MINUTES OF THE ORGANIZATIONAL MEETING

of the

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

January 29th, 2002
Hyatt Regency Reston, Reston, VA 20190 USA

A. BACKGROUND

The International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae was first proposed to the IEA Greenhouse Gas R&D Programme by the Executive Committee representatives from the U.S. Dept. of Energy and EniTecnologie S.p.A. at the ExCom meeting in Cairns, Australia, in August 2000. In follow-up to this proposal, a Workshop on this topic was held in Rome, Italy, in January 2001, where some 35 representatives from interested organizations and technical experts discussed the merits of microalgae technologies for GHG abatement. The Workshop participants concluded that such an international R&D Network should be organized. A Workshop Report is available summarizes the presentations, discussions, and technical background. Following this Workshop, the ExCom of the IEA GHG R&D Programme, during its meeting in Regina, Canada, in March of 2001, authorized the further development of the International Network. The present initial meeting of prospective members was held to discuss organizational matters and activities planned for 2002, prior to a formal request for approval of the Network at the April meeting of the ExCom of the IEA GHG R&D Programme.

B. ATTENDEES

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C. AGENDA of the Organizational Meeting of the International Network on Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae

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Objective: to bring together committed and prospective members of the Network to discuss and adopt the proposed Network Agreement. Governance and organizational matters as well as specific activities scheduled for 2002 are included in the Agenda.

8:30 am	Convene
8:30 - 9:30 am	Introductions: Dr. Heino Beckert and Dr. Dave Beecy (U.S.DOE) Welcome, DOE Perspective Dr. Paola Pedroni (EniTecnologie): Vision and Purpose of Network Mr. John Davison (IEA GHG R&D Programme): IEA Role and Participation, Organizational Issues
9:30 - 10:30 am	Introductions by Participants: Discussion of organizational interests, current activities in GhG mitigation generally, backgrounds of attendees and, if any, current activities/interest in microalgae biofixation.
10:30 - 11:00 am	Break
11:00 - 12:00 am	Proposed Network Agreement and budget: general discussion. Amendments and adoption of plan, budget, future meetings. Discussion of Network governance, proprietary issues, programme of work, future meetings, future expansions of Network.
12:00 - 1:00 pm	Lunch
1:00 - 2:00 pm	Nominations and Discussion of Technical Experts and Network Manager. Roles and expectations for experts participants, Network Manager Duties. Other Organizational matters. Open Discussion
2:00 - 3:00 pm	Technical Presentation and Discussion. John Benemann: The "Microalgae Biofixation Roadmap", Issues in Microalgae Biofixation – R&D, Economics, Potential.
3:00 - 3:30 pm	Break
3:30 - 4:00 pm	Discussion of Network Activities for 2002 – Goals, Collaborative Projects, development of R&D proposals.
4:00 - 5:00 pm	Discussion of Network Plans and Goals for 2003-2006 - Laboratory and field projects, new projects, recruitment of new members, general discussion.

Adjourn (Dinner)

D. INTRODUCTORY PRESENTATIONS

1. DAVE BEECY - DOE OVERVIEW (See attached PDF file)

Mr. Dave Beecy presented the U.S. Department of Energy (DOE) and the Department's National Energy Technology Laboratory (NETL) perspective on carbon sequestration R&D. This program, under the overall management at DOE by Mr. Beecy and co-managed at NETL by Dr. Charles Schmidt, has accelerated substantially over the last few years. The driving rationale for the R&D Programme is the FCCC Convention. The 1992 "Rio Treaty", signed and ratified by President George Bush and Congress, and 160 other nations, calls for a global goal of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". There is also language that is important for ecosystems to be able to adapt to climate change. The third option for GhG reductions, in addition to increased C efficiency and C-neutral energy sources, is C sequestration. However, many uncertainties remain. Acceptable future levels of GhGs are unknown but will eventually require deep reduction in emissions. Improved efficiency and low carbon energy alone are not sufficient to accomplish this goal. There is time for technology R&D and the DOE-NETL Program approach is very broad.

A major effort carried out by the DOE-NETL Program was to develop a C-sequestration "Roadmap", which engaged the scientific community to identify R&D needs. The main focus is on capture and sequestration, whose costs are very high but which have tremendous potential for new technologies that can decrease costs. The DOE-NETL program is also developing indirect approaches of C sequestration involving forests and oceans. Research in ocean sequestration of CO_2 involves multinational activities, with the scientific community involved in ocean fertilization through the National Science Foundation and the DOE Office of Science. The DOE-NETL program focuses on applied R&D and technology rather than basic research, but works closely with the basic R&D organizations in these areas.

One focus is on "value added" markets, early opportunities to achieve C sequestration. There are, for example, processes based on existing practices in the oil and gas industries. The U.S. has injected substantial amounts of CO_2 into depleted oil reservoirs, and the opportunity is there to build on such an existing industrial technology base. In some cases, CO_2 is taken out of the ground in one place and injected someplace else. This CO_2 could be replaced with industrial sources of CO_2. The DOE- NETL Carbon Sequestration Program could produce significant results if the costs of these technologies could be substantially reduced. The Program is expected to deploy some initial "value added" concepts by 2010, assuming that substantial reductions in costs can be realized. Other technologies are longer-term, as for example the biofixation of CO_2.

On January 7, 2002, the "Carbon Sequestration Technology Roadmap" was released. There ~~is~~ are also a White Paper and other publications on ocean and terrestrial carbon sequestration. These are part of the President's NCCTI, the National Climate Change Technology Initiative which involves a public-private partnership. The Roadmap document was to summarize the overall subject of carbon sequestration. Specifically, the following R&D Pathways are identified: (1) Separation and Capture; (2) Geologic Sequestration; (3) Terrestrial Sequestration; (4) Ocean

Sequestration; and (5) Novel Sequestration Systems. Biofixation of CO_2 would fall under the topic of "Novel Sequestration System", as part of the revolutionary advances that need to be stimulated by the Program. It can be expected that the Program will become actively involved in international carbon sequestration efforts.

The key questions to be asked regarding the concept of biofixation are:
What is known, based on research to date?
What additional knowledge is needed to assess the feasibility of economically viable options?
What R&D is needed to achieve that knowledge?
How can R&D needs be fulfilled without overlap and duplication?
Can an R&D Roadmap be developed based on present knowledge?
What are the basic and applied research needs to be addressed?
How can we move forward and engage the appropriate basic research community?

The funding for the DOE NETL Carbon Sequestration Program is now some $32 million. Last year it was $18 million. An increase is expected for next fiscal year. DOE is deeply committed to R&D, to developing revolutionary technologies and global collaborations in carbon sequestration efforts.

DOE/NETL Carbon Sequestration Websites are on the Internet as follows:
The NETL website is at www.netl.doe.gov/coalpower/sequestration/index.html. For links to DOE Headquarters websites for carbon sequestration, click on "Links" on the left side of the NETL Carbon Sequestration Home Page.

2. DR. PAOLA PEDRONI - STRUCTURE AND VISION OF THE NETWORK (See presentation, attached)

The Network will be formally organized and structured according to the IEA GHG R&D Programme's rules. The proposed vision is for a Network led by Participating Organizations through a Steering Committee and assisted by a Network Manager and Technical Advisory Panel. Participating Organizations will be from energy industries, governmental agencies and other R&D funding organizations. Governance is carried out by a Steering Committee, which would represent all members. The Network Manager, appointed by the Steering Committee, would be the main point of contact for technical matters, would coordinate and organize the technical work and would also work to expand the Network membership. The Technical Advisory Panels members, selected by the Steering Committee with the help of the Network Manager, would assist to formulate R&D goals and plans. The role envisioned for the Network is to promote technology development and applications of microalgae biofixation processes for GHG abatement. That is the broad mandate. Other goals are to promote information sharing and coordination between R&D projects.

The Network would focus on the use of concentrated CO_2 sources from power plant flue gases and other stationary sources, to produce microalgae biomass that is converted to renewable biofuels or energy sparing products. Applications foreseen are the development in the long-term of stand-alone processes for biofuels production and in the nearer-term applications in wastewater treatment, for examples. The selection of processes and products focus with best potential will be on the basis of economic analysis and GHG mitigation accounting.

Major R&D targets for the Network are to:
Select algal strains suitable to be mass cultured in open ponds or closed photobioreactors.
Manage algal species in mass cultures - algal species control and culture stability.
Maximize algal productivity under operative conditions.
Maximize algal biomass carbon storage products.
Development of large-scale low-cost cultivation systems.
Development of low cost processes for microalgae harvesting.
Improvement in the processes for conversion of biomass to fuels.
Practical demonstration for near term applications.

Proposed Network activities for 2002. Asides from formally initiating the Network, these include:
Confirm the members of the Technical Advisory Panel and the Network Manager.
Hold first Technical Meeting in Almeria, Spain, May 26, with the App. Phycol. Conf.
Develop the Strategic Plan ("Roadmap") detailing R&D topics, processes and targets for the period 2002 – 2006.
Hold the 2nd Technical Meeting in conjunction with GHGT6, Kyoto, Japan (Oct 1 –4)
Adopt Roadmap during 2nd Technical Meet, including assessment of state-of-the-art.
Develop and select potential field and collaborative projects.

3. JOHN DAVISON - NETWORK AGREEMENT (See presentation, attached)

Dr. Davison briefly described the role of IEA Greenhouse Gas R&D Programme and how the Biofixation Network fits in with the other activities of the Programme and topics to be discussed at this meeting: Draft Agreement, Budget and Fees.

The IEA GHG R&D Programme is one of over 40 Implementing Agreements of the IEA. Once set up, these operate essentially autonomously, with members contributing money and constituting an Executive Committee. Sixteen countries are members and some large industrial companies are affiliated with the GHG R&D Programme. Scope of the work of the Programme is set forth in the Implementing Agreement with a more detailed scope of work set out in Annex 1 (the only Annex). The overall objective is to organize R&D in "Technology relating to greenhouse gases derived from fossil fuel use". Tasks specified in Annex 1 include evaluation of technologies, dissemination of results, promotion of R&D, etc. Other IEA GHG R&D Programme agreements include saline aquifer storage (Sleipner Field, Norway), CO_2 enhanced oil recovery (Weyburn, Canada), oxygen-fired combustion with CO_2 recycle, CO_2 enhanced coal bed methane production and a network on CO_2 capture using regenerable solvent scrubbing.

The Draft Agreement for this Biofixation Network is largely based on what was had put together for these other activities. This Draft Agreement should be discussed, and comments are invited. Then it will be passed along to the lawyers and senior management of the potential participants in the network. The Draft Agreement will also have to be reviewed by the IEA lawyers in Paris. Then, the formal Agreement would be put forward at the next Executive Committee meeting of the Programme in April.

The Network would be governed through the members of the Steering Committee nominated by the Participating Organizations. The Network will be administered by a Network Manager not necessarily one of the participants. A panel of technical experts will advise on technical issues. The IEA GHG R&D Programme team will help with financial administration of the Network and help set up collaborative and practical R&D projects between members. The draft budget is for U.S. $100,000.

E. INTRODUCTIONS BY PARTICIPANTS (In order of introductions).

1. HEINO BECKERT, U.S. DoE/NETL Morgantown, West Virginia. Manages C sequestration projects. Proposals submitted by National Laboratories, universities, and private companies in response to NETL solicitations are submitted to an internal review and selected projects funded.

2. ROGER PRINCE, EXXONMOBIL, Annendale, New Jersey. ExxonMobil contributes to the IEA GHG R&D Programme and funds R&D on climate change. There is a substantial group in Dallas, Texas, dealing with these issues. ExxonMobil has some interest in microalgae R&D.

3. DAVID BARR, RIO TINTO Co., Melbourne, Australia. Rio Tinto is a major coal company, with 85 million tons of production in the U.S. Supports the IEA GHG R&D Programme through an Australian consortium. Rio Tinto is involved in various R&D activities. For example, it is a member of best practice assessments of coal gasification using different burner technologies. It is involved in rehabilitation of coal mine lands. It has a project on microalgae in the U.S. with a biotech company. Also studying bioreactors for microalgae culture. "We understand that it will take some time to get this commercial".

4. FRANK FERREL, US DOE HQ, Washington D.C. Mr. Ferrell is biotechnology program manager in the Office of Fossil Energy and is involved in all aspects of biological C sequestration, from microbiology to terrestrial systems. DoE is looking for R&D breakthroughs.

5. DAVE BEECY, US DOE HQ, Washington, D.C. Mr. Beecy is the US representative to the IEA GHG R&D Programme, the alternate is Dr. Perry Bergman, at DOE NETL. (See above).

6. GUISEPPE QUATTRONI, ENEL, Rome, Italy. ENEL is the largest electric company in Italy. His R&D work includes CO_2 sequestration projects, financed by the government and also internal funding. ENEL is carrying out experiments in the laboratory with microalgae, including use of closed systems (photobioreactors). They have a project for three years, including a feasibility study, to decide in the future what can be done.

7. BLAINE METTING, PNNL, Richland, Washington. Shares responsibility for fundamental sciences at PNNL, about one fifths of the $500 million R&D portfolio of this National Laboratory. This includes the Joint Global Change Institute, with Jay Edmonds. He is also project coordinator for National Climate Change Technology Initiative. Dr. Metting as a background in microalgae R&D, starting in the 1980's with studies of soil microalgae, including with a small biotech company that developed algal cultures for agriculture.

8. YUJI NAKAJIMA, Mitsubishi Heavy Industries, Yokohama, Japan. Works on improving microalgae productivity by reducing antenna pigments in microalgae, as published in several papers. Mitsubishi Heavy Industries has been involved in microalgae R&D for some years.

9. YOSHI IKUTA , NEDO (observer), Tokyo, Japan. The NEDO program concept emphasizing closed photobioreactors, in particular using optical fibers, was found to be not feasible for CO_2 mitigation. Other projects in Japan used open pond reactors, for example in the Kansai Electric Power Co. hydrogen production research. Also a one year continued operation of outdoor microalgae ponds using actual flue gas was carried out in 1992/1993 at Tohoku Electric Co. The result demonstrated that microalgae can be grown on flue gas without any pretreatment. However, that project aimed at solid fuels, which is not economical. Now Mr. Ikuta is working on using such systems for bivalve aquaculture. In future, he wants to apply microalgae technology for GHG reduction and fertilizer production in rice paddies.

10. VIPUL SRIVASTAVA, GTI, Chicago, Illinois. Director of biotechnology, Gas Technology Institute. GTI is merger of GRI (funding agency) and IGT (research performing organization). During late 70's and 80's GRI and IGT conducted research for supply of natural gas, some $50 to 60 million for growth of energy crops, use of CO_2 for enhancement of energy crops, and conversion to energy by gasification (thermal and biological). This work declined in the 90's but is picking up again. Biomass gasification activities ongoing. "Personally I work on water gas shift reactions." Now looking at biological as well as thermal approaches to biogas conversion.

11. PAOLA PEDRONI, ENITECNOLOGIE, Milan, Italy. EniTecnologie, the R&D arm of ENI Group, is actively engaged in carbon management to allow sustained use of fossil fuels. ENI Group is part of the Carbon Capture Project of BP and of the IEA GHG R&D Programme, for examples. The aim is to evaluate current technologies and to develop innovative options aimed at reducing fossil CO_2 emissions. Besides carbon sequestration, EniTecnologie is also interested in biological options. One and a half years ago, EniTecnologie, together with DOE, promoted the Network concept to the IEA GHG R&D Programme. The hope is to develop this technology in collaboration with other organizations interested in supporting R&D on microalgae biofixation and in promoting practical applications. The process being considered by EniTecnologie is to use flue gas from combined cycle power plants and feed it to algae ponds, settle the algae, and produce methane gas by anaerobic digestion. At this time, they are designing small outdoor simulation ponds. Future research will address how to maximize productivities and, by genetic or physiological means, overcome limiting factors, such as light saturation and respiration.

12. RENE WIJFFELS, Wageningen University, Wageningen, Netherlands, representative of prospective participants from the Netherlands. At the workshop last year, several participants from the Netherlands were present: Hans Reith of ECN, J.W. van Groenestijn of TNO, P. Claassen of ATO, and W.K. Heidug of Shell Global Solutions, in addtion to Dr. Wijffels, reflecting the interest in microalgae technology in the Netherlands. A study of microalgae biomass production was carried out in combination with pilot plant studies and the designs of ponds. Several research projects are ongoing, including research on separation of algae and extraction for high value products. How to increase the yield is a major question. One project is to combine high value products with wastewater treatment and energy production. That makes it

a very challenging project, due to conflicting goals. High value compounds have quality issues, not an issue for wastewater treatment. These goals maybe need to be separated. Larger scale systems would be for bulk applications and wastewater treatment and biofertilizer production, which is of some interest in the Netherlands.

13. EVAN HUGHES, EPRI, Palo Alto, California. EPRI is emphasizing co-combustion (co-firing) of biomass with coal. Dr. Hughes authored a recent report on GhG reduction by renewable energy sources.

14. JOHN BENEMANN, CONSULTANT. Participated as a technical adviser (see below).

15. JOHN DAVISON, IEA GHG R&D PROGRAMME. See above for his presentation.

F. DISCUSSION OF BIOFIXATION NETWORK AGREEMENT

John Davison introduced the Draft Network Agreement. The procedure is to discuss this Agreement, modify it as needed and have the IEA lawyers in Paris review it prior to acceptance by the ExCom at its next meeting. Based on comments and suggestions of participants, the following modifications/additions to the draft Agreement were discussed and agreed on:

1. The intellectual property appendix I and the paragraphs about damages (have been removed).
2. Confidentiality and provision of information within the Network have been addressed.
3. The difference between Full and Associate membership has been clarified.
4. The minimal number of Participating Organizations needed to make the Network operative.
5. Participation in and withdraw from the Network have been defined.
6. Details about the Network budget and membership fee ($9,000) have been added.

After this Organizational Meeting, Dr. Davison amended the Draft Network Agreement, it was reviewed by the IEA legal staff , and was circulated to the participants (Final Draft 2-4 attached).

G. DISCUSSION OF THE NETWORK BUDGET

The proposed budget for first year of activities was presented by John Davison. It depends on number of members and their contribution. It assumed a $100,000 budget, divided as follows: Network Manager $35,000, Technical Advisers $20,000; Meetings (two per year) $10,000; IEA Greenhouse Gas R&D $10,000; Other Overheads $5,000; Technical Assessments: $20,000.
Based on inputs and comments from participants, it was agreed that the membership fee for first year of activities will be of US$ 9,000 and that the details of the budget will depend on the initial number of participants and the formal initiation of the Network, expected to be by May 1, 2002.

H. DISCUSSION OF NETWORK ADMINSTRATION AND ACTIVITIES

John Davison outlined the governance of the Network: The participants in the Network form the Steering Committee that governs the Network and appoints the Network Manager. Technical experts will advise the Network and would be recommended by the Network Manager and approved by the Steering Committee. The nomination of John Benemann as Network Manager was unanimously approved by the participants in executive session. The appointment of the Network Manager will be decided by the Steering Committee on an annual basis.

John Benemann recommended six experts to the Technical Advisory Panel as initial members, listing their general background and areas of activities:
Amah Belay, Earthrise Farms, Inc., Calipatria, California; large-scale algal mass cultures
David Brune, Clemson University, SouthCarolina; microalgae wastewater treatment in aquaculture and agriculture.
Gerry Cysewski, Cyanotech Corp., Kona, Hawaii; large-scale algal cultures, flue gas CO_2 use.
Paul Roessler, Dow Chemical, San Diego, California; genetic engineering of microalgae.
Mario Tredici, University of Florence, Italy; algal physiology and photobioreactors.
Joseph C. Weissman, SeaAg, Inc., Vero Beach, Florida; algal physiology and mass culture
He also recommended Mr. Yoshi Ikuta, Tokyo, Japan, who has worked in microalgae utilization of CO_2 from power plant flue gases. He would be asked to be a Technical Advisor to the Network if he was not to representing a Japanese participating organization.

All have extensive experience in microalgae biotechnology and mass culture and could assist the Network and participating organizations in these R&D efforts. Additional members would be recommended later, as the budget may allow and needs dictate.

The participants discussed and agreed on the next two meetings for the Network:
1. Almeria, Spain, May 26, in conjunction with the 1st Congress of the International Society for Applied Phycology (9th International Conf. on Applied Algology), being held May 26 to 30, in Aguadulce, Roquetas del Mar, Almeria, Spain (isap02@ual.es, Chair: emolina@ual.es).
2. Kyoto, Japan, in conjuction with GHGT6, Oct 1–4, 2002 (ghgt@rite.or.jp, www.ieagreen.org.uk. (Note: Abstracts for presentations are due on February 28, 2002).
The roadmap effort (see below) would be discussed in some detail during the Almeria meeting and presented in draft form at the Kyoto meeting.

The participants also discussed and agreed on the need for information dissemination, including construction of a web-site and development of a brochure. Details would be finalized at the Almeria meeting.

I. DISCUSSION OF THE MICROALGAE BIOFIXATION ROADMAP

John Benemann presented some background to microalgae technologies and an introduction to the proposed "Roadmap" effort. The technical background is presented in the Rome, January 2001, Workshop Report, as well as a presentation at the May, 2001, DOE-NETL Conference on C Sequestration (available from John Benemann). Two reports on microalgae technologies for CO_2 mitigation and fuels production are available on request from Dr. Heino Beckert:
1. J. Sheehan, T. Dunahay, J. Benemann and P. Roessler, "A Look Back at the U.S. Department of Energy's Aquatic Species Program - Biodiesel from Algae". NERL/TP-580-24190. July, 1988.
2. J.R. Benemann, and W.J. Oswald, "Systems and Economic Analysis of Microalgae Ponds for Conversion of CO_2 to Biomass". Final Report to the U.S. Dept. Energy, March, 1996.

In brief, microalgae systems can be used for GhG mitigation by converting the captured CO_2 into gaseous or liquid fuels to replace fossil fuels, and, thus, fossil CO_2 emissions. Such systems can be stand-alone, in which the renewable fuel output and resulting CO_2 mitigation are the only economic drivers, or they can be "value added" processes, in which waste treatment, nutrient removal, co-production of higher value products covers some or even most of the costs. Only systems that have potential for scale-up and significant reductions in greenhouse gases would be of interest in this context. Co-production of pharmaceuticals or similarly very high-value products would be much too limited to satisfy this requirement for volume, but co-production of fertilizers or bioplastics would be of interest, as these are large-scale commodities.

Similarly municipal, agricultural and aquacultural wastewater treatment and other environmental applications, such as nutrient removal, would meet the requirements for significant greenhouse gas reduction potential. In the case of wastewater treatment, there is also potential for reduction of other GhGs, methane and nitrous oxide. (See J.R. Benemann, "Greenhouse Gas Emissions and Potential for Mitigation from Wastewater Treatment Processes, U.S. DOE-NETL, December 2001, available from the author). In the near- to mid-term the development and applications of such value-added processes would be emphasized. However, the longer-term, and much larger impact potential of stand-alone processes should also be considered and developed.

Another central issue is the so-called photobioreactor in which the algal process would take place. Closed photobioreactors, of the tube, flat-plate, bag or any other design type (and there are many variations on these themes) are not appropriate for present applications, because of high costs. They would find some utility in inoculum preparation and culture build-up. Open ponds are of sufficiently low cost, capital and operating, to be considered for CO_2 biofixation. Research is also required to achieve higher productivities by microalgae mass cultures. The work carried out by Dr. Nakajima at Mitsubishi Heavy Industries, has demonstrated that microalgae strains with reduced antenna pigments exhibit increased productivities (light conversion efficiencies) at high light intensities, overcoming a major limitation in this field. Other research issues are culture stabilities, harvesting, processing (e.g. conversion to fuels), among others.

The objective of the Network is to integrate and coordinate R&D activities by the participating organizations, to allow a broad coverage among the many issues requiring R&D, from the benchscale to the field. This is the most plausible route to developing this technology, which is not likely to be achieved by any single organization or R&D program. To plot the best route for such technology development, the U.S. DoE uses a "roadmap" approach, which will also be followed in the present case. The Overheads that follow below review this approach. The first one summarizes the Technology Roadmap for Carbon Sequestration report issued January 7, 2002 by DOE-NETL and provides some background to roadmapping. Essentially this is based on expert advice regarding outstanding R&D issues and best approaches to accomplish the goal.

Overhead 2 provides some more specifics on the roadmapping effort, and, most importantly, lists six general "Technology Characterization Pathways" for microalgae biofixation. These are the processes that could be developed to a practical level in the near- to long-term. These approaches would, after description, refinement, and "buy-in" from the Network participants and technical advisers, become the focus of the R&D efforts in this field. Bench, outdoor test, and pilot-scale projects under the Network would be related to one or more of these approaches to practical mitigation of CO_2 and other greenhouse gases. For example, the first listed technology is the use of microalgae processes for nutrient removal from agricultural drainage waters and runoff, as well s other agricultural sources, such as aquaculture.

A specific example is the development and application of such a technology at the Salton Sea, in California, where over 10,000 tons of nitrates and phosphates enter this lake from near-by agricultural operations. Some two thousand hectares of algal ponds could capture these nutrients and generate sufficient fuels from the algal biomass to mitigate over a hundred thousand tons of fossil CO_2. With most costs covered by the benefits of pollution prevention and fertilizer recycling, such a process could be implemented in the relatively near-term, as the very high productivities and low costs required for stand alone systems (e.g. process 6, Overhead #2) would not be required. Similar arguments apply to wastewater treatment systems (Process 2).

Process 3 is envisioned to help develop the technology for recycling or producing (through nitrogen fixation) organic nutrients (also required in the other processes), using existing large-scale microalgae (e.g. Spirulina) production systems. This could demonstrate the feasibility and scale-up of such processes. Process 4 proposes to integrate industrial wastewater treatment with higher value products and Process 5 covers "novel" concepts, such as fertilizer production. These are examples of practical approaches to GhG mitigation with microalgae.

Overheads #3 and #4 lists a dozen main categories of R&D needs and their integration, following the roadmapping methodology. All R&D needs support the development of the above discussed processes, allowing for a large degree of synergy between R&D projects. Overhead #5, outlines some issues to be addressed by the roadmapping effort, the first task to be carried out by the Network.

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

Carbon Sequestration Technology Roadmap
Pathways to Sustainable Use of Fossil Energy

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 #2

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 #3.

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 #4.

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.