nutrients, see further below).

3.3 Dr. Vito Marraffa, ENEL Produzione Ricerca , Brindisi, Italy

ENEL, the Italian electricity company, a member of the Network, is carrying out a microalgae R&D project using actual powerplant flue gases and photobioreactors as cultivation systems.

3.4. Prof. David Brune, Clemson University, South Carolina, USA
Dr. Brune is a Professor of Aquaculture Engineering. His main interest has been in applying microalgae ponds in fish and shrimp aquaculture systems, to help increase the carrying capacity and productivity of such systems. These systems have potential in greenhouse gas mitigation both through reduction in the energy inputs (e.g aeration), feed inputs and carbon recycling.

3.5. Dr. David Barr, Rio Tinto, Technical Services Division, Melbourne, Australia
Dr. Barr is a microbiologist. Rio Tinto is looking at microalgae as a contingency to reduce CO_2 emissions, and as a source of new products and technology. It is working with a biotechnology company, Maxygen, to modify and achieve higher activities for the CO_2 fixation enzyme, RuBisCO. This has been successful, but now the question is how to apply this in practice. Rio Tinto is looking towards the Network to produce hard numbers.

3.6. Dr. Paola Pedroni, EniTecnologie, Milan and Rome, Italy
Dr. Pedroni, a molecular biologist, has worked on a biohydrogen production project launched by the Japanese MITI, and for the past two years has been leading the effort on microalgae biofixation at EniTecnologie, the R&D arm of the Italian oil company Eni. EniTecnologie is interested in producing methane from microalgae to help fuel power plants.

3.7. Dr. Hans Reith, ECN, The Netherlands
ECN performed a feasibility study on microalgae biomass systems a few years ago. Currently they are coordinating a major microalgae program involving six companies and six R&D institutions to produce fine chemicals with biofuel co-production.

3.8. Prof. Mario Tredici, University of Florence, Italy
Professor Tredici works on the design of low cost photobioreactors for large-scale production of high value products and bioactive molecules from microalgae and for aquaculture feeds.

3.9. Dr. Yuji Nakajima, Mitsubishi Heavy Industries , Yokohama, Japan.
Dr. Nakajima is a molecular biologist and physiologist who has worked for several years on improving the photosynthetic efficiency of microalgae by reducing the chlorophyll antenna size.

3.10. Mr. Yoshi Ikuta, Consultant, Tokyo, Japan
Mr. Ikuta has worked in the past with MHI on algal mass culture systems for CO_2 mitigation, carrying out projects for several Japanese electric utilities. He is now working on microalgae for bivalve aquaculture and CO_2 mitigation. A specific interest is in biofertilizer production.

3.11. Dr. Adelina de Benito Abad, ENDESA, Almeria, Spain
Dr. Beninto Abad is a biologist working for ENDESA, a large Spanish electric Utility. The company is interested in developing CO_2 mitigation technologies and she came as an observer.

3.12. Prof. Rene Wijffels, Wageningen University, The Netherlands
Prof. Wijffels is working on photobioreactors to grow microalgae for of high value products.

3.13. Dr. John Benemann, Consultant, Walnut Creek, California
Dr. Benemann is an expert in microalgae applications in CO_2 fixation and the Network Manager.

4. PRESENTATIONS BY PARTICIPANTS (not in order)

4.1. Dr. Paola Pedroni, EniTecnologie

EniTecnologie has initiated an R&D program in microalgae biofixation for the reduction of greenhouse gas emissions from methane-fueled power plants. The process would feed CO_2 from the flue gas of a NGCC power plant to algae ponds for biofixation into biomass which would then be converted to methane gas by anaerobic digestion, thus replacing a fraction of fossil methane with renewable methane. The conceptual process has been developed by engineers at the Monterotondo facility and is essentially similar to the earlier proposal by Oswald and colleagues.

EniTecnologie is starting a small-scale study of this process by operating small ponds and photobioreactors to compare productivity and other performance objectives (e.g. culture stability). Prof. Mario Tredici is assisting in this project. EniTecnologie also initiated the development of the Network, along with DOE.

4.2. Dr. Vito Marraffa, ENEL Produzione Ricerca

ENEL is the largest electric utility in Italy, burning mainly coal, oil, oriemulsion (which use is increasing) and some methane in its power plants. The abatement of CO_2 emissions from power plants is a strategic target for the company and the R&D department has been tasked with developing effective countermeasures. These efforts are focused on sequestration of CO_2 through chemical options, such as mineralization of silicate–based minerals, and biological pathways, such as microalgae-based technologies.

The microalgae work started a year ago, with the objective of producing biofuels and high value chemicals. The focus of this research is to use actual flue gas, with some 8-12% CO_2, NOx, SOx and to investigate the growth of suitable microalgae strains on such CO_2 sources. Strains with high hydrocarbon content were identified and subjected to initial laboratory studies. For high value chemicals, the emphasis is on closed photobioreactors and on "quality rather than quantity". For biofuels production, the emphasis is on open ponds, large land area requirements, achieving high productivity and on reducing the high costs of current technology. Participation in the Network will allow for a critical evaluation of the two approaches for biofixation of CO_2 in integrated systems and technical support in the development of the open and closed photobioreactors.

4.3. Prof. Mario Tredici, University of Florence

Prof. Tredici briefly reviewed the technology for microalgae cultivation in closed photobioreactors, including the many different devices that have been developed and even in some cases applied for relatively large scale (> 1,000 m^2) production systems. He pointed out that most of the commercial operations using closed photobioreactors for strains such as *Spirulina*, *Dunaliella*, or *Chlorella*, which are currently grown in open ponds, failed sooner or later, usually sooner, due to take over by contaminating species. He also reviewed his own work with closed systems, including recent work for high value products and bioactive compounds.

4.4. Dr. Bailey Green, LBL and Oswald Green LLC

High rate ponds (channelized mixed ponds) have been used in wastewater treatment for several decades, and are part of the Advanced Integrated Wastewater Pond System® (AIWPS®). These systems incorporate both high rate ponds and facultative ponds for complete wastewater treatment, and have been used for the treatment of municipal, industrial and even bioremediation of agricultural drainage waters. Comparison of the energy requirements of conventional (activated sludge, extended aeration) and AIWPS® demonstrate that the algal-based processes have energy requirements 50% to as much as 90% lower than the conventional processes. Microalgae processes have many other advantages, from lower costs, to avoidance of sludge handling to reduced greenhouse gas emissions. The longest operating AIWPS® system, in St. Helena, California, is being renovated, and could be considered for a field project for greenhouse gas mitigation.

4.5. Prof. David Brune, Clemson University.

Aquaculture is a rapidly growing industry with millions of hectares of ponds now devoted to fish and shrimp cultures around the world. Work at Clemson University for the past fifteen years on the application of high rate ponds for fish aquaculture has resulted in the development of the recently patented PAS, Partitioned Aquaculture System, in which fish and algae are cultured in separate areas, but connected through the water movement of the paddle wheels. Such systems have been demonstrated to increase fish production (for catfish in the U.S. Southeast) by over four-fold, and similar improvements are also achievable with other aquaculture systems. The PAS process can reduce greenhouse gas emissions by reducing the energy requirements of conventional systems, reducing feed requirements, recycling fertilizers (in particular nitrogen) and reducing other sources of greenhouse gases. (See also the Monterotondo Workshop report).

Prof. Burne also mentioned a new project just being initiated near the Salton Sea, in collaboration with Kent SeaTech, Inc., and Dr. Benemann, on nutrient removal from agricultural drainage waters. The current research effort is to determine the potential of a modified PAS process (CEP, Controlled Eutrophication Process) in which fish would be used to help manage the algal culture densities and species compositions, to result in improved harvestability of the algal biomass and thus nutrient removal. This process, if successful, would require the construction of over a thousand hectares of algal ponds, with over 100,000 tons of CO_2 being fixed into the algal biomass annually (to provide an order of magnitude estimate).

4.6. Prof. Rene Wijffels, University of Wageningen, and Dr. Hans Reith, ECN

Prof. Wijffels reported on a project being carried out in the Netherlands, with thirteen partners (U. of Wageningen, U. Amsterdam, ECN, ATO, Numico, CSK Food Enrichment, Royal Sanders Cosmetics etc.) for the co-production of natural fine chemicals and biofuels. The concept is to cultivate microalgae in effluents from agro-industrial wastewater treatment and/or process condensates, with addition of CO2 from flue gas or fermentation off-gases, for removal of nutrients N and P ('polishing') to a sufficient final water quality for industrial re-use as process water. The purified process water is the main product of the algal system.

The harvested biomass will be used for extraction of high value fine chemicals with the residues and wastes used for biofuels production. Targeted fine chemicals include: colorants, omega fatty acids, polysaccharides, and bio-active products, for potential application in food supplements (Numinco), food colorants (CSK Food Enrichment) and cosmetics/personal care products (Royal Sanders). The energy conversion of remaining biomass would involve either gasification, after drying the algal biomass, or production of methane, through anaerobic digestion.
The present approach is to develop processes under laboratory and small-scale outdoor conditions.

The cultivation system is to be composed of an array of 'bubble column bioreactors' for continuous inoculum production of the targeted algal species, which is fed on a continuous basis to a novel type of open system. The open system is a cascade type, with a number of basins placed in series, and of increasing numbers at each stage, which 'overall' leads to a rapid culture build-up and a 'once through' cultivation system. The idea is that the development of contaminating algae in the system can be kept on a minimum level via the hydraulic retention time.

With respect to algal cultivation the project involves (all in continuous culture):

- experiments and (productivity) modeling of bubble column bioreactors, indoors (Wageningen University)
- experiments and (productivity) modeling, outdoors (ECN)
- experiments with pilot scale integrated system (bubble columns + series of mixed-tank reactors) outdoors (University of Amsterdam).
- development of thin, layer plate-type indoor bioreactors (Wageningen University).

The fundamental issue is that the production of high value chemicals and low value fuels involves conflicting goals, with respect to the volume of products/markets. In the future the approach will be to separate these different goals, and go to controlled systems for high value compounds (which have little to do with CO_2 reductions or energy production) and to use large-scale systems for bulk applications and wastewater treatment, with biofertilizers, biodiesel and other by-products as outputs. These systems lend themselves to CO_2 biofixation.

Hans Reith, reported on prior studies in the Netherlands of microalgae systems for nutrient removal ('polishing') from effluents of an agro-industrial waste water treatment system at a (beet)sugar producing plant. This assumed a productivity of 30 tons per year per hectare for the algal biomass, about a 5% PAR efficiency. The total benefits of such a system were projected at some 67,500 Euro /ha/yr, the great majority from the value of the reclaimed water, with biomass production costs estimated at 3,000 Euro /ton dry weight. Such a system could pay for itself if total benefits, including water purification, are considered.

Hans Reith also reported on a previous engineering-feasibility analysis, that the production costs of biodiesel from lipid rich algal biomass could potentially be lowered to a competitive level (at least competitive with rape seed methyl ester fuel; RME) by co-extraction of xantophylls from the algal biomass.

4.7. Dr. Yuji Nakajima, Mitsubishi Heavy Industries

Dr. Nakajima reported on his work to increase the efficiency of microalgae cultures by reducing the light harvesting pigments of the photosynthetic apparatus. He reviewed his work with both green algae and cyanobacteria and, in particular recent work showing that a single nucleotide base substitution (mutation) can result in the reduction in light harvesting pigments in a mutant of cyanobacteria, resulting in a phenotype with increased productivity at high light. Future experiments will test the effect of co-culturing the wild type with the mutant, to establish their relative dominance in mass cultures.

4.8. Dr. David Barr, Rio Tinto

Rio Tinto is a $10 billion per year mining company. They produce 140 million tons of coal per year, mainly used for electricity production in the U.S., with some coal sold to Japan etc. The company is interested in developing offset technologies for C credits. They are looking at this as a contingencies for alleviating the potential effect of mandatory C reductions. One approach that the company invested in is to explore the potential of biological processes, such as biofixation, and gene shuffling as a technology tool to improve the CO_2 fixation performance of the RuBisCO enzyme. This technology, developed by Maxygen, allows the *in vitro* evolution of genes by shuffling variants from different organisms to come up with a superior enzyme. This was quite successful, with an 8-fold increase in the k_{cat} demonstrated for a modified algal enzyme, compared to the wild-type version. Now the issue is how to actually apply this technology to increase CO_2 fixation in actual algal mass cultures. This is one reason for Rio Tinto joining the Network.

4.9. Mr. Yoshi Ikuta, Consultant

Mr. Ikuta reviewed past work on microalgae mass culture on power plant flue gases carried out during the early to mid 1990's by the Mitsubishi Heavy Industries Co. in collaboration with the major Japanese electric utilities. At Tohoku Electric, for example, a project involving two small outdoor ponds was carried out for one year, using flue gas from low sulfur fuel oil containing about 70 –150 ppm of SOx and NOx. This work demonstrated the culture of self-selected marine microalgae strains and the actual use of a power plant flue gas. He also reported on more recent work in Southern Japan on microalgae mass cultures for the production of clams. He then addressed the potential of using nitrogen-fixing microalgae for the production of fertilizers, in connection with rice-field agricultures. He pointed out that due to change of eating habits, overproduction and imports, many rice fields now are fallow in Japan. These provide an opportunity for alternative agricultural technologies, including the production of nitrogen fixing microalgae, which could be used as high-value organic fertilizers, directly or, after harvesting and production of fuels (e.g. methane) from the biomass. Alternatively, algal cultures produced in high rate ponds could be used as large sources of biomass inoculum to rapidly establish nitrogen-fixing cultures in actual rice paddies, prior to canopy closure. Greenhouse gas mitigation would be through the replacement of fossil fertilizer, and may produce additional benefits, such as preventing weeds due to shading and other direct or indirect effects. Such a technology could have major applications world-wide.

5. INTRODUCTION TO THE MICROALGAE ROADMAP - SUMMARY
John Benemann, Network Manager – Summary of Discussion from the oral presentation.

Dr. Benemann provided an introduction to the Roadmapping effort, describing the nature of this activity, its methodology and goals, as summarized in overheads presented at the January 29th Organizational Meeting **("Reston January 2002 Minutes**"). **Copies of the Overheads are included as Appendix I** and outline the nature and purpose of a Roadmap process, and its applications to microalgae. A Roadmap provides a consensus of technical experts of the critical R&D needed to achieve specified technological goals. One key tool is to characterize the plausible technological processes and general R&D needs, or "pathways", by which the goals, could be accomplished, within a specified framework. In case of the Network that would be 10 years - the planning horizon. From these conceptual technology pathways, the specific R&D issues that must be addressed and resolved to achieve the technological-economic objectives are then derived. These define the "Roadmap", which includes the processes, direction, goals, strategies and research needs. Most importantly, the "roadmapping" effort involves consensus building. **(See Appendix I, Overhead I). In Attachment I ("Issues…"), the presentation in Almeria is expanded to elicit discussion and comments**, by participants in the meeting, technical advisers, and others. This is a first step in the development of the Network Roadmap.

Six proposed Pathways were discussed at the Reston Meeting **(Appendix I, Overhead II).** Here these are condensed into four, encompassing the main attributes of plausible processes that could be practically developed during the next decade by Network:
#1. Municipal wastewater treatment with CO_2 utilization, reduced energy use, fuel outputs, etc.
#2. Agricultural/aquacultural/industrial waste treatment for biofuels and feed co-products.
#3. Nitrogen fixation and nutrient recycling for agricultural and algalcultural applications.
#4. Co-production of biofuels and large volume/higher value products (biopolymers, feeds, etc.)
There is considerable overlap among these different conceptual processes, or "pathways". More importantly, as listed in **Overheadss III and IV,** the R&D needs are rather similar for the various approaches, and range from development of superior strains to processing the biomass.

However, before discussion of R&D needs, more general issues related to the pathways and the overall Network strategy are addressed in **Attachment I**. These issues are, in summary:
1. Utilization of CO_2, in particular from flue gas derived from fossil power plant flue gases.
2. Scale of processes and type of systems allowing for significant greenhouse gas mitigation.
3. Significant aggregate potential greenhouse gas mitigation, in member countries and globally.
4. Plausible economics for microalgae processes, specifically for wastewater treatment.
5. Potential for development, within the 5 to 10 year horizon, of the planned Network effort.
6. Additional environmental benefits and high volume co-products from such processes.
7. Suitability for development of "field" projects to serve as platforms for integrated programs.
8. Integration with current and future R&D activities and interests of Network members.
9. Interconnectivity between different pathway R&D needs for an integrated R&D program.
10. Support ("buy-in") from Technical Advisers and other experts for the Roadmap effort.

Attachment I extends the briefer discussions during the Network Meeting, and its objective is to elicit commentary and inputs from the participants and Technical advisers. **Two reports (Benemann and Oswald, 1996 and Sheehan et al., 1998) contain the technical background to this field** and are available to Network members and meeting participants on request.

6. GENERAL DISCUSSION OF BIOFIXATION PATHWAYS AND ROADMAP

A number of points were discussed during and in follow-up to the presentation on the microalgae pathways and roadmap.

1. Stand-Alone Systems. Dr. Pedroni stated that her Company was more interested in the long-term applications of microalgae for greenhouse gas mitigation in connection with power plants outputs, as an advanced C sequestration option for the sustainable use of fossil fuels. This also in light of the fact that although power plants are presently large-scale systems for centralized energy production, the future trend is for a scale reduction to produce/provide electricity/energy in a distributed way. The fundamental issue for the Network is to evaluate the actual feasibility of such processes in the long-term. Her company is specifically interested in methane, as a bridging fuel towards, in the longer-term, hydrogen. Thus a major emphasis of the Network, and the Roadmap effort, should be to address this issue. Wastewater treatment is presently not an option for ENI. In the short-term, the Company is looking at CO_2 capture and storage in geological formations. It is looking at biofixation with microalgae as a direct use of flue gas CO_2, as compared to trees which represent indirect processes. Another possibility is to apply such technologies not in Italy but in other countries where the Company is expanding its business. Major driving forces for the development of C sequestration technologies are presently represented by sustainability and environmental issues. There is also the potential of developing such renewable systems through European Union funds, such as the Framework 6, which was just launched and is looking for mid- to long-term technologies in renewable energy sources and greenhouse gas reductions. The conclusion of this discussion was that the Roadmap exercise and the Network in general should emphasize more the stand-alone processes, and their techno-economic feasibility, rather than focusing mainly on wastewater treatment systems. In response Dr. Benemann argued that wastewater treatment processes, ranging from municipal to agricultural, represented an intermediate and immediate stage in the practical development of such microalgae technologies. It would, indeed, be both necessary and reasonable to also examine the long-term potential and opportunities for microalgae processes where the fuel output would be the main economic benefit. However, it would be more likely that processes that could be developed within the context of the Network would be multipurpose. In any event, co-production of other high volume by-products (and higher value than fuels) would the most direct route to this goal.

2. Flue Gas Toxic Effects. Dr. Marraffa asked if toxic metals, Ti, Ni, V, etc., or ash in flue gases would interfere with microalgae production. There is very little information on this topic, but it does not appear to be a significant issue, according to a comment from Dr. Benemann. Again, a subject that would need to be recognized and addressed during the Roadmap effort.

3. Wastewater Treatment. Prof. Tredici argued that wastewater treatment, with its organic components, does not provide a clean medium for algae growth and would complicate matters. Also there is the issue of recycling sludges from the anaerobic digestion or processing of the algal biomass back to the ponds. Dr. Green, argued that ponds can destroy most of the sludges, resulting in no residuals. Dr. Benemann agreed to look at these issues further during the Roadmap development. In particular the fundamental question of whether it is possible to cultivate selected strains in wastewater treatment systems.

4. **Unialgal vs. Multialgal Cultures**. This topic received further discussion. One major issue is how to prevent "weed" algal species from invading. Inoculum production processes was discussed (see also presentation by Rene Wijffels and Hans Reith, above). Dr. Benemann suggested multiple stages of photobioreactors of increasing size and decreasing cost for the development of inoculum production processes. The issue was how much inoculum had to be produced. Indeed, even the need, let alone the ability, to grow specific algal strains, or even unialgal cultures was discussed, at least as applied to waste treatment. In current practice the municipal and aquacultural systems described by Dr. Green and Prof. Brune, respectively, use, in essence, "green waters", with no attempt to cultivate specific, let alone selected, algal cultures. Prof. Brune indicated that in his APS system, a major effect of the fish co-culture is that these shift the populations from mainly blue-green algae to dominantly green algae, with great improvements in fish flavor and overall fish productivity. Dr. Benemann argued that to achieve the objectives of the Network, which are to develop highly productive systems, with low-cost harvesting of algal biomass, and CO_2 fertilization, it would be necessary to cultivate selected, indeed, eventually, genetically improved, algal strains.

5. Strain Selection. Dr. Pedroni stated that from an R&D point of view the strain is very important, it is necessary to use the same strains in different settings to allow comparison of experimental data. For example in comparing closed and open systems. One has to start with strains already available that are suitable to be cultivated outdoors. One approach is to "autoselect" these (grow what spontanesouly appears and dominates). This is the approach used in the projects in the U.S. as part of the ASP and in Japan, as part of work carried out by Mr. Ikuta with Mitsubish Heavy Industries, and by other projects in the past. However, such approaches, although an important starting point in the development of improved strains, and still require considerable development, but are not sufficient. Prof. Brune thought that faster growing algae would be of interest. Dr. Benemann mentioned that the U.S. DOE is supporting a project at Pacific Northwest National Laboratory to look at the relationship between fast growth rates and productivity. This is a fundamental issue with important practical applications, such as in inoculum production. A discussion ensued about the need for different algae seasonally. This was a valid point, but at present there has been very little consideration given to this issue.

6. Extremophiles. The selection of such algal strains was a subject of some discussion. One proposal was that "extremophiles" should be searched for, which would easily dominate. For example, thermophilic cyanobacteria. Dr. Benemann was somewhat skeptical of this approach. He pointed out that indeed, at present, the two main algal species being mass cultured, *Spirulina* and *Dunaliella*, are, indeed, extremophiles, growing at high alkalinity and salinity, respectively. This allows the readily maintenance of such algae as unialgal cultures with relatively little effort. However, the trade-off is that under such conditions productivities are rather low. Thermophilic algae would suffer from similar constraints, in particular as large systems cannot be heated. One comment was that such approaches should not be dismissed too quickly. It was agreed that the use of extremophiles would be addressed in the Roadmap effort.

7. Molecular Genetics. Another subject of some discussion was the applications of molecular genetic techniques to microalgae culture. Prof. Brune stated that he had tried to get the "gene splicers" interested, to little effect. The Rio Tinto project is one example of this approach. The

Mitsubishi Heavy Industries project of Dr. Nakajima another. It was agreed that genetic tools would be very important in the future, but it was presently uncertain how or when to apply these in practical systems. This is a topic that will be addressed in more detail in the Roadmap Report.

8. Productivity. This is the central issue in microalgae mass cultures for greenhouse gas abatement applications. Very high productivities, at least twice, and probably three-times of currently achievable productivities will be required to allow for greenhouse gas applications where biofuels are the major economic output. Even for wastewater treatment processes higher productivities would be desirable. Dr. Nakajima outlined one approach to increasing productivities: reduction in the light harvesting pigments. Other issues must also be addressed, such as respiration. A combination of physiological and genetic tools will be required to address this issue. This must be a central focus of future R&D.

9. Harvesting. Dr. Green pointed out that algae do not reliably settle (sediment) and thus chemical flocculation would be required, which can be low-cost and low energy inputs. This option will be required to achieve reliable harvesting. Dr. Benemann agreed that this would need to be considered in the Roadmap report, but that the lack of reliable harvesting by bioflocculation was due to the lack of control over the algal populations. Efficient and low cost algal harvesting will require the cultivation of selected strains of microalgae.

10. CO_2 Utilization. One major issue is the ability to supply open pond microalgae cultures with CO_2. A major concern is that much of the CO_2 would be lost due to outgasing. Another is that the microalgae would run out of CO_2 too quickly. Dr. Benemann reported that these issues have been addressed by prior work, and this would be reviewed in the Roadmap Report.

11. Processing. The harvested algal biomass has to be quickly processed to extract the food, feed, fertilizer and fuel value. For wastewater treatment, including nutrient removal, with methane from anaerobic digestion as the fuel output, there is no need for a highly controlled or specific biomass composition. However for other fuels (ethanol, H2, biodiesel, hydrocarbons) or the co-production of higher value products, the composition of the biomass would need to be well controlled to allow application of the various processing technologies – fermentations, extractions, and purifications of the more valuable components. This, again, requires the cultivation of specific algal species, and strains, as well as careful management of pond operations. The actual processing technologies, e.g. fermentations of algal biomass or extraction of lipids/hydrocarbons, are not likely to present major uncertainties, though their applications to microalgal biomass would likely require investigation and adaptations. The more critical issue would be the nature of the co-products, which need a high enough value but large enough markets to allow a lower cost for the greenhouse gas benefits from such technologies.

12. GHG Mitigation Potential. This topic is the most important to the Network: what is the realistic potential of greenhouse gas mitigation by microalgal systems. Dr. Benemann did not provide any estimate during the Meeting. The potential for greenhouse gas mitigation may become clearer through the pathway development effort. In Attachment I, a more detailed discussion of this and other topics is presented, to obtain further input and commentary as inputs to the Roadmap.

7. CONCLUDING REMARKS AND FUTURE SCHEDULE

This meeting was called principally to provide an initial input to the Roadmapping effort to be carried out during the following four months (June through September) by Dr. John Benemann in conjunction with the Technical Advisers and Network members. The present Minutes, and attached "Issues in Microalgae Biofixation" (Attachment I), provide an opportunity for participants and others to provide inputs and comments during the preparation of the Initial draft of the Roadmap, to be completed by mid August. That document will be subjected to further inputs and reviews with a Final Draft document sent to the Network Members and Scientific Advisers by mid September.

The Roadmap will be presented and discussed at the **next meeting of the Network, to be held in Kyoto, Japan, October4 - 5 (Friday later afternoon and evening, all day Saturday), in conjunction with the GHGT6 Conference (web site www.rite.or.jp/ghgt6 or www.ieagreen.org.uk, e.mail ghgt@rite.or.jp).** This meeting is organized by the Research Institute of Innovative Technology for the Earth (RITE), Kyoto, Japan, and the IEA Greenhouse Gas R&D Programme (web site www.ieagreen.org.uk). All Network members are urged to make plans to attend. Further news on hotel and other arrangements will be forthcoming.

A major objective of the Kyoto Meeting will be to discuss the implementation of Roadmap. Objectives will be to develop interactive laboratory and field R&D projects, enhanced research activities by Network members, and achieve coordination among projects by the Network members.

ATTACHMENT I (Draft June 30, 2002) :

ISSUES RELATED TO THE MICROALGAE BIOFIXATION ROADMAP

John Benemann, (jbenemann@aol.com).

1. Introduction:

This "Issues" Attachment expands on the discussions held in Almeria on May 26th. Comments and viewpoints are solicited on this discussion.

2. Utilization of CO_2 – Source and Significance.

The goal of the International Microalgae Biofixation Network is to develop practical microalgae process for CO_2 utilization and greenhouse gas abatement. Such processes would use CO_2 from powerplants, specifically from fossil fuel powerplants, either directly from flue gases or after capture and concentration of the CO_2. This simple scenario is of greatest interest to most of the Network members. There are, however, good arguments for not making such an *a priori* requirement for processes to be developed in the Network. Other sources of CO_2, including waste and industrial sources not deriving from fossil fuel combustion would also be applicable to microalgal systems. It must be noted that the source of CO_2, whether fossil or otherwise, is not an issue in a greenhouse gas analysis. It makes no difference what source the CO_2 derives from. This is because it is not the act of biofixation that accrues the greenhouse gas mitigation benefit, but, rather, the further utilization of the algal biomass for production of renewable fuels, as well as any indirect effects related to greenhouse gases. As an example of the latter would be any reduction in energy utilization or methane emissions in a microalgae wastewaster treatment process, compared to conventional treatment systems. Indeed, for wastewater treatment processes, these indirect effects can be larger than the renewable fuel outputs from the process.

In brief, therefore, although the need for CO_2 provision is paramount in any microalgae process, the actual source of the CO_2 for the algal process is not a fundamental issue. Use of power plant and/or fossil fuel sources of CO_2 is certainly a major option, and projects specifically targeting such sources could be a priority for the Network, and most of its members. A reasonable approach at present is to emphasize fossil CO_2 resources, although substituting part or even all of CO_2 from non-powerplant or even non-fossil sources would also be acceptable for specific projects within the context of the Network. For example, microalgae could be cultivated on a biomass-fired power plant flue gases. This approach would allow for maximal flexibility within the context of developing greenhouse gas abatement processes.

In this context, the size of the power plant is another issue. The main problem with microalgae systems are the large land areas required contiguous to the power plant for direct flue gas utilization. This makes the applications of this technology to smaller-scale, distributed power generation systems more appealing. Another issue is the day-night and seasonal variations, which reduce overall CO_2 utilization to at most about 30% of outputs (somewhat higher in tropical areas).

One major technical issue can be pretty much laid to rest: microalgae systems can utilize flue gases from fossil fuels as well as other sources of CO_2. The first report of using flue-gases as a source of CO_2 came from Japan, where the flue gas of a small coal combuster was used to grow microalgae (reported in Burlew, 1953, "Algal Culure, From Laboratory to Pilot Plant"). Many studies have been carried out since, in particular in Japan (see presentation by Ikuta, above). The major concern is the effect of NOx and SOx in the flue gas on the microalgae cultivation. However, their effect is, mainly if not exclusively, due to their chemical acidification, that is alkalinity destruction, not a direct effect on the algal growth or metabolism. The effects of these contaminants thus can, and must, be managed within the design parameters of such a process, by providing an alkalinity balance that is within acceptable limits.

For example, when using seawater, with 2.3 milliequivalents of alkalinity, the exchange of seawater would need to be sufficient to counteract this acidification. For inland waters, where water recycling is more important, alkalinity may need to be added to the cultures, if needed. However, HNOx could be used by the algal cells as a source of nitrogen, and this would consume the acid, and re-generate alkalinity. Alkalinity is a key parameter in system designs, and its concentration determines a number of CO_2 related system design issues, such as the spacing/number of carbonation stations. In this regards, there are no reports of other constituents in flue gases that seem to be inhibitory to algal cultivation (e.g. heavy metals, organics), but this may be looked at again, in particular with the use of coal-derived flue gases.

More fundamental is the issue of the use of dilute powerplant flue gas vs. concentrated CO_2. The latter can be transported for considerable distances, and is also much easier (lower cost) to transfer into the algal ponds. Against these advantages, the additional costs involved in CO_2 concentration and transportation must be considered, vs. the higher costs of flue gas utilization. This trade-off appears to favor flue gas utilization, but this is not an overwhelming effect, depending on the CO_2 concentration and other site-specific factors. Indeed, if "decarbonization" of fossil fuels becomes a major future mechanism for shifting to a "Hydrogen Economy", large resources of concentrated CO_2 may become available, potentially reducing the cost of algal biomass production.

In conclusion, considerable information already exists from a variety of sources and studies about the use of fossil fuel-derived CO_2 for microalgae culture, including direct utilization of powerplant flue-gases in outdoor ponds. Thus flue gas utilization does not appear to present any major R&D issues. However, some additional work on flue gas utilization by microalgae would be useful including more detailed engineering and cost analyses of such systems would help to reduce the uncertainties in the actual cost of flue gas vs. pure CO_2 utilization. For Network-related projects routine utilization of flue gas CO_2 would be the preferred option, where reasonably possible.

3. Microalgae Biofixation System Scale.

Small systems, with only a few hectares of ponds, would not exhibit economies of scale and would not have, even in aggregate, likely significant impact on greenhouse gas mitigation, would have diseconomies of scale and present major management challenges. The issue arises of whether the minimum individual system scale to be considered should be 10 or 100 hectares, or something in between. It should be noted that for stand-alone processes (producing only fuels), scales of several hundred hectares would be required to achieve maximum economics of scale. Although large by current standards, these are not much larger than many agricultural operations.

It should also be noted that scale in this case "large" refers to the microalgae ponds, not the power plant. Indeed, the most plausible application of microalgae technologies are not for large centralized power plants, but for smaller (<50 MW) systems, plausibly in connection with waste treatment, in particular nutrient removal, and production of large volume co-products. It should be noted that Cyanotech in Hawaii uses a small power plant to supply its required CO_2 (see Cysewski, Monterotondo Workshop Report). System scales would, of course, depend on the specific objectives and applications, and require further engineering and economic analyses. For research and process development purposes, pilot scale development of this technology at even smaller facilities may be defensible. However, the objective of the Network would best achieved by focusing attention on larger-scale applications, both individually and in aggregate.

The actual minimal system scale would be a matter most importantly of economics, but also greenhouse gas mitigation objectives. A minimum scale of at least tens of hectares would be foreseen for microalgae wastewater treatment, applying the advanced technologies to be developed by the Network: cultivation of selected microalgal strains, increased productivity, bioflocculation harvesting, and biomass processing. In the past some very large-scale processes were advocated. For example, in 1977, "100 square mile" (25,000 hectare) systems were mandated by the Energy Research and Development Administration (predecessor to DOE) as the minimum acceptable scale for a microalgae process. This was dictated by political expediencies, not technology. On the other extreme, projects that purport to achieve greenhouse gas mitigation with processes that produce "high value co-products" and generate only a few tons of biomass before market saturation, are at least equally questionable from a practical perspective.

In the U.S. alone there are some five thousand municipal wastewater treatment plants that use microalgae ponds, and many thousands more operate around the world. Although some extend over hundreds of hectares (the Werrebie Ponds, Melbourne, Australia) are over 1,000 in size. However almost all of these are very small, and would not qualify for a minimal scale required for a microalgae production and greenhouse gas mitigation process as envisioned here. Municipal systems of minimum viable economic scale, would likely have wastewater flows of some 20,000 m^3/day (some 50,000 people equivalent, or about 20 hectares of high rate algal ponds to achieve tertiary treatment, that is nutrient removal). Such systems would need to be fertilized with CO_2, which is the limiting nutrient in such systems. By digesting the algal biomass, and primary sludges, and using the methane on-site for power generation, all the required CO_2 could be provided from the wastes. Such municipal wastewater treatment processes could also be integrated with fossil-based distributed power generation systems, for greater flexibility. This is one initial pathway recommended for development by the Network.

4. Resource Base and Greenhouse Gas Abatement Impacts.

The central objective of the Network is to develop technologies that will make a significant contribution to global greenhouse gas mitigation. Tens of billions of tons of CO_2, and equivalent outputs in other greenhouse gases, are currently being generated globally, and these will further increase in the future. "Significance" must be defined in the context of such overwhelming emissions. Microalgae systems are no "cure-all" solutions to greenhouse gas /energy problems. Prior projections of millions of hectares of algal ponds producing biodiesel fuels in the U.S. Southwest were fanciful. Microalgae are at best minor players in the overall effort to combat global warming. However, both major and minor players will be required in the development of technological countermeasures. Still, to justify an R&D effort, some measure of significance must be considered. An aggregate reduction goal equivalent to at least 100 million tons of CO_2 per year is here proposed as a minimum goal for microalgae biofixation technologies to be developed by the Network. For each individual pathway the plausible potential should be equivalent to at least 10 million tons of CO_2. These metrics are, of course, open to debate.

In this context, as in the prior section, the issue arises of the potential for co-production of "high value" products during a CO_2 mitigation process. The strong inverse relationship between product price and market size, suggest that high value products, such as specialty nutrients or bioactive substances, could not plausibly play a significant role in greenhouse gas mitigation efforts. Even a single modest scale plant (<100 hectares) would saturate the market for such products. However, the concept of co-products is a valid one, though only for co-products that have relatively large markets, which implies relatively low prices (though still higher than the value of renewable fuels, or greenhouse gas mitigation credits). For example, co-products could be major foods or feed ingredients, or biopolymers, including flocculating agents, emulsifiers, etc. Identification of plausible co-products should be a focus of future R&D by the Network.

One of the main "co-products" for microalgae processes will, undoubtedly, be the integration of greenhouse gas reduction benefits with other environmental services that such systems can provide, specifically wastewater treatment and re-use and nutrient recovery/recycling. In the case of municipal wastewater applications discussed in the prior section, such applications would be severely limited by many practical factors, from climate to land availability, to mention the major ones. Thus, for the U.S. only 10% of U.S. wastewater flows are in the climatically more favorable areas, and land availability would further restrict this technology, likely to a small fraction of the wastewater plants above the plausible minimum size, of some 20 hectares. And systems above 100,000 m^3/day, or 250,000 people equivalent, would becoming very difficult to site. And other limitations exist, including the need to equalize seasonal performance, effluent polishing, and nutrient recycling. Thus, a realistic potential of microalgae-based municipal wastewater treatment processes is thus only a percent or two of total U.S. population municipal wastewater flows. This would be in aggregate less than a couple of thousand hectares of algal ponds, reducing greenhouse gas emissions by at most one million tons of CO_2 equivalent (when considering other greenhouse gas benefits from waste treatment, in particular reduced energy consumption, compared to conventional treatment. These are only order of magnitude estimates. A more detailed analysis is possible, but would not likely change conclusions substantially. Similar arguments would hold also for European applications.

Only by considering the global potential would municipal wastewater treatment processes have a significant impact on greenhouse gas reductions. Climatic and economic circumstances favor such systems in tropical and sub-tropical countries, promising a larger potential market penetration, plausibly meeting the above set minimum goal for all microalgae biofixation technologies (100 million tons CO_2 equivalent per year, based on municipal waste treatment for several hundred million persons globally). By further considering the agricultural, aquacultural, and industrial applications of microalgae wastewater treatment technologies, a plausibly much greater global resource potential would apply. Indeed animal and other wastes treated with algal systems could make a substantial contribution even in the U.S. and European context.

It is imperative that, for such processes to achieve their potential market penetration, they operate at high productivities, for maximal nutrient recovery and with minimal footprint. Further, low-cost algal harvesting and processing technologies will be needed. Ultimately this will require the cultivation of specific species, something presently beyond our capabilities for wastewater treatment systems. This is a research challenge which falls within the technological advances that are the goal of the Network, and is, indeed, at the heart of the Network Roadmap, as presently envisioned.

This is a major departure from current microalgae technologies in this field, which rely on "green waters", variable assemblages of microalgae which provide limited opportunities for process control. The argument for this approach is that only through the control over algal species will it be possible to achieve the degree of process control, over productivity, over harvestability, and over biomass composition, as will be required to indeed have sufficiently productive, harvestable and valuable algal biomass to meet the economic goals.

The argument against this approach could be that this is too difficult a goal to grow selected algal strains on complex municipal wastewaters and that processes should be developed initially with more consistent wastes, such as, for example, agricultural drainage waters. These alternatives can be carried out through the Network on parallel tracks. Indeed, it is the promise of the Network to be able to carry out several process development efforts simultaneously, while coordinating the general research on productivity, harvestability, strain selection, genetics, and other technology development issues.

5. Economics.

Ignoring economics allows many processes to be considered that are completely impractical in the context of microalgae biofuels production and greenhouse gas mitigation. For example, one of the first microalgae energy processes supported by the U.S. DOE, when it was formed 25 years ago, was a project on H_2 production by microalgae using an optical fiber photobioreactor. However, during the first review, that project was deemed by the technical review committee to be short by a factor of some 100,000 from being economically plausible, and was promptly terminated and forgotten. Perhaps it should not have been, forgotten that is, as that approach became the centerpiece of the >US$250 million effort on microalgae biofixation in Japan during the 1990's. Although the economic projections of the Japanese system were not published in English, the approach was clearly and *a priori* impractical, even for high value products.

Another historical example of the same approach, was the patented microalgae bioreactor/process which formed the basis for the Aquatic Species Program (ASP), carried out in the U.S. during he early 1980's by the DOE and Solar Energy Research Institute (SERI, now NREL, the National Renewable Energy Laboratory). This patent was for a closed photobioreactor that allegedly achieved extraordinary productivities through, among others, the so-called "flashing light effect". After several years and some millions of dollars of R&D, this concept was subjected to an engineering/economic feasibility analysis (See Sheehan et al., 1998, Section III), and then abandoned as both technically and economically unsound.

Finally, during the mid 1980's SERI sponsored an engineering design competition between both open ponds (represented by Dr. Joseph Weissman, now with SeaAg Microbial Products, Inc.) and closed photobioreactors (represented by Dr. Mark Huntley, Aquasearch, Inc.), for production of microalgae biofuels. The technical evaluation committee concluded that only open ponds could be considered for such applications, based on the plausibly economics for the alternative processes. Thus, closed photobioreactors were excluded from further consideration by the SERI/DOE ASP (See Sheehan et al., 1998 Report). In conclusion, for microalgae greenhouse gas mitigation, prior experience has already established that such approaches are not valid.

However, even process economics projected for open pond systems (see Benemann and Oswald, 1996 for the latest update of those studies) are far from attractive for "stand-alone" processes, in which renewable fuel are the main, even only, outputs. Stand-alone processes can be economically attractive only if many very favorable assumptions are made, in particular regarding the achievable productivities of such processes, exceeding two hundred tons per hectare per year. Such productivities are theoretically possible, but the technologies on which they would based, such as selection of algae with reduced antenna pigments (see Nakajima, above presentation, for example) are only in their infancies. And productivity is not the only factor that needs major improvements.

As already amply discussed, to allow for an economically competitive process based on plausibly achievable nearer-term productivities and other process metrics (e.g. harvesting, processing, etc.), some by- and co-products are required to help drive the economics. Wastewater treatment and commodity feeds and chemicals were suggested as possible options in the four pathways listed in the introduction. As pointed out by Prof. Wijffels and Hans Reith (above) water recycling could in many cases be the major economic driving factor in microalgae waste treatment processes. However, even wastewater treatment systems must consider economics. And, in any event, the objective of the Network is not to produce a better wastewater treatment process but reasonable objectives in terms of greenhouse gas mitigation, both regional and globally. This would require further selection among the options. Which is why small-scale processes (> 10 ha), and conventional algal treatment processes are not suggested as high priority targets for the Network. Again, this is a central issue in the development of the Roadmap: to what extent should this include the "green water" approach currently practiced in wastewater processes. Although the Roadmapping effort would not allow a *de novo* approach to engineering and economic analysis at this time, in the future the Network must carry out engineering/economic studies, in particular of combined wastewater treatment-energy production processes. The Roadmap effort will provide a guide to the needs in this area.

6. R&D Time Frame.

One major conclusion of the prior engineering/economic feasibility studies, first carried out in detail during the 1980's as part of the ASP, was that "stand-alone processes", where renewable fuels are the only economic output, would require long-term (>10 years) R&D. During the 1990's, R&D efforts were curtailed in the U.S., and the large Japanese program did not address the development of the processes identified as most promising by the ASP. At any rate, the time horizon for development of such stand-alone processes is still >10 years, that is long-term R&D. This is beyond the 10 year time-horizon of the Network. This presents a dilemma, as the stand-alone processes would best appear to meet the needs of the Network members, for whose benefit this R&D effort is being "roadmapped". However, nearer-term applications and opportunities will need to be emphasized to allow development of practical processes within the next decade. More fundamentally, such stand-alone systems could be problematic from the perspective of the human footprint on the global environment, a matter of increasing concern. Multifunction processes are more likely to reduce this footprint and allow for greater benefits to mankind.

Thus, the "pathways" selected for development during the Roadmap exercise are based on processes that could be developed to a practical level within a decade and also meet the goal of multiple benefits deriving from one process. Thus, fuel-production-only systems, such as pursued by the ASP in the US, are not included in the Pathways that are included in the Roadmap. However, it should be pointed out that some of the processes being considered come fairly close to the goal of a biofuels-only system. For example, nutrient removal from agricultural drainage waters at the Salton Sea in S. California (see Brune discussion) involves essentially all the elements of a fuels production process, except that water and nutrients are provided free of charge, and with the several thousand hectares of land required assuring economics of scale. Indeed, such systems have to meet reasonably strict economic goals. For example, if algal biomass costs only $100/ton, after credit for the fuel output, this amounts to a $10,000/ton of P recovered (at 1% in the biomass). This will be a challenging cost goal to meet.

Thus the proposed Network focus is on nearer-at-hand processes that can be more plausibly projected to result in practical applications that can make significant contributions to the greenhouse gas abatement efforts of Network members and others. The expertise and judgment of the Technical Advisers will be critical in developing a consensus on this most critical issue.

7. Environmental Benefits and By-products.

It must be emphasized that greenhouse gas mitigation in the proposed pathways would not only come from renewable fuels production but also from avoidance of fossil energy inputs presently required by conventional processes, from nutrient recycling, reducing need for synthetic fertilizer, and from methane and nitrous oxide abatement. Indeed, these benefits often greatly outweigh the fuels outputs, both economically and environmentally, and specifically in terms of greenhouse gas mitigation.

Many issues must be evaluated in the design of such systems, with greenhouse gas mitigation not the highest priority in their design and operations. Still, greenhouse gas abatement would add to the economics of such a process, and could indeed make a significant contribution. Of course, at this point the pricing of such greenhouse gas benefits is uncertain, by over a factor of ten, from roughly $1 /ton to $10/ton of CO2 abatement or its equivalent. This uncertainty makes it even more imperative that such processes be at least initially developed in the context of wastewater treatment or other co-products, which would carry most of the costs of such a process. The environmental benefits of such systems, including water recycling (which could also have greenhouse gas benefits), were already discussed previously.

In regards to "large volume " by-products, nitrogen fertilizers (through action of nitrogen fixing algae) and biopolymers (for bioplastics, flocculants) are two possible options, used as the basis for two of the four pathways proposed in the introduction. It must be immediately recognized that these pathways present even greater challenges than the wastewater treatment processes, which are more complex, but also economically more robust.

Fossil fuel-derived nitrogen fertilizer has a very low cost, which makes any system that depends on such a co-product economically problematic. To aggravate this problem, nitrogen-fixing algae exhibit low productivity, roughly half of a conventional algal culture. Even assuming that a 100 ton/ha /yr productivity would be possible with such algae (twice current productivities), this amounts to only some 10 tons/ha of actual N fertilizer. The value of this fertilizer is even lower than the fuel outputs or even the greenhouse gas mitigation credits that could derive from its production. The only encouraging aspect on the economic front is that such a fertilizer would carry a large premium over synthetic fertilizers, as it could be sold for organic farming. The other encouraging aspects is that it is, or should be, relatively easy to grow unicultures of nitrogen-fixing cyanobacteria, it is very easy to harvest these, and they are very digestible. With such algae it would be possible to greatly simplify the overall process: harvesting would be reduce to a quick settling process, and the algal biomass is highly digestible. These concepts need to be further explored and developed.

8. Development of Field Projects.

The development of the microalgae technologies (pathways) by the Network members over the next five to ten years cannot be limited to laboratory or small-scale studies. Some of these pathways are ready, or will be so in the next two to three years, for establishment of field projects where these technologies would be developed with relatively large-scale (> 100 m^2, and preferably >1,000 m^2) pond systems. These would establish the current state-of-the-art and allow process development under actual field conditions, including climatic, resource (water, nutrient, CO_2, etc.) variabilities. These field projects would allow rapid testing of advances made at smaller scales (e.g. selection of algal strains, for example) and also provide feedback to these laboratory and small-scale operations. Such field projects would require collaboration between Network Members and, possibly, also with other organizations. The potential to develop such field projects would be one key issue in the development of the conceptual pathways under the Roadmapping effort and will be addressed in detail in the Roadmap Report.

9. Integration with Network Member Interests and R&D Activities.

The Network is to be a whole that is more than the sum of the individual R&D projects, activities and interests of the Network Members. Each Member will have its own approaches, plans and objectives. These must be integrated into the pathways and the R&D needs identified during the Roadmap development. As discussed below, some members already have ongoing projects and activities, from photobioreactors to enzyme engineering. Others may develop additional R&D efforts, which may, or may not, be directly connected to a specific pathway. Thus, some members may have no interest in any processes involving wastewater treatment of any type, others may focus on specific end-products, such as methane or hydrocarbons, or on generic technologies such as genetics or photobioreactor designs. The latter could be viewed with skepticism in the development of the Network, in light of the above discussions re. prior closed photobioreactor efforts. However, closed photobioreactors can be useful R&D tools and can be also of value in the development of the inoculum (seed culture) production, which will be required for large-scale processes. Thus their study can be of value to the development of these pathways, and of the overall Network goals, as long as means are not confused with ends, the problem in prior (and indeed some current) projects in this field. One of the objectives of the Roadmap is to provide a tool with which to integrate the disparate R&D approaches by the Network Members, and assess their importance to the achievement of the practical pathways for development. Of course, this would also be an interactive and re-iterative process, with the R&D efforts by the Network Members evolving over time towards such common objectives.

The pathways are to provide a focus for establishing the R&D needs for the development of such potentially practical processes. One of the main initial conclusions of the Roadmap development effort thus far is that the R&D needs are generally quite similar for the different pathways. This assures that research between these different subjects can be integrated into an overall coherent whole. And, perhaps most important, is a strong argument for the value of the Network: by working on any one of the R&D needs (listed below) it will be possible to contribute to the overall effort. This will reduce the risks of this research for each member, by increasing the field of potential applications.

10. CONCLUSIONS.

The fundamental concept of the Roadmap is to develop a consensus among experts regarding the proposed pathways and R&D needs for microalgae greenhouse gas mitigation. The six Technical Advisers to the Network are experienced in algal mass cultures and the whole range of disciplines and technologies which will need to be applied to this subject. Consensus, of course, does not mean unanimity, nor expertise infallibility. For example, some applied phycologists of repute consider $CaCO_3$ precipitation by microalgae a valid method for greenhouse gas mitigation, even though this reaction releases CO_2 to the atmosphere (or, at best, if the CO_2 thus released is then fixed by the algae and somehow sequestered, results in a zero gain).

However, any disagreements on technical issues could be resolved through a strong majority consensus building. For example, at the Monterotondo Workshop, a strong majority favored the further development of microalgae technologies for greenhouse gas mitigation, even though there was no unanimity on some of the approaches or details, in particular regarding process economics. The Roadmap development effort now being undertaken will now move from the general to the specific, and will seeking such consensus on both the specific pathway analyses and the underlying R&D issues, discussed next.

The Roadmapping methodology is to **categorize R&D needs**/areas/major issues that must be addressed to to develop the specific pathways identified and . The specific R&D needs identified at the present time can be categorized into a dozen different subject areas (see also Appendix I, Overheads from the Reston Meeting):

1. Strains. Defined strains must be mass cultured, can they be? Perhaps the greatest challenge.
2. Genetics. Can strains be improved with molecular technologies? Yes, but when, and how?
3. Microalgae Physiology. Can pond operations take advantage of our knowledge in this area?
4. Culture stability. Can we avoid infections, invasions, collapses and pond upsets?
5. Productivity. Maximizing productivity is the imperative of this field. How?
6. Harvesting. Dilute suspension of microscopic particles must be concentrated. A challenge!
7. Biomass conversion. Fuels must be produced to mitigate greenhouse gases. Which fuels?
8. Inoculum production. For this we need photobioreactors. What type, how large, how costly?
9. Wastewater treatment. Organic wastes and nutrient removal increases system complexity.
10. Engineering Designs. Can they be cheap enough? Low energy inputs? Applied widely?
11. Impacts. Can microalgae processes reduce CO_2 emissions by hundreds of megatons?
12. Byproducts. Can low value co-products (fertilizers, biopolymers, feeds) improve economics?

In the Roadmap report being prepared this Summer, each of these R&D topics and issues will developed in some detail, the particular issues related to each pathway addressed, and the required research discussed. Inputs from the Technical Advisers and others will be solicited during the development of the Roadmap Report.

APPENDIX I -
OVERHEADS # I – V FROM RESTON JANUARY 29th, 2002 MEETING

J. Benemann, 1/29/02, Network Organizational Meeting, Overhead # I .

Carbon Sequestration Technology Roadmap
Pathways to Sustainable Use of Fossil Energy

Date of Release: JANUARY 7, 2002

U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory

Contents:

Vision: "*Joining improved energy efficiency and use of low-carbon fuels, carbon sequestration will enable the removal and permanent storage of carbon dioxide (CO_2) from fossil-energy systems at costs and impacts that are economically and environmentally acceptable*. **"**

Outcomes. "In the near- and midterm, implementation of the roadmap can result in a reduction in the rate of growth of GHG emissions… over the next 20 years, thus minimizing the need for steep, economically disruptive reductions in the future."

Public- Private Partnerships. "The effort to develop carbon sequestration technology involves extensive public-private partnerships among government, industry, academia non- government organizations, and the public at large. Many of these partnerships are international in scope, and include the IEA's Greenhouse Gas R&D Programme."

The Roadmap. "The carbon sequestration technology roadmap defines the major drivers and challenges, R&D pathways, and desired outcomes that have been identified. It represents a **general consensus** to date on *what* major science and technology pathways have potential for achieving the goals of carbon sequestration. The implementation of these pathways—*how* the work will be accomplished—will be carried out by stakeholders."

J. Benemann, 1/29/02, Network Meeting, OVERHEAD #II

MICROALGAE BIOFIXATION TECHNOLOGY ROADMAP

"**A Science and technology roadmap provides a structured R&D planning process by identifying the scientific and technological developments needed to achieve a specific strategic goal**" DOE/NETL (1999).

The Roadmapping Process involves "obtaining information from scientists, technology developers and users (e.g. energy companies), program managers, regulators, the public. ... It will be based on ideas, data, and perspectives developed by experts.... The goal is to develop a *consensus* on the key science and technology needs /opportunities... As in any new area of science and technology, there is significant uncertainty. ... Areas of disagreement may exist - what paths to follow, how to follow them." ... It involves a continuing effort – with new concepts developed and old ideas discarded/reviewed. (DOE/NETL Roadmapping Report of Jan 7, 2002)

Technology categorization of major pathways for practical microalgae biofixation systems:

#1. Agricultural/aquacultural waste treatment /nutrient removal (example: Salton Sea)

#2. Municipal wastewater treatment – GhG mitigation from fuel outputs and energy efficiency.

#3. CO_2 utilization and organic nutrient recycling in large-scale microalgae systems.

#4. Industrial wastewater treatment-utilization with co-production of higher value products.

#5. Novel microalgae GHG mitigation processes (e.g. fertilizer production, bioplastics).

#6. Long-term options: stand-alone fossil CO_2 use – algal biomass fuel production processes

J. Benemann, 1/29/02, Network Meeting, OVERHEAD #III.

Research & Development Needs Categorization

Roadmapping methodology: Categorize R&D needs /areas /major issues requiring R&D in or out-doors. Examples for microalgae biofixation are:

1. Development of strains suitable for large-scale cultivation. Isolation, selection, maintenance, testing, etc. Current collection materials - availability, suitability, etc. Strain exchanges and sharing between Network projects.

2. Genetic systems and molecular biology for strain improvement. Development of improved strains with desirable attributes, e.g. high light efficiencies, low respiration, etc.

3. Microalgae physiology: responses to nutrients and cultivation environment - models and reality. Scale-down to small in- /outdoor systems.

4. Culture stability: factors determining strain competitiveness, biotic invasions; reality and models. Determinants of dominance (max. growth rate? productivity?)

5. Development of high productivity algal production systems generating biomass with high levels of storage compounds: carbohydrates, PHBs, hydrocarbons, oils,

6. Algae harvesting – bioflocculation/sedimentation, chemically assisted filtration flocculation. Bioflocculation mechanisms and physiological effects.

7. Microalgae biomass processing to fuels. Fermentations (to methane, H_2, ethanol, chemicals), extraction of hydrocarbon and oils, biodiesel.

8. Development and demonstrations of algae culture systems, photobioreactors for inoculum production, large pond hydraulics and gas transfer (CO_2, O_2).

9. Cultivation of algae in organic nutrients and wastewaters, effect on O_2 and CO_2 management; nutrient recycling (C, N, P), model systems to field projects.

10. Engineering designs, operations, energy balances, GHG mitigation and system analyses. Integrated wastewater treatment: CO_2 utilization, fuels production and higher value co-products. Site-specific economic projections for various pathways.

11. Resources and GHG mitigation: waste resources – agricultural, municipal, industrial; climatic restrictions, land, alternative water and CO2 resources, other.

12. Novel systems and alternative concepts (bioplastics, fertilizer production), new approaches.

J. Benemann, 1/29/02, Network Meeting, OVERHEAD #IV.

Technology Pathways and R&D Integration

Roadmapping methodology: "Identify how and what R&D efforts will advance the various [microalgae biofixation] pathways." Note: all R&D Needs listed in Overhead #3 are required to advance all the technology pathways described in Overhead #2. Specific R&D issues are:

1. Strain Selection and Development. An initial Network R&D issue is the acquisition, selection, maintenance and sharing of strains. Several options will be explored.

2. Genetic Studies and Molecular Biology. This field will eventually impact "open" microbiological processes, even microalgae pond cultures. Recent research is impressive, but applications to microalgae biofixation pathways are not imminent. Issue: perhaps Network R&D in biofixation should focus exclusively on productivity, which is of direct utility?

3. Microalgae Physiology. A powerful tool is scale-down designs of microalgae mass cultures. These require continued development, modeling and validation.

4. High Productivity Systems. Algal production systems generating biomass, generic or with high levels of storage compounds, at high productivity. A challenge.

5. Culture Stability. Culture stability R&D requires operation of ponds of some scale and duration in a practical context. Species competition models need work.

6. Algae Harvesting. Bioflocculation is the lowest cost process, needs fundamental and applied R&D in a practical context. Alternate / complementary approaches?

7. Microalgae Processing. To be carried out in practical context to demonstrate feasibility for planned pilot and demonstration projects. Higher-value co-products?

8. Bioengineering of Microalgae Processes. Hydraulics and mass transfer do not scale well but required for engineering analyses. Needs access to full-scale systems

9. Cultivation in Practical Context. Microalgae pathways include wastewater treatment, of algae in waste waters, organics and heterotrophic growth, O_2 and CO_2 management, nutrient recycling (C, N, P), model systems to field projects.

10. Engineering designs, process economics, sensitivities, energy and overall GHG mitigation analysis of pathways for microalgae biofixation. This will be a key effort in the roadmapping.

11. Resources and GHG mitigation: Near-, mid-, long-term estimates of global GHG reduction potential of microalgae biofixation. Key Roadmap outcome.

12. Novel systems: New processes (bioplastics, fertilizers), new (or even old) research approaches.

J. Benemann, 1/29/02, Network Meeting, OVERHEAD #5.

R&D Planning, Pathways to Practical Processes, Network Development

Public-private collaboration in R&D planning and execution is central to the Network. Roadmap will develop strong consensus on R&D focus and strategy.

The individual pathways may be pursued by different stakeholders, or in collaborations. The Roadmap will provide alternate paths to GHG mitigation goals.

In addition to Network participants, other public and private organizations may have interests to join in specific projects, because of mission or business interests.

Development of microalgae biofixation pathway projects, from field to pilot to demonstration, requires relatively long lead-times and must be initiated early.

Pathways to rapid technological advances and achievement of significant GHG reductions could shortcut by leveraging with field/pilot projects of strategic value.

"*… there are near- and midterm actions to be taken as we work to gain better understanding of the long-term opportunities." (DOE Sequestration Roadmap).*

Six pathways encompassing a broad range of opportunities to microalgae biofixation have been identified (Overhead 2). Each represent practical project opportunities to be carried out by Network participants. Each represents unique issues, approaches and synergies.

The Pathways all require both specific research thrusts as well as support from the generic applied R&D discussed above in the Categorization and Integration sections

The Network development will require that the laboratory-based research projects support the field-based pathway projects, both directly and indirectly.

Network development will be through a dynamic interaction of all participants and their contribution to the overall goals of the Network, which will evolve over time.

Pathway projects will aim at achieving major breakthroughs in applied systems, in terms of practical demonstrations and provision of data for economic projections.

Network development is predicated on achieving a positive return on investment by all participants in terms of practical knowledge gained and goals advanced.

The Roadmap will develop the above concepts, R&D projects and Pathways, with inputs from participants, advisers, other experts and stakeholders.