CONF-930285

A Report from the Second U.S./Japan Workshop on Global Change Research: Environmental Response Technologies (Mitigation and Adaptation)

United States - Japan Science and Technology Agreement

February 1-3, 1993

Hosted on behalf of the
U.S. Committee on Earth and Environmental Sciences (CEES)

by the

Program on Resources
East-West Center
Honolulu, HI

Compiled by Sylvia Edgerton, CEES, National Science Foundation (USA) and Tateki Mizuno, National Institute for Resources and Environment, NIRE, MITI (Japan)

TABLE OF CONTENTS

Acknowledgments

We thank Betty Wong of the National Science Foundation, as well as Patty Crabtree and Marvel Burtis of the Carbon Dioxide Information Analysis Center, Environmental Sciences Division, at Oak Ridge National Laboratory, for their assistance in word processing and assembling this document. We would also like to thank Jane Smith-Martin and Terry Koki of the East-West Center for administrative support during the workshop. Oak Ridge National Laboratory is managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under Contract DE-AC05-84OR21400.

U.S. - Japan Science and Technology Agreement

Second Workshop on Global Change Research: Environmental Response Technologies

February 1-3, 1993
East-West Center
Honolulu, Hawaii

Workshop Communique

The Joint High Level Committee of the U.S. - Japan Science and Technology Agreement, Co-Chaired by the Assistant to the President for Science and Technology in the U.S., and the Minister of State for Science and Technology of Japan, have identified leading areas of scientific research of interest to the two countries. One of the major areas of importance concerns joint research on high priority scientific and technical questions related to global change, including development of response technologies. The Liaison Group on Global Geosciences and Environment of the Joint Working Level Committee of the U.S. - Japan Science and Technology Agreement scheduled a Second Workshop on Cooperative Research on Global Change to focus on response strategies, including technologies related to global change mitigation and adaptation. The First Workshop was held in November, 1991, in Tsukuba, Japan, and focused on climate and hydrologic cycles, ecological systems and dynamics, and global change interactions in polar regions.

The Second U.S. - Japan Workshop on Global Change: Environmental Response Technologies for Global Change was hosted by the Program on Resources at the East-West Center, in Honolulu, Hawaii on February 1-3, 1993, on behalf of the United States Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). This workshop brought together over fifty leading scientists from the two countries to review existing technologies and to identify needed research on the development of new technologies for mitigation and adaptation of global change. The Workshop was organized around three areas of research: (i) capture, fixation/utilization, and disposal of CO_2 (e.g. CO_2 separation and capture technologies, ocean and land disposal of CO_2); (ii) energy production and conservation technologies to reduce greenhouse gas emissions (e.g. combustion efficiency, non-carbon based energy technologies, energy conservation technologies); and (iii) adaptation technologies and practices related to global climate change (e.g., adaptation responses of crops to climate change, adapting urban infrastructure for climate change). Priorities for joint research in each of these areas were discussed.

The Workshop recognized the importance of existing bilateral agreements between the U.S. and Japan which are relevant to the topics of discussion. The Workshop recommended that these agreements be reviewed for their relevancy to these topics and strengthened where necessary. The Workshop also suggested that the two countries review the need for additional bilateral agreements in some areas.

The Workshop strongly recommended that the two countries continue to foster joint research and scientific discussion, recognizing the potentially critical contribution that Japan and the U.S. can make to international global change research efforts in evaluating potential options for responding to climate change.

Both the United States and Japan are parties to the Framework Convention on Climate Change, the ultimate objective of which is "to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The Convention also encourages cooperation among the developed nations to achieve the objectives of the Convention.

The Workshop, through its Co-Conveners, herewith forwards the Workshop Report to the Liaison Group on Global Geosciences and Environment for consideration by the Joint Working Level Committee and the Joint High Level Committee.

Signed on February 3, 1993, by the U.S. Co-Conveners of the Second U.S. - Japan Workshop on Global Change Research:

Robert M. Simon

Robert M. Simon
Principal Deputy Director
Office of Energy Research
U.S. Department of Energy

Gary R. Evans
Special Assistant
Global Change Program Office
U.S. Department of Agriculture
Co-Chair, CEES Working Group on
Global Change Assessment

Signed on February 3, 1993, by the Japanese Convener of the Second U.S. - Japan Workshop on Global Change Research:

O. Yokoyama

Osayuki Yokoyama
Director-General
National Institute for Resources and Environment
Agency of Industrial Science and Technology
Ministry of International Trade and Industry

SECOND U.S./JAPAN WORKSHOP ON GLOBAL CHANGE: ENVIRONMENTAL RESPONSE TECHNOLOGIES (MITIGATION AND ADAPTATION)

OVERVIEW OF WORKSHOP:

The second U.S.-Japan Workshop on Global Change was planned and organized under the aegis of the U.S./Japan Science and Technology (UJST) Agreement. The High Level Committee for the UJST decided in 1989 to support the conduct of U.S./Japan workshops to encourage joint research on high priority scientific and technical questions related to global change. The second global change workshop under UJST was hosted by the U.S. Committee on Earth and Environmental Sciences (CEES) on February 1-3, 1993, and held at the East-West Center, in Honolulu, Hawaii. The subject of the Workshop was Environmental Response Technologies (Mitigation and Adaptation).

It was agreed that the workshop should:

- identify areas in which cooperative research and information exchange on environmental response technologies and practices related to global change would be productive;
- identify topics of high scientific interest and needed research within each area; and
- identify potential mechanisms of research cooperation for consideration by both governments.

Participants in the Workshop included more than fifty scientists from Japanese and U.S. research institutions, universities, and government agencies. The Workshop was chaired by Drs. Robert Simon from the U.S. Department of Energy (DOE), Gary Evans from the U.S. Department of Agriculture (USDA), and Osayuki Yokoyama from Japan's National Institute for Resources and Environment (NIRE). The Workshop participants divided into Working Groups to address three areas of special emphasis:

I. CO_2 Capture, Fixation/Utilization, and Disposal (Working Group I)

II. Energy Production and Conservation Technologies To Reduce Greenhouse Gas Emissions (Working Group II)

III. Adaptive Technologies and Strategies, e.g., urban infrastructure, forest management, adaptation of crops to climate change (Working Group III).

Dr. Frederick Bernthal, Chair of the CEES, gave the keynote address in which he reaffirmed the commitment of the U.S. toward global change research and the continuation of collaborative work with Japan in this area. Dr. Yokoyama presented a plenary address in which he showed the present status of research activities in Japan and introduced the Japanese New Earth 21 Project. Dr. Simon, in his plenary address, pointed out the need for symmetrical technological benefits to the U.S. and Japan from any cooperation in environmental technologies.

Working Group I identified ocean disposal of CO_2 as the most fruitful research area for cooperation. Research on CO_2 capture was also identified as offering significant opportunities. However, current methods are likely to be both expensive and energy intensive, and methods to lower capture costs need to be studied. Although Japan has a very active program in CO_2 fixation and utilization, the participants suggested that these methods will require a long-term commitment to yield desired benefits, since utilization is feasible for only a small fraction of the CO_2 produced, and fixation requires a large outside energy source.

Working Group II concentrated on six key areas of emission reduction technologies: (1) energy conservation, (2) coal combustion and advanced gas turbines, (3) fuel cells, (4) energy from biomass, (5) other renewable energy, and (6) transportation. The Working Group proposed that information be exchanged between the U.S. and Japan to provide an initial indication of the state of technology development in each country on integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC). The Working Group also concluded that use of renewable biomass energy can play a greater role in addressing global warming than growing biomass solely for carbon sequestration. Collaboration between the U.S. and Japan in the area of high-pressure biomass conversion was proposed.

Working Group II also recommended that information be exchanged on non-proprietary areas related to fuel cell development, such as the research on the potential impact of fuel cells on global CO_2 emissions and the economics of, and government incentives for, fuel cell development and deployment. Recognizing the potential for reducing CO_2 emissions through the electrification of vehicles, the group recommended international cooperation in the development of standards for electric vehicles. The Working Group proposed that a shared database be developed on energy efficiency/conservation practices and their costs and benefits to assist with the development of common perspectives on renewable energy options.

The focus of discussions in Working Group III were on adaptation of urban infrastructure and agricultural systems to climate change. The Group discussed how to protect and/or manage agricultural and forest systems to reduce their contribution as a source of greenhouse gases and to enhance their role as a sink. Joint research was proposed in studying crop response to climate change.

Group III further recognized the need by developed countries such as the U.S. and Japan to acquire new knowledge about the organization and design of energy-efficient cities capable of sustaining a mixed system of energy production, and minimizing energy costs associated with residential, industrial, and recreational activities, and the movement of people.

The results and recommendations of each of the Working Groups are summarized in this report which will be forwarded to the Liaison Group for Global Geosciences and Environment for their approval and further conveyance to the Joint Working Level and High Level Committees for their consideration and approval.

WORKING GROUP REPORTS

SECOND U.S./JAPAN WORKSHOP ON GLOBAL CHANGE: ENVIRONMENTAL RESPONSE TECHNOLOGIES (MITIGATION AND ADAPTATION)

February 1-3, 1993

WORKING GROUP SUMMARIES

SUMMARY REPORT OF WORKING GROUP I CO_2 CAPTURE, FIXATION/UTILIZATION, AND DISPOSAL

INTRODUCTION

The topics of our working group were divided into four key areas: CO_2 Capture, Utilization/Fixation, Ocean Disposal, and Land Disposal. Fourteen presentations were made as follows:

> CO_2 Capture: Toshikatsu Hakuta (Japan) and Rod Judkins, Bruce St. John, and Alan Wolsky (US).
>
> Utilization/Fixation: Hironori Arakawa, Yasuo Asada, and Takashi Ibusuki (Japan) and Ed Lipinsky (US).
>
> Ocean Disposal: Yuji Shindo (Japan) and Eric Adams, Gerard Nihous, and Wheeler North (US).
>
> Land Disposal: Shoichi Tanaka (Japan) and Roger Bailey (US/Canada).

Co-chairs for this working group were Toshikatsu Hakuta (Japan) and Howard Herzog (US).

This document contains only a summary outline of research needs in the area of CO_2 capture and sequestration. It should be used in conjunction with other assessments made in this area. For the U.S., a DOE report entitled *A Research Needs Assessment for the Capture, Utilization and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants* will be forthcoming in 1993.

GENERAL R&D NEEDS

The area most fruitful for cooperation is Ocean Disposal research because both the U.S. and Japan agree that this is a high priority topic for CO_2 capture and sequester research and that it is a large and costly research area that would greatly benefit from collaboration. The general R&D needs for all four CO_2 capture and sequestration areas are outlined below.

The feasibility of CO_2 capture has been proven, but it is both expensive (almost doubles the cost of electricity for a coal-fired power plant) and energy intensive (reduces coal-fired power plants overall efficiency by about 35%). Research needs to focus on lowering these costs by developing better separation techniques and optimizing plant designs (e.g. through integrating the power plant with the capture plant). One way to significantly lower capture costs is to introduce new power plant technology like Integrated Gasification Combined Cycle power plants and/or fuel cells. However, the working group reached no consensus on whether to focus research on retrofitting existing power plants or working with new plant designs.

The area of CO_2 fixation and utilization is an area Japan is very active in, with research into biological and artificial fixation. In the U.S., opinions are diverse with regard to the promise for using this route for CO_2 capture and sequestration because CO_2 utilization will use only a small fraction of the CO_2 we produce and CO_2 fixation requires a large outside energy source. However, in a broader sense, the U.S. finds some of this research important and is supporting research in this area for reasons other than CO_2 capture and sequestration. Examples include artificial photosynthesis and catalyst development (e.g. to convert water to hydrogen and oxygen). Research in this area will require a long-term commitment to yield the desired benefits.

The weakest link in CO_2 capture and sequestration schemes is deciding what to do with the CO_2 once it is captured. Ocean disposal is a promising solution, but many questions must be resolved before it becomes feasible. Many ocean disposal schemes have been proposed, but their feasibility has not been proven with respect to cost, time of CO_2 sequester, and environmental effects. Japan has focused on deep injection schemes, which would maximize residence time for the CO_2, but is relatively costly. The U.S. has focused on shallower injection schemes, which would have reduced costs. There is much room for fruitful collaboration in this area, ranging from research on basic issues like determining CO_2 hydrate kinetics and properties to large scale pilot projects, where cost sharing would greatly benefit both sides.

Of all the disposal options, storage of CO_2 in active or depleted oil and gas reservoirs is the most promising disposal option, where available. Storage in aquifers may be viable, but little is known about this land disposal option or its feasibility. The U.S., with its large land mass and its predominantly sedimentary geology has many land disposal options. Japan, with its relatively small land base and volcanic geology, does not. However, the U.S. and Japan can find some common interest in helping develop Enhanced Oil Recovery (EOR) with CO_2 sequester in some of the world's oil production areas, like the Middle East or Asia. In the long-term, exporting CO_2 mitigation technology to the third world will be essential for controlling the atmospheric build-up of greenhouse gases.

MECHANISMS FOR COOPERATION

Since it is unrealistic to expect an immediate dramatic increase in U.S. research funds in the area of CO_2 capture and sequestration, we propose the following mechanisms for initial collaboration in the near-term, which can be accomplished at modest cost and will allow for our interactions to increase as the research programs in this area increase.

1. *Information Exchange.* Information exchange can include workshops on areas of mutual interest (e.g. ocean disposal) and establishing a visiting scientist/engineer program for both short-term (month or less) and long-term (up to 2 years) durations.

2. *Coordination of Research* currently on-going in both countries. For example, research into CO_2 hydrates is a good example of a program that would fit into this category. This field is quite large and would benefit from research coordination, instead of both countries "reinventing the wheel".

3. *Joint Research* with funding from both countries on projects modest in scope (less than 1 year duration). An example of an appropriate project for joint funding is to define the required purity specifications for the captured CO_2 stream for a variety of disposal options.

4. *Joint Projects* that are large in terms of expense and duration. The project identified as most appropriate in this area is the building and operating of an ocean disposal pilot plant for the purpose of field testing various ocean disposal strategies and their environmental effects.

The working group brought up three areas of concern that need to be addressed before a successful joint program can be implemented:

1. Japan has a strong research program currently on-going in the area of CO_2 capture and sequestration with well-defined goals and well funded programs. The U.S. research in this area to date has been ad-hoc, with minimal funding coming from a variety of sources, including some funding from Japan. The U.S. needs to define the role and priority of CO_2 capture and sequestration as a greenhouse gas mitigation option.

2. Carbon dioxide capture and sequestration is only one of several mitigation options. CO_2 capture and sequestration must be integrated into an overall greenhouse gas mitigation program.

3. Other countries such as the Netherlands and Norway have aggressive research programs in this area. Also, an international program under the

auspices of the International Energy Agency is in existence. Bilateral cooperation between the US and Japan should complement these efforts and, where appropriate, the collaboration should be expanded to include other countries.

SPECIFIC AREAS FOR COOPERATION

Attached are eight specific proposals for proposed U.S./Japan cooperation. As stated earlier, ocean disposal research is the most fruitful area for cooperation, with CO_2 capture also offering significant opportunities. On the other hand, land disposal research offers few opportunities because of the very different conditions in the U.S. and Japan. Utilization/fixation also offers opportunities for collaboration, but their scope is beyond the strict bounds of CO_2 capture and sequestration.

Research areas for information exchange:

- CO_2 hydrate research
- Environmental benefits of CO_2 EOR
- Hydrogen from water using new catalysts
- Utilization of CO_2 using natural and artificial photosynthesis

Areas for research coordination:

- CO_2 hydrate research
- Separation methods, particularly membrane separation, of H_2-CO_2 and N_2-CO_2

Joint research projects:

- Determine allowable impurity levels for CO_2 capture product for various disposal methods
- Space shuttle experiment on catalytic conversion of water to hydrogen

Joint research program (may be multilateral):

- CO_2 ocean disposal pilot plant

SUMMARY REPORT OF WORKING GROUP II
REDUCTION TECHNOLOGIES

It is generally accepted that major environmental problems, such as the greenhouse effect, destruction of the ozone layer from CFC's, acid rain due to air pollution by NO_x and SO_x, etc., are caused by excessive industrial and residential energy consumption. Considering the finite world energy resources and limited global space, the day might be already upon us in which the total amount of energy consumption in the world would need to be reduced. To maintain a high living standard without increasing energy consumption, waste energy recovery and energy conservation are vitally important.

In order to meet our energy needs while minimizing greenhouse emissions and other environmental impacts, we need to understand:

- the nature of the energy consumption process
- the characteristics of our energy resources
- the potential of a given technology within the context of available resources and due regard for the ability to reduce emissions.

The Group operated very well and quickly established a degree of comfort with one another (the Aloha spirit) that permitted free and open discussion. This was fortunate in view of the complexity of the subject.

The subject of reduction technologies cuts across all energy use sectors, involving consideration of energy supply, energy demand, and energy utilization. It includes challenges of technology development, the problem of deployment and implementation, with a particular emphasis on technology transfer to the developing world. It is further complicated by giving appropriate recognition to the proprietary concerns of industry and the issue of economic competitiveness. Never the less, cooperation between the U.S. and Japan in providing leadership to the world community is both possible and essential if we are to reduce the likelihood of catastrophic global climate change.

By necessity, the direction of technology cooperation is linked to the choice of specific technological areas. Therefore we chose to concentrate on six key areas as the subject of the working group on reduction technologies. The areas chosen were energy conservation, coal combustion and advanced gas turbines, fuel cells, biomass, other renewable energy, and transportation. A total of thirteen presentations were made along these topical these areas. The working group then broke into the discussion subgroups shown in Table 1, to develop research proposals.

Table 1

Working Group II: Reduction Technologies Presentations and Discussion Groups
U..S. Chairs: H. Hubbard, C. Bloyd Japan Chair: K. Hijikata

Subject	U.S.	Japan
1. Energy Conservation	R. Carlsmith H. Hubbard* C. Bloyd*	K. Hijikata
2. Coal Combustion & Gas Turbines	D. South	H. Moritomi K. Suzuki
3. Fuel Cell	D. Keinschmidt*	H. Takenaka
4. Biomass	C. Kinoshita	S. Yokoyama
5. Other Renewable Energy	T. Bath	M. Akai
6. Transportation	H. Courtright	H. Shimizu

---

* did not present papers, but participated in the discussion group.

1. ENERGY CONSERVATION

Members of the Subgroup agreed that energy conservation was an issue that included all energy sectors, i.e., utilities, transportation, manufacturing processes, residential consumers, and businesses. It is a matter of concern both with regard to the development of new and improved technologies for the supply, distribution and utilization of energy as well as the social, behavioral and economic factors affecting energy and demand.

In the U.S. the term "energy conservation" most often is applied to efforts to reduce energy consumption in the residential and business sectors and to promoting the use of energy efficient devices. Various approaches to addressing these goals have been used in both the U.S. and Japan and applied as well to the question of improving efficiency in industrial processes, transportation of people, goods and materials and the development of more energy efficient infrastructure.

While much of the subgroup discussion dealt with the in-country (domestic) conservation of energy, it was also pointed out that energy conservation, i.e., the improvement of the efficiency of energy use in developing countries was critical to a significant reduction in greenhouse gas reduction.

In the energy conservation session, three very different and very interesting papers were presented illustrating both the importance and breadth of the topic.

Dr. Carlsmith discussed the broad subject of the "Potential For Energy Conservation in the United States", pointing out that the DOE National Laboratories had "estimated that the technical efficiency of energy use can be increased by 25 percent by the year 2010 through gradual adaptation of cost-effective technologies" and that "with this improvement in efficiency total U.S. energy us in 2010 would be only 10 percent higher than it is today." Policy changes will be required if total energy use is to be lowered.

Prof. Hijikata in his paper stressed that to make effective use of energy resources we must clearly understand the nature of energy consumption and the characteristics of energy resources. In his paper the, "technological aspects of energy conservation as stated from the standpoint of available energy" were discussed and evaluations were made of various fossil fuels on a quality basis as measured by energy, a ratio of entropy to enthalpy.

Mr. Coutright's paper from the Electric Power Research Institute in the United States discussed "Energy Conservation Technologies". He pointed out that "even though uncertainties exist on the degree and causes of global warming, efficiency improvements in end-use applications remain in the best interest of utilities, their customers and society" because efficiency improvements reduce environmental exposure, increase industrial productivity, reduce business costs, and provide consumer savings. The paper reviewed equipment efficiency improvements and increased energy efficiency potential from the continuing development of electrotechnology.

It was recognized that cooperation and information exchange must take into consideration the propriety nature of efficiency improvements in devices and processes but that cooperation in the basic underlying research issues, pre commercial technology and approaches to deployment and implementation will be helpful to both sides in addressing both national and international aspects of global climate change.

2. COAL COMBUSTION AND GAS TURBINES

Presentations by representatives of both the United States and Japan indicated that 1) fossil fuel combustion produces carbon dioxide (CO_2) and other greenhouse gas

(GHG) emissions, 2) the large worldwide fossil fuel resource base and economic development plans of developed/developing countries will likely rely on this resource, and 3) advances in the efficiency of coal combustion and conversion systems could substantially reduce future CO_2 emissions and thereby permit the continued use of coal-based technologies for the production of power, electricity and other chemicals.

Both nations recognize the importance of coal-based technologies and have independent RD&D programs (e.g. the Sunshine Program in Japan and the Clean Coal Technology Program in the U.S.) to develop 1) advanced coal combustion and conversion technologies, 2) coal handling and preparation systems, 3) coal liquefaction technologies, and 4) advanced materials and technologies for combustion/conversion systems and turbines.

Under the US/Japan Bilateral Agreement it is proposed that:

> an information exchange program be established to facilitate the accelerated deployment of advanced coal technologies into domestic and worldwide markets; and
>
> the comparative economics and market potential of advanced coal technologies be investigated.

These joint research proposals were suggested because:

1) CO_2 and other GHG emissions are a growing concern and only through an accelerated RD&D program, where the efficiencies of coal technologies are improved, can these emissions be reduced and continued reliance on the technologies be ensured.

2) Both countries would likely benefit from an exchange of information on their RD&D programs, so as to accelerate the commercialization of the technologies under development.

3) There are many technical developments necessary to advance the state of knowledge and the strengths of each nation's research could be drawn on through a coordinated effort.

4) There is a need to both appreciate and standardize the technology configurations, performance characteristics and cost estimation procedures to ensure that a) accurate comparative analyses can be performed and b) necessary economic/regulatory incentives to overcome technological or market barriers for commercialization can be determined.

The information exchange program proposes separate initiatives for integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC). In each program Japan and U.S. representatives would compile a list of the RD&D projects currently underway. This list would be exchanged as an initial indication of the state of technology development in each country. It is proposed that a series of meetings (with site visits to RD&D facilities) be arranged to learn more about each country's coal- based RD&D program and ongoing research, and to identify areas of mutual interest and potential collaboration. Of particular interest is 1) basic materials and fundamental technology research and 2) demonstration/commercialization activities (e.g., the joint industry/government funded Clean Coal Technology Program in the U.S., and the Sunshine Program in Japan).

The comparative economics and market potential program was proposed in response to the need to:

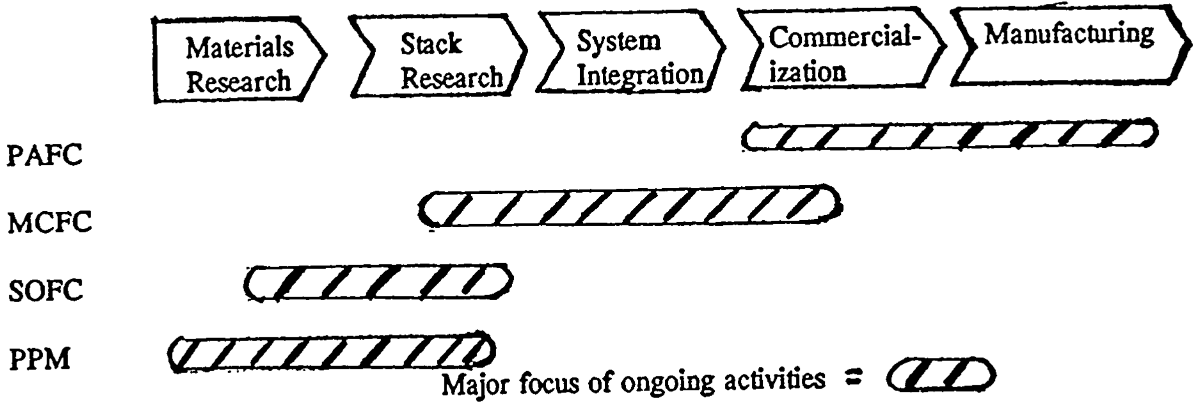
1) standardize cost/performance information to facilitate cross-country technology evaluations

2) assess the role and opportunities for technologies to serve future power, electricity and chemical needs in developed/developing countries, and

3) determine if (and what type/level of) incentives are needed to overcome technological risks or market barriers.

3. FUEL CELLS

It was agreed that fuel cells can dramatically reduce CO_2/NO_x emissions in utility, industrial, commercial, and transportation applications. Significant fuel cell research is being sponsored by both government and private funding in Japan, the U.S. and Europe. It was recognized that fuel cells are in varying states of commercialization and significant technical hurdles remain. Assuming the technical hurdles are overcome, manufacturing costs for PAFC, MCFC, and SOFC systems will remain a major commercialization barrier. The major focus of activities by fuel cell type is shown below.



Agreement was also reached that:

- Fuel cell technologies are at differing states of development.
- The majority of the development activities are considered proprietary and manufactures will be reluctant to collaborate (other than with formal arrangements).
- Manufacturing costs for systems are an area of major concern and would benefit from additional study but are subject to proprietary concerns.
- This type of continuing information exchange on technology, economics, market, impacts on global CO_2 emissions, etc., is beneficial.

A variety of support needs exist as shown below:

Economics	Applications	Markets	Analytic Tools
Methods	New end uses	Gov't Incen.	Global impacts
Manufacturing	Values	High value markets	System costs
MCFC/CO_2 concentrator			

Of these, global impact and government incentives would be most relevant to this type of forum. Both of these topics are of interest to manufactures, but would not be considered proprietary.

4. REDUCTION TECHNOLOGIES — BIOMASS

Renewable bioenergy, i.e., biomass produced in a sustained manner and utilized as a modern energy carrier, can play a greater role in addressing global warming than growing trees solely for carbon sequestration — under the renewable bioenergy strategy, the contribution of biomass in remediating global warming would not be limited to the time scale of forest maturity; moreover, the economic potential for biomass appears to be greater if it were used as a clean substitute for fossil fuels than planted just to capture carbon.

Biomass ranks fourth in the world as an energy resource, and is the most important source of energy in developing nations; however, the contribution of biomass to the energy mix of developed nations is relatively small. While wastes and crop residues offer many viable near-term opportunities for significant penetration of biomass into the energy mix of industrialized nations, in the long term, fast growing energy crops will have to be grown if biomass is to become a significant energy resource.

Estimates of the extent to which biomass can be tapped to supply useful energy and, in turn, help to stabilize atmospheric carbon dioxide vary widely; nevertheless, most studies suggest that the amount of land required for growing high-yielding energy crops to displace a significant portion of currently consumed fossil fuels would not be prohibitively large (i.e., such crops could be grown on a fraction of the land presently in crops, pasture, and forests). Since a major portion of the ultimate cost of marketable energy (e.g., electricity or transportation fuels) is attributable to the cost of feedstock delivered to an energy-conversion plant, developing more productive and less costly means to grow, harvest, and transport energy crops is essential to the future health of bioenergy. Moreover, since the biomass potential and the future need for energy is much greater for developing nations than for industrialized nations, any effort to increase the role of biomass in the world's energy mix must target developing nations. To that end, it is recommended that assessments of bioresidue resources and the potential for producing energy crops, focusing on developing nations, be undertaken.

One specific issue that must be addressed in considering the siting of biomass-for-energy farms is the impact on biodiversification of mono-cropping with fast-growing energy species. Ongoing improvements in energy-crop species and cultural practices have the potential to bring the cost of delivering biomass feedstocks to a level competitive with coal within the next decade. However, costly large-scale energy crop demonstrations will be required to provide the information needed to commercialize the concept of dedicated bioenergy feedstock farms.

Several biomass energy conversion processes show promise and are approaching commercialization; but many promising concepts face technical obstacles that require substantial research and scale-up funding. There was no consensus on which conversion alternatives showed the greatest promise (this lack of consensus largely reflects the diversity of options available with bioenergy). One technical obstacle in the advancement of virtually all bioenergy conversion concepts is the overall lack of understanding of the environmental impacts of conversion processes; therefore, having actual inventories or projections of effluent streams from alternative thermochemical and biological biomass-energy conversion processes would greatly facilitate the siting and permitting of precommercial projects. Research on high-pressure biomass conversion was of mutual interest to the research teams in the workshop's Biomass subgroup; future collaboration in that area is planned.

5. OTHER RENEWABLE ENERGY

The parties agree that energy derived from renewable resources must be a very important component of any response to global warming concerns. We further agree that existing technology-specific information and collaboration efforts are appropriate to our mutual need and any further augmentation of these runs the risk of violating propriety concerns on both sides. We agree that renewable resources characterization of all kinds are of critical interest. Japan is primarily interested in the characterization of resources outside of Japan since its land costs are high and its territory limited. The U.S. is primarily interested in characterizing domestic resources first and global resources second. We have proposed a project in this area bridging the interests of both sides. We also feel that there is benefit to sharing information on processes and tools to inform energy decision-makers and we have proposed a joint project in this area.

6. TRANSPORTATION ISSUES

Agreement was demonstrated during the presentations on the potential for saving primary energy and therefore reducing CO_2 emissions through the electrification of vehicles. The range of efficiencies showed the potential differences from traditional vehicles utilizing electric propulsion versus vehicles specifically designed for electric drives.

Working group discussions focused on:

- Infrastructure-- the need for international cooperation (including Europe) in the development of standards for vehicles changing, safety and maintenance. This will facilitate a global market for electric vehicles (EVs) from any country and maximize emission reductions.
- Vehicle design-- the importance of total integration of components designed specially for EVs to maximize performance and range. This will also contribute to maximum emissions reductions.
- The feasibility of a vehicle manufacturer consortium should be investigated; especially with small specialized EV developers and EV components.
- Battery development appears to be well organized in both countries and joint participation in research may not be practical due to proprietary concerns.

SUMMARY REPORT OF WORKING GROUP III
Adaptation Technologies

Introduction

Working Group III was co-chaired by Dr. Gary Evans, United States, and Drs. Tsuruta and Kontani from Japan. The working group participants were as follows:

Urban Infrastructure	Dr. Takashi Kawanaka, HRI Dr. Kazuo Kontani, MEL Dr. William Sommers, USDA Forest Service
Forest Management	Dr. William Sommers, USDA Forest Service Dr. Gregg Marland, DOE Dr. Takao Fujimori, FFPR
Crop Response	Dr. Hiroshi Seino, NIARS Dr. Hugo Rogers, USDA
Agricultural Methane	Dr. John Duxbury, Cornell University Dr. Haruo Tsuruta, NIAES
Soil Management	Dr. Lee Mulkey, USDA

The range of discussions in this working group not only focused on global climate change, but also included a broader scope that encompassed global environmental change. These discussions involved not only the physical and biological components, but also human lifestyle and well-being.

Because of the broad spectrum of the participants backgrounds, the discussion was carried forward in a very lively manner and resulted in a very constructive interaction.

Urban Infrastructure

Urban infrastructure represents one of the newest topics to enter the sphere of global change discussions. Discussion in this workshop recognized that in addition to understanding the effects of increasing greenhouse gases on physical and biological systems, there is also a need to understand climate change effects on the human community. This workshop takes pride in the fact that discussion on this topic was started. Exploration of this complex and not well understood issue was started by reviewing concepts from three diverse scientific disciplines, including urban planning and architectural design research, urban forestry research, and motor vehicle engineering research. The discussions focused on the fact that end user energy efficiency of the individual should become a major goal of new research programs, either through the design of integrated, energy efficient elements in a city structure, or designs that will minimize the energy costs of moving people over long distances between places of work, residence and participation in other social activities. It was also recognized that a need exists to develop new knowledge about the organization and design of energy efficient cities capable of sustaining a mixed system of energy production, energy transfer from residential, industrial, social and recreational activities and the movement of people.

The need to develop trees and other plants with the biological capability to overcome urban stresses is a research priority for urban forestry, when used as a technology for reducing energy consumption. It was also clearly recognized that commuting to and from urban hubs in industrialized countries consumes the largest amount of the petroleum in the transportation.sector. By seeking to create highly efficient city and suburban structures with a mixed use design, end user energy demand can be reduced. The working group agreed that the issue was beyond the scope of most of their expertise, however, believed that this initial discussion will serve as a springboard for future working sessions.

Forest Management

Perhaps no single biological process for carbon sequestration of atmospheric carbon reduction has been singled out more than forest management. This represents the use of photosynthesis as the reduction mechanism to create and store carbon in above and below ground woody biomass. It was pointed out in this workshop that 59% of the earth's photosynthesis takes place on 30% of the earth's surface. Furthermore, 47% of the earth's forests are located in only two regions of the world, within the boreal forests of Russia and the wet tropical forests of Latin America. An additional major forest region is North America, including the United States and Canada There is, today, approximately 1.3 times more carbon in the boreal forest ecosystems of the world, than in all the atmospheric carbon.

Under intensively harvested systems, the forest is a net source of carbon, rather than a net sink found in well managed systems. Therefore to overcome the problems of forests existing as net sources and to create net sinks requires sustainable approaches, including partial harvesting, plantation forestry, development of agroforestry technologies suitable for temperate and tropical forest systems, and development of systems that significantly reduce soil loss and eliminate soil carbon deterioration. The ultimate goal is to keep carbon emissions from forests in balance, globally, with carbon uptake or to increase the net uptake rather than the net emissions. Management systems must, however, meet the social, cultural, economic and environmental goals of each country or region.

Three global environmental issues were identified that encompass the problems of forest management. These are sustainable development, global climate change, and biodiversity. All of these issues have a common set of mitigative and adaptive strategies that may be considered.

Mitigative strategies include:

(1) an understanding of the total biological carbon cycle;

(2) development of appropriate energy substitution strategies, particularly related to the fuel wood energy demands of developing countries; and

(3) and understanding the appropriate energy demand related to various energy uses.

Adaptive strategies, to focus on the three issues, would include:

(1) understanding regional scale structure and function of each forest ecosystem;

(2) identifying location advantages relative to the type of forest management to be considered;

(3) specifying actions requiring appropriate targets; understanding the persistence of the forest community as it adapts to potential changes in temperature and moisture regimes;

(4) requirements for the sustainability of wilderness regions; and finally,

(5) the use of extreme measures to save components of high value forest communities and associated germplasm pools.

Adaptation of Crops to Climate Change

Agricultural production systems are very vulnerable to potential global warming. Quantitative studies of the effects of global change have indicated that given some current crops and cropping systems, significant sensitivity to warming extremes exists. Studies on a regional scale have been conducted in Japan. Crop physiology models have been run for selected crops predicting production responses based on output from General Circulation Models. When, as predicted by these models, there is an indication of a decrease in crop productivity due to increases in temperatures, the decrease will be overcome through the crop management system by improving irrigation management, changing planting dates, or by selecting different cultivated varieties. This computer derived experimental data immediately creates a larger set of questions. It was identified in the workshop, however, that a wider range of crops and production data will be required to enable crop models, and model projections to answer the new question that may arise.

Several types of carbon dioxide studies in the United States were also reviewed at this workshop. These studies are being conducted using methods and technologies ranging from enclosed chambers to field scale carbon dioxide enrichment. Above ground production and net primary productivity has been well studied, however significant work remains to understand the complete partitioning of carbon to the below ground components of the soil, including roots, organic matter and micro organisms.

Agricultural Methane

Methane from agricultural systems, while not the only source, makes up one of the largest sources that has the potential for being reduced through the application of new technologies. It was pointed out, however, that methane processes are not yet fully understood. Within agricultural systems, the emissions of methane from paddy rice production and from livestock and livestock waste have management options which will enable these sources to be reduced.

Livestock systems, including improved animal diets in developing countries, will reduce methane per animal, and will improve production of each animal. Thus these technologies will likely reduce the quantity required for production purposes of animals over current herd sizes. Both US and Japan have recognized that the solution to this problem will require the leadership of these developed countries in concert with developing countries where the problem exists.

This recognition also follows to the second agricultural source, paddy rice production. Studies are, however still required to quantify the amount of methane rising from various types of production systems. Preliminary data indicate that there is a significant difference in the quantity of methane emitted from acidic soils as opposed to more neutral soils. There are also indications that iron oxidation processes may influence methane emissions. Due to unique social and cultural, ecologic and climatic situations, the workshop recognized that research in these areas will need to be based on the unique regional and local conditions. It will be very difficult to make projections based on national estimates.

Soil Management Assessment

The concluding report for Working Group III provided an overview of assessment methodologies being developed in the US to evaluate the relationship between agricultural management systems and the potential sequestration of carbon in the soil. This assessment will eventually utilize a national data base and projections of the amount of soil carbon that may be sequestered under different cropping, and tillage systems. Such systems include conservation tillage and no-till systems as well as systems utilizing cover or green manure crops to increase plant organic matter available to be incorporated into the soil. Preliminary data was reported from a pilot test conducted in the Corn Belt of the U.S.

WORKSHOP PRESENTATIONS

PLENARY PRESENTATIONS

Keynote Address
US/Japan Workshop on Mitigation and Adaptation Technologies Related to Global Climate Change
February 1, 1993

Dr. Frederick M. Bernthal
Chair, U.S. Committee on Earth and Environmental Science
and Deputy Director, U.S. National Science Foundation

It is a great pleasure for me to have the honor of delivering the keynote address for this important gathering, an honor enhanced further because of the many activities and historic relationships represented by this workshop.

First of all, it represents the spirit of continuing cooperation and good relations between the United States and Japan. With the aid of the framework provided by the U.S./Japan Science and Technology Agreement, our two nations can come together to address a problem that has no national boundaries...and we can think about solutions of potential benefit to all citizens of the global community.

This workshop also symbolizes the spirit of cooperation so characteristic of the conduct of research in science and technology -- cooperation between us as individual scientists and engineers, between the various institutions we represent, and across our diverse disciplines.

This workshop is only the second of its kind. The first US/Japan Workshop on global climate change was held last year in Japan. That workshop focused on cooperative scientific research in the United States and Japan. Out of it came a general agreement to continue collaborative work and to extend cooperation into the area of global change-related technologies, in particular those technologies that hold promise for mitigation and adaptation.

Continuity in U.S. Government Programs

Besides continuity in research cooperation between the United States and Japan, this workshop also is a symbol of continuity in the commitment of the United States Government towards global change research.

As all of you know, President Clinton and Vice President Gore were sworn in to their new jobs just over one week ago, and although the details of the priorities of this new Administration have yet to be articulated, I believe we can expect significant continuity in U.S. global change programs.

Of one thing we can be especially sure: the scientific premises for that policy have not changed. Let me review the elements of continuity in our knowledge of the science of this issue.

There remains no doubt that so-called "greenhouse" gases are accumulating in the atmosphere of our planet. We can measure their increasing concentration. Most of this accumulation is believed to be man-made. And we know from ice-core measurements that the atmospheric inventory of CO_2, the most important greenhouse gas, is now in uncharted territory -- some 20% higher than it has been for any sustained period in at least 200,000 years.

Finally, there is also little doubt from the laws of physics that, other things being equal, such gases will warm the planet. As you know, were it not for the greenhouse effect, ours would be a perpetually frozen planet, some 30 degrees C colder than it is.

But beyond the scientific underpinnings of policy, there is every reason to believe as well that many of the important institutional structures put in place in the U.S. over the last several years will be preserved and extended.

Dr. John Gibbons, recently named Assistant to the President for Science and Technology and Director of the President's Office of Science and Technology Policy (OSTP), has already voiced his support for the existing U.S. organizational structure for the global change research program.

In his confirmation hearing before the Senate, he said that "coordinating Federal global climate change research will be one of OSTP's highest priorities." He plans to give added emphasis to "programs designed to develop and accelerate the adoption of technologies that permit economic growth without damaging the global environment." That should come as good news to everyone here today.

I have been part of this coordination process, both within my own government and working with other governments for several years now, and there have been times when I wondered whether the whole thing might fall apart. "Coordination" is a word not always compatible with either national or international bureaucracies. But thanks to the perseverance of many people far more patient than often am I, the U.S. now has a permanent, statutory structure to deal aggressively with the many and varied issues related to global environmental change, and the international community has agreed to a historic Convention on Climate Change.

The United States Global Change Research Program is perhaps the first research effort of its kind in our history to be codified in an act of Congress. The Global Change Research Act of 1990 was supported by members of Congress from both parties, and was co-sponsored by then Senator and now Vice President Albert Gore.

I want to take a moment to describe the goals and structure of the U.S. Global Change Research Program, because they are germane to the purposes of this workshop. The US Global Change Research Program is designed to be policy relevant -- to support the needs of policy-makers in the U.S. and in other nations. Its research strategy is to reduce key scientific uncertainties and to develop more reliable scientific predictions upon which sound national and international policy and response to global change can be based.

The program has been developed by the Committee of Earth and Environmental Sciences, or CEES, which I chair, and which is under the Federal Coordinating Council for Science, Engineering, and Technology, better known as FCCSET. Jack Gibbons, recent successor to Dr. Allan Bromley as Director of the President's Office of Science and Technology Policy, will now chair the FCCSET. Much of the hard work of developing this program has been carried out by the CEES Subcommittee on Global Change, chaired by Dr. Robert Corell.

I want to highlight two of our CEES subcommittees whose work specifically addresses the issue of environmental technologies. Both of these subcommittees were established in 1992. The first is the Subcommittee on Economic Research on Natural Resources and the Environment. The other is the Subcommittee on Environmental Technologies, which is so new that it has yet to hold its first meeting.

Subcommittee on Economic Research on Natural Resources and the Environment

The establishment of the economic research subcommittee highlights the critical role of economics in global change research. Economic relationships are fundamental to understanding the potential impact of global change on human society, and for developing and assessing effective responses. Responses to the challenge posed by global change are investments for ourselves and for future generations.

The objective of the economics research program includes evaluating options for limiting adverse economic and social consequences of global change. And that requires analysis of emerging technological opportunities, and of the payback on long-range investments, such as development of new technologies for adaptation to climate change.

This effort should help bring about an improved understanding of the spread of technologies and practices relevant to mitigation and adaptation. Of particular importance is how legal, institutional, financial, and other factors affect the rate at which technologies are adopted. Understanding such issues can clarify the relationship between the technically possible and the actually achievable.

Subcommittee on Environmental Technology

The Subcommittee on Environmental Technology was established to foster coordination across U.S. Federal agencies in the research, development, and demonstration of technologies which address environmental issues.

It is clear to anyone who has devoted more than a few moments to the issue of global change that technological innovation is key to any lasting solutions. A recent report by the World Resources Institute framed the issue this way:

> "In principle, demands on the Earth's resources could be reduced by diminishing economic growth, limiting population increase, or increasing the resource efficiency of production. However, the third option is the most viable. Demographic momentum points to a doubling of global population by the mid-21st century. Economic growth is needed to meet the aspirations of most of the world's people.
>
> These realities leave technological transformation as the primary strategy for avoiding environmental degradation." [p. ix, Transforming Technology..., WRI, April 1991]

Given this perspective, it is timely that the Subcommittee on Environmental Technology has been established. It will give impetus to research efforts that extend from basic research on innovative technologies...to the application of such technologies to existing environmental problems...to demonstrations and pilot projects to foster rapid adoption by the private sector.

Action Plan

Finally, I want to emphasize that the U.S. Global Climate Change Research Program is more than boxes on organizational charts and lines of authority -- it is a program to support action.

Accordingly, two months ago the National Action Plan on Global Climate Change was published by the U.S. State Department. This report outlines the steps the US is taking in accordance with the United Nations Framework Convention on Climate Change.

Specific technology-related measures highlighted in the action plan include increasing energy efficiency in residential and commercial buildings through improved design, incorporation of new building materials, and through improved lighting and management of heating, ventilation, and air conditioning systems. It is estimated that improvements in the area of lighting alone could lead to the avoidance of 5 million metric tons of carbon emissions in the U.S. by the year 2000.

Also highlighted in the Action Plan were many programs related to industrial processes, such as the Metals Initiative, a project sponsored by the U.S. Department of Energy to develop new, more efficient technologies for the production of metals. For example, direct reduction steel-making, which eliminates the use of coke ovens, could reduce U.S. CO_2 emissions by 12 million tons annually. Such programs will continue to grow and evolve in the years ahead, and will almost certainly benefit from the ideas and insights we share with each other. And I know that our Japanese friends, through their own programs, can present a similar list of planned actions.

Close: Charge to Workshop

The challenge posed by global climate change, especially in light of its many confounding political, social, economic, and geographic dimensions, casts the role of technology in a new light. It has been said that the global change problem is largely an unanticipated result of technological advance itself, because technological advance has made possible economic progress, development, increased longevity, and indeed, life as we know it today.

In my opinion, no one in his right mind would choose to forsake any one of these advances. We cannot turn back the clock on progress. The vast majority of the occupants of this planet want the benefits and comforts of life that you and I take for granted. And society is pinning its hopes on technology to produce a future not just with more and better, but one which is cleaner, more efficient, and therefore sustainable.

This workshop is a first step toward realizing this vision of the future. Our charge is to do three things: first, to discuss the research and development activities within our respective countries, specifically those technologies that hold promise for mitigating energy-related greenhouse-gas emissions; second, to assess what areas of mitigation and adaptation research need immediate and increased attention; and third, to identify areas of potential future collaborative research and development between the United States and Japan.

All of these activities testify to the spirit of cooperation that this workshop, and indeed the U.S./Japan Science and Technology Agreement itself, represents.

Let me close, then, with some reminders on how we got here, and perhaps on where we are going.

In 1962, a woman named Rachel Carson published a book called *Silent Spring*. In it, she said:

> "Only within the moment of time represented by the present century has one species -- man -- acquired significant power to alter the nature of his world."

Since then, four environmental issues have come to be recognized as so far-reaching in their effects and so vital to our future that they are now generally considered to be truly global in scope -- beyond the ability of individuals, or even nations, to deal with. Those issues are: 1) biodiversity; 2) atmospheric acidification; 3) stratospheric ozone depletion; and of course, 4) global climate change.

These "global change" issues cut a wide swath across science -- embracing as they do the air that we breathe, the land where we live, the oceans that surround us, and the social and economic laws that order our society. Each of these issues is now part of the foreign policy agenda. Each is related to the other in complex ways still only beginning to be understood. And in the end, they all lead us face to face with our own values.

As for the one, global climate change, that brings us here today, of a few things we can be sure:

- This problem is not likely to go away within our lifetimes. Therefore, we can not afford to wait until all of the uncertainties have been resolved before beginning the kind of actions which this meeting represents.

- While our scientific knowledge of this complex problem continues to be refined, it is entirely appropriate that we focus on prudent steps, such as those you will discuss over the next three days.

- Finally, whatever efforts might be made here, and whatever actions might grow out of them, those actions are likely ultimately to be effective only if we can resolve the central challenge of our times--the need to sustain global economic development while at the same time securing and preserving our planetary environment.

You have my very best wishes for a successful meeting.

Opening Remarks by

Dr. Robert M. Simon
Principal Deputy Director
Office of Energy Research
U.S. Department of Energy

at the

Second U.S./Japan Workshop on Global Change: Environmental Response Technologies (Mitigation and Adaptation)

February 1, 1993

I am pleased to be here today as one of the U.S. Co-Chairs for the Second U.S./Japan Workshop on Global Change. This series of workshops is an outgrowth of the 1988 bilateral agreement between the U.S. and Japanese governments on scientific and technological cooperation. That agreement called for comparable access to, and exchange of, information in scientific and technological fields, as well as the joint undertaking of cooperative activities for peaceful purposes in nationally important areas of science and technology. Meetings such as this were envisioned under the agreement to allow experts from both sides to discuss and exchange information on scientific and technological aspects of important problems and to identify research and development projects that might usefully be undertaken on a cooperative basis.

The first U.S./Japan Workshop on Global Change focused on research needed to better understand how the global climate system operates, what the interactions are between the climate system and marine and terrestrial ecosystems, and how Earth systems might respond to global climatic changes.

The focus of this second workshop is on response strategies to global environmental changes; that is, what strategies and practices might be implemented to allow our economic, social, and environmental systems to adapt to global climatic changes, and what might we do to mitigate a human-induced augmentation of the greenhouse effect.

This workshop focus is directly relevant to the commitments undertaken by the United States and Japan in the UN Framework Convention on Climate Change, signed last year in Rio de Janeiro:

- to adopt national policies and to take corresponding measures on mitigating climate change by limiting anthropogenic emissions of greenhouse gases, and by protecting and enhancing greenhouse gas sinks and reservoirs;

- to promote and to cooperate in the development, application, and diffusion of technologies, practices, and processes that control, reduce, or prevent anthropogenic emissions of greenhouse gases not controlled by the Montreal Protocol in all relevant sectors, including energy, transport, industry, agriculture and forestry, and waste management; and

- to cooperate in preparing for adaptation to the impacts of climate change.

Successful interchanges at this meeting could facilitate the efforts of both countries to meet these commitments. The results of this workshop will also be useful to efforts now beginning under the aegis of the Intergovernmental Panel on Climate Change (IPCC). The IPCC is starting work on a second assessment report, due for completion in 1995, that will include an assessment of adaptation options. Our discussions and report should feed into that assessment. Thus, the broad objectives of the workshop are:

(1) to exchange information on research and development activities in the area of mitigation and adaptation technologies and practices related to global environmental change, particularly potential climatic changes associated with the human-induced increase in greenhouse gases in the atmosphere;

(2) to identify topics of high scientific interest in each of areas covered in this workshop; and

(3) to identify research and development needs related to each of these topics where U.S-Japanese cooperation could have high potential for mutual benefits.

I am very pleased that so many distinguished researchers from both countries could join us for this important effort.

President Clinton has declared that U.S. technological leadership is a national priority, and has committed to focusing the national will and the U.S. government's resources to renew America's civilian technology base. In his view, civilian industries, and not defense industries, are the driving force behind advanced technology in the world today, and need to be strengthened in order to provide both national security and improved economic competitiveness. He has already taken steps to bring better coordination and management to these issues by the formation of a high-level National Economic Council, and has indicated that additional steps will be taken to strengthen the way in which the U.S. government coordinates technology policy and enhances cooperation between the private and public sectors.

The National Technology Policy for America, which he announced as a candidate for President in September 1992, outlines six broad initiatives:

- Building a 21st Century Technology Infrastructure for the United States;
- Establishing Education and Training Programs for a High-Skill Workforce;
- Investing in Technology Programs that Empower America's Small Businesses;
- Increasing Dramatically the Percentage of Federal R&D for Critical Technologies;
- Leveraging the Existing Federal Investment in Technology to Maximize its Contribution to Industrial Performance; and
- Creating a World-Class Business Environment for Private Sector Investment and Innovation.

Two of these themes, relating to critical technologies and industrial performance, are relevant to environmental technologies in general--for example, pollution prevention has been highlighted in past U.S. government studies of critical civilian technologies. As the Clinton Administration fleshes out its initiatives in technology policy, we may find that specific topics on our program, such as combustion efficiency and energy conservation, receive considerable attention and focus.

There has been, of course, an increasing emphasis in Japan on technologies that are responsive to global climate change, and Japan is a leader in developing energy-efficient technologies. While I will leave it to our Japanese counterparts to describe their programs in detail, we in the United States are very much aware of initiatives such as the New Earth 21 Program, and I have had the pleasure of speaking to a number of Japanese researchers in your carbon dioxide programs who visited the Department of Energy last year.

The mutual interest of both our countries in environmental technologies, and the conviction on both sides that technological innovation is an important engine for national economic growth, provides us with a challenging context for this meeting. On the one hand, we have both committed ourselves to continued and expanded cooperation on research and development in the area of environmental technologies related to global climate change. At the same time, some of these technologies (and we cannot predict with certainty at this time which ones) may give rise to new and lucrative markets that will be important to the continued growth of our respective national economies. How do we reconcile our commitment to cooperate with the need to safeguard commercially sensitive technological insights and information?

I believe that the solution to this dilemma has several dimensions, and that our program over the next three days is responsive to a number of them.

One part of the solution is to look for those areas of research where we have much to learn from each other, but where the knowledge base to be extended is primarily intended for policy development, and not commercial application. For example, at this meeting we will be discussing the connection between urban infrastructure and adaptation technologies to global change.

Another part of the answer is to look for cooperation in areas where some technological research is underway, but where the ultimate commercial potential is speculative and long-term. An example of such a generic, pre-competitive area might be carbon dioxide fixation, utilization, and disposal--also on our program.

A third partial solution is to look to areas where our knowledge bases are complementary and incomplete, and where there are likely to be symmetrical technological benefits from an exchange of information and from cooperative work. An example might be crop response to global climate change, another topic on our agenda. U.S. research in this area has stressed crops that are dominant in the United States (e.g., maize and wheat) while Japanese research has focused on other crops, such as rice. Comparing our research findings may lead to mutually beneficial advances in our understanding of plant behavior under environmental stress.

A fourth and perhaps most difficult part of the solution relates to those technological areas where cooperative efforts might require access to, or result in the generation of, intellectual property that might be commercially valuable in the near term. To develop a cooperative approach to areas that are close to commercialization, we must frankly acknowledge and address the asymmetries that exist in the U.S-Japanese technological relationship. As the U.S. National Academies of Science and Engineering have observed, "Japan, a country that has perfected the ability to learn from abroad (and from the United States in particular) in science and technology, has now become one of the world's most important sources of technological advances. Japanese industry is the driving force in Japanese R&D, but corporate programs are largely proprietary and therefore not easily accessible to outsiders. The United States maintains a research system that is the world's most open and second to none in basic research. Some therefore conclude that the United States is trapped in an unfortunate division of labor: while the United States continues to generate new ideas and technologies, Japan gains the commercial advantage." Both the United States and Japan need to take steps to resolve the root causes for such asymmetries, and the U.S-Japanese Science and Technology Agreement provides a valuable forum for promoting a more healthy and mutually beneficial cooperation. I would hope that our common technological future would be one in which the United States makes more progress in cultivating a deeper understanding of Japanese science and technology, as well as a greater receptivity to foreign-generated ideas and information. And I would hope that the internationalization of Japanese science and technology would result in greater accessibility of Japanese research personnel, laboratories, and intellectual property to foreign researchers.

In this context, I believe that it is encouraging that among the "Fourteen Proposals for a New Earth" put forward last November by the Japanese Industrial Structural Council and Industrial Technology Council is a suggestion that international cooperation in New Earth 21 "specifically provide for the facilitation and expansion of technology transfer." If this portends a greater possibility for symmetrical technical exchange in the area of environmental technologies, then such a suggestion would be a very positive step.

This set of considerations leads me to the following principles that I would like to leave you with as a charge to the Working Groups.

First, I believe that we should use our time here to:

- exchange information on environmental response technologies related to global change;
- identify specific and general research and development needs related to these response technologies;
- identify potential research and development projects and programs which may be usefully undertaken on a cooperative basis, bearing in mind the need for symmetrical benefits to both U.S. and Japanese partners; and
- identify potential mechanisms of research cooperation for consideration by both governments.

The Working Groups need to develop reports that:

- outline general research and deveopment needs on the topics discussed in each of the three groups;
- identify topical areas and specific research and development projects and programs on environmental response technologies and practices which may be usefully undertaken on a cooperative basis between the U.S. and Japan; and
- if possible, identify potential mechanisms of cooperation.

At the end of each day of this workshop, we will call on the chairs to provide all the participants with a brief update on their discussions, with the aim of promoting cross-fertilization of significant ideas generated in the course of the workshop. The Working Group chairs are expected to summarize the findings of their working groups in the final plenary session. Working Group reports will be included in the report of the Workshop and reflected in the Final Communique.

I would like to conclude by thanking you all again for your willingness to participate in this workshop. I am very much looking forward to the outcome of our discussions.

Present Status of Research Activities Relating Global Warming Problems in Japan (mainly MITI and relating organizations)

O. Yokoyama
National Institute for Resources and Environment
Agency of Industrial Science and Technology, MITI

1. Introduction

Japanese government has issued action program so called "Action Program to Arrest Global Warming" for preventing global warming at Oct., 1990. According to the program, CO_2 emission should be stabilized on a per capita basis in the year 2000 and beyond at about same level as in 2000 by introducing several methods such as energy conservation, improvement of energy using efficiency, expanding use of renewable energy and so on. The basic concept, target and methods are summarized in Table 1. At the same time, MITI published so called "New Earth 21" project which aims remedying the earth environment modified by human activities since industrial innovation began at about 200 years ago in coming 100 years. This plan proposed yearly step of research development of technology for mitigating CO_2 emission. According to the MITI's plan, 15 institutions belonging to AIST have carrying research for developing technology of reducing emission of CO_2 and other greenhouse gases, with cooperation of other research organizations such as RITE (research Institute of Innovative Technology for Earth) and NEDO (New Energy and Industrial Technology Developing Organization). Time schedule of the research development by The New Earth 21 project is summarized in Table 2. Also image of the New Earth 21 scenario is shown in Fig. 1. Now, in Japan, many national institutions and universities, research works relating reduction and mitigation of GHG are carried out according to this guideline.

2. Measures of reducing GHG emission

At first, present status of efforts for reducing CO_2 emission in Japan are briefly described. In order to reduce CO_2 emission, following measures are considered in the New Earth 21 plan.

- Energy Conservation and improvement of efficiency
- Renewable energy and nuclear energy
- Artificial processing of CO_2 (fixation, recycling)
- Activation of natural absorbing potential
- Development of new primary energy

Except last two subjects, research and practical use has started already. Present status concerning to these subjects are briefly described.

Table 1, Outline of the Action Program to Arrest Global Warming (Japanese government, October 1990)

Basic elements to cope global warming

Formation of environmentally-sound Society
Compatibility with economy's stable development
International coordination

Target

Stabilizing CO_2 emission per capita in the year 2000 and beyond at same level as in 1990. CH_4, N_2O emission should not exceed 1990 level.

Measures

Source:

CO_2: Urban and regional structure. Transportation. Production. Energy supply. Life style.
CH_4: Waste management. Agriculture.
N_2O: Agriculture. Combustion.

Sink:

CO_2: Afforestation. Domestic forest management. Reduction of timber use.

Research activity

Promotion survey, observation, monitoring.

Development and dissemination of technology

Reduction of GHG gas emission. Absorption, fixation of GHG.
Adaptation of global warming.

Public awareness

Environmental education

International coordination

Technology transfer. Conservation of tropical forest.
Cooperation of research activity. International cooperation project.

Promotion of the action program

Table 2, time Schedule of technological development in New Earth 21 (MITI, Oct 1990)

Year	Main Technology
2000	Energy Conservation and Improvement of Efficiency
2010	Renewable and Nuclear Energy
2020	Artificial Processing of CO_2 (Fixation, Recycling)
2030	Activation of Natural Absorbing Power
2040	Innovative Energy Technology (Nuclear fusion, Space Solar etc.)

3. Energy use efficiency

Since the first oil crisis occurred at 1973, energy conservation and improvement of energy use efficiency have been tried in Japan. Firstly, industrial sector has attained fairly well results. As a whole, shown in Fig. 2, energy intensity index of Japan which is energy consumption per GNP has been decreasing most rapidly among OECD countries. In order to maintain "sustainable growth" without increasing CO_2 emission, energy intensity index must be decreasing more or less. This improvement of energy use efficiency has achieved firstly in the industrial sector. Some examples of improvement technology is given in Table 3. Each technology earns little amount energy saving, but accumulation is not little.

Table 3, Major Energy Conservation Technologies in Industrial Sector of Japan

Industry	Item	Technology
Steel	Collection of wasted energy Recovery of wasted heat	Blast fames power generation system New coke drying system Scrap preheating system
Synthetic fiber	Collection of wasted energy Energy saving facility	Heat pump for low temperature source Continuous polymer spinning system Multiple thread reeling system
Paper pulp	Total energy Process Improvement Equipment efficiency	Recycling old paper Continuous evaporating system High efficiency sludge dehydrator
Cement	Wasted heat recovery Crashing efficiency	SP kiln, NSP Kiln Ball mill

In past few years, new energy conservation technologies are introduced in commercial and domestic sector in Japan. Main technology is co-generation system and use of wasted and natural heat by using heat pump. Some example of facility of district air conditioning built in Japan is shown in Table 4 with sub-heat source, such as river water, ventilated air from subway. At present, number of such air conditioning system are increasing in Japan. Co-generation system is another method to improve energy use efficiency. Combination of Diesel engine, gas turbine or fuel battery and absorbing chiller is most popular in Japan. Total energy use efficiency of these co-generation system is estimated to be 60-70%

As indicated in The New Earth 21 project, it is most effective of reducing CO_2 emission for the time being by transferring such high efficiency technology to other countries from Japan.

4. Renewable Energy

Development of renewable energy technology is carried out mainly by NEDO with electric power generation Co., national institutions and university. Most big renewable energy is hydraulic power but there remains no large sources in Japan. However, effort is pay for developing small hydraulic power stations of undeveloped small water head resources by Agency of Energy and Resources of MITI.

Wind power stations have been built some places in Japan such as Rokko island by Kansai power electric Co., cape Tappi by Tohoku electric Co., however these are all testing facilities for clarification of characteristics of wind power. Also, survey of wind power potential all over Japan is carried out by NEDO with help of NIRE.

Geothermal power plant is now practically used in Japan and total power output reached about 270 MWt. At present, utilization of hot dry rock is surveyed by NEDO with NIRE.

Solar battery is produced in Japan nearly same amount as in USA, but there are only testing power stations such as in Rokko island (Kansai electric power Co.), Urawa testing station (Tokyo electric power Co.,) and so on. However, potential of solar light power in the future is considered as the biggest amount in Japan too. Research of solar battery power generation is continued by NEDO. Solar heat power is most popular in Japan for getting hot water for each home. However, electric power generation by solar heat is not investigated in Japan as contrarily to practical use in California USA.

Utilization of biomass for energy source is investigated by two ways. One is the process making oil from biomass by using thermal-chemical reaction. This research is carried in NTRE and some result is report in this workshop. One another utilization of biomass is the usual process making methanol by fermentation technology which is also investigated by NEDO.

Finally, I should point out that energy used for building renewable energy facility must be take into account. In Table 5, necessary energy for developing power plant is compared. Index B/A (A: capacity, B: used energy) is not directly expressing CO_2 emission, however renewable natural energy is not necessarily effective for reducing CO_2 emission, because about 90% primary energy comes from fossil fuel.

Table 4, Area Air Conditioning by Using Electric Power

Area	Supply	Capacity Gcal/h	Sub-energy
Hibiya Tokyo	OB	H5.4 C5.8	Trans Substation
Ginza 2,3	OB	H8.4 C8.0 R	Trans Substation
Sibaura	OB	H18 C19.5 R	Transformer
Sinkawa	OB	H116 C90 R	Public Bath
Ginza 4	OB	H32 C32	Trans Substation
Kanda Surugadai	OB	H13 C15 R	Sewage Process
Makuhari Chiba	OB	H880 C853 R	St.
Hakozaki	OB	H28 C39 R	River Water
Utunomiya	CB	H38 C68 R	Trans Substation
Nakanosima	OB	H36 C49 R	Gas
HikarigaOka	Houses	CB R	Incinerator
Nagoya Sakae 4	OB	CB	Gas
Osaka	OB	H15 C17 R	Gas
Sapporo	OB, Road heating	CB	Subway Exhaust
Kanagawa	OB	CB	Gas
Takesiba	OB	CB	Gas
Fuchu	OB	CB	Gas

OB: Office Buildings, H: Heat Pump, C: Chilling Unit, CB: Combined with Boiler Unit (Combined system), R: Heat Reservoir

Table 5, Amount of Necessary Energy for Developing Power Plant

Technology	Capacity (MW:A)	Used Energy (oil t:B)	B/A (t/MW)
Nuclear	1,000	97	0.097
Coal	1,000	140	0.140
Oil	1,000	43	0.043
Small Hydro	10	5,462	546
Geothermal	10	3,983	398
Ocean Wave			
Floating	1	1,179	1,180
Fixed	0.1	180	1,080
Solar Light	1	5,221	5,220
Wind	0.1	125	1,255
Ocean Current	3	4,177	1,390
Sea Temp.	2.5	8,853	3,540
Solar Heat			
Tower Focus	5 x 10	18,060	3,210
Cylinder	5 x 10	28,872	5,770

5. Artificial processing

Research of artificial processing of CO_2 and other GHG is proceeded by RITE, NIRE and other national institutes under AIST, some electric companies. As shown in Table 6, two main subjects are investigated in RITE and NIRE. One is artificial photosynthesis and other is hydrogenation processes. Details of research activity concerning to artificial photosynthesis is reported in this workshop. Also, development of hydrogenation process for CO_2 is carried by cooperation of RITE, NIRE, Osaka Industrial Technology Research Institute and National Institute of Material & Chemical Research. Removal CO_2 from combustion exhaust gas, fixation and recycling are being studied aiming to increase technological options of selection in the future. At present, of course, these studies are at basic stage and it is not certain these measure will be main technology for reducing CO_2 emission.

More practical artificial fixation of CO_2 is dumping of CO_2 in deep sea which is now investigated in some electric power Co., in Japan. This deep sea dumping of CO_2, environmental impact assessment for plants and animals in deep sea must be done.

Concerning to mitigation, reduction and adaptation for emission of GHG, many research are now running in national institutes. Present main subjects and budget are cited in Appendix for the reference.

Appendix Name of Research relating global warming problems and budget in National Institutes.

Development of global environmental technology (1993, AIST, MITI)

	Unit 1000 yen
Reduction of Carbon dioxide	13,027
Recycling technology of carbon dioxide by catalytic Hydrogenation	4,877
Recovery of carbon dioxide by inorganic layered compounds and carbonaceous adsorbents	11,018
Chemical conversion/Decomposition of methane by catalysis	9,929
Carbon cycle in the ocean and atmospheric interface	10,101
Remote sensing techniques for measuring GHG	9,856

Global environmental studies (JEA)

Decomposition of CFC by RF plasma	8,790
Catalytic decomposition of CFC	9,711
Incineration and thermal decomposition methods	2,026
Transformation and decomposition of substitutes for CFC in the troposphere	10,922

Study on the environmental behavior of GHG of industrial origin	30,564
Clarification of source and emission of CH_4 and N_2O (Source inventory of industrial origin)	4,506
Behavior and emission source of marine pollutants	10,536
Sedimentation and accumulation of toxic material on seabed	6,223
Modeling of biological process of material flux in continental shelf by using satellite data	11,595
Modeling of material transport in the troposphere	7,441
Technology and evaluation for abatement of SO_x, NO_x cast Asia	7,933

Promotion of joint studies (Science and Technology agency)

Study of atmosphere, hydrosphere and biota in north pole area Aerosol and original gases material	1,303
Measuring techniques of trace materials	6,136
Decomposition mechanism of detergent by anaerobic bacteria	1,199

Study of global environment (Science and technology agency)

Change of tropical forest and influence on CO_2 balance	14,302
Formation processes of sulfate and nitrate	12,096

Basic study (Science and technology agency)

Polysilane complexes as conversion device of solar energy	

Special study on pollution abatement (JEA)

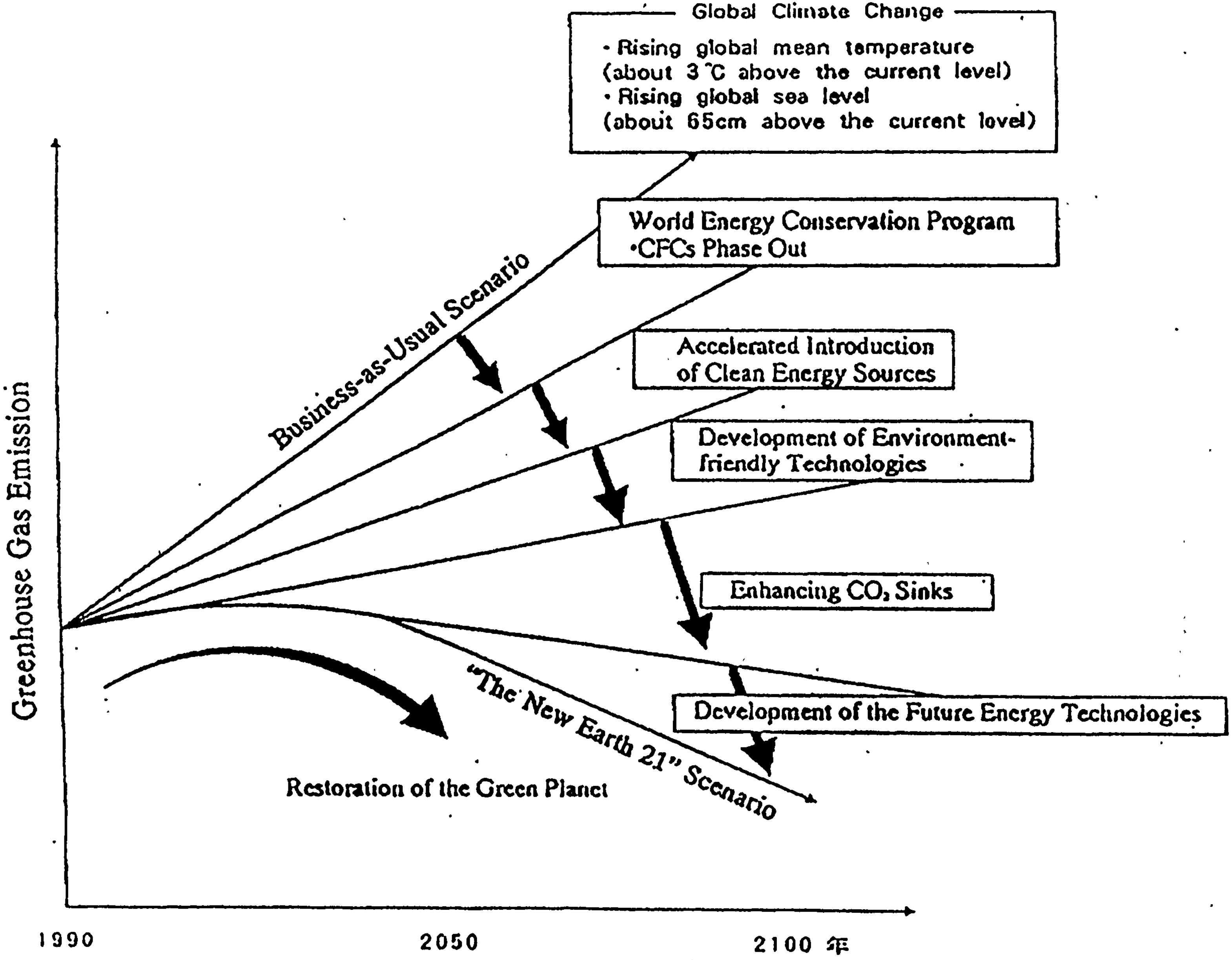
Catalytic combustion for reducing NO_x emission from small sources	13,352
Removal of NO_x from Diesel engine by hybrid system	13,153
Simultaneous control of NO_x and N_2O emission from coal combustion	22,996
Selective separation technique for volatile organic halogenated compounds	17,339
Suppression of emission of toxic material from electric precipitator	23,390
Effective treatment of toxic materials by ecological control	14,943
Development of prediction model for change of shallow water environment	27,673
Savaging and cleaning process of shoreline environment	19,980

Degradation of synthetic chemical in coastal sediment	23,825
Landwater quality protection from toxic chemical compounds	9,476
Treatment of industrial wastes containing mixed toxic chemicals	17,173
Treatment of asbestos waste by transforming fibrous form	21,952
Recovery of rare metal from wasted electronic devices	13,535
Propagation mechanism of impulsive low frequency sound	25,055
Automatic measurement of lower trophic ecosystem	5,267
Sensitive differential determination of hazardous substance in waste by hybrid analytical method	9,983
Diffusion process and monitoring method for toxic material emitted from high-technological factories	34,504

International cooperation on industrial science (AIST,MITI)

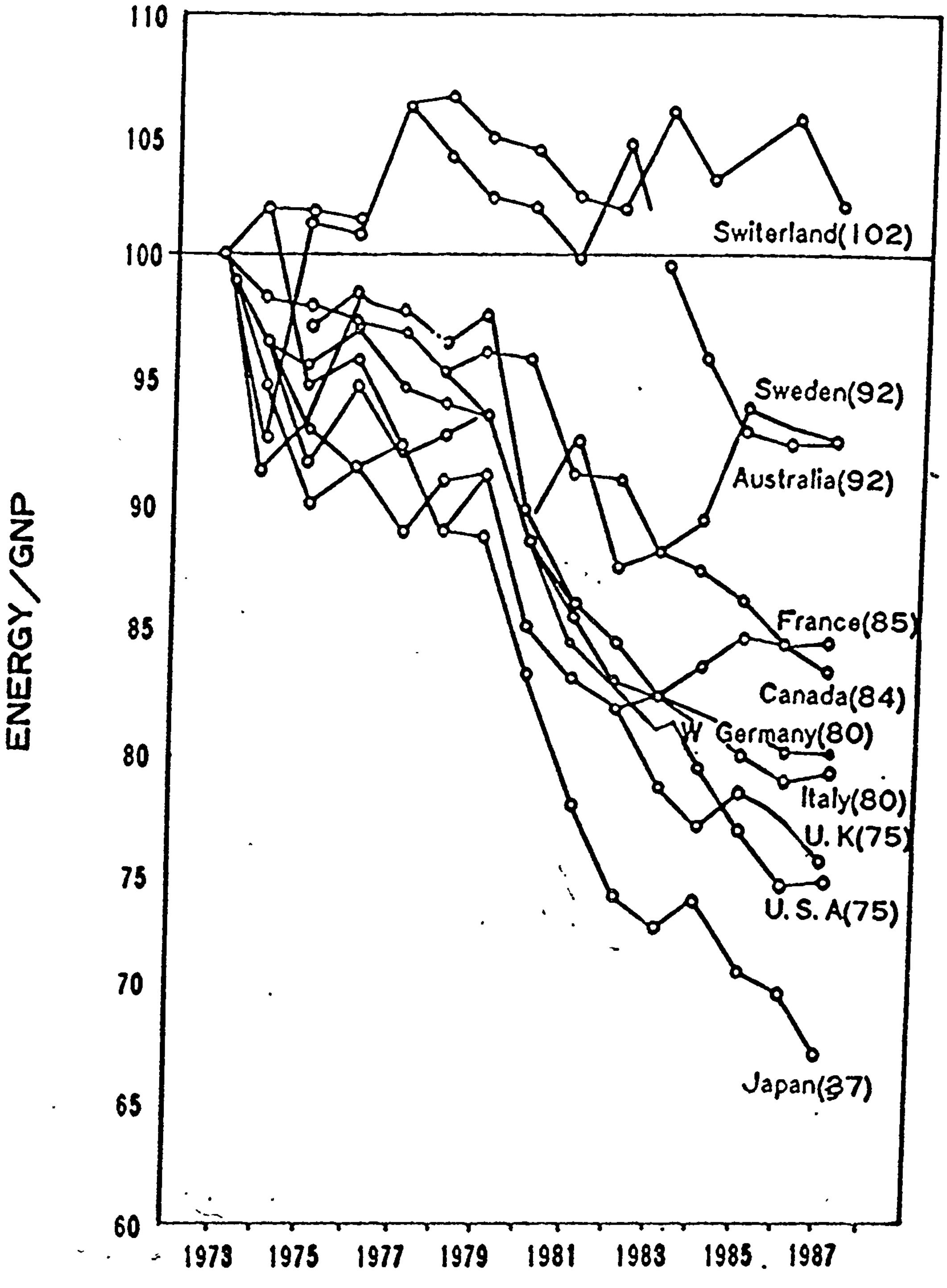
Control technology of acid rain caused by coal combustion

Conceptional Framework of "The New Earth 21" (An illustration)



Energy Intensity of OECD Countries

(1973=100



Prof. Y. Kaya 's eq.

growth rate of CO_2emission = growth rate of Energy/GNP + growth rate of CO_2/Energy + growth rate of GNP

PARTICIPANT EXTENDED ABSTRACT

WORKING GROUP I ABSTRACTS

WORKING GROUP I ABSTRACTS

Howard J. Herzog	*Overview CO_2 Fixation, Utilization, and Disposal Options*
Toshikatu Hakuta	*CO_2 Separation*
Roddie R. Judkins Douglas E. Fain	*Carbon Dioxide Removal With Inorganic Membranes*
Bruce St. John	*An Independent Assessment of CO_2 Capture Research Needs*
Alan M. Wolsky	*Remarks on CO_2 Capture from Electric Power Plants and Recommendations for Future Investigations*
Hironori Arakawa	*Recycling Technology of Emitted Carbon Dioxide*
Yasuo Asada	*Photosynthetic CO_2 Fixation and Energy Production - Microalgae as a Main Subject -*
Takashi Ibusuki Kazuhide Koike Osamu Ishitani	*Carbon Dioxide Fixation by Artificial Photosynthesis*
Edward S. Lipinsky	*It is Time to Put Carbon Dioxide to Work*
Yuji Shindo Toshikatsu Hakuta	*Ocean CO_2 Disposal*
E. E. Adams D. Golomb X. Y. Zhang H. J. Herzog	*Confined Release of CO_2 into the Ocean*
Wheeler J. North Dwain F. Spencer Don E. Johnson Warren Rice James J. Morgan	*Use of Hydrate for Sequestering CO_2 in the Deep Ocean*
Shoichi Tanaka	*Underground Storage of Carbon Dioxide*
R. T. Bailey	*Land Disposal of CO_2*

Overview of CO_2 Fixation, Utilization, and Disposal Options[1]

Howard J. Herzog
Room E40-489
MIT Energy Laboratory
Cambridge, MA 02139

January, 1993

The Energy Laboratory of the Massachusetts Institute of Technology (MIT), with the Technology Evaluation Group of the Argonne National Laboratory as a subcontractor, was awarded a Special Research Grant in December 1991 to identify, assess, and prioritize research needs for the capture and non-atmospheric sequestering of a significant portion of the carbon dioxide (CO_2) emitted from fossil fuel-fired electric power plants. The scope of the study was limited to capture technologies applicable either to existing plants or to those that might be introduced over the next twenty years. A final report from this project will be released in the near future. The information contained in this abstract is based on the data gathered in conducting the research for the U.S. Department of Energy (DOE). However, the conclusions stated below are solely those of the author and do not necessarily represent the position of MIT or the U.S. DOE.

Figure 1 shows a number of different options for reduction of CO_2 emissions into the atmosphere; this review addresses only the one option shown as "flue gas clean-up". A general overview of other mitigation options for global warming is given by Rubin *et al.* (1992).

In an overview assessment of alternative processes for capturing CO_2 from *existing* coal-fired power plants, Herzog *et al.* (1991) concluded that capture is technically feasible, but that the most efficient available technology will reduce energy efficiency by about 30% and will produce an 80% increase in the price of electricity, even before disposal costs are added. These results are consistent with a recent EPRI study on CO_2 capture and disposal (Booras and Smelser, 1991). For existing plants, the best capture technologies seem to be amine scrubbing or oxygen combustion with flue gas recycle. Integrated Gasification Combined Cycle (IGCC) power plants appear to be the leading candidate for new CO_2 capture power plants. In the future, advanced technologies (e.g. fuel cells) could be coupled to gasification plants to yield even better performance.

---

[1] Prepared for the Second U.S./Japan Workshop on Global Change: Environmental Response Technologies (Mitigation and Adaptation), East-West Center, Honolulu, Hawaii, February 1-3, 1993.

Once the CO_2 is captured, it needs to be sequestered in some way that avoids prompt release to the atmosphere. One option is to store the CO_2 in depleted gas and oil wells. Another option might be to inject CO_2 into deep aquifers or into other mined subterranean structures.

The ocean already contains about 60 times as much carbon as the atmosphere (and more than 10 times as much carbon as in all recoverable fossil fuels), so it appears to be a potential repository of ample capacity if the CO_2 is not quickly released back into the atmosphere. However, even the deep ocean is known to recirculate on a time scale of the order of a thousand years, so eventually the atmosphere and the ocean will reach a new equilibrium reflecting the total quantity of CO_2 generated during a period of intense fossil fuel usage. Thus, the main effect of deep ocean disposal is to reduce the transient peak in atmospheric CO_2 concentration. However, a reduction in long term atmospheric CO_2 levels is a possibility if the CO_2 can be removed from the ocean circulation.

Another sequestration option is to find recycle opportunities for power plant CO_2 in products or processes that might utilize CO_2 as a feedstock. The total industrial utilization of CO_2 today in the U.S. is about 2% of the CO_2 generated from power plants, with about 80% of the usage in enhanced oil recovery (EOR) operations. Also, much of the CO_2 use, as in EOR and the food industry, results in rapid return to the atmosphere. Therefore, new utilization opportunities are needed if significant quantities of CO_2 are to be recycled in some manner.

Seven statements relating to CO_2 capture and disposal are presented below. While other workshop attendees may disagree with some of the conclusions, they are presented to help stimulate and focus discussion on the CO_2 fixation, utilization, and mitigation option.

To implement CO_2 capture and sequestration on a national scale will require a significant amount of research to establish the basic feasibility of large-scale disposal, decrease power plant net efficiencies, and significantly increase the cost of electricity. All capture and sequestration options consume additional energy, thus lowering a power plant's fuel to electricity efficiency. This creates more CO_2 per unit of net electricity to capture and sequester. Using today's technology, the capture and sequestration of CO_2 would more than double electricity costs. The best estimates with new technology would still increase electricity prices by 30%.

Commercial CO_2 capture technology, though expensive, exists today. Proven disposal technology is not presently available or even known to be feasible for a significant fraction of the generated CO_2. Therefore, the highest priority research should focus on disposal options. CO_2 capture plants are in operation today using MEA scrubbing to produce CO_2 for industrial utilization. Research still needs to be done on advanced capture methods for new types of power plants (e.g. IGCC), but the basic technology is well understood. The development time required would be relatively short (3-5 years), and commercial companies would undertake the task if a commercial incentive were present. However, no viable CO_2 disposal option is ready today. While storage of some CO_2 in depleted gas wells seems fairly straightforward, the more ubiquitous options -- widespread disposal in depleted wells, disposal in aquifers or disposal in the deep ocean -- have many unknowns and will require significant research over a fairly long time-frame (10-20 years). We feel that this weak link (e.g. feasibility of large-scale CO_2 disposal) in the capture/sequestration mitigation option requires the highest priority for research funds. The bottom line is that it makes no difference how efficiently one can capture CO_2 if there is no place to dispose of it.

Land or ocean disposal appear technically feasible, but will require much research to better understand residence times and environmental impacts. Even with such information, the public may be reluctant to accept some disposal options. Where available, disposal of CO_2 into depleted oil and gas reservoirs is probably the best option. Most of the know-how for CO_2 injection in petroleum reservoirs exists, even though much practical knowledge developed by private oil and gas companies is proprietary. Environmental impacts for petroleum reservoir disposal should be minimal, since the carbon in the CO_2 originated in the same place that will be used for disposal. Disposal in the oceans or in aquifers offers more ubiquitously located disposal options worldwide with potentially much larger capacities than depleted wells. However, many technical questions must be answered before either ocean or aquifer disposal can become a reality. In addition to technical questions, environmental and safety questions need to be addressed. While it seems that either option should be environmentally acceptable, much research will be needed to convince the public of this fact. For example, the local effects near injection sites in the ocean have raised many questions about the ecological impact of ocean disposal. For land disposal, concerns about a catastrophic failure of reservoir integrity causing a large release of CO_2 must be satisfied.

Transportation of CO_2 to disposal sites has not been adequately addressed. Issues include cost, safety, technological and institutional barriers. Transportation issues inherent in the CO_2 capture and sequestration option have been identified (Steinberg *et al.*, 1984), but have not been considered in detail. For example, even today people call for disposing of CO_2 at depths of 3000 m in the ocean without any analysis on how to inject the CO_2 at those depths. Our analysis shows that injection at this depth will be extremely difficult and is probably infeasible in the foreseeable future. While some studies have discussed costs of a single CO_2 pipeline, what are the implications of a major CO_2 pipeline network? In looking at the transportation issue, one possible long-term outcome may be to decide to site power plants close to disposal sites and transport electricity long distances.

These and many other related issues must be addressed as part of the research on CO_2 disposal options.

The most promising approach to economical CO_2 capture is to develop power cycles that facilitate the CO_2 capture. Implementation of CO_2 capture technology should be done in conjunction with replacement of power plants. Retrofitting existing power plants will result in large energy penalties and large investments. The best retrofit technology commercially available today has an energy penalty of 35%. New integrated gasification combined cycle (IGCC) power plants can have energy penalties of 20% or less. New plants using IGCC or fuel cells will also have higher base efficiencies, requiring less CO_2 to be captured per kWh_e produced. Finally, new plants can be sited taking into account the methods of disposal. Assuming new plants like IGCC will become competitive with today's pulverized coal-fired power plants, research priorities should address capture methods to be used in conjunction with these new plants as opposed to methods for retrofits of existing plants.

Utilization options are not promising for sequestration of significant amounts of CO_2. Utilization options either have too limited an applicability or require too much energy to be considered as viable options for reducing atmospheric CO_2 levels. Therefore, research in these areas should have low priority. Industrial or biological utilization can handle at most 5% of the 1.7 Gt of CO_2 produced annually from U.S. power plants. Converting CO_2 to a fuel by chemical means would require a significant energy source that could be used at least 6 times more efficiently by directly replacing fossil fuel-fired power plants with renewable or nuclear-fired plants.

To make responsible societal decisions, accurate and consistent economic and environmental analysis of all alternatives for atmospheric CO_2 mitigation are required. CO_2 capture and disposal is just one of many options that can reduce atmospheric CO_2 levels (see Figure 1). As shown by Rubin *et al.* (1992), cost estimates for the various mitigation options vary over a large range. Capturing CO_2 using today's best MEA scrubbing process costs about $61/tonne of CO_2 avoided, while capture from IGCC plants using physical sorbents are projected at about $23/tonne of CO_2 avoided. Note that these cost estimates are for CO_2 capture and compression only and that they may significantly increase when disposal costs are added. While these estimates for CO_2 capture are relatively high, they must be considered in the context of other mitigation options, including conservation and fuel switching. To make a valid comparison, the various options must be evaluated on a common basis.

References

Booras, G.S. and S.C. Smelser, "An Engineering and Economic Evaluation of CO_2 Removal from Fossil-Fuel-Fired Power Plants," *Energy*, 16(11/12), pp. 1295-1305 (1991).

Herzog, H., D. Golomb, and S. Zemba, "Feasibility, Modeling, and Economics of Sequestering Power Plant CO_2 Emissions in the Deep Ocean," *Environmental Progress*, 10(1), 64-74 (1991).

Rubin, E.S., R.N. Cooper, R.A. Frosch, T.H. Lee, G. Marland, A.H. Rosenfeld and D.D. Stine, "Realistic Mitigation Options for Global Warming," *Science*, 257, pp. 148 ff., (1992).

Steinberg, M., H.C. Cheng and F. Horn, "A Systems Study for Removal, Recovery, and Disposal of Carbon Dioxide from Fossil Fuel Power Plants in the U.S.," BNL 35666, Brookhaven National Laboratory, Upton, NY (May 1984).

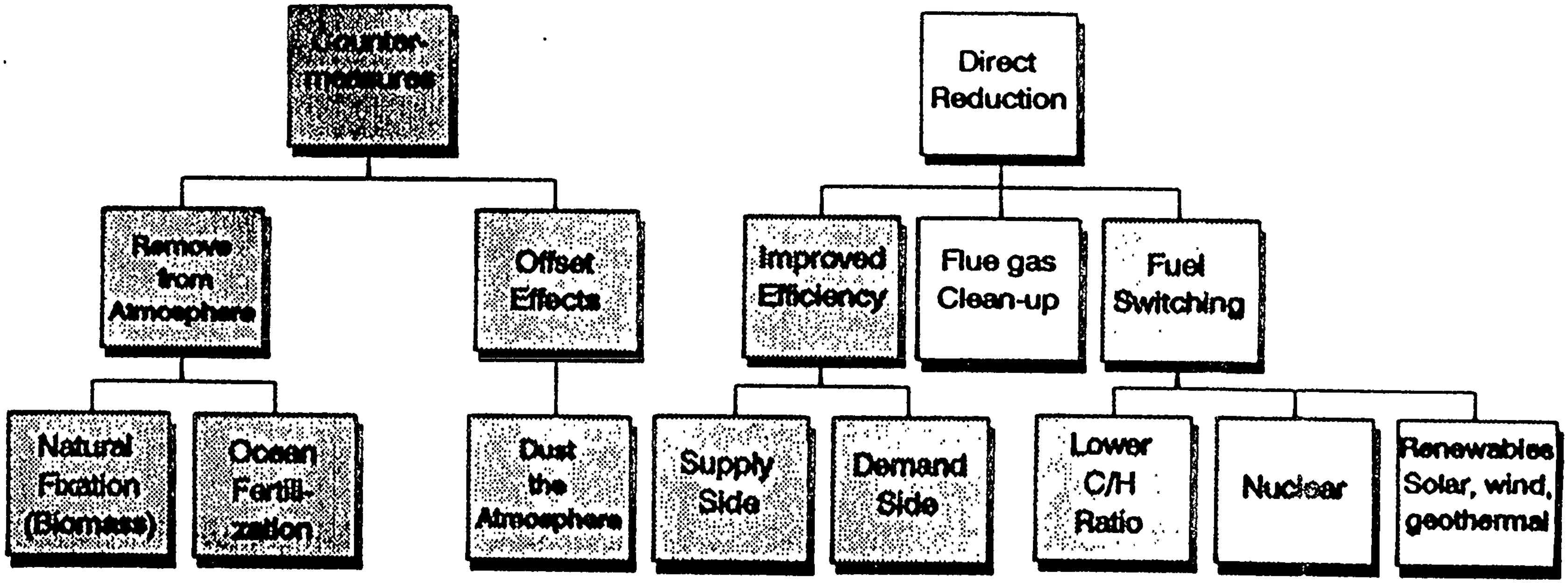


Figure 1. Spectrum of options for reduction of atmospheric CO_2.

CO_2 SEPARATION

TOSHIKATU HAKUTA
NATIONAL INSTITUTE OF MATERIALS AND CHEMICAL RESEARCH
HIGASHI, TSUKUBA, IBARAKI, 305 JAPAN

The climate change induced by CO_2 and other greenhouse gases is probably the most serious environmental threat that mankind has ever experienced. Nowadays fossil fuels occupy the majority of the world commercial energy supply. Most nations will be dependent on fossil fuels even in the first half of the next century. Around 30 % of CO_2 in the world is emitted from thermal power plants. Recovering CO_2 from energy conversion processes and storing it outside the atmosphere is a promising option for the mitigation of global warming. CO_2 fixation and storage include CO_2 disposal into oceans and underground, and utilization of CO_2.

CO_2 separation process will be used in any CO_2 storage system, and is estimated to consume almost half the energy of the total system. Research and development of highly efficient CO_2 separation process is most important from the viewpoint of practical application of CO_2 fixation system.

Ongoing Research in Japan

1) Separation process

CO_2 can be recovered from flue gas either by membrane process, absorption and adsorption. Survey and evaluation for separation and concentration processes of CO_2 on the basis of total system has been conducted[1,2]. Since each separation process has merits and demerits, a combination of two separation processes sometimes lead to higher efficiency. For example, membrane process or absorption process is employed at first step to capture CO_2 in high recovery rate, then adsorption process is used to purify CO_2. Specific separation process should be selected depending on the composition, pressure and temperature of the flue gases.

2) Membrane process

The Research Institute of Innovative Technology for the Earth (RITE) was established with the aim of tackling the growing threat of the global environment problems[3]. RITE carries on two large-scale research and development of technologies for CO_2 fixation; chemical-based CO_2 fixation and biotechnology-based CO_2 fixation.

As a part of the technologies of the chemical-based CO_2 fixation, membrane process for the separation of CO_2 are developed. Polymer membranes[4] and liquid membrane process are studied in cooperation with National Institute of Materials and Chemical Research (NIMC).

3) Chemical absorption

A pilot-scale test of CO_2 recovery by chemical absorption from a natural-gas fired power plant is conducted at Kansai Electric Power Company (KEPCO)[5]. The solvent is MEA, and the amount of CO_2 to be treated is 600 m^3N/h. Efforts have been directed towards evaluating CO_2 absorption performance, treating impurities in the flue gas and finding the most efficient integration of the CO_2 recovery system into thermal power plants.

A pilot-scale test for CO_2 recovery of 1000 m^3N/h including CO_2 absorption and adsorption process is carried on at Tokyo Electric Power Company (TEPCO)[6]. A large-scale experiment for CO_2 recovery by chemical absorption in 880 m^3N/hr at maximum is conducted at Central Research Institute of Electric Power Industry (CRIEPI)[6]. Energy and material balances of solvents are investigated in order to improve the energy efficiency of the chemical absorption process.

4) Physical absorption

A pilot-scale test for CO_2 recovery by physical absorption is carried on at Hokuriku Electric Power Company (HEPCO)[6]. A circulating fluidized bed is used instead of conventional fixed bed.

It is considered that physical absorption is suited for CO_2 highly concentrated gas mixtures. It has been investigated at University of Tokyo[7] that in the case of coal gasification process CO_2 can be captured from flue gas in a high efficiency by physical absorption utilizing the sift-reaction before the gas is burnt.

5) Pressure Swing Adsorption

A bench-scale experiment of 2 m^3N/h for CO_2 recovery by pressure swing adsorption (PSA) was conducted at Tohoku Electric Power Company[8]. The experimental apparatus was placed beside a coal fired power plant. A pilot-scale test of 1700 m^3N/h by PSA is carried on together with a CO_2 liquefaction process of 75 m^3N/h.

6) Combustion with O_2/CO_2 mixture

Fossil fuel combustion with O_2/CO_2 mixtures is expected to be effective for improving combustion efficiency and for CO_2 recovery from flue gas without the process of CO_2 separation. In this process air separation to produce highly pure O_2 is necessary in stead of CO_2 separation, and pure O_2 is diluted by CO_2 for the control of combustion temperature. Some studies at Osaka University[9] and Electric Power Development Company (EPDCO)[10] indicate that this process is more economic than the process of CO_2 capture after burning.

It is noted that all the ongoing research concerning CO_2 reduction in Japan cannot be introduced owing to limited space. Many other studies are carried on at companies, universities and national institutes.

Future View for Collaborative Research with U.S.

1) Research on highly efficient membrane

There is large possibility that high-performance membrane for CO_2 separation will be developed, and this will allow to improve the efficiency of CO_2 recovery process. Promising membranes for CO_2 capture include polymer membranes and liquid membranes. Synthesis of membranes from various raw materials and the evaluation of membrane such as permeability, separation factor and durability are important.

2) Development of absorption process

Many pilot-scale tests of CO_2 separation by absorption have been conducted. Exchange of the experimental results, and larger scale test in cooperation of two nations are expected. Improvement of durability of solvents and reduction of corrosion on the vessel caused by solvent are also important.

3) Optimal design of separation process

There are many kinds of thermal power plant such as natural gas fired, oil fired, pulverized coal fired and integrated coal gasification combined cycle. Selection of separation process for CO_2 recovery will be done depending on the type of the thermal power plant. Design of separation process for each type of power plant, and optimal design of combined process are expected.

References

1) Hakuta, T. *et al.*: *Survey on Fixation and Utilization of Carbon Dioxide I*, NEDO/SCEJ (1991).
2) Hakuta, T. *et al.*: *Survey on Fixation and Utilization of Carbon Dioxide II*, NEDO/SCEJ (1992).
3) Shindo, Y., Hakuta, T. and Miyama, H.: *Energy Convers. Mgmt*, 33, 773 (1992).
4) Kazama, S. *et al.*: *Proc. 25th Autumn Meeting of SCEJ*, F302, Tokyo (1992).
5) Saji, T. *et al.*: *Energy Convers. Mgmt*, 33, 317 (1992).
6) *Specail article in OHM*, 79, 84 (1992).
7) Matsuhashi, R. *et al.*: *T. IEE Japan*, **110-B**, (1990).
8) Makita, T. *et al.*: *Energy and Resources*, 14, 62 (1993).
9) Pak, P. S., Nakamura, Y. and Suzuki, Y.: *T. IEE Japan*, **110-B**, 155 (1990).
10) Nakayama, S. *et al.*: *Energy Convers. Mgmt*, 33, 379 (1992).

Carbon Dioxide Removal With Inorganic Membranes

Roddie R. Judkins, Fossil Energy Program Manager
Oak Ridge National Laboratory

Douglas E. Fain, Membrane Technology Department Head
Oak Ridge K-25 Site

Introduction

The increasing concentrations of greenhouse gases, particularly carbon dioxide, in the atmosphere has sparked a great deal of interest in the removal of CO_2 from flue gases of fossil fueled plants. Presently, several techniques for the removal of CO_2 are considered to have potential, but are lacking in practicality. For example, amine scrubbing of flue gas streams is effective in removing CO_2, but costs are high; efficiency suffers; and other acid gases must be removed prior to amine stripping. Membrane systems for CO_2 removal are held in high regard, and inorganic, particularly ceramic, membranes offer the potential for high temperature, thus energy saving, removal.

A great deal of research on inorganic membranes has been performed for the U.S. Department of Energy over the last 50 years. This research was primarily associated with the development of membranes for use in the gaseous diffusion process for separating uranium isotopes. That work is and likely will remain classified. However, this research covered a very broad range of investigations of inorganic membranes. Some of that research is not applicable to uranium isotope separation and could be useful in the development of inorganic membranes for a broad array of commercial applications. Over the last three years, research has been sponsored by the DOE Office of Fossil Energy to develop a membrane that can separate hydrogen from synthesis gas (syngas) produced from coal at up to 1000°C. The Office of Fossil Energy is also interested in the removal of carbon dioxide from gas streams. This paper will review briefly some of the progress on the development of a hydrogen membrane and discuss the potential for modifying those membranes to remove CO_2 from gas streams. Several approaches to developing a membrane, based on different transport mechanisms, will be discussed. The system operational conditions needed to take advantage of the different membrane characteristics and the efficiency for removal of CO_2 will also be discussed briefly.

Research sponsored by the U.S. Department of Energy, Office of Fossil Energy, Advanced Research and Technology Development (AR&TD) Materials Program, Work Breakdown Structure (WBS) Element K25-1. The Oak Ridge National Laboratory and the Oak Ridge K-25 Site are managed by Martin Marietta Energy Systems, Inc. for the U. S. Department of Energy under Contract No. DE-AC05-84OR21400.

Fundamentals of Gas Separation With Membranes

The separation factor for a binary mixture or the relative velocities for a multicomponent mixture depends on the membrane and is the primary factor affecting its usefulness for separation of the two gases. Membrane separation results in a stream enriched in one component and a second stream depleted in that component. The driving force for the separation, or for transport of a gas through a membrane, is the partial density difference across the membrane for each component. The enrichment of a component that occurs is greatly influenced by the density ratio across the membrane. The partial density, or partial pressure of gases, of a component on the enriched side of the membrane cannot be greater than the partial density, or partial pressure, of that component on the feed side of the membrane. Figure 1 provides indications of membrane separation abilities based on assumed separation factors and pressure ratios of the components in binary mixtures. Figure 2 provides model calculation separation curves for several binary mixtures based on the assumptions of ideal diffusion of hard sphere molecules. Ideal separation in this figure refers to Knudsen diffusion controlled separations. Of course, molecules are not hard spheres, nor is pure Knudsen diffusion the only operative transport mechanism. Figure 3 provides model separation curves for He-CO_2. The model used to produce these separation curves considers the several influences on separation that occur in real systems. As may be noted from the family of curves, at lower temperatures and lower average pressures, some of these influences actually lower the achievable separation factor as pore radius is lowered. At some point, however, molecular sieving becomes operative and very high separation factors are indicated by the model. Experiments have been conducted (Fig. 4) which lend credence to the model as these very low mean pore radii are approached.

Difficulties in Using Membranes for CO_2 Separation

For systems involving the separation of CO_2 from flue gases using membranes, several difficulties need to be considered. Inorganic membranes tend to favor enrichment of lighter gases. Some of the systems of importance, most notably pulverized coal power plants, operate at or near atmospheric pressure. For these systems, the feed gas must be pressurized or, alternatively, a vacuum must be created on the permeate side. Thus, membrane separation of CO_2 from pulverized coal power plant flue gases is not likely to be economical. However, for pressurized systems such as Pressurized Fluidized Combustors or Coal Gasifiers, separations may be achieved much more efficiently because the driving force, feed pressure, may be sufficient.

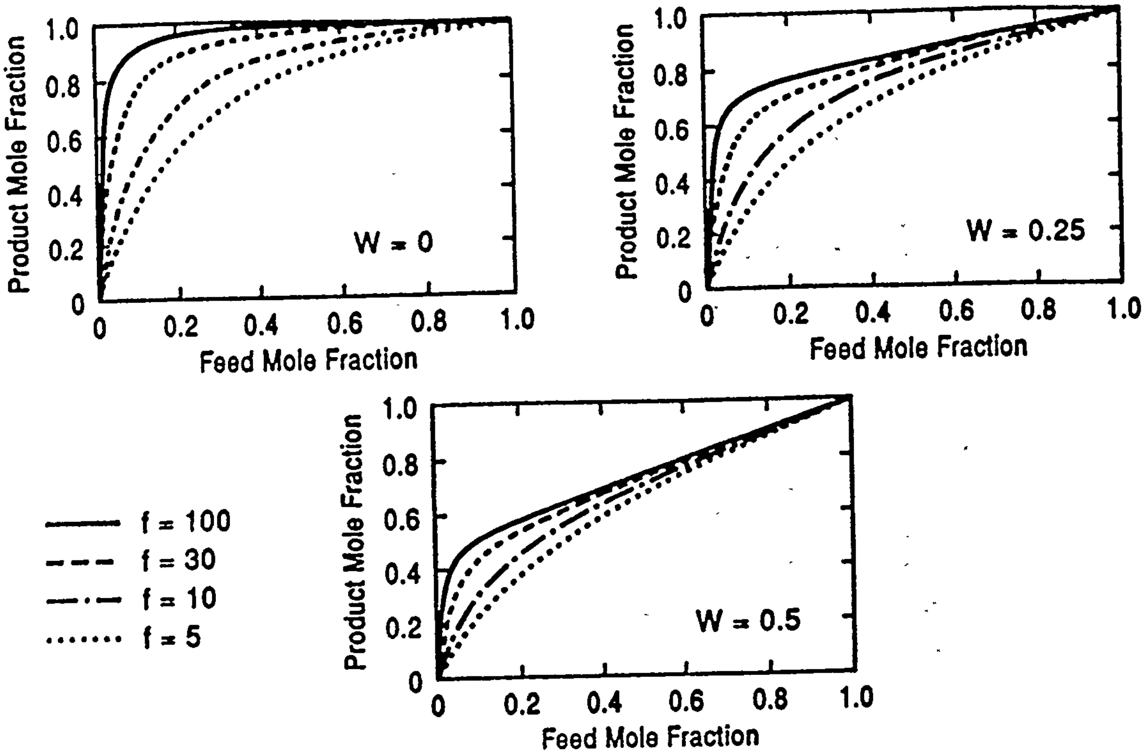


Fig. 1. Hydrogen product purity as a function of feed mole fraction at different pressure ratios (W) and separation factors (f) [ORNL-DWG 93Z-5154].

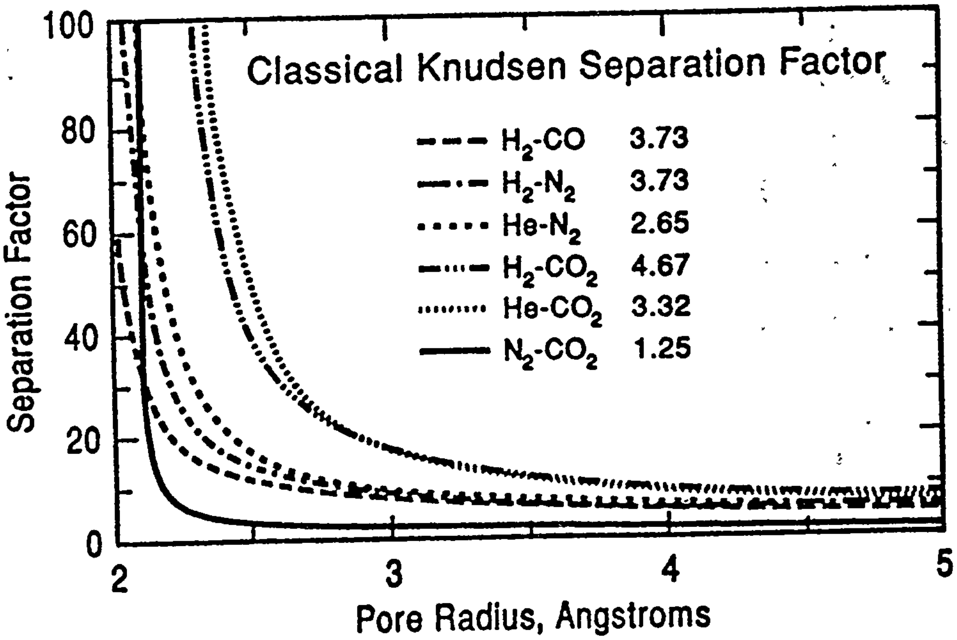


Fig. 2. Separation factors for ideal diffusion of hard sphere molecules [ORNL-DWG 93Z-5156].

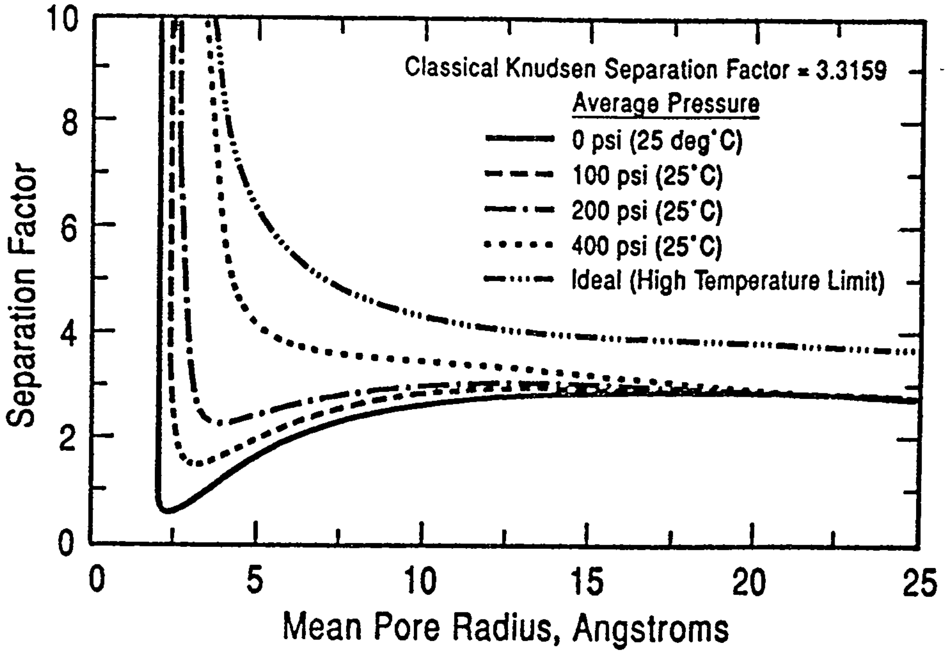


Fig. 3. Model separation factors for He-CO_2 calculated from individual gas flows [ORNL-DWG 93Z-5157].

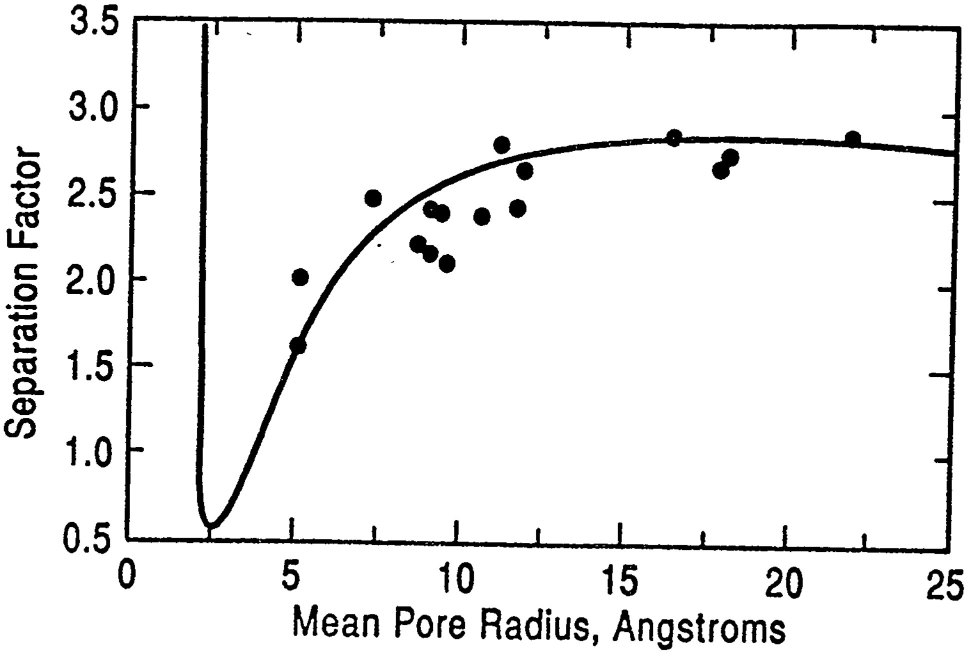


Fig. 4. He-CO_2 separation factors comparing model calculation and experimental data [ORNL-DWG 93Z-5163].

Currently available membranes have separation factors and permeabilities too low to be economically viable. Organic membranes have been operated successfully, but they can not be operated at high temperatures and environmental degradation is a concern. In spite of these difficulties, there is some cause for optimism based on recent developments. Figures 5 provides indications of the efficacy of inorganic membranes in effecting separation of CO_2 from coal gasification systems (Cases 1 and 2; Table 1) operated to maximize H_2 production (i.e., employing a shift reaction to convert CO and H_2O to CO_2 and H_2) and from PFBC flue gas mixtures (Case 3; Table 1).

Potential for Improvements in Membrane Separation of CO_2

Removal of CO_2 can be accomplished in either the enriched or depleted stream. This provides some flexibility in the operation of the separation device. Also, new molecular pore size inorganic membranes have the potential for producing very large separation factors. Figures 6-7 provide examples of the state-of-the-art in producing very small pore size membranes. Figure 6 shows the pore size and pore size distribution achieved for a membrane made in the first year of the inorganic membrane development, and Fig. 7 provides the same information for a more recently made membrane. Several other modifications to membranes may also be made to improve their separation efficiency. For example, the membranes may be designed to transport all molecules smaller than CO_2 or they may be designed to greatly enhance the transport of CO_2. This enhanced transport may be accomplished by increasing CO_2 surface flow, adsorption blocking of other molecules, or transport by capillary condensation of CO_2.

Conclusions

Economic removal of large amounts of CO_2 from gas streams using currently available membranes appears unlikely. However, the prospects for new molecular pore size inorganic membranes provide optimism that very large separation factors and very high permeabilities can be achieved in pressurized high-temperature systems. System designs that address the membrane operating requirements will be vital to the success of membrane separation of CO_2. These new molecular pore size inorganic membranes may accomplish CO_2 separation and/or removal at more advantageous points (i.e., high temperature, high pressure locations) in process streams.

Table 1. Composition of Gases From Coal Gasification Operated With a High Temperature Shift and Flue Gas From a Pressurized Fluidized Bed Combustor.

Case 1 (Coal Gasification):

Pressure = 4.7 MPa (680 PSI)
Temperature = 220°C (428°F)

Component	Mole %
H_2	55.6
CO	1.7
CO_2	39.9
H_2, Ar	1.4
H_2S, COS	1.1
H_2O	0.3

Case 2 (Coal Gasification)

Pressure = 2.4 MPa (350 psi)
Temperature = 370°C (698°F)

Component	Mole %
H_2	53
CO	3
CH_4	2
H_2S	0.1
H_2O	0.9

Case 3 (Pressurized Fluidized Bed Combustion)

Pressure = 1.03 MPa (150 psi)
Temperature = 800°C (1472°F)

Component	Mole %
O_2	3.45
N_2	75.25
CO_2	13.63
SO_2	0.34
H_2O	7.33

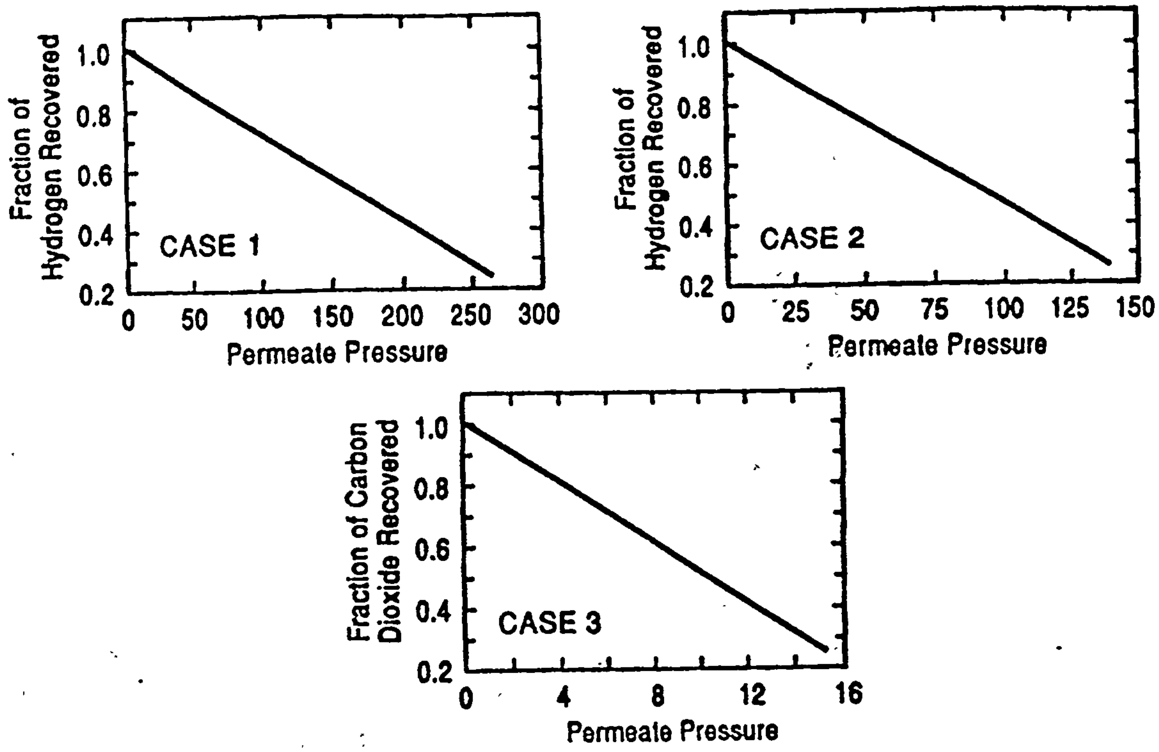


Fig. 5. Recovery of H_2 (coal gasification) or CO_2 (PFBC) as a function of permeate pressure. [ORNL-DWG 93Z-5162].

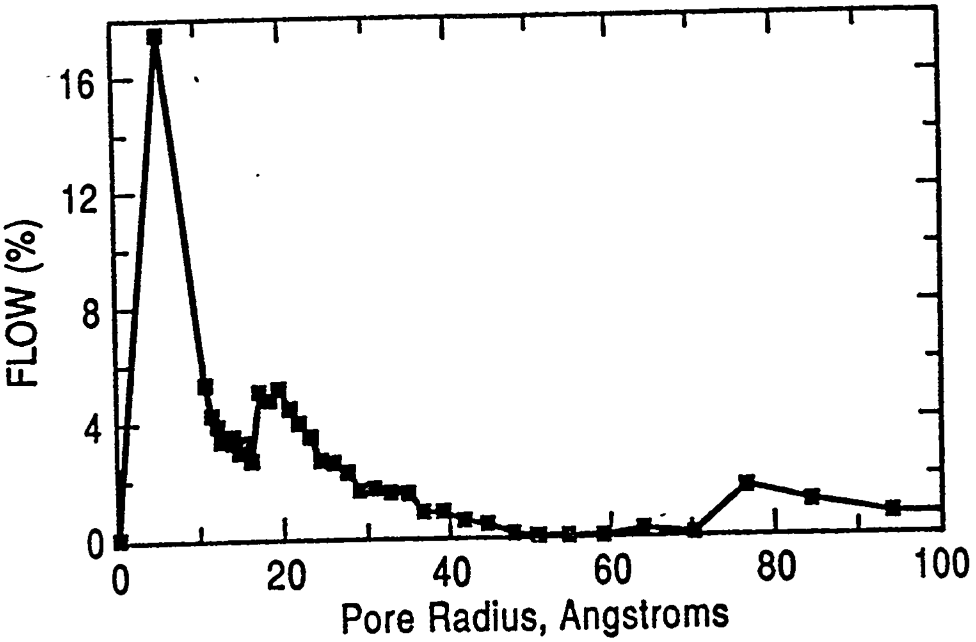


Fig. 6. Pore size distribution of an inorganic (Al_2O_3) membrane fabricated in the first year of membrane development [ORNL-DWG 93Z-5164].

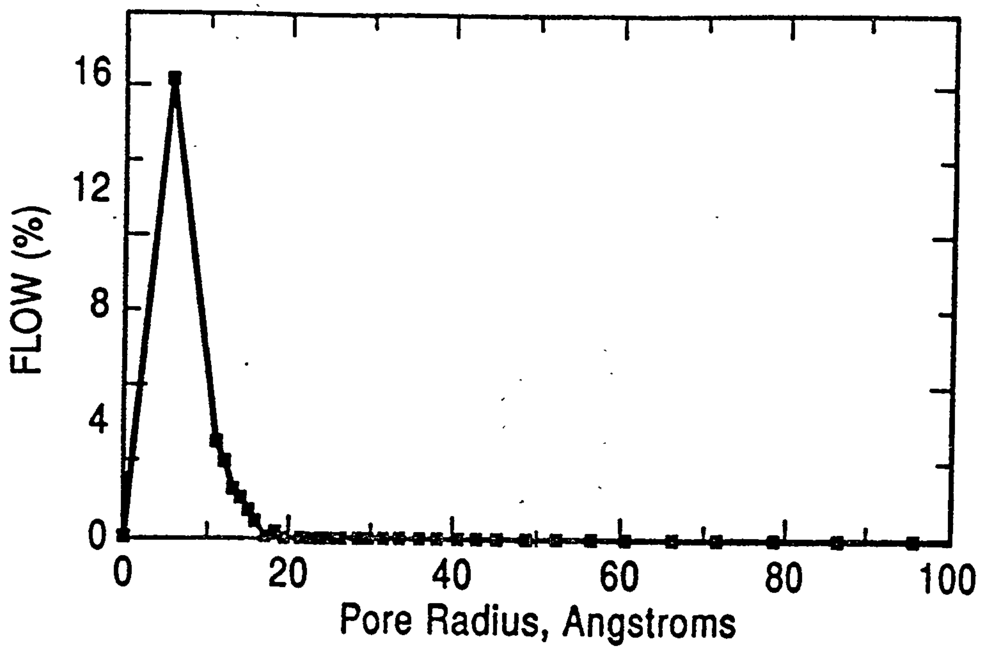


Fig. 7. Pore size distribution of an inorganic (Al_2O_3) membrane fabricated with an improved technique [ORNL-DWG 93Z-5165].

AN INDEPENDENT ASSESSMENT OF CO_2 CAPTURE RESEARCH NEEDS

Bruce St.John
INTECH, Inc
28B South Frederick Av
Gaithersburg, MD 20877

INTRODUCTION

The United States generates on the order of five billion metric tons of CO_2 annually. Of this, approximately 1.8 billion metric tons is from electric utilities. Other industrial sources of CO_2, such as cement plants, coke ovens, ammonia plants, oil refineries, etc. are small relative to the emissions from power plants. The majority of the emissions from U.S. electric utilities are from coal-fired power plants. Thus, any large scale program to control CO_2 emissions needs to include abatement of CO_2 from power plants.

Currently, there are very few proven options to mitigate CO_2 emissions:

- Improve thermal efficiency, thereby decreasing the amount of CO_2 generated per unit of output.
- Improve the efficiency of end use.
- Convert to lower carbon fuels or non-fossil energy sources.
- Plant trees to offset CO_2 emitted.
- Produce a concentrated CO_2 stream for utilization or disposal.

The first four options are well known and are being actively pursued at the present time. This paper examines the last option from the perspective that the gap between what is needed and what is available defines the research and development opportunities.

PROCESSES TO PRODUCE CONCENTRATED CO_2

A number of investigators in Europe, Japan, and the United States have evaluated methods of producing a concentrated CO_2 stream from power plants. The different investigators, working independently, have identified four processes for this application: monoethanol amine, combustion in a mixture of oxygen and recycle CO_2, membrane separation, and separation from coal gasifier synthesis gas. A number of other commercial gas treating processes have been determined to be unsuited to CO_2 removal from power plant flue gases, primarily because of the low CO_2 partial pressure.

The monoethanol amine (MEA) process is the only commercially demonstrated process for scrubbing CO_2 from low pressure flue gas. Thus, this is the technology for near term application to fossil fueled power plants. Several MEA units have been operated on power plant flue gas to recover CO_2 for enhanced oil recovery projects, and there are three MEA scrubbers currently operating in the United States on low pressure flue gases. Two are on coal-fired boilers and the third is on a natural gas-fired combustion turbine. One plant has operated since 1978, recovering CO_2 from coal fired boiler flue gas for use in soda ash manufacture. The two newer CO_2 plants are part of cogeneration projects. These plants treat a flue gas slipstream, and the CO_2 product is sold to industrial customers.

The operating MEA plants have demonstrated the ability of the MEA process to treat boiler flue gas containing problem compounds, such as SO_2, O_2, hydrocarbons and particulates. The plants all had some startup problems which were solved.

There is general agreement that CO_2 scrubbing is a commercially demonstrated technology which could be applied to collect CO_2 emissions from power plants, but the cost and energy penalty is very high and the collection is only a first step in the ultimate disposal of the CO_2. Research needs in the collection technology area could include

- consideration of new process approaches, such as catalytic reduction of the SO_2 to H_2S with CH_4, followed by simultaneous separation of the H_2S and CO_2, This approach would eliminate the separate FGD system.
- development of new solvents, and
- decreasing the energy consumption of solvent regeneration.

Instead of removing CO_2 from the flue gas, a CO_2-rich flue gas could be produced by removing the nitrogen from the combustion air. Combustion in a mixture of oxygen and recycle CO_2 has been tested in a laboratory furnace and appears to be technically feasible as a method of producing a flue gas of CO_2, SO_2, NOx and H_2O, which is not diluted with N_2. Research topics in this technology area could address

- integrating the oxygen plant, the power plant, and the flue gas recycle to optimize the energy efficiency of the total system,
- studies of co-disposal of CO_2, SO_2, and NOx in carbon steel pipelines.
- development of a combustion-in-oxygen cycle for combustion turbines.

These two technologies could be applied to existing power plants. For each, the energy penalty associated with CO_2 concentration and a high pressure disposal option, such as ocean disposal, reduces the net power plant output by approximately 40%, which instantly creates the question regarding the need for replacement power. If replacement power is not needed, then an equivalent 40% decrease in power generation would decrease CO_2 emissions by 40%

at no cost. If the lost power must be replaced, it may be more economical to retire the existing plant and build a new 100% capacity plant than to retrofit the existing plant and build a 40% capacity plant.

Membranes can separate gases in proportion to the speed at which they diffuse through a polymeric material. The permeate reports at low pressure. Single stage membranes can either achieve a high recovery, or a high purity, but not both. If high purity and high recovery are required, a multistage membrane design is required. The multistage membrane designs are expensive and are frequently uneconomical compared to distillation processes.

Several investigators have evaluated using membranes to separate the CO_2 from the flue gas. The results show that current membrane technology is not economically competitive with monoethanol amine scrubbing. Current membrane materials have CO_2:N_2 selectivities below 100. However, it may be possible to develop improved membrane materials with higher selectivity which will be economically superior.

A number of investigators have investigated CO_2 removal from coal gasification. In the coal gasification process, the synthesis gas is produced at high pressure (on the order of 600 psi (4.2 kg/cm^2)). A number of gas treating processes (such as physical solvents, membranes, etc.) can separate the CO_2 from the high pressure synthesis gas with very little energy penalty. In addition, coal gasification-based electric power generation processes have higher thermal efficiency than pulverized coal power plants. Thus, the coal gasification power plants appear to be a superior option for new coal-fired generating capacity. Some research needs for this technology are:

- Development of technologies to use hydrogen-rich fuels:
    - High temperature combustion turbines
    - Molten carbonate fuel cells
- Process and economic optimization
    - Development of a gasification retrofit for existing power plants
    - Investigation and optimization of simultaneous removal of H_2S and CO_2, with co-disposal of the mixed H_2S/CO_2 stream.

OPEN ISSUES

It is technically possible to concentrate the CO_2 from fossil fuel burning. The next question is what to do with the concentrated CO_2. Utilization can employ a small fraction of the CO_2; the remainder must be disposed of. This paper has examined what CO_2 capture options are presently available to control CO_2 emissions from power plants. But CO_2 capture is meaningless without an effective disposal option. Thus, disposal is the major research need.

Disposal will be discussed in other papers presented during this workshop.

From the perspective of the power industry, there are a number of unanswered questions.

- First, is the lack of a proven disposal method which can sequester large quantities of CO_2 for a long period of time.
- Then, a feasible CO_2 separation technology to retrofit existing power plants has not been defined.
- Third is that when the cost of CO_2 removal and disposal is incorporated into the electric rate, the price of electricity will increase substantially. What will be the effect on the demand structure? If the total demand and the demand structure change substantially, this could make other low CO_2 technology options more economical.

REMARKS ON CO_2 CAPTURE FROM ELECTRIC POWER PLANTS AND RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

presented to the Second US/Japan Workshop on Global Change
1 - 3 February 1993

by

Alan M. Wolsky
Argonne National Laboratory
Argonne, IL 60439

I. Introduction

This paper recommends investigation of several topics that have not yet received sustained attention. Each bears directly on the cost and funding of CO_2 capture and sequestration. The reasons why each topic deserves attention are briefly sketched.

II. Combination of Sulfur Compound and CO_2 Capture

As shown in Fig. 1, there are three approaches to avoiding CO_2 emissions:

A) separation of CO_2 from the post-combustion fluegas of an otherwise conventional power plant,
B) separation of N_2 from air before combustion, leaving a post-combustion fluegas, composed principally of CO_2 and H_2O, from which CO_2 can be easily separated
C) separation of C from the fuel before combustion (e.g. via shift to CO_2 and H_2), leaving a post-combustion fluegas composed principally of H_2O

If the fuel were natural gas, CH_4, the choice among approaches would be straight forward. However, the principal U.S. fuel is and will be coal. Coal often contains non-negligible amounts of sulfur. Some fluegas CO_2 separation technology (e.g., amines, used to implement approach (A)) cannot operate economically when its input contains too much SO_2. In that case, a sulfur scrubber must be inserted ahead of the amine unit. Another separation technology, implementing approach (C), consists of gasifying coal, removing H_2S, and then shifting the syngas to H_2, capturing the CO_2, and then burning the H_2. As before, the result is a sulfur stream and CO_2 stream. In both cases, CO_2 capture comes after a substantial investment in sulfur capture. However, another possibility exists. Instead of separating sulfur compounds from CO_2, one can consider capturing them together and sequestering them together. This can be implemented by approach (B) in which the fuel is burned in O_2 (e.g., with CO_2-O_2 recycle) and the resulting CO_2 stream retains some SO_2. This might also be implemented in approach (A) if a cryogenic separation, rather than an amine, were used on the conventional fluegas. Also, this might be partially implemented in approach (C) if no attempt is made to separate H_2S after gasification and the hydrogen were burned in a mixture of CO_2 and O_2.

The economic choice among CO_2 avoidance technologies must be made in conjunction with the choice among sulfur emissions avoidance technologies and the equipment to which they will be applied. Moreover, some of the equipment is common to different approaches (e.g., an O_2 plant is required in approach (B) where it is often debited to CO_2 capture and in approach (C) where it is often debited to sulfur capture).

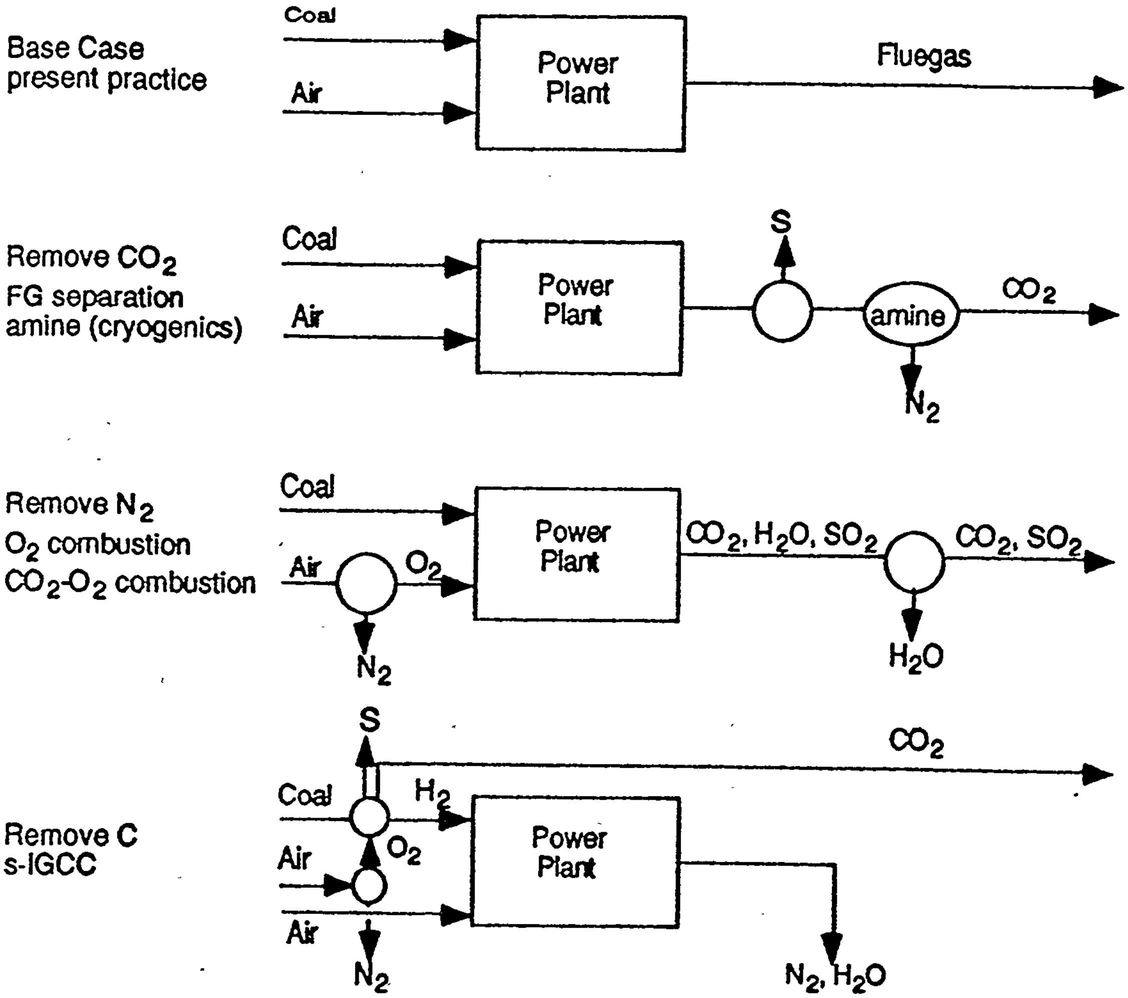


Figure 1

CO_2 capture and sequestration from coal-fired plants must be considered in conjunction with sulfur capture and disposal.

Two investigations are recommended. First, an engineering economic study is recommended of the total costs of both CO_2 and sulfur emissions avoidance in the various approaches. This study should use the same cost assumptions for equipment common to the various approaches and it should distinguish between the cost of separating sulfur from CO_2 and the cost of capturing a single gas that is a mixture of CO_2 and SO_2. The latter might provide significant cost savings. Second, an investigation is recommended of the feasibility and desirability of sequestering CO_2 that contains SO_2 (e.g., 1-2%). Prior work on enhanced oil recovery maybe relevant.[1] It may also be relevant to note that the deep ocean is already the site of naturally occurring emissions of H_2S.

III. Off-Peak CO_2 Capture and Compression

The capture of CO_2 and its compression for transport will require a substantial amount of shaft power. This is clear for approach (B) which uses an O_2 plant and for approach (C) when an O_2 plant is needed for gasification. However it is also true for approach (A) if cryogenic separation is used or if steam is extracted from the turbine to heat an amine regenerator. If not, then another source of heat will have to be provided.

At any given time, the cost of this shaft power is not accurately reflected in the annual average price of electricity. The marginal cost of new shaft power depends very much on whether traditional loads have driven the utility system near its peak load or whether excess capacity is available. Most US utilities have substantial excess capacity during most of the day, the so-called off-peak period. During this period, the marginal cost of shaft power is essentially the cost of fuel, roughly \$0.02 per kWhe in the US. During the many fewer peak hours of the year, the marginal cost of new shaft power must pay for the cost of new generating capacity, roughly \$0.12 per kWhe or more. This substantial difference between the peak and off-peak cost of shaft power deserves attention. It may be that one could afford to capture and compress more CO_2 than otherwise by foregoing capture and compression during peak hours.

Two investigations are recommended. First an investigation is recommended of the ease of turning the capture and compression technology on and off, as well as the trade-off between capital and shaft power costs. Second, an investigation is recommended of the availability of excess capacity during the different hours of the year and the savings from using it. In short, an estimate of the optimal operation of the capture and compression technology is recommended.

IV. Integrated Consideration of the Pressures for Capture, Transport, and Disposal

Most published discussion of CO_2 capture technologies estimates costs for delivering CO_2 at 1Bar (1atm = 14.7 psi). Most published discussion of CO_2 transport via pipeline concerns pressures of 140 Bar (140 atm = 2,000 psi). Most US discussion of ocean disposal is concerned with finding ways to avoid the cost of deep injection by injecting at relatively shallow depths, roughly a few hundred meters (roughly 20 - 30 Bar). These pressures are qualitatively different from each other.

Disconnected considerations may obscure important cost savings. For example, cryogenic separation of CO_2 from fluegas appears to be more expensive than either amines or CO_2-O_2 recycle. However, no one has estimated the savings, if any, in compression costs from integrating a cryogenic separation with compression for pipeline transport. Similarly, shallow injection only saves the shaft power that can be recovered from letting down pipeline pressures. Perhaps 30% of the shaft power would be lost in a cycle of compression and decompression. Today's choice of average pipeline pressure reflects both the desire for high thruput and the depths at which CO_2 flooding is done for Enhanced Oil Recovery.

An investigation is recommended of the effect of pressure on cost in an integrated system of capture, transport, and sequestration. The results are expected to be insensitive to the details of each stage.

V. Equitable and Efficient Funding for CO_2 Capture and Sequestration

While investigation of the topics already raised may disclose ways to significantly reduce the cost of CO_2 capture and sequestration, the least cost will still be substantial. Indeed the anticipated cost and its assumed allocation have persuaded some policy makers and many in the electric power industry to advocate a "wait and see" policy instead of a pro-active one.

If mitigation is needed then its cost should be born in a way that is both equitable and efficient. Such a policy is proposed below.

Two aspects must be considered: a) method and cost of sequestration and b) how to pay for it. With regard to the first, no specific technology is advocated, instead an auction is proposed. Members of the private sector would be invited to submit bids to the U.S. government (or an international authority) for sequestering whatever quantity of CO_2 the bidder wished to commit to. The bidder offering the lowest marginal cost would get the first contract. The next lowest bidder would get the second contract and so on until the available funding is exhausted. (The source of the available funding is described below.) Thus, members of the private sector would have an incentive to enter the sequestration business and the need to offer the least expensive method. The government's role would be to certify the practicality of the proposed sequestration method and later monitor its effectiveness. (For example, the government would not accept a bid from someone who proposed to grow trees in the desert.)

While unnecessary, it is interesting to speculate about who would enter the auction. Perhaps, some land owners might find a profit by reforestation. After inexpensive land is no longer available, some electric utilities might become the next lowest bidders, entering the sequestration business with partners (e.g., pipelines and off-shore platform operators). The crucial point is that only those firms that choose to would involve themselves in the auction and only the lowest bidders would sequester.

The second aspect of this proposal is the mechanism for raising the revenue to fund the "sequestration auction." To do this a carbon tax is proposed. This severance tax would be collected at every gas-well, oil-well, and coal-mine. An equivalent carbon tariff would also be collected at every sea-port (and pipeline) entering the U.S. The revenue would be used exclusively for the sequestration auction. In this way, everyone who uses coal, gas, or petroleum would share the cost of avoiding CO_2 emissions. The carbon tax/tariff would also encourage substitution of non-fossil for fossil fuel.

As alluded to above, an international agreement would further the purposes of this proposal. The agreement would establish a uniform, international carbon tax and allow any firm to enter the sequestration auction. In this way, the goals of efficiency and equity could be universally implemented.

An investigation of this proposal is recommended.

VI. Conclusion

While progress has been made in identifying and clarifying promising approaches to avoiding CO_2 emissions, much remains to be done. At present, many believe that delaying or reducing the projected Greenhouse Effect is too expensive to be attempted. Thus, efforts to scope the issue, estimate systematically the cost of CO_2 avoidance, find ways to reduce it, and discuss how to fund implementation are timely.

VII. Acknowledgment

The exposition of these ideas was improved by helpful comments from E.J. Daniels and B. Jody.

REFERENCE

1. Taber, J.J., Fate of Small Concentrations of SO_2, NO_x and O_2 when Injected with CO_2 into Oil Reservoirs, ANL/CNSV-50 (June, 1985).

Recycling Technology of Emitted Carbon Dioxide*

Hironori ARAKAWA

National Institute of Materials and Chemical Research (NIMC)
Agency of Industrial Science and Technology (AIST)
Ministry of International Trade and Industry (MITI)
Higashi 1-1, Tsukuba, Ibaraki 305 Japan

1. Action to Halt Global Warming and Technologies to Fix Carbon Dioxide

Ways to halt global warming are being discussed worldwide. Global warming is an energy problem which is mainly attributed to the large volumes of carbon dioxide (CO_2) released into the atmosphere from the rapid increase in energy consumption since the Industrial Revolution. The basic solution to the problem, therefore, is to cut consumption of fossil fuels. To this end, it is important to promote energy conservation by improving the fuel efficiency of machines, as well as shift to energy sources that do not emit carbon dioxide and develop related technologies. If current trends in economic growth continue in the developing world as well as the developed countries, there can be no doubt that energy consumption will increase. Therefore, alongside energy conservation and the development of alternative energies, the importance of technologies to recover and fix CO_2 will increase in the fight against global warming.

Several ways have been suggested to recover and fix CO_2. There included physical methods (dumping or storing CO_2 in the deep sea, abandoned mines or waste oil pits), biological methods (fixing CO_2 in algae and plants using solar energy) and chemical methods, which will be described in detail below.

In discussing the feasibility of technologies to fix CO_2, the important thing is whether a given method can be used to quickly dispose of large volumes of CO_2 safely and without environmental harm.

It is estimated that about 20 billion tons of CO_2 are released into the atmosphere each year worldwide, and 800 million tons come from Japan. Assuming that Japan manages to recover and fix only 1% of its emissions, the resulting eight million tons become a massive disposal problem. Collecting, fixing and storing it, where physically, biologically or chemically, cannot be a permanent solution because it means only an accumulation of CO_2 and only changes the form in which CO_2 builds up from its natural state to an artificial one. The ideal approach is to think of CO_2 as a carbon source and work out how to recycle it.

Emissions from large fixed sources, such as power plants and factories, would be the first target for recycling since they are much denser (accounting for 10-25% of emissions) than those from small, mobile sources like automobiles, and easier to recover.

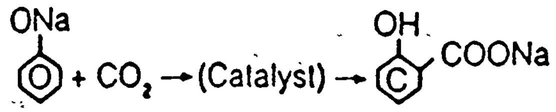
2. Catalytic Hydrogenation of Carbon Dioxide

Several ways have been suggested to recycle CO_2 chemically.[1] Through organic synthesis and polymer synthesis, CO_2 may be fixed as organic chemicals and polymers. The synthesis of aromatic carboxylic acid using the Kolbe-Schmit reaction (see formula 1) and of urea using the reaction between CO_2 and ammonia (see formula 2) have already been put into practice. The synthesis of polycarbonates by making copolymers from CO_2 and ethylene oxide (see Formula 3) is an attractive method that is nearing practical use.

---

*Prepared for the Second Japan/U.S.A. Workshop on Global Change: Environmental Response Technologies (Mitigation and Adaptation), East West Center, Honolulu, Hawaii, U.S.A., February 1-3 (1993).

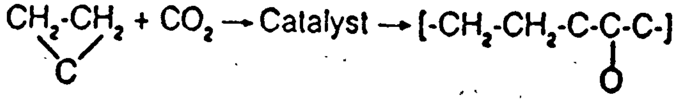
Formula 1: Synthesis of Aromatic Carboxylic Acid



Formula 2: Synthesis of Urea

$$2NH_3 + CO_2 \longrightarrow (Catalyst) \longrightarrow H_2NCONH_2 + H_2O$$

Formula 3: Synthesis of Copolymers



Methods for reducing CO_2 by synthesizing chemicals include electrochemical fixation and fixation using photocatalyst (artificial photosynthesis) (see Formula 4).

Formula 4: photochemical and Electrochemical Fixation

$$CO_2 + 8H^+ + 8e \text{ (Electrical or Light Energy)} \longrightarrow CH_4 + 2H_2O$$

The catalytic hydrogenation method also reduce CO_2 using hydrogen as a reducing agent in place of electrical or light energy. The reaction of CO_2 with H_2 to CH_4 proceeds easily over the catalyst (see formula 5).

Formula 5: Catalytic hydrogenation

$$CO_2 + 4H_2 \longrightarrow Catalyst \longrightarrow CH_4 + 2H_2O$$

This is one of the most promising technologies for fixing large amount of CO_2 for reuse as other chemicals or fuel. The main advantage is that the catalytic hydrogenation method fixes a large amount of CO_2 quickly per unit of time and area and can be used to easily deal with large volumes of CO_2.

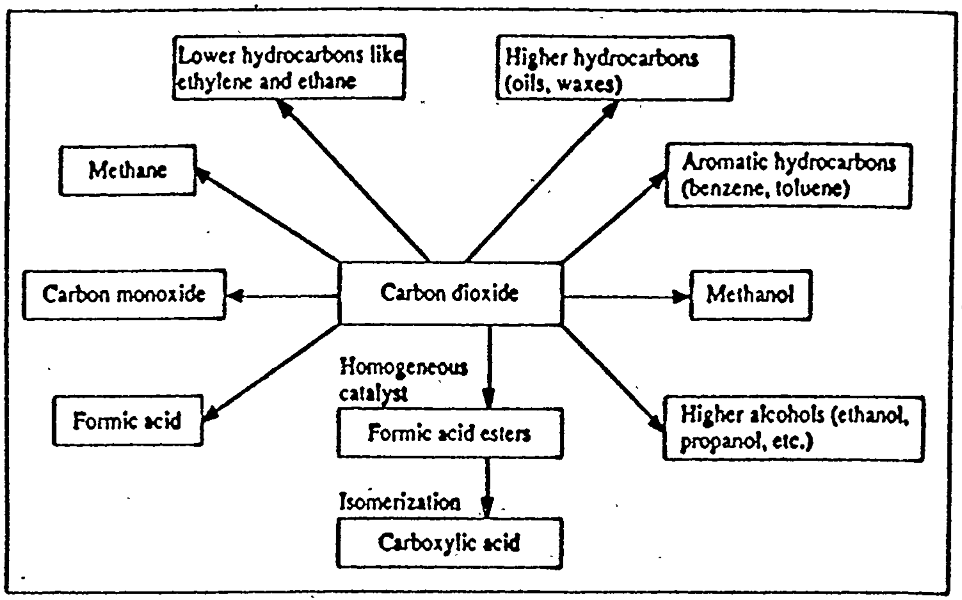


Fig. 1: Chemicals Synthesized by Catalytic Hydrogenation of CO_2

Furthermore, as seen in Fig. 1, it is possible to synthesize various basic chemicals, including hydrocarbons and oxygenated compounds, using the catalytic hydrogenation method.

If catalysts are developed that work well for each chemical process, fast expansion can be expected for that part of chemical industry that uses CO_2 as a raw material. The synthesis gas reaction (catalytic hydrogenation of carbon monoxide) which resembles catalytic hydrogenation of CO_2 has been used to synthesize methanol and so on. Therefore, some synthesis gas reactions may be used in or replaced by catalytic hydrogenation of CO_2.

3. Chemicals Synthesized using Catalytic Hydrogenation of Carbon Dioxide

It is reported that many kinds of chemicals can be synthesized using catalytic hydrogenation of CO_2 (see Fig.1), from low hydrocarbons like methane, ethane and ethylene to higher hydrocarbons (e.g., oils, waxes), alcohols (methanol, ethanol) and carboxylic acid derivatives (formic acid, formate).

Industrial processes to effectively and selectively synthesized there chemicals have not been established; they are at the stage of basic research at universities and research institutes around the world. Research will become more active as more take on the problem of recycling CO_2. Table 1 gives some examples of catalysts that have proven effective in chemical synthesis.

It is interesting to note that the use of different catalysts results in different compounds. Generally, catalysts from the nickel, cobalt, ruthenium and rhodium families most frequently produce methane.

Table 1: Representative Catalytic Hydrogenation of CO_2

Synthetic reaction/ Catalyst	Reaction condition	Co_2 conversion (%)	Product (selectivity %)
Methane			
Ru/SiO_2	233°C, 11 atm	9.0%	CH_4 (99.7%)
Fe/SiO_2	291°C, 11 atm	9.9%	CH_4 (39.9%), CO (53%)
Co/SiO_2	205°C, 11 atm $H_2/CO_2 = 4$	11.2%	CH_4 (89.0%), CO (10%)
C_2^{+}- hydrocarbon			
Cu/SiO_2 $-Rh/Nb_2O_5$	340°C, 1 atm $H_2/CO_2 = 4$	25%	C_2H_6, C_3H_8 (44%)
Cu-ZnO dealuminated-zeolite	320°C, 21 atm $H_2/CO_2 = 2$	17% (H.C 4.1%) (CO 11.8%)	C_2H_6 (24.5%), C_3H_8 (35.8%), C_4H_{10} (29.9%)
Methanol			
$Cu-ZnO-La_2O_3$	300°C, 110 atm $H_2/CO_2 = 3$	29.5% (ROH 16.4%) (CO 13%)	CH_3OH (99.9%)
Pd/La_2O_3	350°C, 120 atm $H_2/CO_2 = 3$	10.8% (CO 4%) (ROH 6.1%)	CH_3OH (89.4%) CH_4 (10.5%)
Higher Alcohols			
Mn/Fe/Cd/CuOxide	400°C, 150 atm $H_2/CO_2 = 3$	46%	EtOH (20%), PrOH (18%), BuOH (8%)
$KCl/Mo/SiO_2$	250°C, 16 atm $H_2/CO_2 = 1$	rate (0.34 C-mmol/ g-cat.h)	CH_3OH (24.8%), EtOH (30.9%), $C_3^{+}OH$ (42%)
Formic ether			
$Pd(dpm)_2$ (440 μmol)	125°C, 30 atm $EtOH/Et_3N$ $H_2/CO_2 = 1$	TOF (100/24 h)	HCOOEt (4000 μmol) CH_4 (40 μmol) $(COOEt)_2$ (0.4 μmol)

H.C.: hydrocarbon, ROH: alcohol, $C_3^{+}OH$: propanol, butanol, dpm: diphosphinomethane

The use of iron-family catalysts generally results in carbon monoxide, C_2+ hydrocarbons, and the use of those related to copper, palladium, platinum and rhenium produces methanol. Palladium and ruthenium catalysts are effective in synthesizing carbonic acid esters. Expect in the synthesis of methane, there synthesizing reactions lack selectivity and activity. To commercialized catalytic hydrogenation methods, the development of catalysts that allow efficient and selective synthesis of target chemicals will be needed.

4. Making Methanol from Carbon Dioxide

So we see that various chemicals may be synthesized using catalytic hydrogenation of CO_2. To help stop global warming, the most promising area is to synthesize methanol this way, primary because it is in great demand. Currently methanol is mainly synthesized from natural gas via synthesis gas, and 20 million tons are produced each year worldwide. Methanol is catching attention as a cleaner fuel for diesel engines, since it produces fewer NO_x and carbon particulates. Its use blended with gasoline and neat use as a clean fuel is being considered. In addition, the process of gasoline synthesis from methanol is already established. Therefore, demand for methanol fuel will almost certainly grow.

Methanol is also important as a basic chemical. The processes of synthesizing various chemicals, including formaldehyde, glycol aldehyde, ethylene glycol, dimethylcarbonate, acetaldehyde acetic acid, methyl acetate and methyl formate, are in commercial use or under development for the near future. In addition, methanol synthesis is much cheaper than hydrocarbon synthesis, since it requires less hydrogen and produces less water. There are two other positive factors: the development of a high-performance catalyst for commercial methanol synthesis is probable, and an academically significant finding has been made that at below 250 °C, methanol from CO_2 may be synthesized much more quickly compared with that from synthesis gas.2)

If a high-performance catalyst is developed, 400,000 tons of methanol can be made from 600,000 tons of CO_2 per year in a chemical plant using 10 tons of catalyst. About 16,000 tons of CO_2 are emitted each day by a million-kilowatt power plant that uses heavy oil. A chemical plant with the capacity stated above will be able to convert 10% of that CO_2 to methanol.

From this standpoint, we have been studying an efficient catalytic hydrogenation of CO_2 to methanol3,4) and its derivative, dimethylether5), which is also a higher added-value-chemicals as well as a precursor of gasoline synthesis using zeolite catalyst. So far, promoted Cu-ZnO catalyst has proved to be an effective catalyst for methanol synthesis from CO_2. Table 2 shows an example obtained by Cu-ZnO-Al_2O_3-Cr_2O_3 catalyst.3)

Table 2: Selective and Effective Synthesis of CH_3OH by Catalytic CO_2 Hydrogenation

Pressure (MPa)	Temperature (°C)	GHSV (h^{-1})	CO_2 conversion (%)	CH_3OH selectivity (%)	(Yield)	CO selectivity (%)	CH_3OH STY (g/l-cat.h)
7.0	240	1500	24.9	78.8	(19.6)	20.8	89.8
7.0a)	250	1800	25.2	78.9	(19.9)	20.5	97.6
7.0a)	250	3000	25.3	74.2	(18.8)	25.6	165.6
5.0a)	230	1800	20.0	67.3	(13.5)	32.4	71.2
5.0a)	230	12000	9.3	67.0	(6.2)	33.0	219.5
3.0	210	10000	6.8	71.3	(4.8)	28.7	144.4
3.0	210	20000	4.7	75.8	(3.5)	24.2	216.0
3.0	210	25000	4.2	76.5	(3.2)	23.4	235.5
3.0	190	10000	4.8	84.3	(4.0)	15.6	121.7
3.0	220	20000	7.7	70.9	(5.5)	29.1	330.2
3.0	230	20000	10.2	62.0	(6.3)	38.0	381.6
3.0	240	20000	12.8	53.1	(6.8)	46.9	410.9

Catalyst: Mark E (1.0 g of CuO(43)-ZnO(20)-Al_2O_3(34)-Cr_2O_3(3), 16-32 mesh size), H_2/CO_2: 3/1
a): Catalyst E of powder type was used.

Methanol is produced with high efficiency such as 25% conversion of CO_2 with 79% selectivity of methanol at the condition of 7 MPa, 250 °C, GHSV=1,800 /h $H_2/CO_2=3/1$ and 410 g/l-cat h of space time yield at the condition of 3 MPa, 240 °C, GHSV=20,000 /h, $H_2/CO_2=3/1$. Supposing that 100 tons of this catalyst are used for the catalytic hydrogenation of CO_2 to methanol as recycling process of emitted CO_2 at one industrial factory, about 1,000,000 tons of CO_2 will be treated and 360,000 tons of methanol in a single pass will be produced per year using such condition as 3 Mpa, 240 °C and GHSV=20,000 /h.

5. Stable Hydrogen Supplies

A stable supply of cheap hydrogen is essential if the catalytic hydrogenation method is to be commercially viable: Hydrogen was once produced using electrolysis of water, but today it is more often produced from fossil fuels---coal, oil and natural gas.

Formula 6:

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

Formula 7:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

Reactions that produce both hydrogen and CO_2, as in Formula 7, are environmentally meaningless. Hydrogen production from fossil fuels, as shown in formula 6, and methods that use byproduct hydrogen are needed. Most desirable for the future would be to produce hydrogen from water using nuclear fission and natural energy sources, such as solar, that do not generate CO_2.

Recently we have seen enough progress in solar power generation systems, such as the development of amorphous silicon cells, that solar energy is expected to become a major energy source in the next century. The ideal system will combine solar power with high-yield electrolysis, which has long been under research, to produce large volumes of hydrogen at low cost. This will also be an essential component technology in recycling CO_2 using catalytic hydrogenation.

Efforts and systems will be needed to make the method economically feasible using low-cost hydrogen, such as byproducts from other reactions and that produced using off-peak power capacity.

At the same time, a new technology for direct hydrogen production from water using solar light energy will be expected to be developed. Photocatalysis is one of promissing candidates for that. Recently we found a significant promoting effect of Na_2CO_3 addition on the decomposition of water to hydrogen and oxygen by semiconductor photocatalysts.6,7,8) Hydrogen production rate is not enough to apply to the practical use at this moment, however, this is just the first step to develop. Research and development in this field will be strongly required.

6. A Catalytic Hydrogenation Project has Begun

Under the circumstances described above, a foundation called Research Institute of Technology for the Earth (RITE) was set up in 1990. It then started on a 10 year, 10 billion yen project to develop technologies to fix and effectively use CO_2 using catalytic hydrogenation.

The project is divided into three department areas: a membrane to concentrate and separate CO_2 from power plants and other fixed sources; an electrolysis method to efficiently produce large amounts of hydrogen from water; and a high-performance hydrogenation catalyst that can synthesize methanol and other chemicals efficiently from CO_2 and hydrogen. Fig. 2 outlines a possible system linked to solar power generation.

Separately, sunshine project promotion headquarters of AIST, MITI started now to study an overseas clean energy transportation technology shown in Fig. 3.9) In this system, methanol is supposed to be one of available energy carriers because it is easy to carry as liquid state like a crude oil at room temperature and one atmosphere by a supertanker. Above mentioned catalytic conversion of emitted but captured CO_2 to methanol is also applicable to this system.

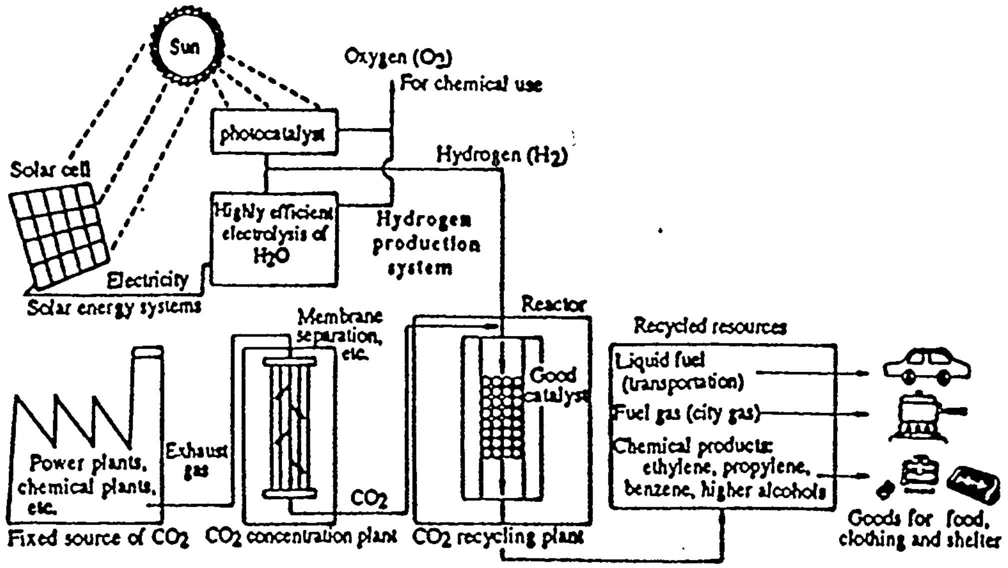


Fig. 2: A Future Image of Catalytic Hydrogenation System for Recycling CO_2 Combined with Hydrogen Production System Using Sunshine Energy

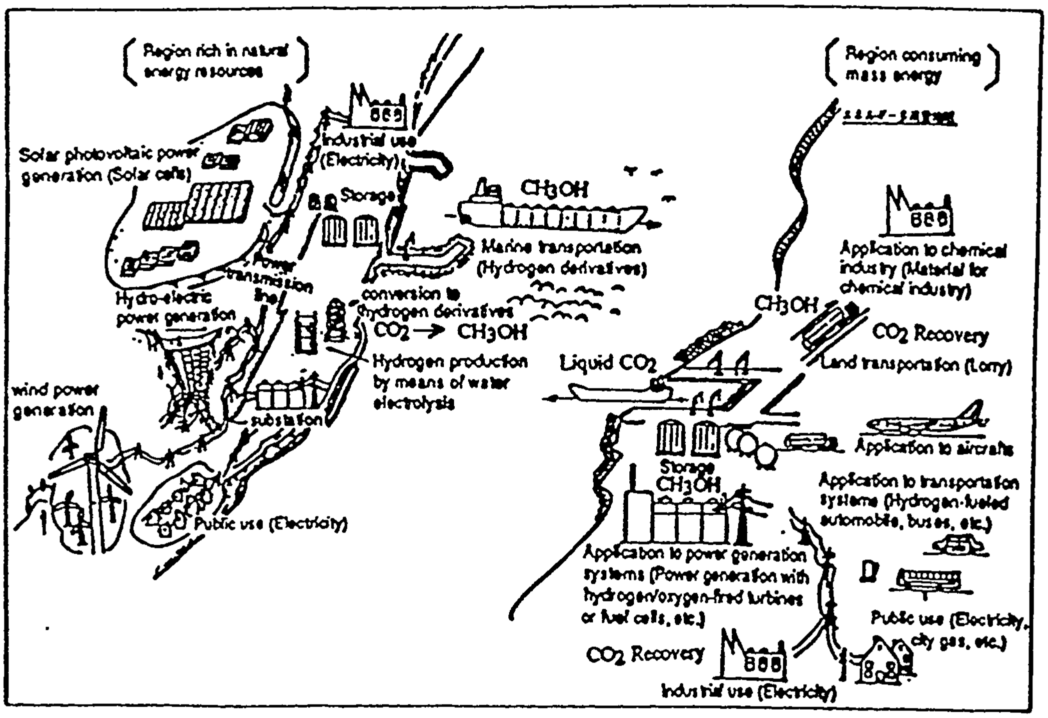


Fig. 3: Schematic View of an Overseas Clean Energy Transportation System

7. Future View for Collaborative Research with U.S.A.

1) Research on catalytic conversion of CO_2 to useful chemicals and fuel

There is a large possibility to use CO_2 as a carbon source for syntheses of hydrocarbons and oxygenates which are consumed as basic chemicals and fuel. C_1 [si: wʌn] chemistry based on CO_2 should be paied attention from the the point of the the new synthetic chemistry as well as the conservation of fossil resources consumption. Especially catalytic hydrogenation of CO_2 will be important.

2) Research on photocatalysis (Artificial photosynthesis)

Needless to say, photosynthesis is the most important and efficient production process using solar light energy, water and atmospheric CO2. Development of an efficient artificial photosynthesis process is an ambitious research topic and it will be required for the future life of human being. Photocatalytic process is one of such candidates. Especially research on photocatalytic production of hydrogen and oxygen from water using solar light energy will be more attractive and important.

References

1) H. Arakawa, "Roles of Catalytic Technology in Reduction of Greenhouse Effect Caused by CO_2 Emission," Shokubai (Catalyst) in Japanese, **31**, 558 (1989).

2) H. Arakawa, K. Sayama, K. Okabe, K. Shimomura, H. Hagiwara, "Recycling Technology of Emitted CO_2-Selective Synthesis of Methanol from CO_2 by Catalytic Hydrogenation over Cu-ZnO/SiO_2," Shokubai (Catalyst) in Japanese, **33**, 103(1991).

3) H. Arakawa, J.-L. Dubois, K. Sayama, "Selective Conversion of CO_2 to Methanol by Catalytic Hydrogenation over Promoted Copper Catalyst," Energy Convers. Mgmt, **33**, 521(1992).

4) J.-L. Dubois, K. Sayama, H. Arakawa,"CO_2 Hydrogenation over Carbide Catalysts," Chemistry Letters, 5 (1992).

5) J.-L. Dubois, K. Sayama, H. Arakawa, "Conversion of CO2 to Dimethylether and Methanol over Hybrid Catalysts," Chemistry Letters, 1115 (1992).

6) K. Sayama, H. Arakawa,"Significant Effect of Carbonate Addition on Stoichiometric Photodecomposition of Liquid Water into Hydrogen and Oxygen from Platinum-Titanium(IV) Oxide Suspension," J. Chem. Soc., Chemical Communications, 150 (1992).

7) K. Sayama, H. Arakawa,"Remarkable Effect of Na_2CO_3 Addition on Photodecomposition of Liquid Water into H_2 and O_2 from Suspension of Semiconductor Powder Loaded with Various Metals," Chemistry Letters, 253 (1992).

8) K. Sayama, H. Arakawa,"Photocatalytic Decomposition of Water and Photocatalytic Reduction of Carbon Dioxide over ZrO_2 Catalyst," J. Phys. Chem., in press **97**, (1993).

9) M. Hashimoto,"Major Activities of The Sunshine Project in The Fiscal Year 1992," Sunshine Journal, No.3, 1 (1992).

PHOTOSYNTHETIC CO_2 FIXATION AND ENERGY PRODUCTION - MICROALGAE AS A MAIN SUBJECT -

Yasuo ASADA
National Institute of Bioscience and Human-Technology
(formerly, Fermentation Research Institute) ,
Agency of Industrial Science and Technology,
Ministry of International Trade and Industry
Higashi 1-1, Tsukuba-shi, Ibaraki-ken, Japan 305

Research activities for application of microalgal photosynthesis to CO_2 fixation in Japan are overviewed. Presenter's studies on energy (hydrogen gas) production by cyanobacteria (blue-green algae) and photosynthetic bacteria are also introduced.

CO_2 FIXATION BY MICROALGAL CULTURES

If incident solar energy, e.g., 4.8 kWh/m2/day in a lower latitude is used to CO_2 fixation at efficiency, 100%, about 1.58 kg of CO_2 can be fixed. The theoretical maximum of higher plant type photosynthesis efficiency, however, is limited to about 10% due to characteristis of light energy conversion; quantum processes.

We could estimate the actual efficiency achieved in current mass cultures of algae or cyanobacteria (combustion energy of algal cells/incident solar energy) using artificial open ponds to be around 3%.

There may be two factors affecting energy conversion efficiency; growth rate or CO_2-fixing rate of algae or cyanobacteria, and way of light energy supply for microalgal cultures in open ponds or photo-bioreactors.

Some topics concerning survey of fast-growing algae, CO_2 metabolism or development of photo-bioreactors in some national research projects related to MITI, e.g. in RITE (Research Institute for Innovative Technology for the Earth), or MBI (Marine Biotechnology Institute) and in AIST (Agency of Industrial Science and Technology) and some universities will be overviewed.

HYDROGEN PRODUCTION BY CYANOBACTERIA AND PHOTOSYNTHETIC BACTERIA

Hydrogen gas is a clean and renewable energy carrier which does not evolve CO_2 at combustion. We have been studing on hydrogen production by cyanobacteria and photosynthetic bacteria, which can be potentially useful to resolve CO_2 problem and energy supply, simultaneously. I will introduce our studies on hydrogen production by photosynthetic bacteria and cyanobacteria and a RITE project, "Environmentally-Acceptable Hydrogen Production" with which we are now in cooperative relationship.

Carbon Dioxide Fixation by Artificial Photosynthesis

Takashi Ibusuki, Kazuhide Koike and Osamu Ishitani

Photo Energy Application Division,
Global Warming Control Department,
National Institute for Resources and Environment, AIST, MITI
16-3 Onogawa, Tsukuba, Ibaraki 305, Japan

1. Purpose and Back Ground

Green plants can absorb atmospheric CO_2 and transform it to sugars, carbohydrates through their photosynthetic systems, but they become the source of CO_2 when they are dead. This is the reason why artificial leaves which can be alive forever should be developed to meet with global warming due to the increase of CO_2 concentration.

The goal of artificial photosynthesis is not to construct the same system as the photosynthetic one, but to mimic the ability of green plants to utilize solar energy to make high energy chemicals. Needless to say, the artificial photosynthetic system is desired to be as simple as possible and to be as efficient as possible.

From the knowledge on photosynthesis and the results of previous investigations, the critical components of artificial photosynthetic system are understood as follows:

1) light harvesting chromophore,
2) a center for electron transfer and charge separation,
3) catalytic sites for converting small molecules like water and CO_2 (multielectron reactions),

which are schematically described in Figure 1.

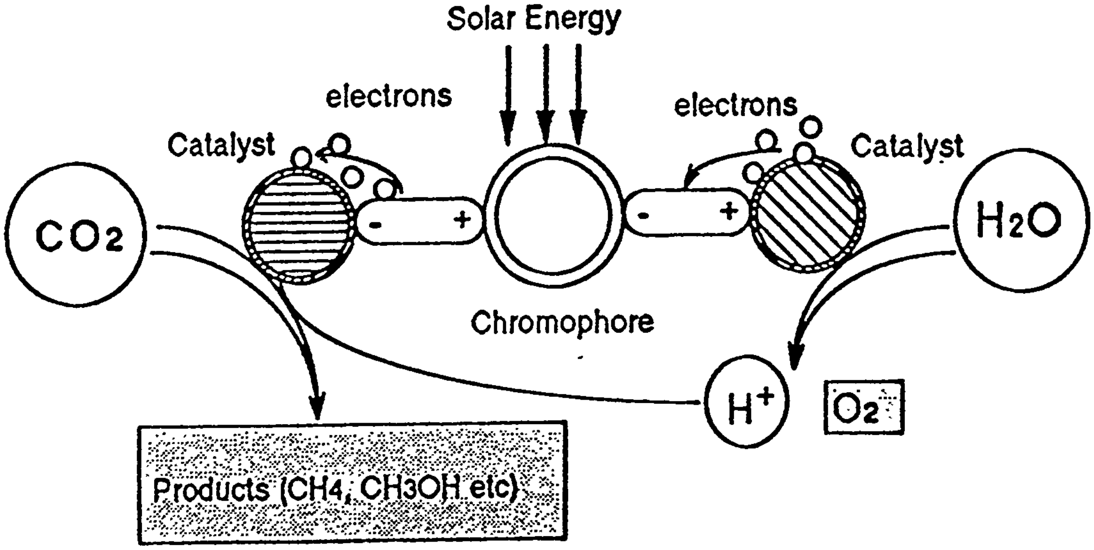


Figure 1 Scheme of artificial photosynthesis

In this workshop we would like to review the present state of researches, especially in Japan and the United States and to look for the direction of the research field or the future plan necessary for developing the artificial photosynthetic system.

2. Ongoing Research and Future Plan

2.1. Photochemical electron transfer and charge separation

A number of detailed investigations have been carried out on the research fields of 1) and 2). The electron transfer chemistry of molecular excited states is well developed, particularly with respect to metal complexes such as polypyridine complexes of transition metal ions such as rhenium and ruthenium and metalloporphyrines. These metal complexes can efficiently absorb visible lights and the stable excited molecules with different energy levels can be designed.

In the past 5 years, much progress have been made concerning the charge separation. The chromophores and electron acceptors or donors are incorporated into spatially controlled molecular assemblies (Figure 2); complex molecules, soluble polymers or polymeric films on electrodes in which intramolecular electron transfer and the charge separation can be realized.

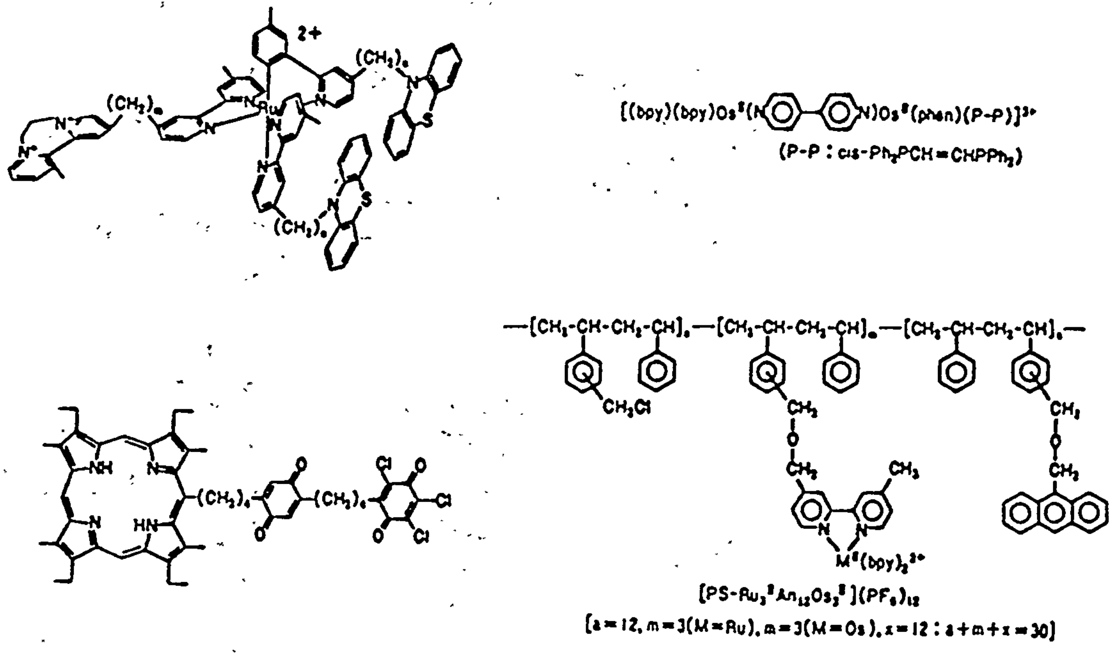


Figure 2 Molecules and polymers in which light absorption and charge transfer are realized

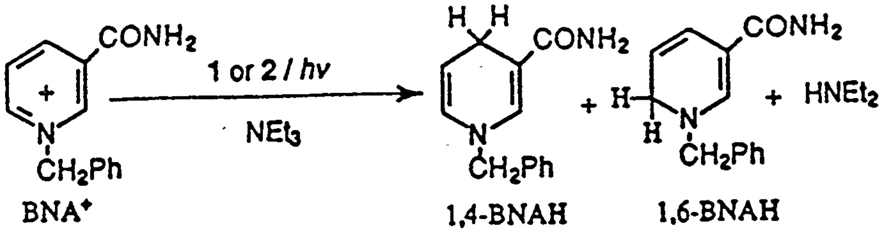
2.2. Catalysts for multielectron reactions

Compared to the progress of studies on the light absorption and the electron transfer/the charge separation, that of catalysis (multielectron reactions) has not been sufficient to date, although it is of primary importance in order to realize artificial photosynthesis.

Photocatalytic reduction of BNA+ to BNAH

We recently found a novel type of hydride-transfer photocatalysis of BNA^+ to BNAH by ruthenium(II)-pyridine complexes. BNAH (1-benzyl-1,4-dihydronicotinamide) is a typical model compound of NADPH (the reduced form of nicotinamide adenine dinucleotide phosphate) which plays the role of a reductant in biological CO_2 fixation. Although several attempts have been made on the non-enzymatic photoreduction of BNA^+ (1-benzyl-3-carbamoylpyridinium cation), the following problems remain unsolved: (1) uncontrolled hydride-transfer reduction, i.e., production of mixtures of 1,4- and 1,6-BNAH and (2) reoxidation of BNAH through photoillumi-nation.

Irradiation (>500 nm) of a 5-mL N,N-dimethylformamide (DMF) solution of $[Ru(trpy)(bpy)(py)][PF_6]_2$ (1) (trpy=2,2':6',2"-terpyridine, bpy=2,2'-bipyridine, py=pyridine) 2 umol, $BNA^+PF_6^-$ 10 umol and triethylamine (Et_3N) 0.5 M under Ar for 50 h regioselectively gave 1,4-BNAH in a 59 % yield along with an equimolecular amount of diethylamine.



On the other hand, with $[Ru(LL)_2(py)_2]^{2+}$ as the photocatalyst (LL= a bidentate ligand) (2a-2d), mixtures of 1,4- and 1,6-BNAH were formed in ratios dependent on LL as shown in Table 1. It appears that increasing the electron-accepting ability of LL favors a higher selectivity for 1,4-BNAH formation. In all cases, no half-reduced dimers were detected by HPLC analysis and moreover BNAH is accumulated without parallel photoconsumption during the photoreaction even after prolonged irradiation.

By contrast, photocatalysis using $[Ru(bpy)_3]^{2+}$ gave only BNA_2's in 34 % yield as the consequence of single electron transfer photocatalysis. It is therefore very unlikely that the photocatalytic hydride-transfer reaction is initiated by simple intermolecular electron transfer of the excited-state ruthenium complexes with either Et_3N or BNA^+. Actually, a photobleaching of **1** and **2** took place at an early stage of the reaction, both in the presence and the absence of BNA^+, being attributable to the substitution of one pyridine ligand with Et_3N and/or DMF to give **3** or **4**.

$$[Ru(trpy)_n(LL)_{2-n}(py)_{2-n}]^{2+} + L' \xrightarrow{h\nu} [Ru(trpy)_n(L\text{-}L)_{2-n}(py)_{1-n}(L')]^{2+} + py$$

$$1\ (n = 1);\ 2a\text{-}d\ (n = 0) \qquad\qquad 3\ (L' = Et_3N);\ 4\ (L' = DMF)$$

Since the photocatalytic reduction of BNA^+ did not occur at all in the absence of Et_3N even though **1** and **2** were invariably photobleached, the photocatalysis clearly requires formation of **3**. It is highly probable that the hydride-transfer photocatalysis proceeds through the photoformation of a reductant from **3**. It was indeed confirmed that $[Ru(trpy)(bpy)(H)](PF_6)\ 1/2H_2O$ (**5**) can selectively reduce BNA^+ to 1,4-BNAH in the dark in quantitative yield based on **5** and can also photocatalyze the selective hydride transfer (Table 1).

Table 1 Photocatalyzed reduction of BNA^+ with triethylamine

photocatalyst	selectivity[a] %	yield[b] / µmol 1,4-BNAH	yield[b] / µmol 1,6-BNAH	TN
1	100	5.86	~ 0	2.9
5	100	8.85	~ 0	4.4
$[Ru(LL)_2(py)_2]^{2+}$				
2a LL = phen[c]	97	3.94	0.04	2.0
2b LL = bpy	93	5.84	0.16	3.0
2c LL = Me_2bpy[c]	79	4.54	0.68	2.6
2d LL = $(MeO)_2bpy$[c]	38	2.12	2.18	2.2

[a] 100 x [1,4-BNAH]/([1,4-BNAH] + [1,6-BNAH]), after 2-h irradiation. [b] Irradiation for 50 h. [c] phen = 1,10-phenanthroline; Me_2bpy = 4,4'-dimethyl-2,2'-bipyridine; $(MeO)_2bpy$ = 4,4'-dimethoxy-2,2'-bipyridine.

From these observations a reaction mechanism of the photocatalysis can be schematically shown in Figure 3: the photocatalysis proceeds through the prior photosubstitution of one py ligand of **1** and **2** with Et_3N, the subsequent photoformation of a hydride complex **5** or

$[Ru(LL)_2(py)(H)]^+$ accompanied by elimination of $Et_3N^+{=}CHMe$, and regeneration of 3 (and 4) coupled with hydride transfer from the hydride complexes to BNA^+. The formation ratio of 1,4- and 1,6-BNAH would be kinetically controlled by the hydride-transfer capabilities of the photoformed reductants.

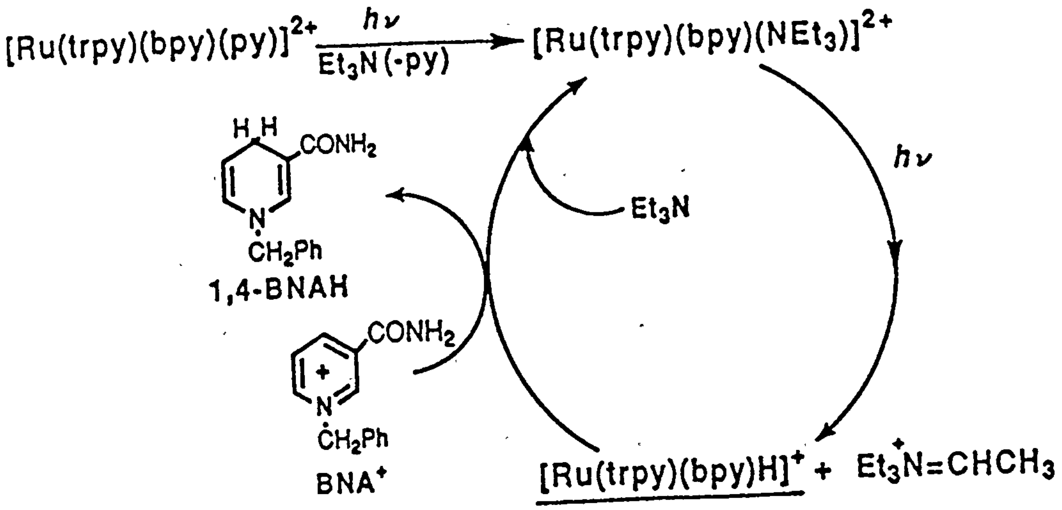


Figure 3 Scheme of photoreduction of BNA^+ to BNAH by Ru complex

Water splitting by metal complexes and semiconductor catalysts

There have been many attempts to decompose photocatalytically water to oxygen and hydrogen, since this reaction is an essential half-reaction in photosynthesis (Figure1). Indeed it has been ascertained that several sets of chromophores (metal complexes) and catalysts (metal/metal oxides) can produce hydrogen or oxygen by using electron donors or acceptors as sacrificial reagent.

Table 2 metal complex catalyst for O2 evolution by four-electron oxidation of water (Kaneko)

Metal / Molecule	e^- / Molecule	Complex	Phase	Activity
Di- V-V/III-III	4	$[(bpy)_2Ru\text{-}O\text{-}Ru(bpy)_2]^{4+}$	Homog. Heterog.	Yes Yes
Tri- V-V-V/IV-III-IV	4	$[(NH_3)_5Ru\text{-}O\text{-}\underset{(NH_3)_4}{Ru}\text{-}O\text{-}Ru(NH_3)_5]^{6+}$	Homog. Heterog.	Yes Yes
Di- IV-IV/III-III	2	$[(bpy)_2Mn\genfrac{<}{>}{0pt}{}{O}{O}Mn(bpy)_2]^{3+}$	Homog. Heterog.	No Yes
Mono- V/III	2	$[Ru(NH_3)_5H_2O]^{3+}$	Homog. Heterog.	Yes Yes

As summarized in Table 2, several polynuclear metal complexes can be catalyst for water oxidation to evolve oxygen. Dinuclear (T.J. Meyer et al.) and trinuclear (J.E. Earley et al.) ruthenium complexes have been reported as homogeneous catalysts for water oxidation.

Kaneko et al. have found a high activity of these metal complexes as heterogeneous catalysts incorporated into clay or polymer solid for the chemical and electrochemical water oxidation. A dinuclear manganese complex as a model compound in photosynthesis was found to be active only as a heterogeneous catalyst.

Hydrogen or oxygen evolution from water has been achieved by using semiconductor particles, although the efficiency was not high in the absence of some sacrificial reagents which trapped electrons or positive holes. Deposition of precious metals such as platinum, rhodium and others could increase the catalytic activity of the semiconductors for simultaneous evolution of hydrogen and oxygen. Recently Arakawa et al. revealed that addition of carbonate ion (CO_3^{2-}) to aqueous platinum (0.3 wt%)-TiO_2 suspension water remarkably enhanced the uptake of hydrogen and oxygen.

Overall water splitting was realized with layered photocatalysts (K. Domen et al.). The structure of nickel loaded niobates ($K_4Nb_6O_{17}$, $Rb_4Nb_6O_{17}$) was studied by means of XPS, EXAFS, TEM and XRD. $K_4Nb_6O_{17}$ has an ion-exchangeable layered structure which has two different kinds of alternating interlayer spaces as schematically shown in Figure 4. Intercalated water is reduced to hydrogen in interlayer I and is oxidized to oxygen in interlayer II. Each niobate macroanion sheet is regarded as a "two-dimensional" photocatalyst where hydrogen and oxygen evolve at different sides of the layer.

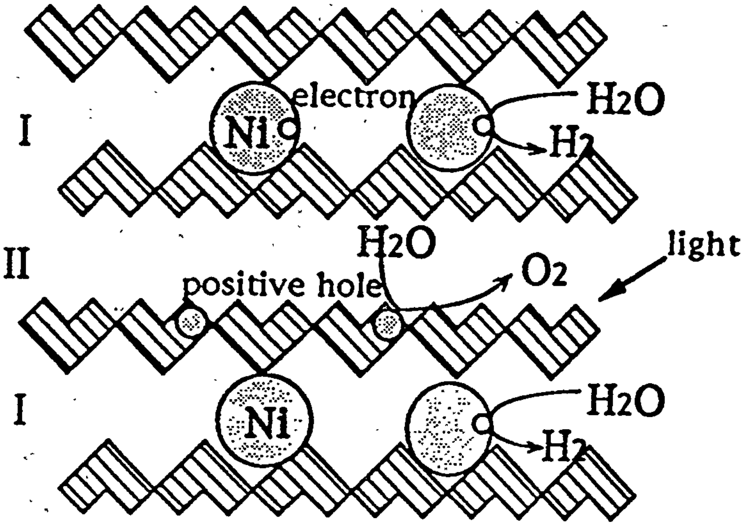


Figure 4 Schematic structure of the active NiO(0.1wt%) - $K_4Nb_6O_{17}$ photocatalyst and the reaction mechanism of water dedcomposition to O_2 and H_2

CO_2 reduction by metal complex and semiconductor catalysts

A series of metal complexes have been identified which carry out the reduction of CO_2 by electron transfer catalysis. In most of this work the emphasis has been on electrocatalysis. In Table 3 (T.J. Meyer), some molecular or polymeric film based electrocatalysts for the reduction of CO_2 and the products of the reductants.

TABLE 3. REPRESENTATIVE CATALYSTS FOR THE ELECTROCATALYZED REDUCTION OF CO_2[a]

Catalyst	Medium	E,V(NHE)[b]	Products
$Rh(bpy)_2^+$	CH_3CN/H_2O	-1.36	HCO_2H
Ca(pc)	H_2O	-0.95	CO
$Ni(cyclam)^{2+}$	H_2O	-1.05	CO
poly-[$Re(bpy)(CO)_3Cl$]	CH_3CN	-1.26	CO,oxalate

---

[a] Pc is phthalocyanine dianion; bpy is 2,2'-bipyridine; cyclam is 1,4,8,ll'-tetra-azacyclotetradecane; poly refers to a polymeric film on a Pt electrode.

[b] E is the applied potential in V vs the NHE electrode.

By combining these catalysts with appropriate photosensitizers/ chromophores and electron donors, photochemical reduction of CO_2 has been carried out. Lehn et al. first reported that *fac*-[$Re(bpy)(CO)_3Cl$] complex acting both as photosensitizer and as catalyst in its reduced state, could reduce CO_2 to CO at 14 % quantum yield. Tanaka et al. reported that $[Ru(bpy)_2(CO)_2]^{2+}$ with $[Ru(bpy)_3]^{2+}$ as photosensitizer and triethanolamine (TEOA) or BNAH as electron donor photochemically reduced CO_2 to formate ($HCOO^-$) and CO at a high quantum yield.

We recently synthesized rhenium complexes having two phosphates as ligand, *fac*-$[Re(bpy)(CO)_2\{P(OEt)_3\}_2]^+X^-$ (X=Br, PF_6, BF_4, ClO_4, BPh_4). The complex in DMF solution photochemically reduced CO_2 to CO with TEOA and BNAH as electron donor at higher quantum efficiency than 15 %. Although its reaction mechanism has not been completely elucidated, it has been confirmed based on some spectroscopic measurements that the excited state of the complex is a metal-ligand charge transfer complex (MLCT) and the luminescence of MLCT was quenched reductively by DABCO (amine).

Photocatalyzed reduction of CO_2 by semiconductor particles suspended in water was first reported by Honda et al in 1979. Since then, a number of studies have been conducted, although the efficiency of CO_2 reduction was not high without extra sacrificial reagents and the details of this reaction have not been made clear yet. A series of electrochemical reduction of CO_2 have shown that product distribution and reduction efficiency markedly change depending on the kind of metal electrode. It is of much interest that copper electrode favors hydrocarbons (ethylene, methane and others) as product (Hori). In contrast, irradiation of aqueous TiO_2 suspension mixed with copper powder gave methanol as a main product (Harada et al.).

We prepared several metal (2 wt%) loaded TiO_2 by the photochemical deposition method with methanol as reductant. TiO_2 itself and the metal (M)-TiO_2 powders were very carefully washed with water and filtrated until any organic contaminants were not detected in the filtrate. A suspension of TiO_2 or M-TiO_2 (ca. 150 mg) in 1.5 ml of water was placed in a quartz vessel and degassed by the freezing and thawing method. This was followed by introduction of CO_2 up to 650 Torr and the suspension was irradiated at >300 nm by a 500 W high pressure Hg lamp with a cut-off filter. The vessel was kept at 5 °C and CO_2 was circulated with a glass pump during irradiation. The products both in the gas phase and in the liquid phase were analyzed by gas and ion chromatography.

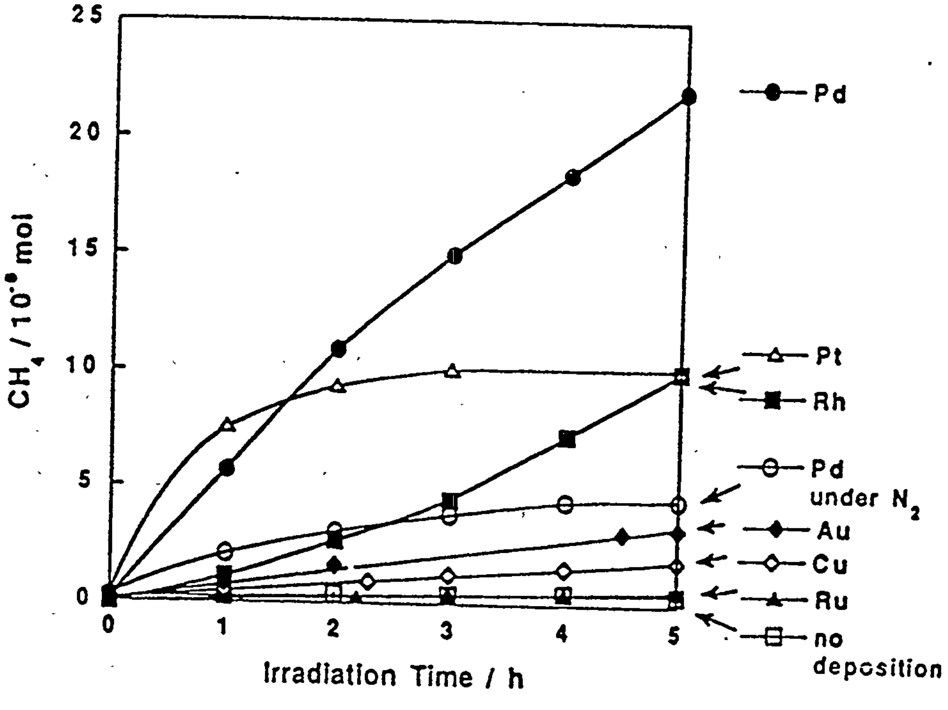


Figure 5 Time-course of CH_4 yield by using M-TiO_2 photocatalyst

Figure 5 showed photocatalyzed formation of methane by TiO_2 or M-TiO_2. A small quantity of methane was produced by using the non-deposited TiO_2. However, deposition of Pd, Rh, Pt, or Au on TiO_2 greatly enhanced methane formation and methane increased with irradiation time, except for Pt-TiO_2. In particular, Pd-TiO_2 produced more methane than TiO_2 by a factor of about 35. In contrast, deposition of Cu or Ru hardly accelerated the methane formation.

Table 4 summarized the yields of the products detected after 5 hours irradiation. Pd and Pt-TiO_2 mainly produced methane. On the other hand, a certain amount of acetic acid (CH_3COOH) was produced using other catalysts. Especially in the case of Cu and Ru-TiO_2, acetic acid was the main product.

Table 4 Photocatalyzed reduction of CO_2 with water by M-TiO_2

M-TiO_2	IP / eV	Products / 10^{-8} mol				
		CH_4	C_2H_6	CH_3OH	HCO_2H	CH_3CO_2H
TiO_2		0.7	0.1	< 1	< 0.5	<1
Pd-TiO_2	8.34	24.7	1.4	< 1	< 0.5	< 1
Rh-TiO_2	7.46	10.0	0.9	< 1	< 0.5	5.0
Pt-TiO_2	9.0	5.0	< 0.1	< 1	< 0.5	< 1
Au-TiO_2	9.225	3.3	0.6	< 1	< 0.5	2.8
Cu-TiO_2	7.726	1.9	0.2	< 1	0.6	4.1
Ru-TiO_2	7.37	0.6	< 0.1	< 1	< 0.5	2.0

[a] A suspension of M-TiO_2 (150 mg) in water (1.5 ml) was irradiated at >300 nm for 5 h under CO_2 atmosphere.

Based on the following evidence, we conclude that the major carbon source of methane is CO_2; (1) the photocatalytic reaction under $^{13}CO_2$ instead of $^{12}CO_2$ produced $^{13}CH_4$, which was detected by GC-MS measurement; contrastively, $^{13}CH_4$ was not detected under $^{12}CO_2$. (2) As shown in Figure 5, irradiation of the aqueous Pd-TiO_2 suspension under N_2 produced a much smaller amount of methane than that under CO_2 and the build-up of methane stopped within 4-5 h of irradiation. In this case carbonate adsorbed on TiO_2 or Pd-TiO_2 was supposed to be the carbon source because a certain amount of carbonate still remained in the water which rinsed M-TiO_2, while the organic compounds were washed away.

After 5 h irradiation PdO in the photocatalyst was rarely detected by XPS and neither Pd^+ nor Pd^{2+} were detected by ESR and ICP analysis, in spite of the considerable formation of methane and others. Since contamination with organic compounds was depressed to a much lower level than the reduction products of CO_2, the main reductant is probably water.

Much attention has been focused on quantum size (colloidal) semiconductor particles, since they can produce profound changes in the optical, electronic and photocatalytic properties of semiconductor particles and are convenient to mechanistic studies on account of optically transparency of their solutions. A group of National Renewable Energy Laboratory (Dr. Nozik et al.) has been conducting a number of basic researches in this field. In addition to colloidal metal oxides such as TiO_2 and ZnO, quantum-sized metal sulfides like ZnS, CdS and metal selenides were prepared and their photocatalytic activities have been investigated in details.

They have reported that immobilization of Pd onto TiO_2 powders and colloids results in active photocatalysts for the selective reduction of CO_2/HCO_3^- to formate in the presence of oxalate as sacrificial electron donor. As a reaction mechanism, the surface reaction of Pd-activated HCO_3^- with hydrogen atoms (or hydrides) produced from reduction of proton with electrons has been proposed. Inoue et al. studied a photocatalytic reduction of CO_2 by ZnS colloids in the presence of 2-propanol. The quantum efficiency for formate production were increased by increasing the $[Zn^{2+}][S^{2-}]$. The fact that the greater the excess of $[Zn^{2+}]$ to $[S^{2-}]$, the smaller the ZnS microcrystallites, suggested that the smaller the ZnS photocatalyst the richer the nonstoichiometry in the photocatalyst surface, which must be favorable for adsorption of CO_2.

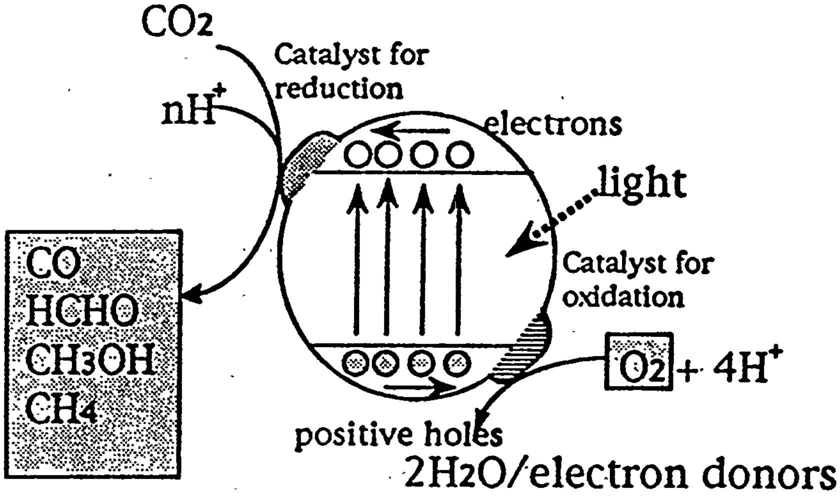


Figure 6. Scheme of CO2 reduction by semiconductor particles

As a short summary, semiconductor particles can be the photocatalyst for multielectron reduction of CO_2. Although the reaction mechanisms have not been fully evaluated, the oxidative decomposition of water and/or other electron donors with positive holes and the reduction of CO_2 with electrons/proton/hydrogen take place as shown in Figure 6. Metals deposited on the semiconductor may not only attract electrons which reduce protons to hydrogens or hydrides, but also adsorb and activate CO_2. In the absence of reactive electron donors as sacrificial reagent, as the reduction products accumulate in water, they are reoxidized by holes in preference over water. In order to increase the efficiency, it is of great importance to increase the efficiency of charge separation, to separate oxidation/reduction sites and to recover/separate the products immediately.

Future Plan

The metal complexes can use visible lights and reduce CO_2 efficiently as high as over 10 %, while most of products result from two-electron reduction of CO_2 and some sacrificial reagents are needed for the catalysis. The semiconductor catalysts can use water as electron donor for reduction of CO_2 and multielectron (up to 8) transfer steps are realized, while most of semiconductors can not use visible lights for generation of electrons and positive holes and the quantum efficiency seems generally low, particularly in the absence of extra electron donors to trap positive holes.

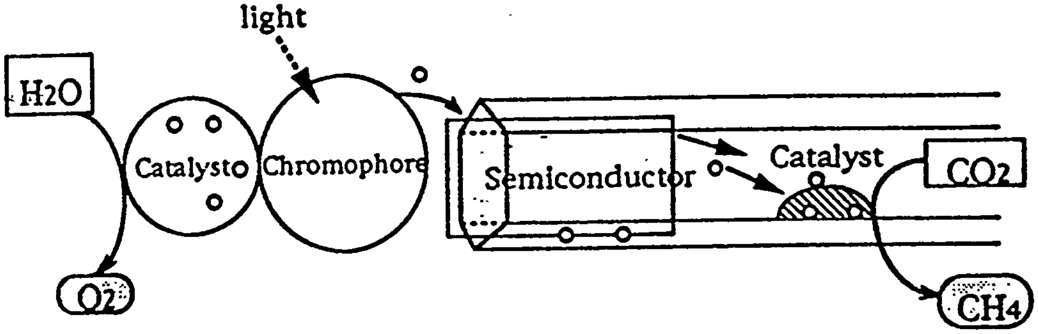


Figure 7 Artificial photosynthetic system to realize light absorption, electron transfer, and catalysis (multi-electron reactions)

For developing the artificial photosynthetic system, we have to challenge the design and synthesis of a spatially controlled molecular assembly which consists of the photochemical apparatus (the chromophore for absorbing visible lights and transfering electrons/ charge separation) and the catalysts required for water splitting and for reduction of CO_2. One example of the assembly is schematically shown in Figure 7.

As described in this paper, basic principles are available and some progress has been made, but when applied to artificial photosynthesis, this research area is still in its infancy. To realize this kind of molecular arrays containing inorganic, organic and polymer substances, an interdisciplinary approach are required, together with various sophisticated analysis techniques for evaluating the properties of the assembly. This can not be performed by a single research group, which is the reason why national and international cooperation is strongly desired.

3. Future View for Collaborative Research with the United States

Japanese researchers already have good contacts with those in United States universities and national laboratories. We do hope that this workshop can stimulate the research cooperation between Japan and United States and increase the opportunities for exchanging researchers and having joint seminars, which are essential in order to disseminate results rapidly and to share research strengths.

IT IS TIME TO PUT CARBON DIOXIDE TO WORK

by

Edward S. Lipinsky
Battelle
505 King Avenue
Columbus, OH 43201

Introduction

The need to control emissions of carbon dioxide into the atmosphere is the subject of vigorous debate at this time. There is growing evidence that rising levels of carbon dioxide increase global warming, with perhaps highly adverse impacts for the human economy. There are calls for carbon taxes and other harsh measures. Japan has established a national goal of holding carbon dioxide emissions in the year 2000 to 1990 levels. I hope that this conference will be a turning point in the United States position on this issue.

The current major end uses for CO_2 include refrigeration, beverage carbonation, soda ash production, fire fighting, and urea fertilizer production. They are all based on chemistry that would not surprise a good chemist of the 19th century.

Consumption of carbon dioxide in synthesis of industrial chemicals is limited. Usually one explains low production of chemicals from a candidate feedstock in terms of poor availability, price, purity, or reactivity. We can eliminate the first three as the causes of the underutilization of carbon dioxide.

Carbon dioxide is plentiful, and recovery of more carbon dioxide can be accomplished relatively easily. When I say that, I mean recovery from ammonia production, hydrogen production, not from 500 MW fossil fueled power plants!

The price is low and probably would decrease as production increases. Carbon dioxide is an extremely economical feedstock with a current price of $40/ton, compared with ammonia at $115/ton, ethlyene at $450/ton, and sulfuric acid at $75/ton (Chemical Marketing Reporter, 1992).

High purity carbon dioxide is available using current technology. Its physical properties (e.g., sublimability) render it easily purified.

That leaves only one excuse for not developing carbon dioxide into a major chemical feedstock: poor reactivity. The chemical literature refers frequently to the lack of reactivity of carbon dioxide as a reason that carbon dioxide is so little used as a chemical feedstock.

This is a weak excuse! Nature uses a remarkable series of catalytic processes to convert carbon dioxide into billions of tons/year of biomass via photosynthesis. If we humanoids are unable to use more than one percent of the carbon dioxide that we produce, it is because we have not yet mastered chemistry very well and/or have not applied ourselves diligently to this important opportunity.

Utilization Strategies

A major aspect of the carbon dioxide utilization challenge is to make a larger number of promising chemicals available via processes that are reasonable by standards of the chemical industry and its customers.

What is a "promising chemical" by these ground rules? One way to answer this question is to invoke the concept of direct substitution and indirect substitution. Utilization strategies can seek direct substitution for a chemical that is used now by synthesis of the current compound, or one can use an indirect substitution strategy in which the function of the chemical is retained even though the molecular structure is different.

Direct Substitution

There are many opportunities for carbon dioxide to substitute directly for established primary chemicals. Carbon dioxide is engaged in a competition with carbon monoxide with regard to various C_1 chemicals. Phosgene, which is made from carbon monoxide and chlorine, is especially vulnerable because of its toxicity and the worthlessness of the chlorine-derived products of phosgene reactions (sodium chloride or HCl) as well as the adverse impact on the environment of the by-product chloride.

Phosgene is the classical reagent to use to make carbonates from alcohols or phenols.

$$COCl_2 + 2ROH \rightarrow ROCOOR + 2HCl$$

In addition to the safety hazards of phosgene and the carbon monoxide and chlorine gases from which it is made, the HCl by-product is corrosive and can lead to the introduction of chlorine impurities into the product. Separation of the carbonate product from the HCl may require neutralization with alkali which adds to the pollution and cost problems.

One of the carbon dioxide-derived intermediates that is battling phosgene is urea which is safer and much cheaper. The reactions that displace chloride with phosgene displace ammonia with urea. Research at Marburg University and Bayer has shown that aliphatic alcohols can displace ammonia from urea to form dialkyl carbonates.

$$_2HNCONH_2 + 2ROH \rightarrow ROCOOR + 2NH_3$$

The standard processes for the manufacture of urethane polymers employ isocyanates as the key monomer ingredient. Isocyanates now are made mostly from phosgene and aromatic amines. Routes to isocyanates that use addition of isocyanic acid (HNCO) to olefins to obtain aliphatic diisocyanates without use of phosgene are under consideration.

HNCO is best made by thermolysis of urea. The overall effect is to make isocyanates from carbon dioxide, instead of from phosgene.

$$CO_2 + NH_3 \rightarrow {}_2HNCONH_2 \rightarrow HNCO + NH_3$$

$$R_1CH{=}CHR_2 + HNCO \rightarrow R_1CH_2\text{-}CHR_2NCO$$

$$CO_2 + NH_3 \rightarrow {}_2HNCONH_2 \rightarrow HNCO + NH_3$$

$$R_1CH{=}CHR_2 + HNCO \rightarrow R_1CH_2\text{-}CHR_2NCO$$

Indirect Substitution

Indirect substitution involves a creative process in which needs are analyzed and converted into functions that are desirable. The following examples illustrate the reasoning that is involved in indirect substitution.

Pigments and Fillers

Paper manufacturers and paint companies use large quantities of titanium dioxide. It has a worldwide market of about three million tons/year. About 80 percent is used in paper and 20 percent in paint and other polymer applications. Titanium dioxide sells for about $2,000/ton for use as a whitening filler for papers that are used for laser printing, office copying, and other high quality uses. These fillers also provide powerful "hiding" properties for paints.

New configurations of precipitated calcium carbonate for use as replacements for titanium dioxide in paper applications are gaining rapid acceptance among manufacturers of alkaline papers. Calcium carbonate that has a desirable crystalline structure is manufactured by controlling the reaction of carbon dioxide with lime. The carbon dioxide that is used frequently is obtained from the flue gas of the paper mill that buys back the calcium carbonate. Control of the crystal size and structure of calcium carbonate allows a $200/ton - $500/ton calcium carbonate product to compete with the $2,000/ton established product. The new calcium carbonates already have won a 500,000 ton/year position, and the growth phase is still underway. About 25 facilities are in operation now.

Compare these positive economic figures with the costs of capturing carbon dioxide from electric power plants. This is the difference between putting carbon dioxide to work vs. killing it and burying it!

Environmentally Benign Solvents

Carbon dioxide itself is an excellent solvent in its supercritical state. Both Union Carbide and BASF have introduced supercritical carbon dioxide paint solvent systems for automotive spray paint lines. Very high solids formulations are possible so that the advantages are not solely environmental.

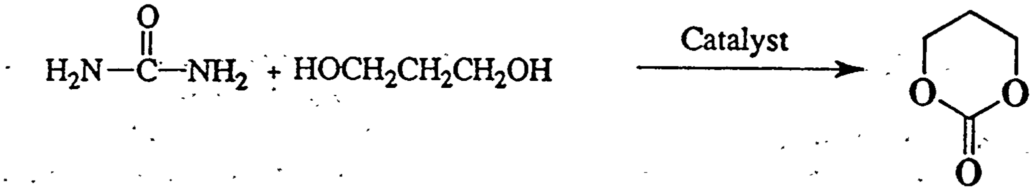
Cyclic carbonates are powerful solvents for many solids that otherwise might require chlorinated solvents. Also carbon dioxide itself is quite soluble in cyclic carbonates. These hard-working solvents are made from carbon dioxide and olefins.

Environmentally Benign Polymers

Direct production of polymers from carbon dioxide occurs in the reaction of diamines with carbon dioxide to form polyureas.

$$_2\mathrm{HN(CH_2)_nNH_2} + \mathrm{CO_2} \rightarrow \mathrm{-[CONH(CH_2)_mNH]_n\text{-}H} + \mathrm{H_2O}$$

The Marburg University and Bayer technology mentioned above as a route to dialkyl carbonates can be employed to produce cyclic carbonates without using oxiranes.



Cyclic carbonates with larger rings can be made from homologous diols by reaction with urea. Yields of the desired products are well over 90 percent, when the catalyst consists of an appropriate mixture of Lewis acid and base.

The Importance of Accounting

Many of the carbon dioxide-based products return to carbon dioxide quite soon (e.g., methanol fuels, plastics for packaging applications). These uses are not generally accepted as helping the global warming situation. However, a little accounting can help to clarify the situation. If a polymer that was 100 percent ethylene is replaced by one that is 50 percent carbon dioxide, only half as much ethylene needs to be produced. The ethylene came from natural gas or petroleum which had to be produced, transported, refined, and cracked. These steps would emit carbon dioxide that is avoided by putting to work the carbon dioxide that is already being produced. Of course, the carbon dioxide side of the ledger must include its cost of capture and transformation into the plastic.

Another argument against utilization of carbon dioxide is that the quantities of carbon dioxide that are utilized would be small compared with the gigatons that are emitted by electric power plants, deforestation activities, etc. Successful utilization provides a profit margin that can pay for capture, purification, and storage. This is one of the lessons of photovoltaic R&D. The United States R&D focused on large panels for operating hot water heaters, while Japan focused on solar-powered watches and calculators. Accountants can tell you which team showed the better judgment.

If carbon dioxide cannot yet perform big tasks, let's provide doable challenges. Then, we will have added know-how for addressing bigger, harder issues.

Conclusions

The above examples illustrate the latent powerful reactivity of carbon dioxide. They also show that this reactivity can be directed to important industrial targets. Carbon dioxide's power remains latent because of under-investment by chemists and the chemical industry in this inexhaustible, low cost chemical. Research should be focused on innovative catalyst systems to activate carbon dioxide and on innovative pathways to polymers. It is time to put carbon dioxide to work!

OCEAN CO_2 DISPOSAL

Yuji SHINDO and Toshikatsu HAKUTA
National Institute of Materials and Chemical Research, AIST, MITI
Higashi, Tsukuba, Ibaraki, 305 JAPAN

Most countries in the world will continue to depend on fossil fuels for their main energy at least for half a country, even in the confrontation with the threat of global warming. This indicates that the development of CO_2 removal technologies such as recovering CO_2 from flue gases and sequestering it of in the deep oceans or subterranean sites is necessary\1, at least until non-fossil fuel dependent society is developed.

Ocean CO_2 disposal is one of the promising options for the sequestration of CO_2 recovered from flue gases. Oceans have sufficient capacity to absorb all the CO_2 emitted in the world. It is very significant to research and develop the technologies for ocean CO_2 disposal.

Ongoing Research in Japan

1) Research on the formation of CO_2 hydrate at NIMC

Research on the formation of CO_2 hydrate has been carried on at National Institute of Materials and Chemical Research\2 (NIMC) in cooperation with University of Tokyo. A model of formation of CO_2 hydrate is proposed based on some assumptions, and a partial differential equation taking into account the diffusion and reaction in the CO_2 liquid phase is derived. The most important assumptions are that water dissolves into liquid CO_2 and reacts to form CO_2 hydrate, and that the hydrate blocks the dissolution and diffusion of water. Computational simulations were conducted, and the model proposed interprets well the many observations on the CO_2 hydrate formation in previous studies.

Some conclusions were obtained from a viewpoint of the kinetics on the formation of CO_2 hydrate. At the interface of water and liquid CO_2 under the conditions of temperatures less than 10.2°C and pressures higher than 4.45 MPa, CO_2 hydrate forms instantly and its thickness is very thin. For example, liquid CO_2 drops injected in the ocean at depths below about 450 m will be covered with a thin film of CO_2 hydrate, but it is difficult to produce drops completely made of CO_2 hydrate. Of course, drops with very mall diameter will convert into CO_2 hydrate, but at the same time considerable amount of the liquid CO_2 will be dissolved into sea water.

Liquid CO_2 disposed at depths greater than 3000 m in the ocean will form a very thin film CO_2 hydrate at the interface with sea water. This thin hydrate film will prevent the CO_2 diffusion in the ocean and control the change of pH. If a small fragment of liquid CO_2 comes off from the surface of liquid CO_2, it will instantly be wrapped by a very thin film of CO_2 hydrate. It is proposed that liquid CO_2 will be transported through a pipe to the ocean floor from a station on the sea, and it is worried that the outlet of a pipe for liquid CO_2 transport will be blockaded by CO_2 hydrate. There will be no blocking, because the hydrate film is not so thick to blockade the outlet. We believe that the ecological impacts of liquid CO_2 will be considerably reduced due to the isolating and wrapping effects of the thin CO_2 hydrate film.

2) Liquid CO_2 disposal

Physico-chemical dynamics of CO_2 injected in deep ocean is studied at Mechanical Engineering Laboratory[13]. Studies on dissolution and diffusion process of CO_2 under simulated deep sea environment, and on dynamics behavior of CO_2 are focused. CO_2 transportation system is studies at Mitsubishi Heavy Industries[14] (MHI) from a standpoint of mechanical and chemical engineering. It was concluded that the fatal technical difficulties were not found so far as the transportation system, and the liquid CO_2 was estimated main to be carried on to the next phase of study for transportation system. It was also confirmed experimentally that liquid CO_2 became heavier than seawater under conditions of the depth of more than 3000 m.

Studies concerning ocean CO_2 disposal are carried on at Central Research Institute of Electric Power Industry[15] (CRIEPI). Technique of computer simulation for the prediction of solute CO_2 behavior in the bottom ocean current was developed in order to evaluate the degree of possible damage by the CO_2 to the benthic ecosystem. A computational result shows that the low pH seawater would crawl and spread out on the ocean floor from the site of CO_2 disposed. It has been also pointed out that CO_2 disposed of at deep ocean would be neutralized by $CaCO_3$. Experiments on the formation of CO_2 hydrate at high pressure were conducted. It was observed that CO_2 hydrate rapidly formed at the interface between seawater and liquid CO_2, and that its thickness was very thin.

A jet mixing model of CO_2 injected into deep ocean is developed at Tokyo Electric Power Company[16] (TEPCO) to understand the fundamental processes of deep ocean disposal, namely diffusion to liquid CO_2 and dissolution of CO_2 into seawater.

3) CO_2 hydrate disposal

Some experiments on the CO_2 hydrate are conducted at TEPCO[17]. CO_2 hydrate formation was observed under the conditions of pressures up to 2 MPa and temperatures between room temperature and -10°C. It was confirmed that the experimental results well coincided with phase-equilibrium relation reported in the previous paper. The properties of CO_2 hydrate were also measured at the pressures up to 3.2 MPa.

Research on the formation of CO_2 hydrate is carried on at Chubu Electric Power Company[18]. Experiments were conducted at the temperature from 275 K to

278 K and the pressures from 2.94 MPa to 3.72 MPa. It is found that CO_2 hydrate formation needs a considerable time before its initiation under the conditions described above.

Feasibility of CO_2 storage in the Japan Deep and utilization of CO_2 hydrate is studied at Osaka University[9]. Crystal of CO_2 hydrate is observed by an electron microscope, and a mechanism of the formation of CO_2 hydrate is proposed.

4) The other studies on ocean CO_2 disposal

In addition to the studies described above, many other studies concerning ocean CO_2 disposal are conducted in Japan. Some of them will be introduced due to limitation of space. Microstructure of multi-phase and turbulent flows of CO_2-sea water system is studied at National Institute for Resources and Environment. Feasibility study on total system of ocean CO_2 disposal has been conducted at University of Tokyo[10]. Basic studies of CO_2 hydrate are carried on at Hokkaido University, and Government Industrial Development Laboratory at Hokkaido. Transportation method of CO_2 is studied at Government Industrial Research Institute at Osaka[11], and Osaka Gas Company.

Future View for Collaborative Research with U.S.

1) Research on the formation of CO_2 hydrate

Formation of CO_2 hydrate occurs in most of ocean CO_2 disposal, because CO_2 hydrate is stable at the conditions of pressures greater than 4.45 MPa and temperatures less than 10.2°C. Formation of natural CO_2 hydrate was also observed at submarine gas vents on ocean floor. Many complicated phenomena at the interface between liquid CO_2 and water have been reported. For example, CO_2 hydrate instantly forms and its thickness is very thin. There are, however, few studies on the kinetics of CO_2 hydrate formation. Research on the kinetics and mechanism of the formation of CO_2 hydrate are expected.

2) Research on the properties of CO_2 hydrate

Fundamental research on the physico-chemical properties of CO_2 hydrate is very significant from the standpoint of practical application of ocean CO_2 disposal. Elucidation of the mechanism of the collapse of CO_2 hydrate under various conditions is important. Measurement of physico-chemical properties of CO_2 hydrate, and evaluation of the stability of CO_2 hydrate in the seawater are expected.

3) Simulation technology of the behavior of disposed CO_2

The most important problem of ocean CO_2 disposal is the ecological impact. There are few studies on the simulation of the behavior of CO_2 after disposal. Development of simulation technology and research on the behavior of disposed CO_2 are very significant. These studies include modeling of CO_2 diffusion, estimation of physical properties of substances, and computational stimulation.

This technology will allow the precise assessment of ocean CO_2 disposal.

4) In situ investigation of ocean CO_2 disposal

Ocean CO_2 disposal includes various methods such as liquid CO_2 disposal, dry ice disposal, CO_2 hydrate disposal, and dissolution of CO_2 at shallow water. In situ test is also significant. Studies such as observation of released CO_2 by a video camera and measurement of the change of pH will be done by the use of an investigation ship, research station on the sea, or submersible platform.

It is noted that researches at national laboratories and universities are subject on the workshop, while researches on ocean CO_2 disposal are carried on at many private companies in Japan.

References:

1. Kaya, Y., Shindo, Y. *et al.: Comprehensive Assessment of Technological Options for Mitigating Global Warming*, IPCC-EIS, Geneva (1992).
2. Shindo, Y. *et al.: to be presented at IEA Carbon Dioxide Disposal Symposium*, (1903).
3. Akai, M.: *Kagaku Kogaku*, **55**, 706 (1991).
4. Asai, K. *et al.: Nihon Zosengakkai Ronbunshu*, **170**, 369 (1991).
5. Ohsumi, T. *et al.: Energy Convers. Mgmt*, **33**, 685 (1992).
6. Morishita, M. & Stegen, G. R.: *Energy Convers. Mgmt*, **33**, 691 (1992).
7. Nishikawa, N. *et al.: Energy Convers. Mgmt*, **33**, 643 (1992).
8. Saji, A. *et al.: Energy Convers. Mgmt*, **33**, 643 (1992).
9. Ohgaki, K. & Akano, T.: *Energy and Resources*, **13**, 375 (1992).
10. Ishitani, H. *et al.: Energy and Resources*, **12**, 296 (1991).
11. Honjou, T. & Sano, H.: *Energy and Resources*, **13**, 202 (1992).

Proc. 2nd U.S./Japan workshop on Global Change: Environmental Response Strategies
Honolulu, Hawaii, Feb. 1–3, 1993

Confined Release of CO_2 into the Ocean

E. E. Adams[a], D. Golombb[b], X. Y. Zhang[a], & H. J. Herzog[a]

To help reduce global warming, it has been proposed[1-3] to sequester some CO_2 in the deep ocean. However, current pipe technology is limited to about 600–650 m[4], so deeper transport requires other means. Recently, it was suggested[5-6] that CO_2 could be released at depths of 200–400 m as a concentrated seawater solution. The dense solution would form a negatively buoyant gravity current and sink to greater depth. In the following we expand our previous calculations[7] showing that an unconfined release of CO_2 will not create sufficient concentration or negative buoyancy. However, release of either compressed gaseous or liquid CO_2 into an appropriately designed confinement vessel could produce sufficient concentration to transport the current to deeper water. Furthermore, such a scheme may facilitate formation of CO_2 hydrate particles that are heavier than seawater, causing further sinking. A recently completed Research Needs assessment study which we conducted for DOE[8] concludes that shallow water disposal of CO_2 may be the most promising CO_2 disposal option.

A solution of CO_2 in seawater can be created on-shore by pumping seawater to a power plant where it contacts pressurized CO_2 in an absorption tower, or in situ by pumping compressed CO_2 to the ocean. Herzog et al.[3] conclude that the second option is far more efficient and that transport of liquid CO_2 is more economical and less problematic than gaseous transport. Whether liquid or gaseous, injection into shallow waters requires finding a site with sufficient slope, and creating sufficient negative buoyancy that the plume can penetrate against the resistance of entrainment and ambient stratification.

---

[a] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[b] Univ. of Massachusetts at Lowell, Lowell, MA 01854, USA

For release depths less than about 500 m, injected CO_2 forms gaseous bubbles either directly from breakup of a gaseous injection or indirectly as liquid CO_2 flashes to a gas. The bubbles rise, creating a plume which dilutes the CO_2. From Liro et al.[9] we estimate that 95 kg s^{-1} of CO_2 (capture from a 1000 MW gas plant[6]) discharged through ten ports, with 2-cm-diameter bubbles, dissolves over a height of 100 m. The induced flow of about 400 m^3 s^{-1} dilutes excess total CO_2 concentration to 0.2 kg m^{-3}, yielding seawater densities only 0.04 kg m^{-3} above ambient, far too little to sustain a gravity current. Similar conclusions pertain to liquid droplet plumes if CO_2 is discharged below about 500 m. Clearly a device is needed to dissolve CO_2 with limited dilution.

How much dilution can we afford? Because dilution determines the initial density of the gravity current, one must first understand how density affects gravity current behavior. We did this using mass, momentum, and buoyancy conservation equations plus model parameters reported by Drange and Haugan[6]. Figure 1 shows maximum current depth versus initial flow rate for a CO_2 flux of 95 kg s^{-1}, release at 200 m, bottom slopes of 1% and 10%, and ambient density stratifications of $N^2 = 1.25\times10^{-5}$ and $0.5\times10^{-5} s^{-2}$ where $N^2 = (g/\rho)(\partial\rho/\partial z)$; g is gravity, ρ is ambient density, and z is depth. Note that $Q_0 \simeq 2.5$ m^3 s^{-1} represents CO_2 saturation[6], while $Q_0 \simeq 400$ m^3 s^{-1} is the flow induced by an unconfined release[9]. Although details depend on model and environmental parameters, the trend is clear: penetration decreases sharply as initial flow increases; e.g., the maximum flow rate allowing penetration below an assumed pycnocline depth[6] of 600 m is between 6 and 30 m^3 s^{-1}. Corresponding initial density differences are 0.6 to 3.2 kg m^{-3}, much greater than those from an unconfined release, confirming that initial dilution must be artificially reduced.

How can dilution be minimized? One idea is to build a confining vessel surrounding an array of CO_2 ports (Figure 2). Liquid CO_2 jets break into drops, then flash into gaseous bubbles if injection depth is less than about 500 m. The bubbles rise due to buoyancy while they are absorbed by surrounding water. Vents near the ceiling allow inflow of relatively light seawater while a bottom sluice lets the relatively heavy CO_2 solution flow downward. No external power is required; vessel size and inlet/outlet areas rely on gravitational circulation (like an inverted chimney or natural draft cooling tower) to achieve a target flowrate. While the depicted vessel is cubical with a horizontal array of ports other configurations are possible, such as a cylindrical mixing chamber open at both ends.

Assuming equal aggregate inlet and outlet areas A, induced seawater flow Q_0 can be related to CO_2 mass injection rate $\dot{m}$ and vessel height H by

$$Q_0^3 = C_d^2 \beta \dot{m} A^2 H \tag{1}$$

where C_d is a discharge coefficient ($\lesssim 1.0$) reflecting inlet, outlet, and internal losses and β relates buoyancy flux to mass flux, i.e., $g\Delta\rho Q_0/\rho = \beta\dot{m}$, where[6] $\beta \simeq 0.0019$ m^4 kg^{-1}s^{-2}, and $\Delta\rho$ is the density difference between CO_2-enriched and ambient seawater. Avoiding seawater intrusion through the sluice of height h_0 requires[10] $\mathbf{F}_0^2 \gtrsim 1$, where the Froude number $\mathbf{F}_0$ is defined as

$$\mathbf{F}_0^2 = \frac{Q_0^2}{\frac{g\Delta\rho_0}{\rho} h_0 A^2} \tag{2}$$

Conversely, plume dilution increases with $\mathbf{F}_0^2$, so $\mathbf{F}_0^2$ should be minimized[11]. Requiring $\mathbf{F}_0^2 = 1$, for a cubical vessel with height H and a full-width sluice,

$$H = \left[\frac{Q_0^3}{C_d^2 \beta \dot{m}}\right]^{0.2} \tag{3}$$

Table 1 computes H and h_0 for $\dot{m} = 95$ kg s^{-1}, $6 < Q_0 < 30$ m^3 s^{-1} and $C_d = 0.5$. Clearly, as flow rate decreases, vessel size (hence cost) is reduced and initial density is increased, allowing a more sustainable gravity current (Figure 1). However, CO_2

dissolution becomes more difficult as vessel concentrations approach saturation; we select $Q_0 = 10\ m^3\ s^{-1}$, yielding an average vessel concentration of about 25% of saturation at a depth of 200 m. The corresponding vessel with $H \simeq 13$ m might house 100 ports, each forming a small bubble plume which helps homogenize the tank through turbulence and mean circulation. We estimate[9] that an initial bubble diameter of 0.5 cm or less is required to effect complete dissolution over a height of 13 m. The inlet and outlet create an average vertical fall velocity of 6 cm s^{-1} and an exit velocity of 24 cm s^{-1}.

At depths greater than about 500 m thermodynamic conditions are conducive to forming solid CO_2 hydrates[12]. These particles are heavier than seawater and hence sink to the ocean bottom where they could be sequestered indefinitely. However, hydrate formation appears to be controlled kinetically, rather than thermodynamically; Sloan[13] describes experiments in which their formation rate is of order minutes. Applying the above example to a confined release of liquid CO_2, the vessel residence time would be 3–4 minutes—at least an order of magnitude greater that the effective contact time without confinement—thus increasing the likelihood of hydrate formation. In terms of CO_2 sequestering, this would be an additional benefit of a confined release.

References

1. Marchetti, C. On geoengineering the CO_2 problem. *Climate Change* 1, 59–68 (1977).

2. Baes, E. F., Jr., et al. The collection, disposal and storage of carbon dioxide. In *Interactions of energy and climate*, (eds. Bach, W , Pankrath, J., and Williams,.J.) 495–515 (Reidel, Dordrecht, 1980).

3. Herzog, H., Golomb, D., & Zemba, S. Feasibility, modeling and economics of sequestering power plant CO_2 emissions in the sea. *Env. Prog.* 10, 64–74 (1991).

4. Sriskandarajah, T., & Mahendran, I. K. *Conference papers* (IBC Technical Services Ltd, London, 1987).

5. Haugan, P. M., & Drange, H. Sequestration of CO_2 in the deep ocean by shallow injection. *Nature* 357, 318–320 (1992).

6. Drange, H., & Haugan, P. M. Carbon dioxide sequestration in the ocean: The possibility of injection in shallow water. *Enversion and Management* 33, 697–704 (1992).

7. Adams, E., Golomb, D., Zhang, X., & Herzog, H. Confined release of CO_2 into the ocean. *Nature* (resubmitted, 1993).

8. MIT Energy Lab. A research needs assessment for the capture, utilization and disposal of carbon dioxide from fossil fuel–fired power plants. Draft final report to U.S. DOE, Grant No. DE-FGOL-92ER30194.A000 (1992)

9. Liro, C. R., Adams, E. E., & Herzog, H. J. Modeling the release of CO_2 in the deep ocean. *Energy Conversion and Management* 33, 667–674 (1992).

10. Wilkinson, D. L. Avoidance of seawater intrusion into ports of ocean outfalls. *Journal of Hydraulic Engineering*, ASCE, 114(2), 218–228 (1988).

11 Turner, J. S. *Buoyancy effects in fluids*. (Cambridge Univ. Press, 1973).

12. Golomb, D., Zemba, S. G., Dacey, J. W. H., & Michaels, A. F. The fate of CO_2 sequestered in the deep ocean. *Energy Conversion and Management* 33, 675–683 (1992).

13. Sloan, E. D., Jr. *Clathrate hydrates of natural gases*. (Dekker, New York, 1990).

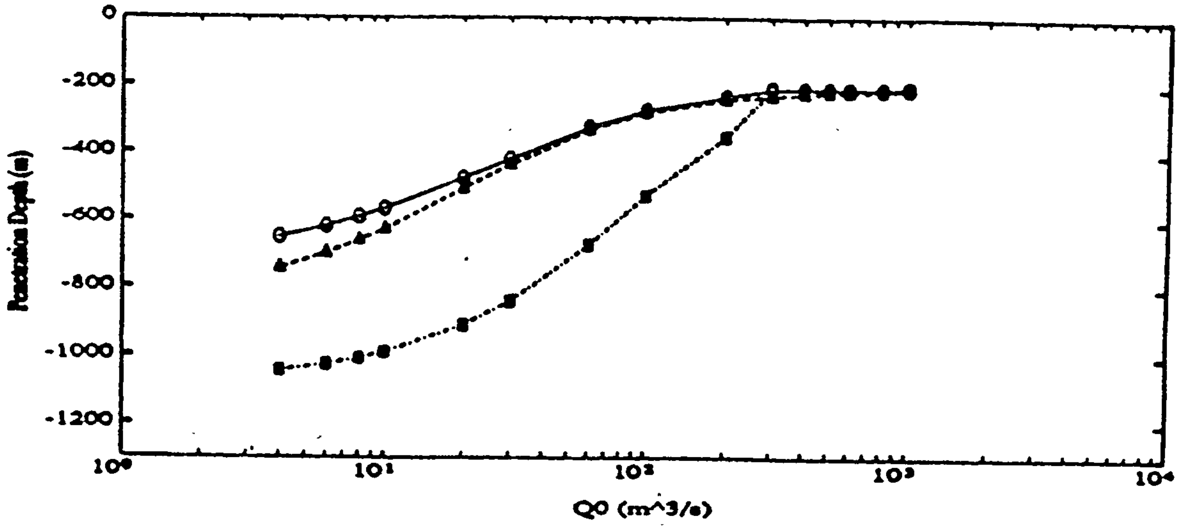


Figure 1. Simulated penetration depth of CO_2 plume vs. initial seawater flow rate for a 95 kg s^{-1} release of CO_2 at 200 m depth. Solid curve is for a bottom slope of 1% and an ambient stratification of $N^2 = 1.25 \times 10^{-5}$; dashed curve is same as solid curve except slope is 10%; dashed-dot curve is same as solid curve except $N^2 = 0.5 \times 10^{-5} s^{-2}$.

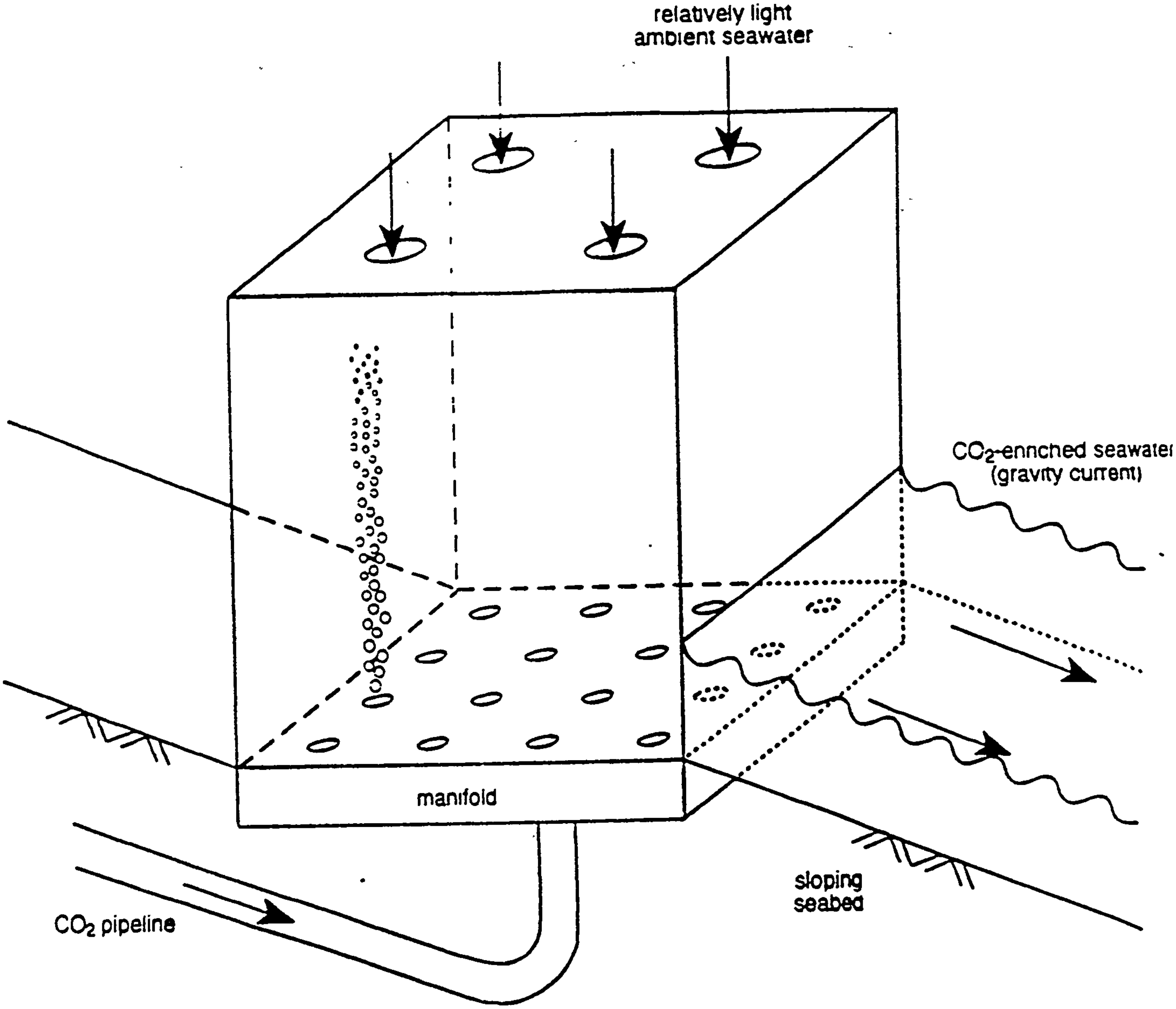


Figure 2. Conceptual design of in situ confinement vessel in which CO$_2$ could be dissolved in ambient seawater with limited dilution.

Table 1

Vessel and sluice dimensions for various initial flow rates for carbon dioxide injection rate of 95 kg/s at 200 m depth

Initial flow rate Q_0 (m^3/s)	Percent saturation at 200 m depth (%)	Box dimension H (m)	Sluice height h_1 (m)
30	8	24.6	6.2
20	12	19.3	4.8
15	17	16.2	4.1
10	25	12.7	3.2
6	42	9.4	2.3

EXTENDED ABSTRACT

USE OF HYDRATE FOR SEQUESTERING CO_2 IN THE DEEP OCEAN

By Wheeler J. North*, Dwain F. Spencer#, Don E. Johnson^,
Warren Rice~ and James J. Morgan*

Presentation at Second United States/Japan Workshop on Mitigation and Adaptation Technologies Related to Climate Change

Honolulu Hawaii, February 1-3 1993

*California Institute of Technology, Pasadena CA
#Electric Power Research Institute, Palo Alto CA
^Johnson Family Enterprises, Mesa AZ
~Arizona State University, Tempe, AZ

ABSTRACT

USE OF HYDRATE FOR SEQUESTERING CO_2 IN THE DEEP OCEAN

INTRODUCTION

Tremendous amounts of CO_2 are accumulating annually in the atmosphere (ca 3 gigatons of carbon per year at present). Prevention or significant amelioration of this atmospheric buildup will obviously require a grand scale corrective activity. A potential solution to the problem might involve sequestering CO_2 in an alternate reservoir. The ocean immediately comes to mind as a reservoir of appropriate magnitude to accommodate the huge quantities of CO_2 involved. Presumably there would be a trade-off: we would achieve a semi-clean atmosphere for an as-yet-to-be-determined impact in the ocean. Minimizing any oceanic impacts would enhance attractiveness of the trade-off.

Retention of some degree of control over a waste substance after disposal is obviously preferable to lack of any control. Oceanic disposal of CO_2 as a solid would probably be more easily controlled than dispersing CO_2 as a gas or liquid. A solidified CO_2-containing substance thus appears to be the most promising avenue for minimizing oceanic impacts. Ice-like CO_2 hydrate might be a suitable CO_2-containing solid. CO_2 hydrate and hydrates of other gases are reported to occur naturally on the sea floor (Sakai et al. 1990; Max et al., 1991). An estimated 10^4 Gt of carbon may exist as natural deposits of methane on the sea floor or beneath permafrost (Kvenvolden, 1991), releasing from 2 to 4 million tons of carbon per year or about one percent of the annual input of methane to the atmosphere. There is thus interest in methane hydrate as an energy resource and also concern as to its role in the carbon cycle with possible climatic influences (Machta et al., 1991). Hydrates of nitric acid may occur in polar stratospheric clouds and be involved in depletion of ozone at high altitudes (Worsnop et al., 1993).

Feasibility of using CO_2 hydrate for CO_2 disposal will depend on a variety of interrelated technical, economic and environmental factors. For the past year, we have been investigating some of the technical questions regarding production of CO_2 hydrate as well as studies of its stability and other characteristics.

HYDRATE CHARACTERISTICS, TEMPERATURE & PRESSURE EFFECTS

Hydrates are a category of clathrates or "inclusion compounds" wherein lattices of water molecules can accept guest molecules such as gases of low molecular weights (e.g. CO_2, CH_4, N_2, etc). Numbers of guest molecules per lattice varies somewhat and the lattices are never 100% occupied (Miller, 1974). The ideal formula for CO_2 hydrate is $CO_2.5\ 3/4H_2O$.

Hydrate stability is related to ambient pressure and temperature (Figure 1). Considering only temperatures and pressures relevant to the oceanic depths, CO_2 hydrate would be stable at temperatures below 10° C and above 9 atm pressure. Influences of these two parameters will differ from one location to the next. For example, at high latitudes (e.g. the Bering Sea, Figure 2) or in regions of strong upwelling, where sea surface temperatures are less than 10° C, hydrate stability would depend solely on pressure as reflected by water depth. Temperature and depth would both require consideration at intermediate latitudes such as the eastern Pacific off Baja California in Figure 2. Finally, hydrate could not exist in certain locations such as the Mediterranean or the Sulu Sea where temperatures may exceed 10° C throughout the water column.

The curve denoting the lower limits of hydrate stability (water+hydrate+CO_2 gas in Figure 1) rises very steeply between 0° and 10° C. Consequently temperature tends to be more controlling than depth in much of the world ocean (i.e. the appropriate isotherm frequently lies at depths representing pressures favorable for hydrate formation).

HYDRATE PRODUCTION

Given suitable pressures and temperatures, the rate of hydrate formation is influenced by the mole fraction of CO_2 and by agitation within the medium (Takenouchi & Kennedy, 1965). A thin film of hydrate presumably forms at the water-CO_2 interface, impacting the reaction rate (presence of a hydrate film was actually observed by Mori and Isobe, 1991, in their studies of fluorocarbon hydrates). Vigorous stirring disrupts the film and hydrate formation then occurs almost instantaneously.

Engineering aspects of hydrate production were studied intensively in the late 1960s and early 1970s when hydrates were being considered as a means of desalinization. Research results were detailed in several publications from the U.S. Department of Commerce, Office of Saline Water. Thus Pangborn (1968) described a continuous flow reactor he developed for producing the hydrate of methyl bromide, operating at about 20 psia. A similar reactor for producing CO_2 hydrate would necessitate operating at pressures at least one order of magnitude higher than used by Pangborn's device.

INTRODUCING CO_2 HYDRATE INTO THE DEEP SEA

Given that a device for large scale production of CO_2 hydrate can probably be constructed and operated successfully, let us examine some of the constraints associated with sequestering this material in the oceanic depths. For discussion purposes we have utilized a vertical temperature profile determined off southern California (33° 18.5' N, 118° 40' W) by Holm-Hansen et al. (1966). The profile is representative of

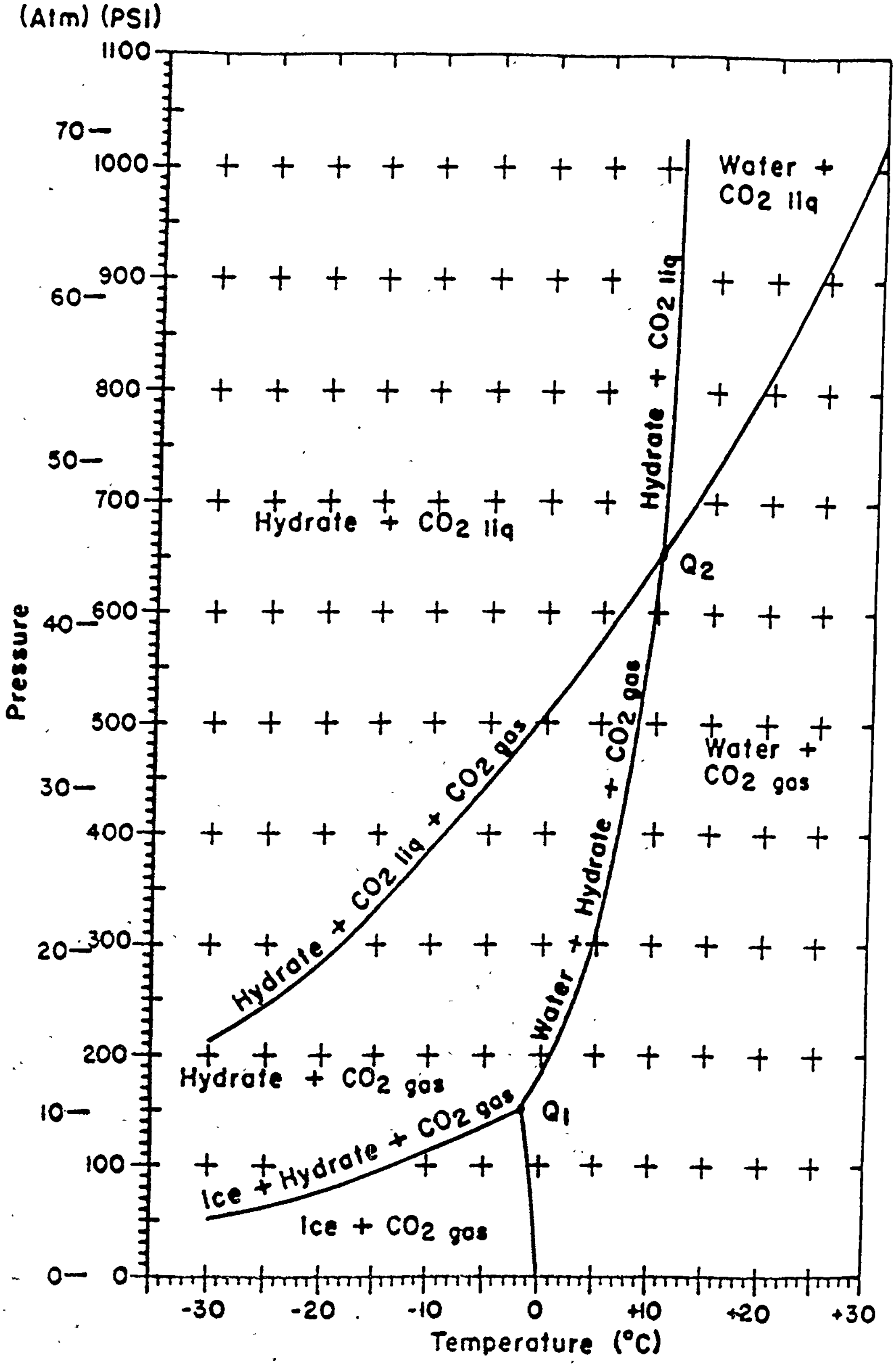


Figure 1. Phase diagram for CO_2 hydrate, CO_2, water and ice, modified from Miller (1974) and Chen (1972).

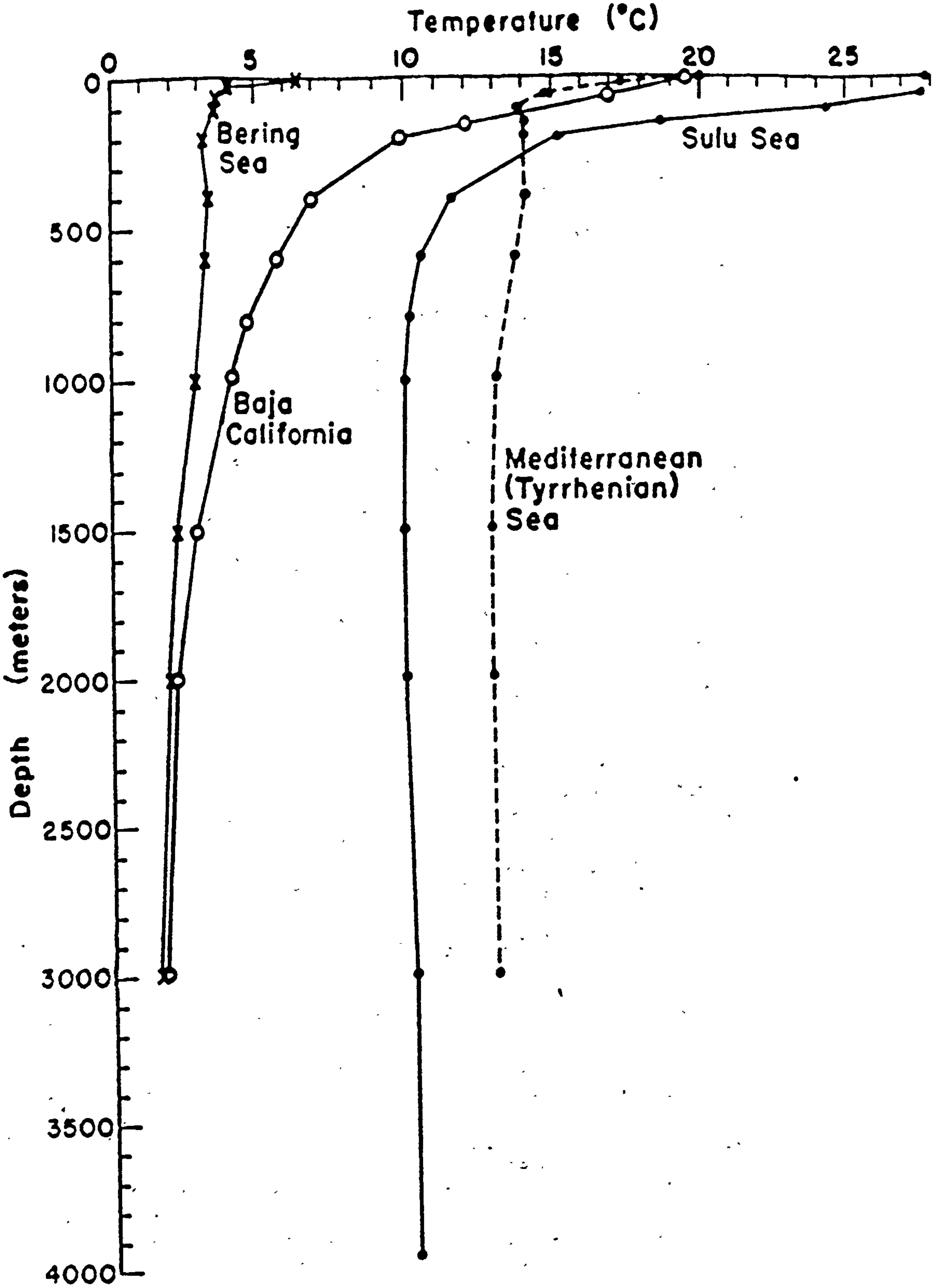


Figure 2. Vertical temperature profiles for four marine locations. based on data presented in Sverdrup *et al*. (1946; Bering Sea, 52°37'N, 177°20'W), Defant (1961; Mediterranean, 40°13'N, 12°6'E & Sulu Seas, 7°N, 120°E), and Craig & Weiss (1970; Baja California, 28°29'N, 121°38'W).

water masses where one must consider effects on hydrate stability from both temperature and pressure. Hydrate formation is exothermic and produces about 14.4 K cal/g-mole for CO_2 hydrate at the oceanic temperatures we will be considering (Chen, 1972). We have therefore set our higher temperature boundary for in situ hydrate production at 8° C instead of 10° C, to create a thermal margin of protection against hydrate decomposition. We can then determine the operational region of an oceanic water mass within which hydrate can be produced (Figure 3) by using information from the phase diagram as presented above in Figure 1.

In situ production of CO_2 hydrate from the gas could be accomplished at this southern California location at a depth slightly below 300 m and at about 350 m if the liquid is used. Presumably one would first need to compress the CO_2 to roughly 40 atm, corresponding to pressures encountered at these depths. The compression process is energy-demanding. Simply to compress the CO_2 emitted from an electric generating station using fossil fuel, would consume an estimated 5 to 10 percent of the generated power. There are also additional costs associated with scrubbing the stack gases and transporting CO_2 to a disposal site (Steinberg et al., 1984; Spencer, 1991).

An alternative option involving lesser CO^2 compression requirements would entail producing hydrate on the surface from gaseous CO^2 at around 2° C and about 13 atm pressure. This would require refrigeration but the power requirement would be reduced substantially.

The calculated density of CO_2 hydrate at 10.5° C is 1.16 g/cm^3 (Takenouchi & Kennedy, 1965). The density of seawater is about 1.03 g/cm^3 at great depths and low temperatures. So a solidly packed CO_2 hydrate would be expected to sink when released in the ocean, assuming that temperature and pressure were favorable for hydrate stability.

A hydrate mass sinking through the water column would, however, probably decompose to some extent, even when ambient values of temperature and pressure were favorable. Apparently CO_2 molecules within the hydrate lattice exchange positions with external CO_2 dissolved in the surrounding water. CO_2 hydrate would thus decompose when surrounded by water that is not completely saturated with CO_2. If we first prepare CO_2 hydrate on the surface and then release it at some depth in the ocean, some decomposition would occur with the liberated CO_2 then dissolving. If we wish to deposit solid hydrate on the sea floor, it should be dispersed near the bottom, say through a pipe. The hydrate mass could be temporarily encased in a containment if released at a midwater depth. For permanent disposal on the sea floor, it would also be necessary to deposit hydrate at a location where bottom currents were small or non-existent, for example in an anerobic basin or deep trench. A location where sediments accumulate rapidly would also be favorable. Hydrate deposition in a trench bordering a subduction zone might eventually lead to deep burial of the CO_2 within the planetary crust.

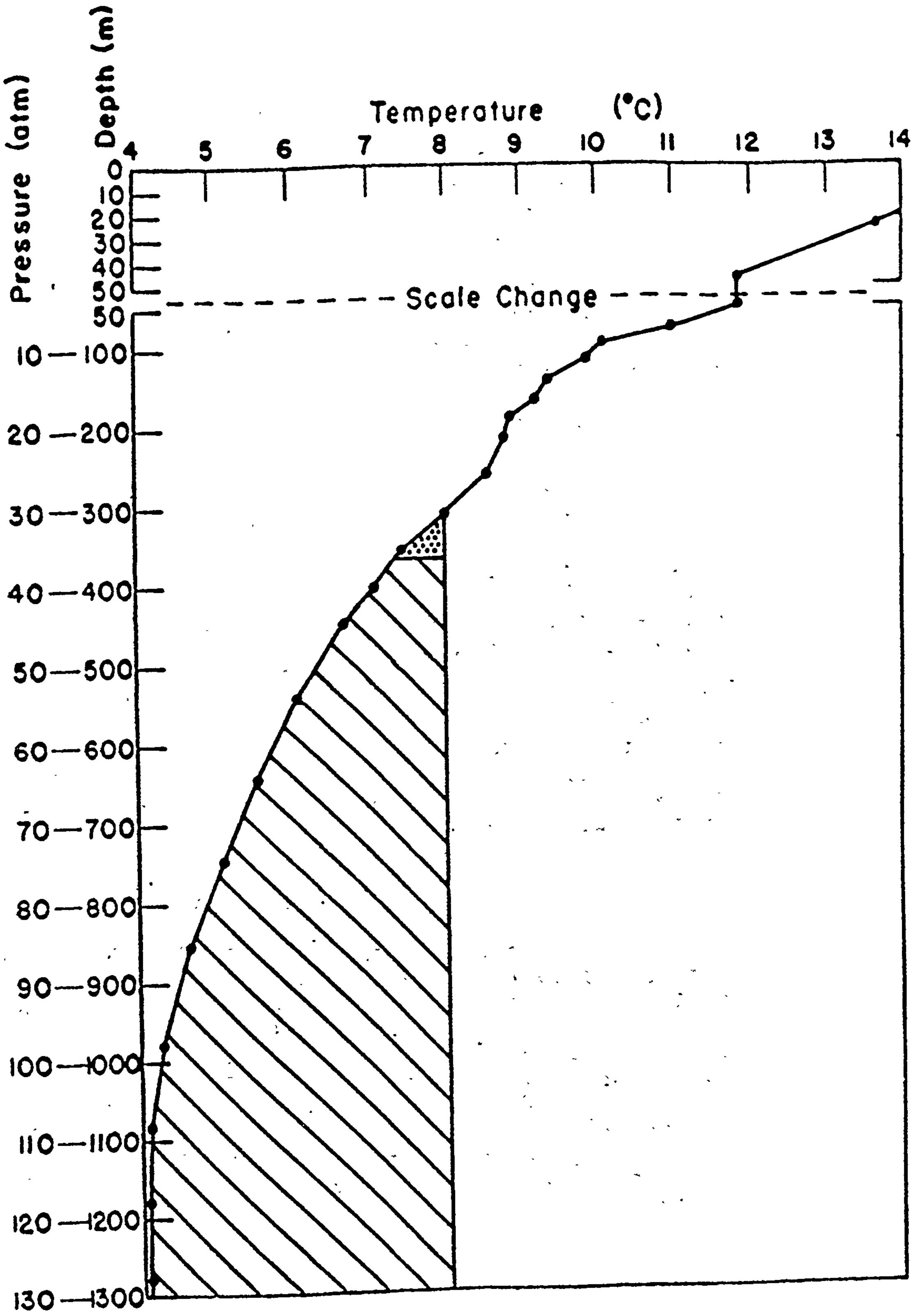


Figure 3. Vertical temperature profile at a station over the Santa Catalina Basin off southern California (33°18.5'N, 118°40'W), showing the region within the diagram where water temperature and pressure would be suitable for *in situ* production of CO_2 hydrate from water and CO_2 gas (stippled) or $CO_{2\ liq}$ (cross-hatched). From a profile shown in Holm-Hansen *et al*. (1966).

ENVIRONMENTAL IMPACTS

Environmental impacts from oceanic disposal of CO_2 hydrate would probably vary according to precise details of the disposal site and methodology employed. Hydrate disposal at midwater levels, as noted above, would probably lead to a temporary increase in dissolved CO_2. The resulting H_2CO_3 would react with any carbonate ion present. The process would not produce an ecological impact so long as substantial changes in pH were avoided (physiological studies on midwater organisms might be needed to identify tolerable limits of pH change). Bacastow & Stegen (1991) recommended that midwater injections of CO_2 should be done at depths of 1000 m or greater to avoid early return of the material back to the surface.

Impacts from depositing solid hydrate on the sea floor could include smothering of any benthos and physiological effects due to local pH changes. Both types of impact are likely to be severe. The large amounts of hydrate created could blanket considerable areas (a billion tons of CO_2 hydrate would occupy a volume of about eleven km^3). Ambient pH would decline to about 3.3 (Ohsumi, 1992). Only a few species of microorganisms might survive and grow in this highly acidic environment. One might ameliorate impacts by selecting biologically-impoverished areas as disposal sites (i.e. anerobic basins or locations where large hydrate deposits already occurred). We might justify biological impacts from introductions of CO_2 hydrate to the ocean by comparing them to the impacts that might occur if CO_2 is allowed to accumulate in the atmosphere.

SUMMARY

Use of hydrate for sequestering CO_2 in the oceanic depths appears to be technically feasible. While there is no off-the-shelf equipment presently available for manufacturing vast quantities of CO_2 hydrate, considerable information on hydrates is available from prior studies. Producing the required apparatus could probably be achieved with only a moderate additional effort. Economical factors will probably figure importantly in determining the most desirable method for introducing CO_2 hydrate into the oceanic depths. Environmental considerations are likely to predominate in selecting disposal sites.

REFERENCES

Bacastow, Robert, & Gilbert R. Stegen, 1991. Estimating the potential for CO_2 sequestration in the ocean using a carbon cycle model. Oceans 1991 Proceedings, pp. 1654-1657.

Chen, Hsiao-Sheng, 1972. The thermodynamics and composition of carbon dioxide hydrate. MS Thesis, Syracuse Univ. N.Y., 67 pp.

Craig, H. & R.F. Weiss, 1970. The GEOSECS 1969 intercalibration station: introduction, hydrographic features, and total CO_2-O_2 relationships. J. Geophys. Res., V 75; pp 7641-7647.

Defant, Albert, 1961. Physical Oceanography. V 1. Pergamon, N.Y. 729 pp.

Holm-Hansen, O., J.D.H. Strickland, and P.M. Williams, 1966. A detailed analysis of biologically important substances in a profile off southern California. Limn. & Ocgpy., V 11, pp 548-561.

Kvenvolden, Keith A., 1991. Review of gas hydrate research (abstr.). In Report on National Workshop on Gas Hydrates, Ed. by M.D. Max, W.P. Dillon & R.D. Malone. U.S. Dept of Energy, DOE/METC-91/6124 (DE91016654), pp 24-25.

Machta, Lester, Monte Poindexter, Bruce Hicks & John Miller, 1991. Methane hydrate -- Clathrates and climate (abstr.). In Report on National Workshop on Gas Hydrates, Ed. by M.D. Max, W.P Dillon &R.D. Malone. U.S. Dept of Energy, DOE/METC-91/6124 (DE91016654), pp26-27.

Max, Michael D., William P. Dillon & Rodney D. Malone, 1991. Report on national workshop on gas hydrates. U.S. Dept of Energy, DOE/METC-91/6124 (DE91016654), 44 pp.

Miller, Stanley L., The nature and occurrence of clathrate hydrates. In Natural gases in marine sediments, Ed. I.R. Kaplan, Plenum, N.Y., pp 151-177.

Mori, Yasuhiko H., & Fumiho Isobe, 1991. A model for gas hydrate formation accompanying direct-contact evaporation of refrigerant drops in water. Int. Comm. Heat Mass Transfer, V. 18, pp 599-608.

Ohsumi, Takashi, 1992. Field experimental approach for realization of the idea of disposing CO_2 in the deep ocean. MTS Jour V 25, p 61.

Pangborn, Jon B., 1968. The kinetics of methyl bromide hydrate formation. In Office of Saline Water R&D Prog. Rpt. 333, R. Fernandez, J.B. Pangborn, S.L. Colten & A.J. Barduhn. U.S. Govt. Printing Office, Wash. DC, 20402. pp 22-106.

Sakai, H., T. Gamo, E-S. Kim, M. Tsutsumi, T. Tanaka, J. Ishibashi, H. Wakita, M. Yamano & T. Oomori, 1990. Venting of carbon dioxide-rich fluid and hydrate formation in mid-Okinawa trough backarc basin. Sci. V 248, pp 1093-1096.

Spencer, Dwain F., 1991. A preliminary assessment of carbon dioxide mitigation options. Ann. Rev. Energy Environ., V 16, pp 259-273.

Steinberg, M., H.C. Cheng & F. Horn, 1984. A systems study for the removal, recovery and disposal of carbon dioxide from fossil fuel power plants in the U.S. U.S. Dept. of Energy, Off. of Energy Res., DOE/CH/0016-2 Dist. Cat. UC-11, 76 pp.

Sverdrup, Harald U., Martin W. Johnson & Richard H. Fleming, 1946 The oceans, their physics, chemistry, and general biology. Prentice-Hall, N.Y., 1087 pp.

Takenouchi, Sukene & George C. Kennedy, 1965. Dissociation pressures of the phase $CO_2 \cdot 5\ 3/4H_2O$. J. Geol. V 73, pp 383-390.

Worsnop, Douglas R., Lewis E. Fox, Mark S. Zahniser & Steven C. Wofsy, 1993. Vapor pressures of solid hydrates of nitric acid: implications for polar stratospheric clouds. Sci. V 259, pp 71-74.

Underground Storage of Carbon Dioxide

Shoichi Tanaka

Department of Mineral Development Engineering
Faculty of Engineering
The University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113, Japan

ABSTRACT

Desk studies on underground storage of CO_2 were carried out from 1990 to 1991 fiscal years by two organizations under contract with New Energy and Indestrial Technology Development Organization (NEDO). One group put emphasis on application of CO_2 EOR(enhanced oil recovery), and the other covered various aspects of undergroud storage system.

CO_2 EOR is a popular EOR method in U.S. and some oil countries. At present, CO_2 is supplied from natural CO_2 reservoirs. Possible use of CO_2 derived from fixed sources of industries is a main target of the study in order to increase oil recovery and storage CO_2 under ground. The feasibility study of the total sytem estimates capacity of storage of CO_2 as around 60 Gton CO_2, if worldwide application are realized.

There exist huge volumes of undergroud aquifers which are not utilized usually because of high salinity. The deep aquifers can contain large amount of CO_2 in form of compressed state, liquefied state or solution to aquifer.A preliminary technical and economical survey on the system suggests favorable results of 320 Gton CO_2 potential.

Technical problems are discussed through these studies, and economical aspects are also evaluated.

1 INTRODUCTION

Possible underground storages for CO_2 are cavity, water reservoir, depleted gas reservoir, depleted oil reservoir, and active oil reservoir. Water reservoir and active oil reservoir are selected as targets for the study, since depleted gas and oil reservoirs have the same characteristics as the selected ones on CO_2 injection problem. Cavity do not have capacity enough to store gas.

The water reservoir chosen as the target is a deep saline formation, which is not used as public and industrial water sources and have a trap structure like as oil and gas reservoir to contain injected CO_2.

Since conditions in deep formations are of high pressure and high temperature, they are usually supposed above critical point of CO_2. Solubility of CO_2 into water depends on pressure, temperature, salinity and content of gases. Solubility of CO_2 ranges of 20 - 30 vol. gas/vol. water at surface conditions. Underground water contains usaually a amount of CH_4, which solubility is about 2 vol./vol. Solubility of CO_2 into water is ten times more than that of CH_4. Oil can dissolve more amount of CO_2 than water.

State of CO_2 in the water reservoir is supposed as above-critical conditions, and some portion of injected CO_2 dissolves into water. A large capacity of CO_2 storage is expected in the water reservoir.

The active oil reservoirs are candidates for CO_2 EOR. Injected CO_2 into oil reservoir has state of above-critical conditions, and some portion of CO_2 dissolves into oil and water. The large capacity is expected for CO_2 storage in the system.

About this problem, two desk works were carried out in Japan. The water reservoir system was studied during 1990 to 1991 fiscal years by a committe organized by Electric Power Development Co. contracted with the New Energy and Industrial Development Organization(NEDO). The study on CO_2

EOR system was conducted during 1990 to 1991 fiscal years by experts in each company, after the Engineering Advancement Association of Japan(ENAA) contrcted with NEDO.

The Technical Research Center(TRC), Japan National Oil Corporation(JNOC), makes laboratory works and pilot tests on CO_2 EOR in Japan and abroad.

2 CO_2 EOR USING FLUE GAS

Oil fields in Japan are so small that they can only afford opportunities for pilot tests of CO_2 EOR. Oil producing countries are supposed to be candidates to apply CO_2 EOR. The CO_2 EOR could increase oil production of these countries as well as store CO_2.

To evaluate technical and economical aspects of the system, total system shown in Fig.1 and Table 1 are studied. CO_2 recovered from flue gas is liquefied and transported to oil countries by tankers. Liquefied CO_2 stored in a landing base is sent to oil field by pipeline of 100 km, and injected into oil reservoir. According to field performance in U.S., a figure of 6 MSCF CO_2/1 BBL oil is chosen as an avarage.

In the study, an increse of oil production by CO_2 EOR is assumed as 100,000 bopd. A 42,300 ton/d CO_2 injecting system is planned. As shown in Fig.2, 32,000 ton/d CO_2 is carried from Japan and remaining 10,300 ton/d CO_2 is recycled from field production. Fig.3 shows process conditions of CO_2. A path of points A to I is for liquefied CO_2, and a path of points D to I for gaseous CO_2. Each case takes a path through a single phase region to avoid unnecessary confusion.

Delivered costs of CO_2 at field are estimated as shown in Table 2. The cost of CO_2 in U.S. is ranges from \$ 1.25 - 2.5 /MSCF CO_2. The total cost of CO_2 in Southeast Asia case ranges from \$ 4.8- 6.4/MSCF CO_2(11,900 - 15,900 Yen/ton CO_2). This is 2-3 times higher than that of U.S. If costs in Japan is supported by any kind of financial means, the cost delivered at field reduces to \$ 1.9/MSCF CO_2(4,850 Yen/ton C

O_2). This figure is equivalent to that of U.S. In Middle East case, the cost reduces to \$ 3.34/MSCF CO_2 (8,350 Yen/ton CO_2) under the same assumpution.

Additional CO_2 generated throughout the system (recovery to injection) is an amount of 120 kg CO_2/ton CO_2 injection for Southeast Asia case, and 160 kg CO_2/ton CO_2 injection for Middle East case.

A potential capacity of CO_2 storage by EOR is estimated as 63 Gton shown in Table 3. There are, however, a long period necessary to attain this figure.

3 CO_2 INJECTION INTO WATER-DISSOLVED GAS RESERVOIR

Some water zone contains CH_4 and Iodin in Japan. A location of sedimentary basins containing water-dissolved gas is shown in Fig.4. Produced water is reinjected into water zone after recovering CH_4 and Iodin. Production of water-dissolved gas is about 500 MMm^3/y in Japan. As mentioned above, CO_2 dissolves in water more easily than CH_4. CO_2 may be injected into water zone with reinjected water. A potential capacity of CO_2 storage in water-dissolved gas reservoir is estimated as large as 11 Gton CO_2 in Japan. To realize CO_2 injection into the water, further study is necessary to clear effect of CO_2 on CH_4 and Iodin production.

4 CO_2 STORAGE IN WATER RESERVOIR

Water reservoirs have an ability to store CO_2 as gaseous state and/or dissolved-in-water state. If 1 % of sedimentary basins all the world has structures suitable to trap gas, a potential capacity of 320 Gton CO_2 is calculated as shown in Table 5 under the assumption shown in Table 6.

A schematic of CO_2 injection terminal is shown in Fig.5, and a pattern of injection and production well distribution is shown in Fig.6. Five-spot pattern like as water flood is adopted to evaluate technical and economical problem.

Injection cost is roughly estimated as 3,010 Yen/ton CO_2

as shown in Table 7. Additional generation of CO_2 is about 5 % of treated CO_2.

5 PILOT TESTS OF CO_2 EOR BY TRC

Technical Research center(TRC), JNOC, carried out two small scale CO_2 EOR, one in Japan and other in Turkey as shown in Table 8.

6 FUTURE VIEW FOR COLLABORATIVE RESEARCH WITH U.S.

Technical tasks for CO_2 underground storage are listed up in Table 9. In general, main tasks are as follows:

*Minimizing energy consumption
*Enlargement of equipment
*Cost down
*Improvement of CO_2 EOR
*Confirmation of underground storage

Some items are selected from Table 9 as collaboartive ones as follows:

1.Fundamental items
(1)Data collection on CO_2 and CO_2-water sytem near critical point and in super-critical conditions
(2)Data collection on corrosion of steel goods by CO_2-water-impurities system
impurities:H_2S,salt,NO_x,SO_x
steel goods:tubular goods, downhole equipments, surface facilities
2.CO_2 recovery from flue gas
(1)Enlargement of equipment
(2)Minimizing energy consumption
(3)Cost down
3.CO_2 liquefaction
(1)Development of refrigerant
(2)Enlargement of equipment
(3)Minimizing energy consumption
(4)Cost down

4.CO_2 storage and shipping

(1)Large size CO_2 storage tank

5.CO_2 recovery from CO_2-hydrocarbon system

(1)Improvement of membrane life

6.CO_2 EOR

(1)Extention of CO_2 EOR to heavy oil

(2)Improvement of volumetric sweep efficiency of CO_2 EOR

7.CO_2 injection into water reservoir

(1)simulation study of behavior of injected CO_2

(2)Study on injection of flue gas from oxygen-rich combution system including NO_x and SO_x

8.Confirmation and pilot tests

(1)CO_2 EOR for heavy oil

(2)CO_2 injection into water reservoir

(3)Detection sytem of leakage of CO_2 from underground storage

9 CONCLUSION

As a countermeasure against global warming, CO_2 EOR and injection into water reservoir have a large potential capacity. There are many technical and economical problems remained to be solved.

REFERENCES

Tanaka,S. et al.(1992).Energy Convers. Mgmt Vol.33, No.5-8,pp.587-593.

Koide,H. et al.(1992).Energy Convers. Mgmt Vol.33, No.5-8,pp.619-626.

Table 1.Total System Study Base of CO2 EOR Using Flue Gas

	Fluid Source	CO_2 Recovery	CO_2 Liquefaction	CO_2 Storage & Shipping	CO_2 Tanker	CO_2 Receiving	CO_2 Injection	Oil/Gas Production	CO_2 Recycle
Number of Works	3	3	3	1	-	1	1	1	1
Capacity of the Works (tonnes/day)	19,008	17,646	17,646	32,000	9 (17)	32,000	32,000	10,518	10,300
Capacity of the Train (tonnes/day)	6,336	5,882	5,882	32,000	80,000 (80,000)	32,000	6,400	10,518	10,300
CO_2 Capacity (tonnes/day)	6,336	5,882	5,882	32,000	32,000	32,00	32,000	10,518	10,300
CO_2 Purity (%)	8.55	99.9	99.9	99.9	99.9	99.9	99.9	64.7	95.0
CO_2 Pressure (atm)	1.03	1.3	7.0	7.0	7.0	7.0	180	10	180
CO_2 Temperature (°C)	100	50	-50	-50	-50	-50	-50	50	50
CO_2 Recovery Rate (%)	-	90	-	-	-	-	-	-	98
EOR Capacity (BBL/day)	-	-	-	-	-	-	-	100,000	-
Gas Production (MMSCF/day)	-	-	-	-	-	-	-	300	-
Note		Consider Chemical Absorption		CO_2 Tank 20,000m³ x 8	Southeast Asia 20 days/voyage Middle East 38 days/voyage	CO_2 Tank 20,000m³ x 8	6MSCF/BBL	GOR 3MSCF/BBL (CO_2: 2MSCF/BBL, H.C.Gas: 1MSCF/BBL)	CO_2 Recovery Membrane and Absorption Method 2MSCF/BBL

(Tanaka et al.1992)

Table 2.Delivered Cost of CO2 at Field, CO2 EOR Case

(Unit: Yen/tonnes CO_2)

	Southeast Asia	Middle East
CO_2 Recovery	4,000 - 8,000	4,000 - 8,000
CO_2 Liquefaction	2,600	2,600
CO_2 Storage	450	450
CO_2 Sea Transportation	4,000	7,500
CO_2 Receiving	500	500
CO_2 Transferring to the Field	350	350
Total CO_2 Cost from Japan	11,900 - 15,900	15,400 - 19,400
Recycle CO_2 Cost	3,300	3,300

(Tanaka et al.1992)

Table 3.Potential Capacity of CO2 Storage by CO2 EOR

A) Discovered oil in-place is estimated at 4,500 billion barrels. (R.E. Roadifer estimated 4,740 billions in his paper of OGJ, Feb. 24, 1986).

B) Oil for CO_2 flooding is assumed to be lighter than 25 API from G. Moritis report on EOR (OGJ, April 23, 1990). C.D. Masters *et al.* submitted worldwide and regional distributions of crude oil API gravity to World Petroleum Congress (1987). They estimated that 89% of oil fell in the range.

C) Van Poolen (1980) pointed out that it is necessary to be deeper than 2,500 ft to attain miscible conditions. From G. Moritis report (1990). 82% of CO_2 flooding fell in depth range of 3,000-11,000 ft. Depth distribution of oil was shown in M.T. Halbouty's AAPG Memoir 40 (1986). This is for giant or super giant fields, but there is no other data. It showed that 90% of fields fell in the range.

D) NPC report (1984) said that CO_2 share was 30% of EOR in the U.S. From above mentioned screenings of B and C, it is estimated that 54% of oil in the U.S. become to be candidates for CO_2 flooding. An adoption factor is introduced to reflect company's preference for CO_2 flooding. In the U.S., the factor is estimated at 56% (=30/54). The factor of 56% is assumed to be applied everywhere.

E) An increases in oil recovery by EOR is estimated at 10% of oil in-place.

F) Target of CO_2 flooding is obtained as follows:

$$4{,}500 \text{ billions} \times 0.89 \times 0.90 \times 0.56 \times 0.1 = 200 \text{ billions oil}$$

G) An average amount of CO_2 from outside into oil fields is estimated at 6 MSCF/STB from W.R. Brock *et al.* (SPE 18977, 1990).

H) The weight of 1MSCF CO_2 is equivalent to 52.6kg.

I) Potential cumulative requirement on CO_2 for EOR is estimated as follows:

$$200 \text{ billion oil} \times 6 \times 52.6 / 1000 = 63 \text{ billion tonnes}$$

(Tanaka et al.1992)

Table 4 Potential Capacity of CO_2 Storage in Water-Dissolved Gas Field in Japan

Unit:m^3,15.6C, atm.
Original In-Place: 800 10^9
Recovery factor:0.5
Recoverable Gas:400 10^9
Solubility of Gas in Water:
  CH_4:1 2.5 m^3gas/m^3water
  CO_2:20 m^3gas/m^3water
  average 15 times solvable
Potential Capacity of
  CO_2 Storage:
  400 10^9 15
  =6,000 10^9 m^3,15.6C,atm.
  (=11 10^9 ton of CO_2)

Remarks:
Iodine recovered from produced water supplies 60 70% of world market.

(Koide et al.1992)

Table 5 Potential Capacity of CO_2 Storage of Water Reservoirs in Sedimentary Basins

Region	Area of Sedimentary Basin, 10^6 km^2	Potential Capacity, CO_2 10^9 ton
East Asia	3.58	17.7
Southeast Asia	2.76	13.6
Middle East and West Asia	5.00	24.7
CIS	9.71	48.0
Europe	2.76	13.6
South America	9.07	44.8
North America	9.21	45.5
Africa	15.23	75.3
Australia and Oceania	7.47	36.9
World Total	64.79	320.1

(Koide et al.1992)

Table 6 Parameters Assumed to Calculate Table 5

1. Calculation method:
   volumetric method
2. Availability of basin for CO_2injection:
   1 % of area
3. Reservoir properties:
   Mean depth 2,500 m
   Formation pressure 250 kgf/cm^2
   Formation Temperature 90 C
   Effectine Pay THickness 300 m
   Porosity 20 %
4. Saturated solubility of CO_2 in formation water:
   0.0412 ton/m^3
5. Displacement efficiency:
   20 %

(Koide et al.1992)

Table 7 Cost Estimation of CO_2 Injectio
System into Water Reservoir

1. Capacity:
   Total 5,000 ton CO_2/d
   Per well 250 ton CO_2/well/d
2. Initial installation cost:

Unit:10^9Yen

Items	Unit cost	No. of units	Total cost
High-pressure compressor	7.0	1	7.0
Pipeline			
main line	0.1	10 km	1.0
branch line	0.05	70 km	3.5
Injection terminal			
water treatment equipment	0.2	10	2.0
water injection pump	0.15	10	1.5
Injecton wells	0.8	20	16.0
Pumping wells	0.35	30	10.5
Drain piping	0.1	30 km	3.0
Remote monitoring/control system	1.5	1	1.5
Grand Total			460

3. Operation cost

Accounts	Cost,Yen/ton CO_2
Equipment depreciation	1,260
Interest cost (10%/yr)	530
Repairs	340
Salary and wages	270
Supplies	610
Total	3,010

4. Costs omitted from estimation
Cost of electric power
Cost of CO_2 recovery from industrial sources
5. Energy consumed by this system
Per ton CO_2:73 kWh/ton CO_2
Corresponding energy consumption and CO_2 generation:

Crude oil	0.016 ton,	0.050 ton CO_2
Natural gas	0.012 ton,	0.034 ton CO_2
Coal	0.026 ton,	0.058 ton CO_2

Input base: kWh=2,250 kcal
73 kWh=164,250 kcal

(Koide et al.1992)

Table 8 Pilot Tests of CO_2 Flood by Japanese Organizations

1. Kubiki Field, Japan
   Depth:1,100 m
   Gravity of stock tank oil:
     24 API (0.91)
   CO_2 injection:15 ton/d
   Injection : 1 well
   Observation: 5 wells
   Start:March,1991 continue
2. Ikiztepe Field, Turkey
   Depth:1,400 m
   Gravity of stock tank oil:
     4 13 API (0.979)
   CO_2 injection:1.0 MMSCFD
     28,800 m^3/d(57 ton/d)
   Injection : 1 well
   Producer : 4 wells
   Observation: 1 well
   Huff and Puff method
   Period:1992 1993(tentative)

Table 9 Technical Tasks for CO_2
Underground Storage

1.Fundamental Items
(1)Accurate physical properties of CO_2
  Density, specific heat
    (near criticalpoint)
  Effect of water content
  Phase behavior of CO_2/water system
  Solubility of triethylene glycol and glycerol
(2)Corrosion properties of CO_2/water mixture, and corrosion protection
(3)CO_2 solubility in water under various conditions
2.CO_2 Liquefaction
(1)Alternarives of R22 refrigerant
(2)Energy saved CO_2 dehydration process
(3)High efficiency $CO_2$and refrigerant compressor
(4)Optimum process of CO_2 liquefaction by using LNG cold heat
(5)Enlargement of CO_2 liquefaction plant
3.CO_2 Storage Tank
(1)Large size CO_2 storage tank
  (welding of thick wall and stress relief technology)
(2)Foundation of large/heavy CO_2 Storage Tank
4.CO_2 Tanker
(1)Large size CO_2 storage tank
(2)CO_2/LPG Storage tank purge procedure
(3)Design of CO_2/LPG tanker
5.CO_2 Pipeline
(1)CO_2 pipeline simulation program
(2)Supercritical CO_2 pipeline blow down technology
(3)Optimization of CO_2 receiving, transportation, and injection system
6.CO_2 Flood (EOR)
(1)Extension of CO_2 flood into heavy oil
(2)Process of maximizing CO_2 retention volume in oil reservoir
(3)Process of maximizing recovery of oil by CO_2 flood
(4)Protection technology of CO_2 leakage from well, and reservoir
(5)Detection tecjnology of CO_2 leakage
7.CO_2 Injection into Water Reservoir
(1)Simulation of behavior of injected CO_2
(2)Use of flue gas from oxygen-rich combusion
8.CO_2 Recovery Syatem at Field
(1)Optimization of CO_2 recycle process
(2)Improvement of CO_2 separation membrane
9.Confirmation and Pilot Test Items
(1)Evaluation of impact to the environment by CO_2 underground storage
(2)Evaluation of large scale facilities from point of energy saving, and cost reduction
(3)Pilot tests of CO_2 flood under various conditions
(4)Pilot tests of CO_2 injection into water reservoir under various conditions
(5)Pilot tests of injection of flue gas from oxygen-rich combusion into water reservoir

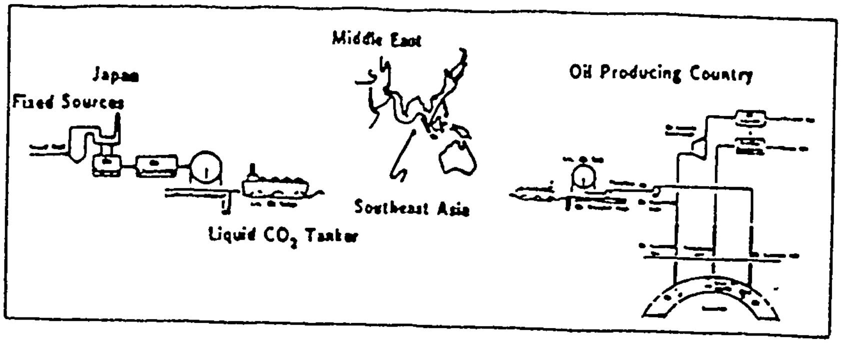


Fig.1 Total System of EOR Using CO2 from Flue Gas

(Tanaka et al.1992)

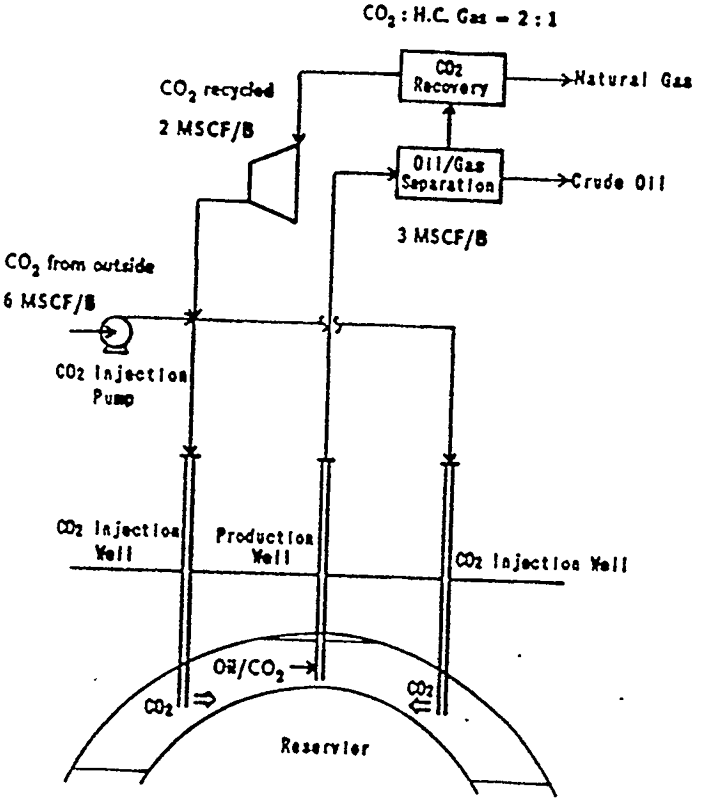


Fig.2 Assumed Parameters of the CO2 EOR System

Oil Production : 100,000 B/D

Net CO_2 : 32,000 T/D

Recycled CO_2 : 10,000 T/D

(Tanaka et al.1992)

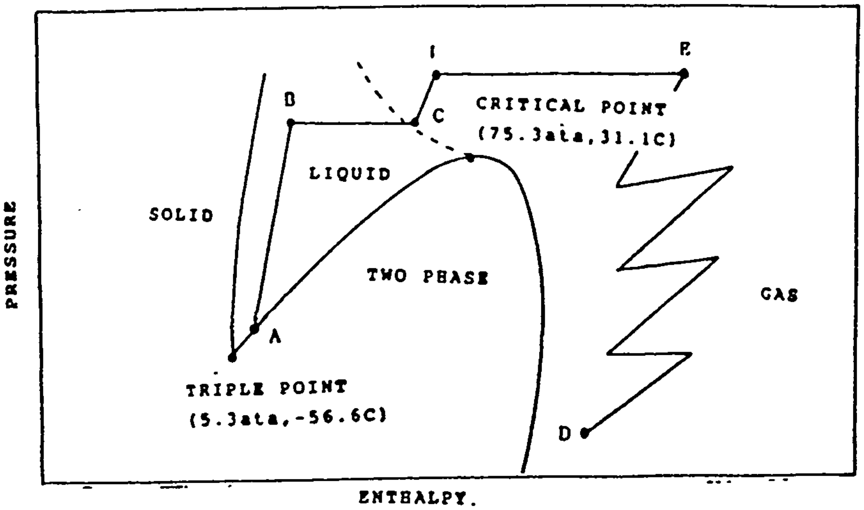


Fig.3 Assumed Conditions of CO_2 Injection Processes

A:liquid CO_2 storage tank (7ata,-50C)
B:inlet of pipeline (100ata,-40C)
C:inlet of field (90ata,27C)
D:separated CO_2 from produced fluid (4ata,50C)
E:treatment of recycled CO_2 (180ata,120C)
I:injection into reservoir (180ata,40C)

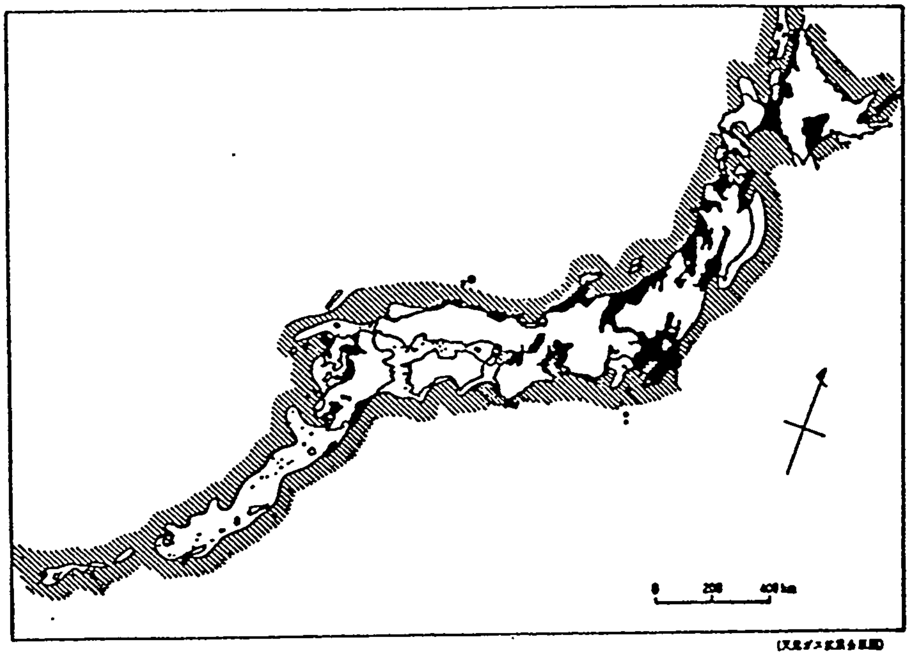


Fig.4 Location Map of Water-Dissolved Gas in Japan

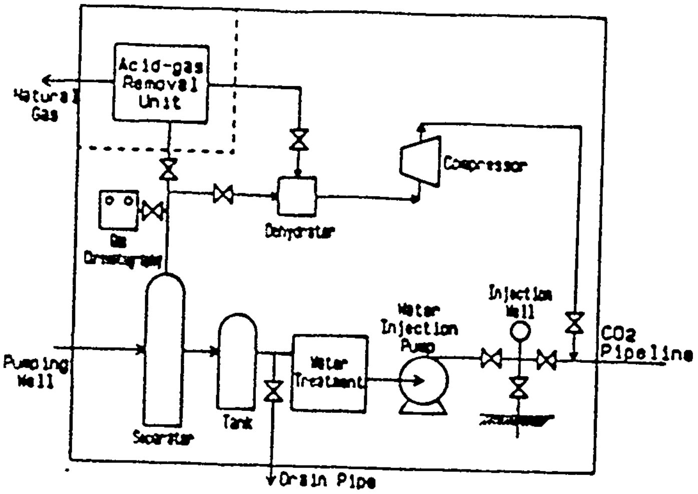


Fig.5 Schematic of Injection System for Water-Dissolved Gas Field and Water Reservoir

(Koide et al.1992)

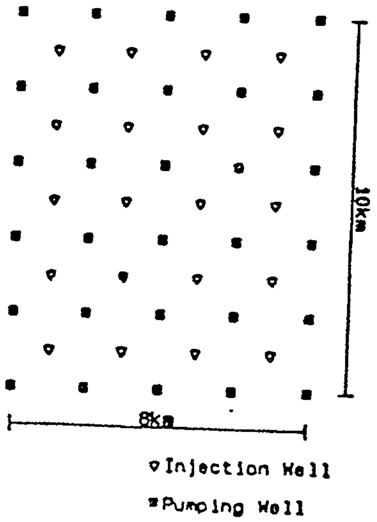


Fig.6 Well Pattern for CO_2 Injection into Water Reservoir

(Koide et al.1992)

US/JAPAN WORKSHOP ON GLOBAL CHANGE

LAND DISPOSAL OF CO_2

By: R.T. Bailey, Alberta Oil Sands Technology and Research Authority

The general responses proposed to reduce CO_2 emissions to the atmosphere are conservation, improved efficiency and fuel substitution. These are valid options but other alternatives such as CO_2 capture and disposal may be more attractive for specific areas.

There are good reasons why the capture and disposal option fits the situation in Western Canada. The first and obvious reason is the importance of hydrocarbon energy to the regional economy. Here the economy is based on the production, utilization and sale of hydrocarbons such as coal, oil and natural gas and we intend to stay in business. Besides meeting the Canadian demand, natural gas from Alberta is used in the US as far away as Boston and Los Angeles. Canadian heavy crude oil serves much of the American midwest and coal from the Canadian Rocky Mountains is exported to Japan. Although many may consider these hydrocarbon reserves and fossil fuel production as part of the greenhouse gas problem, they may offer part of the solution through the capture and disposal of CO_2.

Capture is facilitated in Western Canada because the majority of the emissions are from large point sources. For example, in Alberta one third of the CO_2 emissions are from coal fired power plants and one third are from the oil and gas industry. Capture from these large sources should be easier and less costly than from smaller dispersed sources. The capture processes are generally the same as the processes used to purify natural gas. This chemical absorption technology is practiced in hundreds of gas processing plants in Western Canada.

Disposal is facilitated with the large underground reservoirs in the western sedimentary basin. Although the potential is not obvious for the storage of CO_2 gas within solid rock, the same rock formations which form the Rocky Mountains, these are the source of the hydrocarbon liquids and gases. The porosity, permeability and stratigraphic traps which held oil and gas over geological time can be used for storage of carbon dioxide. In fact the potential for storage goes far beyond the oil and gas reservoirs and applies to many sedimentary deposits. The major advantages of utilizing oil and gas reservoirs are that the geology is better known, the storage capability has been demonstrated over geological time and enhanced hydrocarbon recovery benefits may be obtained. Carbon dioxide at reservoir pressures is a dense supercritical fluid which can mix miscibly with oil. The miscible fluid can displace virtually all the oil that it contacts in the reservoir leading to substantially improved oil recoveries and economic benefits.

The capture and disposal option is therefore of significant interest in Western Canada. Here there are the sources, the sinks, the technology and a potential economic incentive.

The option to capture CO_2 emissions is generally recognized as an abstract possibility, but is often dismissed in policy discussions because it is not universally applicable and there is a lack of data on feasibility, potential, costs and benefits. This study was undertaken to correct this deficiency, to define the technology for CO_2 capture, to quantify the amount of CO_2 that can be stored in underground reservoirs, to estimate the cost of capture, purification and transmission and to project the benefits from CO_2 flood enhanced oil recovery (EOR).

In 1990 Alberta Oil Sands Technology and Research Authority (AOSTRA) accepted a proposal from industry leaders to undertake a study with the following objective: *to determine the technical and economic feasibility of reducing the rate of growth of CO_2 emissions by collecting CO_2 from major sources and disposing of the collected gases in hydrocarbon bearing reservoirs where hydrocarbon recovery benefits could be obtained.*

The project sponsors, Esso, Shell, TransAlta Utilities and the Coal Association were soon joined by more than twenty others representing all aspects of the question. The participants included oil and gas companies, power and coal companies, CO_2 supply companies, and government groups, both federal and provincial, representing research, energy and environment departments. As well as sharing the project cost ($600,000) the participants provided specific technical expertise and data through a number of working committees. The project benefited greatly from this focused support.

The specific target was to capture 50,000 t/d for 15 years starting in 2000 and use the captured CO_2 to optimum benefit in EOR.

The CO_2 sources selected for the study included the largest; coal fired power plants, the most abundant; natural gas fired furnaces and the richest; CO_2 vents from petrochemical plants. Coal fired power plants were the major source. Capture technologies were selected based on the concentration, pressure and purity of the CO_2 gas streams. Conditioning to remove SO_2 and particulates was required for flue gas from coal combustion. Capture processes were generally based on chemical absorption using inhibited amines but physical solvents were used for concentrated higher pressure streams. Purification was generally limited to dehydration because of the high purity produced by the amine processes. But SO_2 and oxygen removal systems were required to meet EOR specifications in the case of CO_2 recycle (Argonne Process).

The specific cases and results are summarized on the table below.

Case No.	Location	CO2 Source	SOx / H2S Capture Technology	CO2 Capture Technology	CO2 Conc. (%)	CO2 Available (tonnes/day)	CO2 Captured (tonnes/day)	Capital Cost US$MM	Operating Cost US$MM/Y
1	Boundary Dam Saskatchewan	Coal Fired power plant	Andersen 2000	Amine	14	8927	8034	502	62
2	Sundance Alberta	Coal Fired power plant	Dravo Lime	Amine	14	41500	37440	2265	273
3	Joffre Alberta	Natural gas combustion	N/A	Amine	8	3717	3345	142	41
4	Hanlan Robb Alberta	Sour gas processing	Selexol	Amine	10	1023	840	54	8.6
5	BP Upgrader Saskatchewan	Hydrogen plant vent	N/A	Amine	47	1033	1026	66	12.6
6	Sundance Alberta	Coal Fired power plant	Dravo Lime	Argonne	80	41600	37440	2704	246
7	Alberta	IGCC power plant	Selexol	Selexol	35	10481	8487	295	19.7

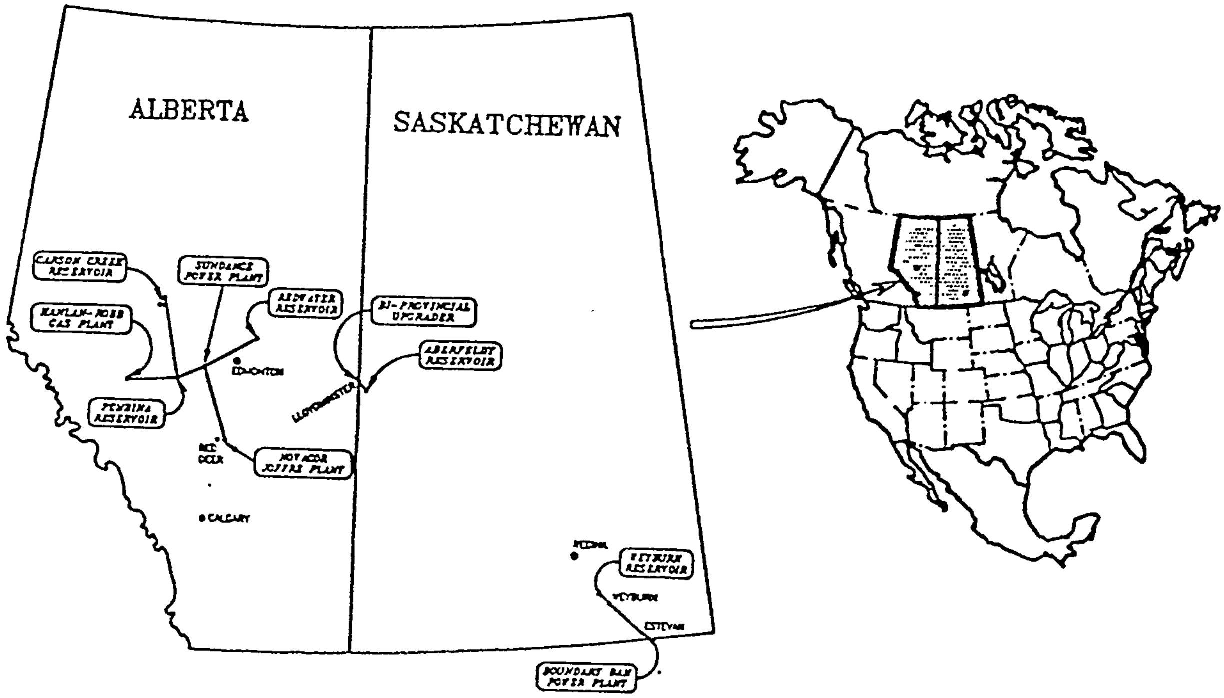
The costs of capturing CO_2 are high due to the capital cost for the equipment and operating cost from the energy requirements of the processes. This energy intensity resulted in large CO_2 emissions to drive the capture processes, typically 40% of the CO_2 captured. The net reduction of CO_2 emissions was typically 60% of the gross CO_2 captured.

The hydrocarbon reservoirs were selected to represent the major types of reservoirs in Western Canada, reefs and sandstones. Both have the characteristics required: porosity to provide space for fluids, permeability to allow fluid flow and a seal impermeable over geological time periods. Many sedimentary rock formations have these characteristics. This study looked only at hydrocarbon bearing reservoirs to determine the benefits from EOR.

In the Devonian period approximately 350 million years ago much of North America was covered by a warm shallow sea. Reefs formed by stromatoporids left relatively porous structures. This porosity was increased by dolomitization, the partial substitution of magnesium for calcium in the carbonate deposits. In central Alberta these reefs were buried in low permeability shales which sealed the top and sides. This formed a trap which captured hydrocarbons generated from organic deposits and flowing through lower more porous formations. These reefs, now buried about 1500 meters below the surface, have been the source of much of the conventional oil produced in Alberta. In this study the Redwater and Carson creek reservoirs represent this type of reef. The Elswick reservoir in Saskatchewan is a similar carbonate deposit.

In later Jurassic and Cretaceous periods the Rocky Mountains were formed from up thrust sedimentary rock. The erosion products from these mountains were deposited in the foreland basin east of the mountains. Sandstone formations from beaches and sandbars in the Cretaceous period about 90 million years ago have formed huge oil reservoirs when the conditions were right: e.g. porous, permeable rock sealed by an impermeable cap but open to a source of hydrocarbons. The Pembina Cardium formation, the most productive oil reservoir in Canada was selected for the study to represent this type of formation. Five specific pools were selected because of the diversity of oil reservoirs within the Pembina Cardium formation. The sandstone of the Sparky formation in Saskatchewan was also selected as a representative heavy oil formation using immiscible CO_2 flooding for EOR.

The location of the selected reservoirs and CO_2 sources is shown on the map below. The cost of transporting the CO_2 from sources to sinks thorough the pipeline network is relatively small (2 to 10¢/MSCF) due to the volume moved and the relatively short distances.



Enhanced oil recovery (EOR) refers to oil production following primary recovery which uses the natural reservoir energy and secondary processes such as waterflood or gas injection for pressure maintenance. The target for EOR is the residual oil saturation, the film of oil held in the pores and voids of the rock by surface tension and capillary forces.

Carbon dioxide is used in EOR as both a miscible and immiscible solvent. The initial effect of CO_2 is to dissolve in the oil reducing the viscosity and causing the oil to swell. These effects can be large even when the oil and CO_2 are separate (immiscible) phases. Viscosity reductions by orders of magnitude are possible due to the very low viscosity of CO_2. Swelling of up to 50% is possible with sufficient dissolved CO_2. Both effects can increase oil mobility and production.

At a high enough pressure, defined as the minimum miscibility pressure (MMP), sufficient CO_2 will dissolve in the oil and oil in the CO_2 that the interface between the fluids disappears. They become a single phase fluid, like ethanol mixed with water rather than like oil mixed with water. The interfacial tension vanishes with the disappearance of the interface. The capillary forces holding the oil in the pores are dramatically reduced so the oil can be mobilized and displaced to the production well.

For successful CO_2 flooding the following reservoir conditions and oil characteristics are important. The reservoir temperature must be above 31°C, the critical point for CO_2 to exist as a supercritical fluid with no gas/liquid interface. The reservoir pressure must be above the minimum miscibility pressure (MMP) for the oil in order to ensure miscible mixing. The reservoir fracture pressure must be above MMP to prevent fracturing of the reservoir rock creating high permeability thief zones. The mobility (relative permeability divided by viscosity) of the oil and CO_2 should be similar. If the mobility ratio is not close to 1, flow instabilities such as viscous fingering can occur. The fluid densities should also be similar to avoid gravity override. Both viscous fingering and gravity override can result in early breakthrough and poor sweep efficiency. Both mobility ratio and density indicate that the best candidates for CO_2 flooding are light, low viscosity crude oils. CO_2 flooding can be improved using water as the driving fluid following the injection of a CO_2 slug or as an alternating process, water alternating gas (WAG).

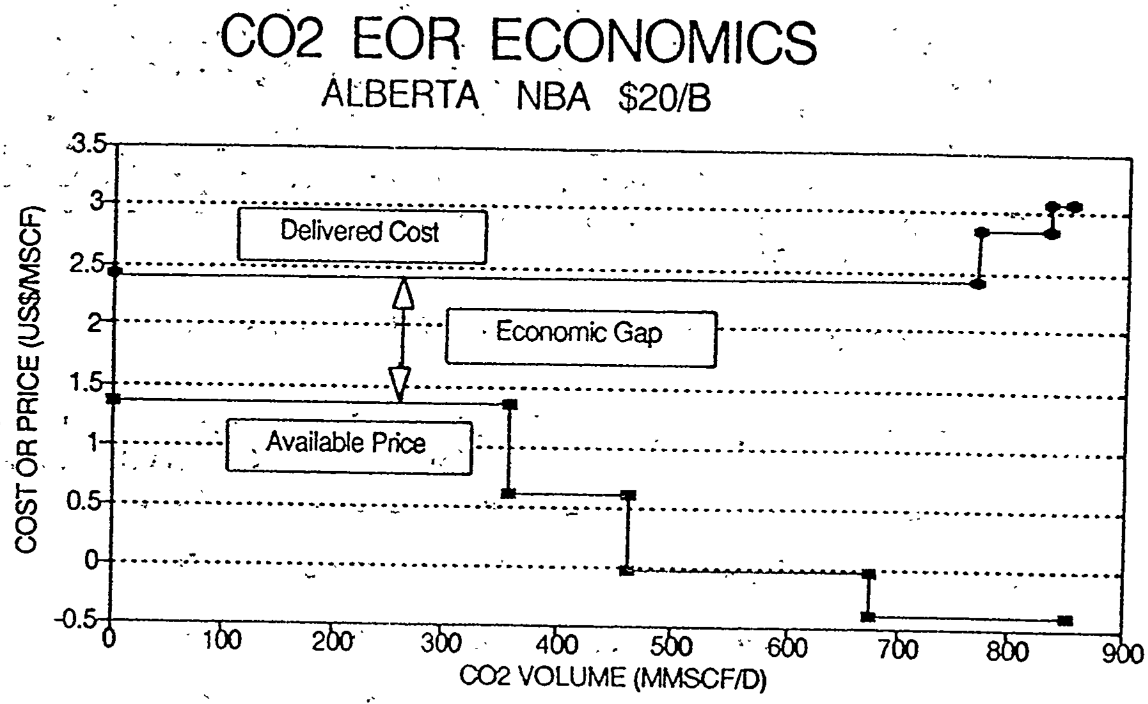
The specific cases and results are tabulated below.

Reservoir	Type	OOIP	Peak CO2 Injection	Prod. Rates		Incremental Oil Recovery	CO2 Disposa
		MMB	MMSCF/D	Oil BPD	CO2 Recycle MMSCF/D	MMB	BSCF
Carson Creek	Reef	366	202	22,000	176	49	148
Redwater	Reef	1060	140	27,500	33	69	660
Pembina	Sandstone	1523	637	39,300	590	196	339
Aberfeldy	Sandstone	594	31	32,400	25	118	66
Elswick	Carbonate	27	5	1,800	3.8	6	10

The reservoir simulations predicted an incremental oil recovery 438 million barrels. The net CO_2 injected was 2760 billion SCF (6.3 MSCF/B) of which 1223 billion SCF remained stored in the reservoirs.

The cases studied in detail did not fulfill the target of 50,000 t/d for 15 years. They represented 29.5% of the target. To estimate the potential for further CO_2 EOR, a review was done on other reservoirs in Alberta. This concluded that similar reservoirs could store a further 55% of the target. The balance could be disposed in depleted gas reservoirs. These gas reservoirs were estimated to have 3 to 4 times the capacity required to dispose of all the CO_2 targeted for capture.

The economic criteria used in this study is the transfer price for CO_2 at the oil field. What is the delivered cost, including capture and pipelining, compared to the price an oil producer could afford to pay based on revenue from incremental oil production and oilfield costs? The results have been determined for a variety of economic models and assumptions. The general conclusion is that the benefits from EOR provide a substantial offsetting benefit compared to CO_2 disposal but the benefit is insufficient to totally pay for the cost of capture. This is summarized for Alberta for a specific set of economic parameters in the figure below. As the quantity increases towards the target of 50,000 t/d, the gap widens.



If CO_2 capture is not justified by the benefits from EOR, the justification to proceed with a project must be the environmental benefits. In this case the measure of merit is the-reduction in CO_2 emissions through implementation of the project, the net CO_2. The economic analysis in this study has been based on gross CO_2 captured. The typical gap is US $20/tonne CO_2. However the typical net CO_2 capture is only 2/3 of the gross CO_2 capture. The environmental justification would therefore be based on 2/3 of a tonne net per tonne gross. The typical gap increases by 3/2, from US $20/tonne CO_2 gross to US $30/tonne CO_2 net.

These economics explain why CO_2 flooding is not extensively practiced in Canada. Miscible flooding using hydrocarbons like ethane now produces over 200,000 BPD in Canada. Implementation of CO_2 flooding in Canada at a level high enough to affect the rate of growth of CO_2 emission is feasible but currently limited by economics, the price of oil vs the the cost of CO_2.

In the United States, CO_2 is the fluid of choice for miscible flooding due to the availability of low cost CO_2 from natural reservoirs. Currently 2410 MMSCF/D of CO_2 is being injected in 45 active projects. Incremental oil production is 142,000 BPD (Hadlow 1992).

Although this improves oil recovery and provides domestic oil production, it adds significantly to CO_2 emissions to the atmosphere. As in Canada, CO_2 captured from industrial plants is too expensive for large scale use in CO_2 EOR.

CO_2 is also used for EOR in Japan at a pilot project at the Kubiki field in Niigata prefecture where over 5500 tons of CO_2 have been injected and 1385 barrels of incremental oil have been produced. (Kikuchi, 1992).

I have only discussed CO_2 disposal in hydrocarbon reservoirs where there are offsetting benefits from EOR. The storage capacity of underground reservoirs is much larger if depleted gas fields and the numerous dry holes are included. The ultimate potential is several orders of magnitude greater when aquifers and other porous permeable rock formation are considered. The problem with CO_2 disposal remains the cost of capture rather than the storage reservoir.

REFERENCES:

"Update of Industry Experience With CO2 Injection" R.E. Hadlow, Exxon Co. USA, SPE 24928, Washington, D.C. October 1992.

"A CO2 Tertiary Recovery Pilot, Kubiki Field, Japan" H. Kikuchi and S. Urabe, IEA/PRI Workshop, Banff, Alberta, September 1992.

WORKING GROUP II ABSTRACTS

WORKING GROUP II ABSTRACTS

Kunio Hijikata	*Energy Conservation from an Environmental Viewpoint*
Roger S. Carlsmith	*The Potential for Energy Conservation in the United States*
Hiroshi Moritomi	*Advanced Clean Coal Utilization Technologies*
Kazuo Suzuki	*Research and Development of Ceramic Gas Turbine*
R. Kane D.W. South A.L. Fish	*Combustion Efficiency: Greenhouse Gas Emission Reductions from the Power Generation Sector*
Hiroyasu Takenaka	*R&D on Fuel Cells in Japan and Possible Contributions of Fuel Cell to the Global Reduction of CO_2 Emissions*
Shin-ya Yokoyama Tomoko Ogi Tomoaki Minowa	*Energy Conversion of Biomass in Coping with Global Warming*
C.M. Kinoshita	*The Role of Renewable Bioenergy in Carbon Dioxide Sequestration*
Thomas D. Bath	*Renewable Energy, Today and Tomorrow -- An Overview*
Makoto Akai	*Hydrogen Based Global Renewable Energy Network*
Henry A. Courtright	*Energy Conservation Technologies*
Hiroshi Shimizu Yuichi Moriguchi	*Evaluation of Technological Measures to Cope with Climate Change*

ENERGY CONSERVATION FROM AN ENVIRONMENTAL VIEWPOINT

Kunio HIJIKATA

Tokyo Institute of Technology
Department of Mechanical Engineering Science
2-12-1, Ohokayama, Meguroku, Tokyo 152 Japan

1. Introduction

It is not incorrect to state that all major environmental problems, such as the greenhouse effect, destruction of the ozone layer from CFC's, acid rain due to air pollution by NOx and SOx, etc., are caused by excessive industrial and residential energy consumption. Considering the finite world energy resources and limited global space, the day might be already upon us in which the total amount of energy consumption in the world should be reduced. To maintain a high living standard without increasing energy consumption, waste energy recovery and energy conservation are vitally important. In order to effective use of energy resources, we should really know the meaning of the energy consumption and the characteristics of energy resources. In this paper, the technological aspects of energy conservation are stated from the standpoint of available energy.

2. Conservable energy and consumable energy

One of the most fundamental laws in physics is the first law of thermodynamics, which states that the total amount of energy remains constant during any energy conversions and/or transmissions. For example, in the global energy balance, the inlet energy (the energy flow to the earth) balances with the outlet energy at any horizontal plan. Outside of the atmosphere, the energy flow to the earth consists only of the incoming solar radiation and is equal to the energy leaving the earth; that is, the sum of the emitted atmospheric radiation and the solar radiation reflected from the atmosphere and from the earth. Even at the surface of the earth, the incoming energy is exactly balanced by the outgoing energy.

This shows that energy is always conserved and is never lost, which is inconsistent with the idea of energy saving or effective energy use. Usually the word 'energy' has two meanings: *conservable* energy and *consumable* energy. Exactly speaking, the total energy, like that considered in an energy balance, refers to the conservable energy, but the consumable energy, also called the *available* energy, is the energy that can actually be used to do useful work. For example, the surrounding atmosphere has *conservable* energy but no *available* energy.

The available energy A refers to the maximum possible work output of a system. For an open energy system, it is given by [1]

$$A = H - H_0 - T_0(S - S_0) \tag{1}$$

where H and S are the enthalpy and the entropy, respectively, and the subscript o means the surrounding environmental condition. In other words, the available energy A is the difference between the conservable energy, $Q = (H - H_0)$, and the energy spent to maintain the disorder of the system, $T_0(S - S_0)$, where the entropy S is essentially a measure of the disorder of a system. From Eq. (1), it is clear that the system available energy is zero at the environmental condition and Q also becomes zero at the surrounding condition, but in such a situation that energy is not lost; rather, it increases the energy of the surrounding medium. Since the surrounding medium has infinite heat capacity, its temperature does not change, but the total energy of the surrounding medium is still increased. The available energy, however, is reduced due to the energy conversion and transmission. Plainly speaking, this means that the energy offered to us is always more than we can accept, or that we can use. Therefore, we can say that our lives are spent consuming the available energy.

It is very important to consider the ratio of the available energy to the thermal energy, or in other words how much of the total energy can be converted into work. For simplicity, we assume $T > T_0$ and $P = P_0$, where P is pressure. Under these conditions, the ratio of the available energy to the total conservable energy, which is hereafter referred to as the *available energy rate* ε, is given as

$$\varepsilon = 1 - T_0(S - S_0)/(H - H_0) \tag{2}$$

The available energy rate for air, as a function of temperature, at 101.3 kPa is shown as the solid curve in Fig. 1. The available energy rate ε is zero at the surrounding temperature and increases with temperature. The *quality* of thermal energy is relatively low compared to, for example, that of electrical energy. Here, energy quality refers to both its available energy and to its ease of use.

The available energy rate corresponds to the maximum efficiency of energy conversion to useful work, but it is not equal to the Carnot cycle efficiency, which is generally considered to be the maximum possible efficiency. In the Carnot cycle, the temperature of the high temperature heat source is kept constant, but when considering the available energy rate, the system temperature decreases due to the energy flow out of the system. Since the available energy rate decreases with decreasing temperature, in all processes involving a temperature change, we can obtain useful work corresponding to the available energy change. The process in which the temperature decreases, but results in no output work, is the most ineffective process.

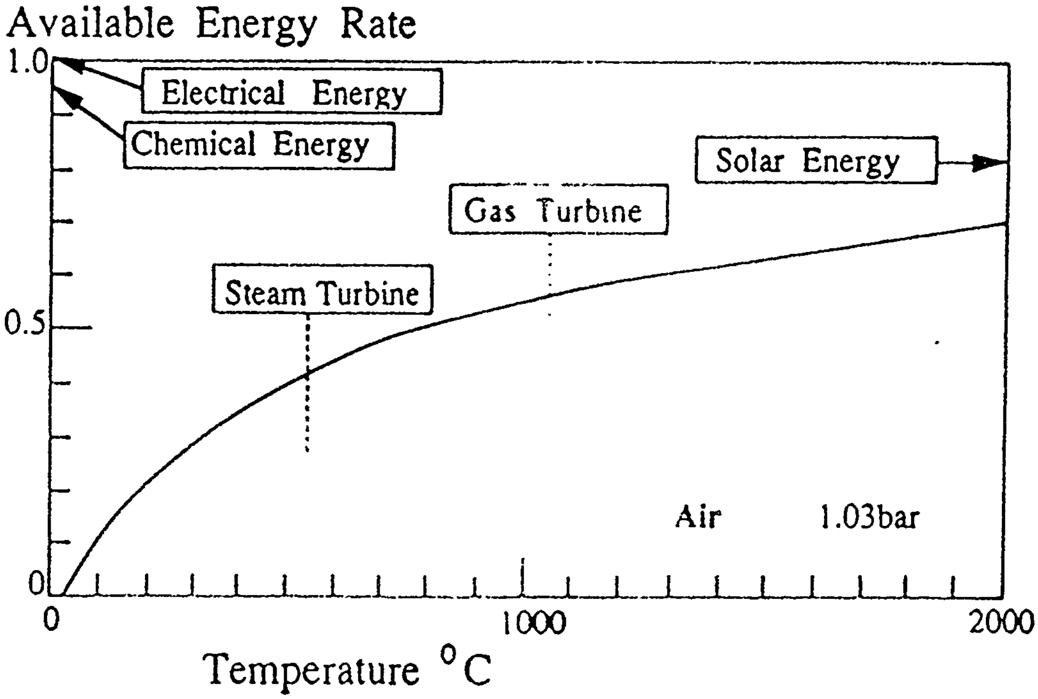


Fig. 1 Available Energy Rate against Temperature

3. Flow of Thermal Energy

As shown in Fig. 1, the available energy rate of electric power is 100%, because all of the electrical energy can be converted to work in an ideal situation. Electrical energy is thus the highest quality energy available today. Fossil fuels, like natural gas, petroleum and coal, have about 95% available energy rates. However, the effective available energy rates of fossil fuels are much lower, because to make thermal energy from these energy resources, the maximum temperature must be kept below 1500 °C, from engineering restrictions of the combustor wall materials and production of pollutants like NOx and SOx. The available energy rate of air at 1500 °C is only 65%, and therefore 30% or more available energy is lost during the combustion process. Thus, as long as a combustion gas is used as a high temperature heat source, the conversion efficiency will never exceed 65%, and this is why the conversion efficiency using thermal energy is so small.

It is usually said that effective use of high temperature energy sources is most important for improving the total energy efficiency. However, Fig. 1 shows that this is not quite true, since the gradient of the available energy rate with respect to temperature is very small in the high temperature region. For example, for air the available energy rate increases 0.15%/°C below 100 °C, but it becomes about one tenth of that value at 1500 °C. A reduction in the temperature drop of 1 °C in the heat transfer process is more effective in the low temperature range compared with the high temperature region, and this improvement is easier from a technological viewpoint. Therefore, efforts towards improving low temperature thermal energy utilization, which is mainly used in nonindustrial fields, help to solve our energy/environmental problems.

It is clear that a quality of the thermal energy is uniquely determined from its temperature and the available energy rate varies in wide range according to the temperature. Another important characteristics of the thermal energy is difficulty for storage, because of its low energy density. Therefore, the cascading use of thermal energy is most appropriate for the effective energy usage.

4. Available Energy Loss by Mixing

For a qualitative discussion, the reduction of available energy rate by mixing is shown in Table.1. A 0.1% diluted methane in air mixture still has 97.9% of the available energy of pure methane (for the same amount of methane). Thus, the diluted fuel is still capable of generating high temperatures, but only by employing a special combustor. Since these lean fuels have very small reaction energies, combustion must occur at high temperature. Therefore, the fuel and air mixture must be heated before combustion by a heat exchanger. Only the generated heat is removed from the combustor, and the remaining heat, which is introduced by the heat exchange process, is used as the thermal energy source of the heat exchanger

CH_4 (%)	Available Energy (kJ/mol)	Available Energy Change (%)	CO_2 (%)	Available Energy (kJ/mol)	Available Energy Change (%)
100.	829	0.0	0.03	0.	0.
1.	817	1.4	100	20.	5.
0.1	811	2.1			

Table 1. Available Energy Change by Mixing

An available energy used for separation of gases from a mixture is very small compared with the enthalpy. Since an available energy of a pure oxygen is not so large compared with the oxygen included in the air, a combustion processes used pure oxygen as a oxidizer are the most attractive in the future energy conversion processes. These combustion processes will enable us to establish a NOx free and also CO2 free combustion if we will use the hydrogen as a fuel.

5. Available Energy of Chemical Compounds

From an available energy analysis, one of the most effective improvements in energy efficiency use that could be done is by changing a process from chemical to thermal energy. The cause of available energy reduction during this process is that the temperature obtained by the actual combustion process of the chemical material is much lower than that expected from the available energy rate. Normally, the available energy rate of gaseous fuel is 95%; however, even a material whose available energy rate is 70% has an ability to produce 2000°C by combustion. Therefore, if work can be obtained by decreasing the available energy rate from 95% to 70% before combustion of the gaseous fuel, that work directly contributes to increasing the energy conversion efficiency.

The available energy rates of some important gaseous fuels are listed in Table 2 with the heat of those reactions.

Reaction Equation	Heat of Reaction (kJ/mol)	Free Energy (kJ/mol)	Available Energy Rate of Reaction
$H_2 + \frac{1}{2}O_2 = H_2O$	285.83	237.18	0.83
$CH_4 + 2O_2 = CO_2 + 2H_2O$	890.3	817.92	0.92
$CH_3OH + \frac{3}{2}O_2 = CO_2 + 2H_2O$	726.59	702.53	0.967

Table 2. Heat of reactions and available energy rates of fundamental reactions

The available energy rate of methane and methanol are in the 90% range, but the available energy rate of hydrogen is only 83%, which means that the combustion of hydrogen is much more effective for obtaining the thermal energy from chemical energy as compared with other combustible materials. Since the reforming of methane and methanol to obtain hydrogen is not so difficult, the most important point is how much available energy is recovered from thermal energy in these processes. The available energy changes in these processes are listed in Table 3.

Reaction Equation	Heat of Reaction (kJ/mol)	Free Energy (kJ/mol)	Available Energy Rate of Reaction
$CH_4 + 2H_2O = CO_2 + 4H_2$	-253.01	-130.8	0.517
$CH_3OH + H_2O = CO_2 + 3H_2$	-130.9	-9.01	0.06

Table 3 Available energy rates of reforming reactions of methane and methanol

The reforming of methane and methanol are both endothermic processes, and the available energy rates are 50% for methane during reforming and below 10% for methanol, which means that thermal energy having an available energy rate larger than these values could, in principle, be used for reforming these materials. Therefore, methane could be reformed by thermal energy at 800°C and methanol by thermal energy below 100°C. In actual processes, the reactions can occur at slightly higher temperatures than these values.

In the reaction processes listed in Table 2, the available energy gaps between methane and hydrogen and between methanol and hydrogen are used to convert thermal energy at 800°C and 100°C to hydrogen, which can generate temperature over 3000°C by combustion. From an energy conservation view point, the heat of 890.3kJ/mol generated by the combustion of methane is increased to 285.83kJ/mol *4=1143.32kJ/mol, which enhances the heat generation by 28.4%. On the other hand, the reforming of methanol to hydrogen increases the heat generation from 726.59kJ/mol to 857.49kJ/mol, which is an about 18% enhancement in the heat generation by combustion. These enhancements of combustion energy are supplied from the thermal energy used in the reforming process, but these temperatures are much lower than the temperature obtained in the combustion process of hydrogen. Therefore, in the reforming process, the total energy is of course conserved, but the available energy of low temperature thermal energy, whose available energy rate is 50% or 10%, is converted to that of hydrogen having an 82% available energy rate. This is a significant contribution to energy saving and available energy enhancement.

It has already been discussed that hydrogen has the advantage of cleanliness during the combustion process; however, from an energy consumption point of view, its lowest available energy rate among combustible materials is more important. Therefore, all of the hydrocarbons used as fuels should be reformed before combustion for absorbing low quality thermal energy. The energy efficiency will then be improved greatly.

The reforming of methane to hydrogen before combustion was proposed for the effective separation of carbon dioxide[2], but it has a much greater advantage for energy saving. The advantage of reforming to hydrogen is not restricted only to methane utilization, but for can also be applied for organic compounds used as combustion fuels. These kind of reforming of the chemical compound is able to reduce the available energy loss in the combustion process and a reproduction of the hydrogen from waste thermal energy for the energy storage because the lowest available energy rate of hydrogen means that the hydrogen is the easiest to reproduce from the thermal energy.

6. Present Electrical Energy Use

Since a reduction in available energy rate is caused by energy transfer or conversion, a suitable combination of energy conversion facilities will increase the system efficiency. An especially important example is when the system load changes on a day-to-day basis and also on a year-to-year basis. In such a case, the combination of two or more smaller facilities are effective. For commercial users, the system load is often big enough to be divided among two or three facilities. Even in a small refrigeration system, the daily output power can be varied by using a inverter system. By using an inverter system, an electrical power savings of 20% can be achieved. The system operates constantly at the optimum condition for energy saving. These improvements have only recently been realized by the development of cheaper power control circuits. This inverter control system will be applied to many different applications for energy conservation purposes.

Energy consumption in the residential area is about half of the total nonindustrial use, which is about 16.7% of the total energy consumption in Japan. This is not negligible from an energy conservation viewpoint. Natural gas, LPG, and kerosene are used for cooking, hot water supply, and heating, where the operating temperatures are relatively low. The available energy rates are roughly10 to 20%. If electrical energy is converted to this low-temperature thermal energy, 80 to 90% of the total required energy can be obtained from the surrounding atmosphere by utilizing a heat pump, leaving only the remaining 10 to 20% to be supplied as electrical energy. Thus, there still exists a great possibility of energy saving in the residential field.

Another energy-saving idea is the so-called co-generation system of electrical power and heat. By using this system, a reduction in air pollution is also expected, because while reduction of air pollution is impossible in small heating furnaces in individual houses, it is possible in large systems. Most of the heat supply systems in northern European countries were constructed for this purpose. In Japan, these systems were mainly constructed for the effective use of waste thermal energy. Both objectives are acceptable from the standpoint of energy conservation and environmental concerns.

Except for a district heating system, for an individual house, a heat pump using a fossil fuel as an energy source is the ideal system, where high-temperature drain water, river water, or atmospheric air can be used as the heat source. Since fossil fuels have a high available energy rate, the thermal efficiency will increase drastically if a heat pump cycle operated directly on fossil fuels is developed. An absorption heat pump, a heat pump combined with a gas engine, and a combined system of two Stirling cycles named the Vuilleumier cycle [3] are newly proposed systems, but they still require further improvement.

7. Conclusions

For effective use of energy, following aspects should be considered.

1. The energy conversion and transmission efficiency should be analyzed from the processes, available energy aspects, which correspond to effective use of energy resources, but not to the economical costs.
2. All organic fuels should be reformed to the hydrogen before combustion by using waste thermal energies, because the hydrogen has the lowest available energy rate among fuels.
3. Low cost separation process of oxygen from the air should be developed for NOx free and CO2 free combustion.
4. Multi-path energy conversion processes among energies of chemical, thermal and electric should be developed for effective use of energy.

References

[1] Japanese Industrial Standard "General Rules for Energy Evaluation Method by Available Energy", Z9204, 1980

[2] K.Hata & Y. Mori, "Global Environment Protection Strategy Through Thermal Engineering", Hemisphere Publishing Corporation. 1992[8] Energy Conservation Center, "Energy Conservation Handbook", (1989)

[3] S. Fujimaki et al.., "Development of New Air Conditioning System using Vuilleumier Cycle", *Proceedings of Japan Refrigerant Society Meeting*, (1989) pp.65-68

The Potential For Energy Conservation In The United States

Roger S. Carlsmith, Director
Conservation and Renewable Energy Program
Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37831

The period of high oil prices between 1973 and 1985 was traumatic in the United States, as it was also in the rest of the world. It was also instructive in showing the kinds of adaptation that could occur rapidly in a very large industrialized economy. During the period, energy use remained essentially constant while the economy continued to grow. The efficiency of energy use, as indicated by the ratio of energy consumption to gross domestic product, increased by 24 percent. Since 1985 there has been little further improvement in energy efficiency.

Can this kind of improvement in efficiency be repeated, and if so, what can make it happen? A number of energy analysts have recently made projections for the next 20 years.[1,2,3,4,5] The projections all indicate steady increases of about 1 percent per year in the level of energy use. Since these projections assumed that gross domestic product will increase by about 2.3 percent per year, the implication is that energy efficiency is expected to increase slowly during the next two decades.

In contrast, studies of the technical potential for energy efficiency agree in concluding that energy use could be substantially reduced by more widespread use of available technologies. For example, a study by five of the Department of Energy national laboratories[5] estimated that the technical efficiency of energy use can be increased by 25 percent by the year 2010 through gradual adoption of cost-effective technologies. With this improvement in efficiency, total U.S. energy use in 2010 would be only 10 percent higher than it is today.

It is often argued that substantially higher energy prices are warranted by the national security and environmental impacts of energy use. In combination with regulatory actions such as higher mileage requirements for automobiles and tighter energy standards for buildings and equipment, there would be significant reductions in energy use. A recent analysis[6] examined three levels of incentives. At the most aggressive level, including a $25 per ton tax on CO_2 emissions, the projected energy use decreases by 27 percent between 1990 and 2030. In this scenario it was also postulated that subsidies for renewable energy would bring about a shift away from the use of fossil fuels. The combination of decreased energy use and fuel shifts was estimated to reduce CO_2 emissions from 5.3×10^9 tons in 1990 to 1.5×10^9 tons in 2030. The analysis provides a plausible description of an energy system which could meet the needs of a U.S. economy while providing solutions to current environmental problems. The assumptions of the scenario may be overly optimistic regarding practical difficulties, but the results illustrate the power of a concerted effort. Recent legislation, known as the Energy Policy Act of 1992, is an initial step in the same direction. If fully implemented, the Act would bring about a 30 percent reduction in the anticipated growth in carbon emissions by the year 2000.[7]

---

* Managed by Martin Marietta Energy Systems, Inc., under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

In the long run the potential for energy efficiency depends primarily on new processes and products developed through research. The importance of R&D is receiving increasing recognition. Thus, the Department of Energy budget for Conservation and Renewable Energy has increased 37 percent in the past two years. The largest increase (67 percent) was for the transportation sector, in recognition of the role of transportation in oil usage. Major objectives in transportation are development of alternative fuels, increased fuel economy, fuels from biomass, and electric vehicles. Increased funding has also been authorized for research in the industrial sector, the buildings sector, and the utility sector.

References

1. *Annual Energy Outlook 1992 With Projections to 2010*, DOE/EIA-0383(92), U.S. DOE, Energy Information Administration, January 1992.

2. *DRI/McGraw-Hill Energy Review*, Fall-Winter 1992-1993, DRI/McGraw-Hill, Lexington, Mass., 1992.

3. *1992 A.G.A.-TERA Base Case*, American Gas Association, Policy and Analysis Group, Arlington, Va., January 1992.

4. P. D. Holtberg et al., *Baseline Projection Data Book*, Gas Research Institute, Strategic Planning and Analysis Division, Chicago, Ill., 1992.

5. R. S. Carlsmith et al., *Energy Efficiency: How Far Can We Go*, ORNL/TM-11441, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, January 1990.

6. Alliance to Save Energy et al., *America's Energy Choices*, The Union of Concerned Scientists, Cambridge, Mass., 1991.

7. H. Geller, S. Nadel, and M. Hopkins, *Energy Savings Estimates from the Energy Efficiency Provisions in the Energy Policy Act of 1992*, American Council for an Energy-Efficient Economy, Berkeley, Calif., November 1992.

2nd U.S./Japan Workshop on Global Change Research
Honolulu, Hawaii
February 1-3, 1993

ADVANCED CLEAN COAL UTILIZATION TECHNOLOGIES

Hiroshi MORITOMI

Combustion Engineering Department
National Institute for Resources and Environment
Tsukuba, Ibaraki 305, JAPAN

Global Environmental Technology/Sunshine Project Promotion HQ
Agency of Industrial Science and Technology (AIST)
Ministry of International Trade and Industry (MITI)
1-3-1 Kasumigaseki, Chiyoda, Tokyo 100, Japan

1. INTRODUCTION

The most important greenhouse gas is CO_2 from coal utilization. Ways of mitigating CO_2 emissions include the use of alternative fuels, using renewable resources and increasing the efficiency of power generation and end use. Adding to such greenhouse gas mitigation technologies, post combustion control by removing CO_2 from power station flue gases and then storing or disposing it will be available. Although the post combustion control have to be evaluated in a systematic manner relating them to whether they are presently available technology, to be available in the near future or long term prospects requiring considerable development, it is considered to be a less promising option owing to the high cost and energy penalty. By contrast, abatement technologies aimed at improving conversion efficiency or reducing energy consumption will reduce emissions while having their own commercial justification.

Table 1 Contribution to the greenhous effect.

	CO_2 emissions, 1988		Greenhouse effect, %	
	GtC/y	%	over 1 y	over 100 y
Coal	2.4	37–28	20–16	23–17
Oil	2.4	37–28	20–16	23–17
Gas	0.9	14–11	8–6	8–7
Fossil fuel	5.7	88–68	48–37	53–41
Cement manufacture	0.2	3.1–2.3	1.7–1.3	1.9–1.4
Deforestation and land use	0.6–2.6	9–31	5–17	6–19
Total CO_2	6.5–8.5	100	55	61
Other greenhouse gases:				
CH_4			15	15
N_2O			6	4
CFC			24	12
others			–	8
Total			100	100

Emission of CO_2 arise from fossil fuel consumption and deforestation (Table 1). Energy consumption has increased by about 20% over the last decade. The industrial countries of the Organization for Economic Cooperation and Development (OECD) account for about 50% of the world's primary energy consumption. Coals supply about 28% of commercially traded world energy supply. Approximately half the coal is used in power generation worldwide whereas 73% is used in this sector in OECD countries. The energy intensity in non-OECD countries is higher due to less efficient use of energy than in OECD countries. There is a great deal of scope for improving the efficiency in the former by transferring technologies used in OECD countries[1].

2. FORECAST OF ENERGY SUPPLY AND CO_2 CONCENTRATION

The world energy consumption in 1988 was about 11,200 Mtce. The OECD countries account for about 50% of this value, East European countries, USSR, and China together account for about 32% of the world energy demand, and the less developed countries (LDC) about 17%. Figure 1 shows that coal has provided 27-28% of the energy demand, oil has decreased slightly from 45% in 1980 to 38% in 1989, gas has increased from 19% to 22% over the same period, and nuclear capacity has doubled from 2.5% in 1980 to 5% in 1989 [1].

In 1988, CO_2 emission from coal use amounted to 2.4 GtC/y out of a total of 6.5-8.5 GtC/y. The increased concentration of CO_2 in the atmosphere resulting from coal use accounts for 16-21% of the enhanced greenhouse effect, that is the part of the global greenhouse effect which is due to human activities. The issue of potential climatic change due to emissions of greenhouse gases was placed firmly in the political arena by the Toronto Conference on the Changing Atmosphere in June 1988. The conference advocated a reduction in CO_2 emissions by approximately 20% of 1988 values by the year 2005 as an initial global goal. In Japan the coal demand recorded in FY 1989 was 113.6 Mt. A long-term energy and demand forecast in 1990 estimates that it will become 142 Mt in FY 2000, the share of coal demand of total primary energy in Japan will be 17.5% in FY 2000 and 15.7% in FY 2010, from 17.2% recorded in FY 1989[2].

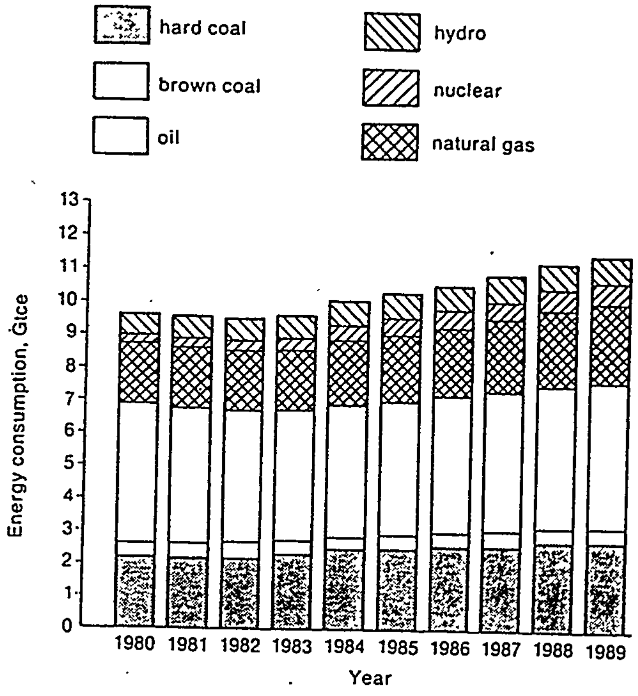
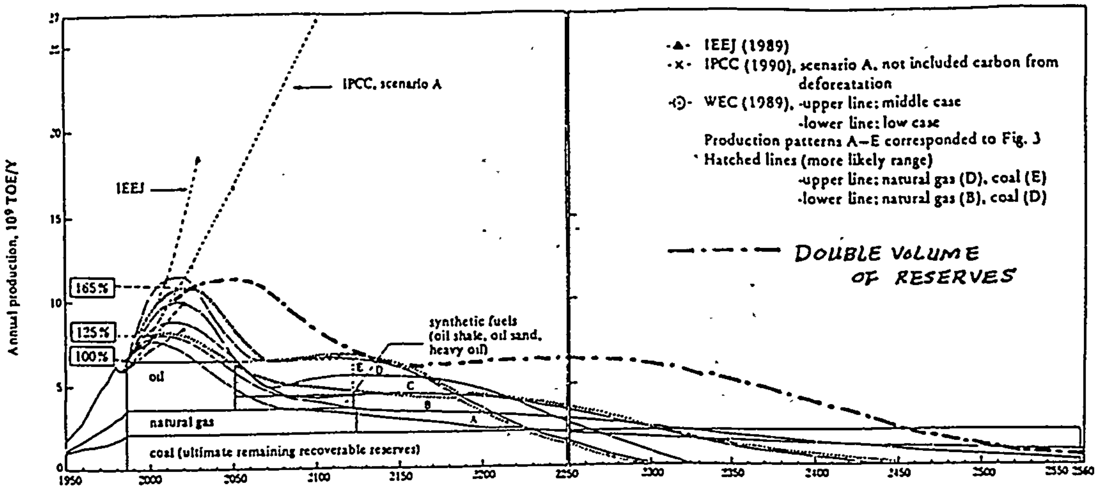


Fig. 1 World primary energy consumption[1]

Annual world production of oil passes its peak in 2010-2020. Life cycle of natural gas follows oil 20 years later. Therefore, annual production of total fossil fuels have a peak in the year of 2020-2040, though annual production of coal will be gradually increasing then in Figure 2. Figure 3 shows that atmospheric CO_2 concentration will reflect and then increase slowly in the shape of S in early decades of twenty first century, and level off around 800 ppmv in the following several centuries[3].

For environmental reasons, built-up of gas fired power generation is to be accelerated and coal fired power generation is to be restrained. Then, CO_2 annual emission from fossil fuels will come down to the same level of 1990 in the middle of the next century. However, this is not not by the environmental pressure but by the limit of fossil fuels supply. Therefore, this scenario of additional use of natural gas is fruitless effort in long-sighted environmental view. Preferable use of valuable natural is for town gas and higher efficient small scale co-generation, and for chemicals and transportation fuels[3].



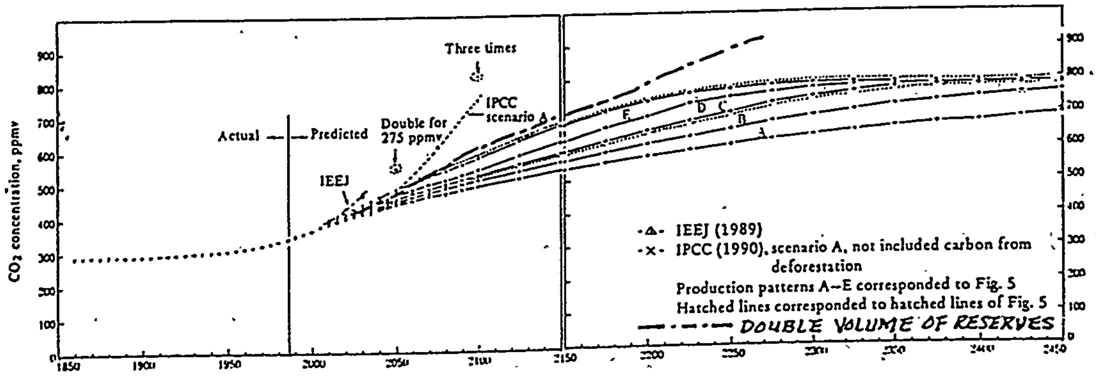


Fig. 2 Lifecycle of primary fossil fuels, total.

Fig. 3 Prediction of atmospheric CO_2 concentration from fossil fuels.

3. COAL UTILIZATION TECHNOLOGY

3.1 CO_2 from Fossil Fuels[1)]

The CO_2 emission factors for fossil fuels are calculated by dividing their carbon content in weight % as a fraction by the calorific, heating value or specific energy. The CO_2 emission factor (HHV) for bituminous coals is widely accepted to be 24.1 gC/MJ for power generation from the principal coal exporting countries. Anthracites are less variable than steam coals and have a higher CO_2 emission factor of 26.0 gC/MJ. Brown coals and peat have similar emissions factors but are more variable due to wide differences in moisture and ash content. The CO_2 emission factors are compared with those for oil and natural gas. The average CO_2 emission factor (HHV) was 25.2 gC/MJ for the brown coals. All the coals show significantly higher emission factors (HHV) than crude oil (19.9 gC/MJ) and natural gas (13.8 gC/MJ). The ratio of the CO_2 emission factors (LHV and HHV) is : bituminous coal : oil : natural gas = 1: 0.8 : 0.6.

Based on the CO_2 emission factors, natural gas fired power generation appears to be much more available than coal fired power generation to reduce CO_2 emission. However, it is fruitless effort in long-sighted environmental view as described above. In this regard, coal utilization have an important role. Concerning the CO_2 emission factors for the products from coal, it may be lower than those of the raw coal but there is always some energy and greenhouse gas emissions penalty in the production process. For instance, upgrading coals to coke, briquettes and other solid fuels involves some energy overheads resulting in higher effective emission factors by 5-12 gC/MJ compared with the coals. The total of the indirect CO_2 emissions for the production of synthetic fuels from coals increases, a general trend of higher conversion efficiency results in lower CO_2 emission factors as shown in Figure 4[4]. The values for the Exxon donor solvent and Sasol Processes using US Eastern coal are respectively 39 and 42 gC/MJ. Coal conversion into liquid or gaseous fuels brings in an additional consideration. If the subsequent use of the product fuel might be more efficient than the burning of coal, it would be compensate in part for the indirect emissions involved in the production process.

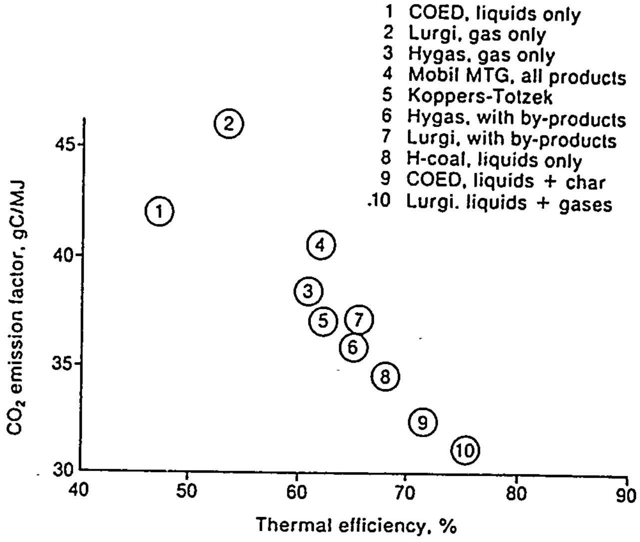


Fig. 4 CO_2 emission factor (HHV) for synthetic fuel conversion processes

3.2 Coal Combustion Technology

1) Conventional power generation technologies

Coal demand and power stations are inextricably linked. In 1988 almost 2490 Mt was burnt in power plant, and the share of total coal use was 54%. Coal provided 39% of the world's electricity in 1988, which was almost twice the share of any other fuel; Oil 12%, Gas 13%, Hydro 20% and Nuclear 17%[5].

Coal combustion may be carried out in one of three different which fall in the following broad fluid-particle contacting and temperature regimes in Figure 5. Most currently operating coal-fired power stations are fueled with pulverized coal. Emission of sulfur oxides can be controlled by treating the flue gases in a flue gas desulfurization system which can be retrofitted to an existing power station, while emission of oxides of nitrogen can be most readily controlled by modifying the burners. These techniques are widely practiced in Japan, the United States, and Germany. Modern plant incorporating these technologies can operate with an overall efficiency of the order of 37%.

In recent years, a number of small power plants has been built which are based on the use of a novel combustion technology such as atmospheric bubbling and circulating fluidized bed combustors (AFBC). In this method of combustion, a mixture of course coal and limestone or dolomite is reacted in a dense or dilute recirculating phase with heat recovery usually via a subcritical steam cycle. The major benefits of this method of coal combustion are the insitu removal of sulfur oxides and the low

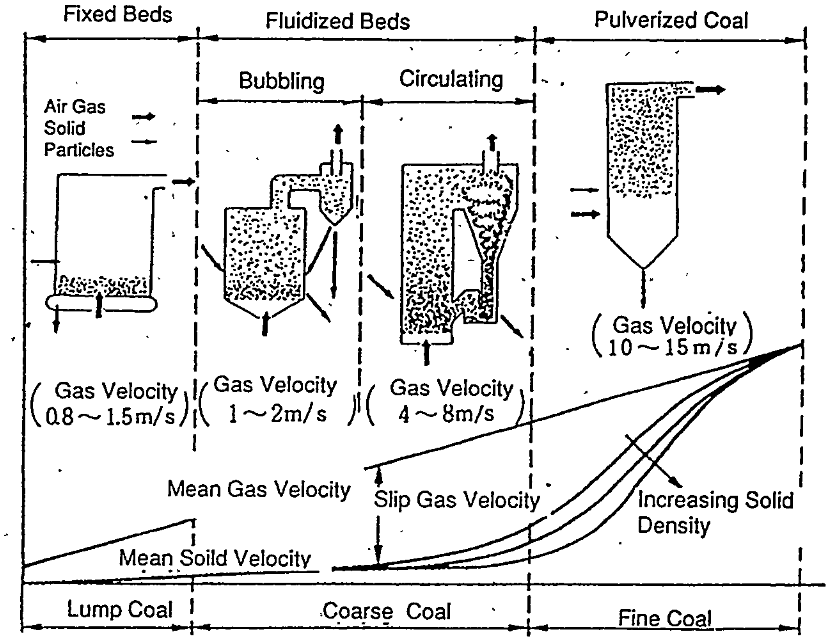


Fig. 5 Three different types of coal combustion reactors.

emission of nitrogen oxides arising from the lower fuel combustion temperature. With removal of SOx and NOx by techniques inherent to the combustion process, net plant efficiencies are roughly 2 %point higher than the reference pulverized coal-fired plant. A further benefit is the ability of AFBC to burn cheap low-grade fuel, resulting in offering the possibility of generating power at a price competitive with large pulverized coal stations. However, there is a slightly higher emission CO_2 from the use of sorbents for desulfurization and $\underline{N_2O}$ from the fuel nitrogen. From an environmental point of view, increasing the generating efficiency leads to a reduced emission of CO_2 with less fuel cost for a given power output.

2) Advanced power generation technologies

(1) Integrated coal gasification combined cycles (IGCC)

In IGCC power station, a fuel gas produced from coal gasification is used to power a gas turbine. Exhaust heat from gas turbine and the partial recovery of sensible heat from fuel gas in the coal gasification and gas cleaning train drives a bottoming steam turbine cycle. Gas cleaning processes for the removal of particulate, alkali vapor and gaseous sulfur contaminants increase the overall energy losses in the system. Entrained flow reactors which operate at higher gasification temperatures and with a fine pulverized coal feed have excellent fuel conversion efficiencies. With low temperature gas cleaning, however, a significant fraction of the sensible heat in the flue gas leaving the gasifier must be removed from the system, by-passing the turbine cycle, but increasing the power output of the steam cycle from partial recovery of the sensible heat. Therefore the IGCC technology is dependent on the development to minimize the efficiency loss through the use of high temperature gas cleaning.

(2) Pressurized fluidized bed combustion (PFBC)

In PFBC, a bubbling or circulating bed operating at temperature of 850-950 ℃ and pressures of up to 1.2MPa is used for coal combustion and to power a gas/steam turbine combined cycle. This method of coal combustion generates lower emissions of sulfur and nitrogen oxides with reduced penalties on the overall power station efficiency. While AFBC achieve heat release rate of 1.5 MWt/m^2 for bubbling type and 5-7 MWt/m^2 for circulating type respectively, PFBC increases combustor heat load by a factor of ten resulting reducing the size of the combustor. Early problems encountered in the development of PFBC technology include high rates of erosion of the in-bed and freeboard steam heat transfer tubes and the development of high temperature particulate and alkali vapor gas cleaning devices to minimize corrosion and erosion of the turbine[6,7].

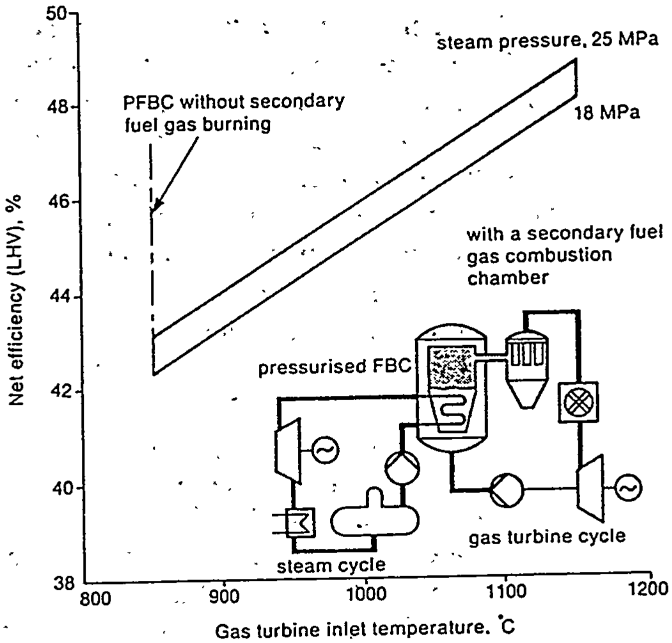


Fig. 6 Effect of fuel gas burning on the efficiency of a PFBC/topping combined cycle[1]

(3) Topping cycle PFBC

In an approach to increase the overall cycle efficiency of PFBC plant configuration, hybrid schemes which rely on the partial gasification of coal in a topping cycle have been proposed. The flue gas from coal gasification is burnt in the gas stream produced from the separate combustion of the coal char produced from the partial gasifier. Figure 6 shows a plot of the increase in the net power station efficiency that could be obtained from the increasing inlet temperature to the gas turbine and with further improvements in the cycle efficiency obtained from additional use of a supercritical steam bottoming cycle[8,9].

(4) Pulverized coal/natural gas combined cycle
(5) Pressurized pulverized coal combustion
(6) Magnetohydrodynamics (MHD)
(7) Fuel cells
(8) Others
   1. Fuel blending and other abatement measures
   2. Combustion in a CO_2/O_2 gas
   3. Hydrogen from Coal

Table 2 presents a summary of the various CO_2 abatement measures[1]. In terms of existing or conventional technology, the use of supercritical steam conditions, and natural gas combined cycle and co-generation schemes based on pulverized coal (PC) combustion meet or exceed the Tront guideline with a 20-58% overall reduction in CO_2 emissions relative to the reference PC power station with FGD.

For the near term power generation technologies such as PFBC and gasification combined cycles, the use of high temperature gas cleaning techniques and supercritical steam conditions are expected to play a crucial role in determining the ability to exceed the goal of a 20% reduction in emissions. The demonstration of the PFBC/gasification hybrid cycle with a 23.9-25.4% reduction in CO_2 emissions offers the greatest promise among these near term commercial options.

On the basis of the current development status, technologies such as PFBC or direct coal-fired turbines, MHD and fuel cell based systems may be classed as more futuristic, second generation abatement options.

4. RESEARCH AND DEVELOPMENT IN MITI, JAPAN

4.1 Action program for the twenty-first century

Various efforts are in progress to solve global warming by green house gases and other environmental problems in all the world. Japan has internationally proposed a plan called "The New Earth 21 (Action Program for the Twenty-First Century)," which involves comprehensive and long-term actions taken under the cooperation of the all nations (Figure 3). This plan comprises five elements:
1) Global promotion of energy efficiency
2) Massive introduction of clean energy sources
3) Development of innovative environment-friendly technologies
4) Enhancement of CO_2 sinks
5) Development of energy-related technologies

4.2 The New Sunshine Program

The Sunshine Project for alternative energy technology R&D, The Moonlight Project for energy conservation technology R&D, and The Global Environmental Technology Program for environmental technology have been promoted as Japan's national projects by the Agency of Industrial Science and Technology (AIST) in the Ministry of International Trade and Industry (MITI). It lead a way to sustainable economic growth by overcoming energy and environmental constraints simultaneously. The New Sunshine Program are established in 1993 by integrating these three programs to provide a new concept for an environmentally friendly technology system. It comprises the following three R&D programs in the field of energy and environmental technologies;

Table 2 Summary of CO_2 abatement measures for power generation

Technology	Steam conditions	Net power station efficiency (LHV), %	CO_2 emissions, gC/kWhe	CO_2 reduction, %	Comments
Conventional					
PC + FGD	subcritical	35	262.1	0	Reference plant for CO_2 emissions.
AFBC	subcritical	37	257	1.95	In-bed desulphurisation, $deNO_x$.
PC + FGD	supercritical (25 MPa)	45.3	208.1	20	540–560°C, 0.002 MPa condenser
PC + FGD	supercritical (30 MPa)	47.5	198.7	31.9	500°C, 0.002 MPa condenser
PC-natural gas co-firing	subcritical	36–37.5	233.3–242.1	7.4–11	15% natural gas input
PC design - coal oil mixture	subcritical	35	251.2	4.2	40% fuel oil input
PC-CO_2 flue recycle	subcritical	27.6–28.6	–	(100)	Energy use for air separation 187–220 kWhe/t CO_2, additional energy use for CO_2 gas disposal.
PC design, H_2 combustion	subcritical	8.4	–	(100)	Energy use for H_2 separation 76% of coal heating value, additional energy use for carbon disposal.
Combined cycles					
IGCC	subcritical	43	212.7	18.9	Low temperature gas cleaning.
IGCC	subcritical	29.9–38.7	–	(90)	CO shift with low temperature gas cleaning. CO_2 reduction for gas disposal.
PFBC	subcritical	42	226.7	13.5	High temperature gas cleaning.
PFBC-gasification cycle	supercritical (25 MPa)	48–49	195.6–199.5	23.9–25.4	High temperature gas cleaning.
Pressurised pulverised coal	subcritical	48	194.2	26	Additional energy use for gas cleaning, increased CO_2 emission from desulphurisation.
PC-natural gas + FGD, $deNO_x$	subcritical	40	202.1	22.1	33% natural gas input
PC-natural gas + FGD, $deNO_x$	supercritical (30 MPa)	49	166.1	36.6	33% natural gas input
MHD	subcritical	40–45*	192.5–216.5	17–27	Additional CO_2 emissions from desulphurisation.
Fuel cells	subcritical	45–58*	147.1–192.5	26–44	Additional CO_2 emissions from desulphurisation.
Co-generation					
Combined heat and power (CHP)	subcritical	77–84	108.9–118.5	54–59	Range for PC + FGD, PFBC and PFBC-gasification cycle. CO_2 reduction figure for the direct replacement of PC plant without low grade heat recovery. CO_2 reduction of 34–39% when replacing existing and separate coal-fired power and district heating plants.

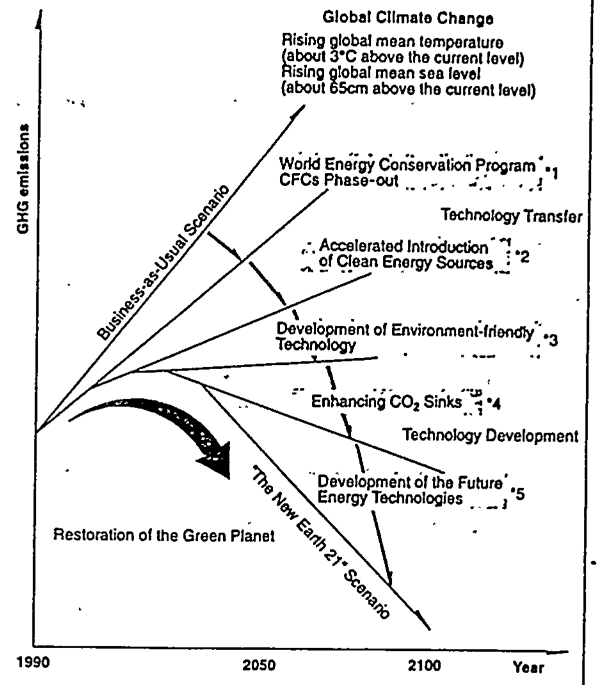
* HHV

1) Innovative R&D Program,
   e.g. Broad Area Energy Utilization Network System
2) International Collaboration Program for Large R&D Projects,
   e.g. International Clean Energy Network Using Hydrogen Conversion
3) Cooperative R&D Program on Appropriate Technologies,
   e.g. Hybrid Energy Supply System Using Potovoltaic and Solar Thermal Energy

4.3 Coal Utilization Technology Activity in Japan2)

The main organization responsible for the technical development of coal in Japan include the Center for Coal Utilization, Japan (CCUJ) and the New Energy and Industrial Technology Development Organization (NEDO) responsible for utilization technologies and the Coal Mining Research Center (CMRC) responsible for production and safety technologies. These organizations are subsided by the government, Agency of Natural Resources and Energy (ANRE) and Agency of Industrial Science and Technology (AIST) in MITI. As Japan needs to establish a system which can promote clean coal technology, a Clean Coal Technology Center is established in NEDO in 1992.

Conceptual Framework of "The New Earth 21"



*1. Accelerated energy conservation, CFCs phase-out, etc.
*2. Safer nuclear power plants, New & renewable energy sources, etc.
*3. CO_2 fixation & re-utilization technology, Environment-friendly production processes, third-generation CFC substitute, etc.
*4. Reforestation, Stopping desertification through bio-technology (develop salt-drought resistant plants), Enhancing oceanic sinks, etc.
*5. Nuclear fusion, Space solar power generation, etc.

Fig. 7 Conceptual framework of the "The New Earth 21.

1) Short-term tasks
   (1) Coal combustion technology
      1a. Pressurized fluidized bed boiler technology: 70MW DP
      1b. Highly pollutionless internal circulating fluidized bed combustion technology: 10t/h DP
      1c. Pressurized internal circulating fluidized bed boiler technology: Basic survey
      1d. Pressurized circulating fluidized bed boiler technology: Basic survey
      2. Industrial furnace technology (Cement manufacture)
      3. Metal fusion system technology directly using coal-oxygen combustion
   (2) Coal slurry technology
      1. High-performance coal water paste (CWP) combustion technology
      2. CWM manufacturing technology by modifying low quality coal
      3. Demonstration of CWM distribution and relaying systems
   (3) Coal handling technology
      1. Demonstration of CCS technology
      2. Low-grade coal utilization technology
   (4) Coal ash utilization technology
      1. Utilization technology of unused resource in coal ash

        2. General industrial coal ash utilization technology
        3. Study on hardened matter
        4. Black ash utilization technology
        5. Fluidized bed boiler combustion ash utilization technology
    (5) Coal partial combustor technology
    (6) Direct iron ore smelting reduction technology
2) Long-term tasks
    (1) Bituminous coal liquefaction technology
    (2) Brown coal liquefaction technology
    (3) Integrated coal gasification combined cycle (IGCC) power generation technology
    (4) Coal-based hydrogen production technology
    (5) Others
        1. Topping cycle PFBC
        2. Oxygen injected coal combustion
        3. Coal flash pyrolysis
        4. Advanced coal cleaning

5. FUTURE PLAN FOR COLLABORATIVE RESEARCH

Mutual collaboration between U.S. and Japan on coal combustion technology and/or advanced power generation can broadly be regarded as falling into three levels. The first level includes system evaluation based on Full fuel Cycle. For advanced power generation technologies such as PFBC, topping cycle PFBC and IGCC, it must be important to evaluate by using a consistent set of criteria to examine their potential in Full Fuel Cycle schemes aimed at the reduction of greenhouse gas emissions. This channel of the U.S./Japan workshop is expected to give and take much more available information on the measure to evaluate the Full Fuel Cycle scheme, although the IEA green house gas R&D programme has been carrying out the sort of the evaluation.

The second level to be considered in this channel is to exchange information on state of technology development, the general information of which is available to evaluate the cycle scheme. For instance, the state of the art of the system for PFBC, topping cycle PFBC and IGCC involved coal handling and high temperature gas cleaning.

The third level is on basic research such as effects of pressure on coal combustion rate, coal gasification rate, and projection of acid gases of NOx, SOx, H_2S, CS_2, COS, HCN and NH_3 and abatement technic of N_2O. The emission has a global warming potential of 270 relative to CO_2. On this basis 100 ppm N_2O is equivalent to 2.7 % CO_2. Although the emissions from soils dominate the N_2O budget and those from stationary sources due to fossil fuel combustion are very small, the levels measured for fluidized bed coal combustor are quoted as ranging from 50-200 ppmv on a 6% oxygen in flue gas basis[10)].

REFERENCE

1) Smith I M, Thambimuthu K V; *Greenhouse gases, abatement and control: the role of coal.* IEACR/39, London, UK, IEA Coal Research (Jun 1991)
2) Center for Coal Utilization, Japan (CCUJ), New Energy Industrial Technology Development Organization (NEDO), Japan Coal Association (JCA); Coal research and development in Japan, *I.C.C.R. Meeting*, York, UK (Sep 1992)
3) Shitaka Y (Center for Coal Utilization, Japan); A viewpoint on CO_2 global warming from fossil fuel reserves, *Personal communication* (1993)
4) Marland G; Carbon dioxide emission rates for conventional and synthetic fuels. *Energy*; 8(12); 981-992(1983)
5) Daniel M; *Power station coal use: prospect to 2000.* IEACR/41, London, UK, IEA Coal Research (October 1991)
6) Newby R A, Keairns D L, Lippert T E, Alvin M A, Bachovchin D M; PFBC at higher combustion temperature. *Modern Power Systems;* 9(11) ;41-47(Nov 1989)
7) Whitehead J C *The status and potential of clean coal technologies for power generation.* World coal institute; Clean coal conference, savona, Italy, (Apr 1989)
8) Jansson S A; The status of pressurized fluidized bed combustion: an energy technology for the future. Proceedings of the clean coal conference, London, UK, Friends of the earth, pp121-132
9) Martin H; Assessing options for burning coal in the 1990s and beyond.; *Generation technology*; 42-48 (Jun 1989)
10) Moritomi, H et al. NOx formation mechanism of circulating fluidized bed combustion; *Proceeding of the 11th international conference on Fluidized Bed Combustion: Clean energy for the world*, 1005 (1991)

Research and Development of Ceramic Gas Turbine

Kazuo SUZUKI

National Aerospace Laboratory
7-44-1 Jindaijihigashi-machi, Chofu-shi, Tokyo, JAPAN

1.Background

The CO2 caused by the consumption of hydrocarbon fuel is one of the main gases which affect the global climate. In order to reduce the formation of CO2, it is necessary to conserve energy as effectively as possible. Therefore the heat energy provided by the fuel should be utilized in multi-cascades. The energy at the high temperature shoud be used for the generation of electric power and the energy at low temperature could be used for making the steam and the hot water.

The gas turbine is preferable for this purpose. The heat energy of exhaust gas can be reused more easily. The two systems are proposed by using the gas turbine as the high temperature stage. One is the cogeneration system and the other is the combined cycle. The former generates electric power by the gas turbine and make steam or hot water in the exhaust gas. The latter employs the gas turbine as the high temperature cycle and the steam turbine as the low temperature cycle.

In order to obtain the higher total efficiency in these systems, the temperature of the starting cycle should be rised as high as possible. The conventional gas turbine has rised the temperature of the cycle and increased the efficiency by introducing the air-cooled metal turbines. But the excessive use of this cooling air decreases inversely the total efficiency. And the turbine blades in the small gas turbine are too small for the sophisticated air-cooled structure. If the turbine inlet temperature can be made higher without cooling the turbine by air, the effiency can rise much more.

The ceramics can give the excellent properties even in the high temperature condition. The great progress is observed in the field of industrial ceramics, such as molding, machining and surface treatment. From this viewpoint the ceramic materials are very hopeful to innovate the gas turbine technology.

The ceramic gas turbine is one of the energy conservation technologies.

2. Outline of the project "Ceramic Gas Turbine"

The research and developement entitled " Ceramic Gas Turbine " is carried out as the national energy conservation project. This program was begun at 1988 and is to be continued up to 1996. The objects are shown in the table 1.

The three types of ceramic gas turbines are being developped. These are shown in Fig. 1.

The agency of industrial science and techenology of MITI manages the whole program. The private manufacturers, the national laboratories and the NEDO take part of this project. Generally the private manufacturers develop the application technology and the national laboratories make the bsic researches.

This R&D is composed of

1. fabrication of the ceramic parts of the gas turbine,
2. improvement of the performance of the gas turbine components,
3. design and assembly technology of the regenerative ceramic gas turbine,
4. combustion technology of low poluttant emission (NOx,CO,HC),
5. optimization in using this ceramic gas turbine as cogeneration.

3. Ongoing researches and Future Plan

The three types of engines are being assembled. Each type has the features and the particular problems. But the common difficulty is the durability of the ceramic turbine rotor. In 1993 these engines are tested and evaluated at the condition of TIT=1200 C. In 1996 they are to opperate at TIT=1350 C and to get the efficiency of 42 %.

The method of making the ceramic parts accurately is studied. The profile of the turbine blade should be designed under the limitation of ceramic materials. We must consider both the structural demand and the aerodynamic performance to gain the high efficiency. The estimation of the life of the ceramic parts in the gas turbine is very difficult and is approached. At this stage the turbine blade, the combustor, the shroud and the heat exchange which are made from ceramics, are required to function at the condition of TIT=1200C. At the final stage they must work at TIT=1350 C. The improvement of the materials and the manufacturing technology is studied to meet this demand.

The clearance between the rotor and the shroud affects intensely the performance of the compressor and the turbine in the small gas turbine. The reduction of this clearance is researched. Many experimentals are conducted in order to rise the performance of the gas turbine components. The numerical simulation assists the design of the components. The numerical method can predict the performance without the experimentals.

The combustion researches are performed to reduce the pollutant from the gas turbine. The regulation of NOx is severe in Japan. The low-NOx combustion is emphasized.

All the researches of the ceramics and of the gas turbine compoents are cotinued to obtain the final goal imposed on the engines.

4.Future View for Collaboration with U.S.

The ceramic technology is the most difficult, such as manufacturing, predicting reliability and evaluating in application to the actual parts. The collaboration in this field will be fruitful.

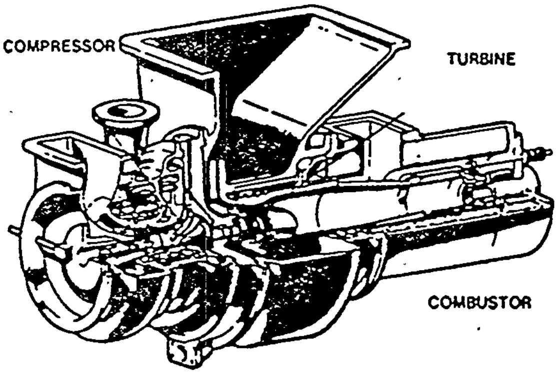
The exchange program has been already proposed. The American researchers has been invited to the manufacturere or the national laboratories in japan to exchange the experiences and the knowledge in this field.

The ceramic test pieces are exchanged among the laboratories to build up the common data base.

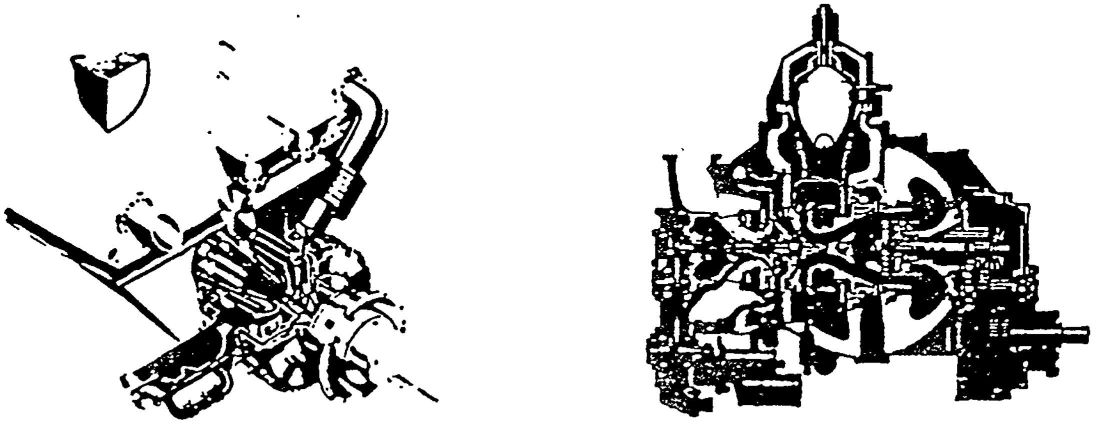
We are ready to extend this collaboration in the field of the basic gas turbine technology which is conducted in the national laboratory. For example the low-NOx combustion technology is researched actively in NAL.

Table 1 GOALS OF 300kW CERAMIC GAS TURBINE

THERMAL EFFCIENCY	TURBIN LNLET TEMPERATURE	AXIAL OUTPUT	EXHAUST EMISSIONS
≧ 42% (LHV)	1350°C	300kW	CLEAR REGULATIONS



SECTIONAL VIEW OF CGT301



SECTIONAL VIEW OF CGT 302

CGT 303 CROSS-SECTION

Fig.1 Three types of ceramic gas turbines

EXTENDED ABSTRACT

COMBUSTION EFFICIENCY: GREENHOUSE GAS EMISSION REDUCTIONS FROM THE POWER GENERATION SECTOR

R. Kane
Office of Fossil Energy
U.S. Department of Energy

D.W. South and A.L. Fish
Technology and Environmental Policy Section
Argonne National Laboratory

2nd U.S./Japan Workshop on Global Climate: Environmental Response Technologies
U.S. Interagency Committee on Earth and Environmental Sciences (CEES)

Honolulu, Hawaii
February 1-3, 1993

Introduction

Concern for the possibility of an enhanced greenhouse effect and global climate change (GCC) has often been associated with energy use in general, and fossil fuel combustion in particular, because of associated emissions of CO_2 and other greenhouse gases (GHG). Therefore, energy policies play a significant role in determining greenhouse gas emissions.

The generation of electricity and power from more efficient fossil energy technologies provides an opportunity to significantly lower GHG emissions, together with other pollutants. The U.S. government oversees a broad-based program to facilitate the development, demonstration, and deployment of these technologies.

Advanced fossil technologies offer other benefits as well, in that they permit continued use of widely available fuels such as coal. An international perspective is critical for assessing the role of these fuels, since countries differ in terms of their ability to maximize these benefits. Often, new technologies are considered the domain of industrialized countries. Yet more efficient technologies may have their greatest potential — to concurrently permit the utilization of indigenous fuels and to lower global GHG emissions — in developing countries, especially those in the Asia-Pacific region.

Existing and Future Energy-Related Greenhouse Gases

The relationship among GHG emissions with potential climate change and with their sources and sinks remains an area of evolving knowledge. Among these emissions, CO_2 is the most abundant. CO_2 levels also respond to changes in land cover/use, hence the concern with tropical deforestation.

Methane (CH_4) and nitrous oxide (N_2O) are by weight more potent GHGs than CO_2, although not as abundant. Emissions of these two gases are associated partially with the production, transportation and combustion of fossil fuels and with a variety of agricultural, industrial, and waste-related activities. Chlorofluorocarbons (CFCs) are also very potent greenhouse gases not emitted from fossil fuel combustion.

Another GHG is ozone. While not directly emitted by any source, one of its precursors (NO_x) is a byproduct of fossil fuel combustion. NO_x emissions are reduced via the application of several advanced fossil energy technologies.

Characterizing the net contribution of various GHG emissions to an enhanced greenhouse effect is complicated by the uncertainties surrounding indirect effects. The formation and effect of tropospheric ozone on atmospheric warming is still inadequately modeled, and the overall atmospheric role of CFCs, is undefined.

In summary, advanced fossil technologies significantly decrease the energy needed to produce a given amount of electricity, and therefore, they reduce GHG emissions. Fuel substitution provides another option to affect GHGs, because emissions from combustion vary among fuels. Natural gas emits 40% less CO_2 than coal; petroleum 17% less.

Over time, the international origin of GHG emissions should be considered. By 2025 developing countries are expected to generate more energy-related CO_2 than the industrialized nations of the Organization for Economic Cooperation and Development (OECD). The share of CO_2 emissions from the former Soviet Union and the European Economies in Transition (EETs—Central/Eastern Europe), are projected to steadily decline between now and 2100, by which time developing countries should be responsible for the vast majority of global CO_2.[1] The fortunate aspect of these emission projections is that much of them will come from *new* coal and fossil fuel power plants. This provides the opportunity for emission reductions through increased penetration of high-efficiency power generation technologies.

---

[1] Based on 1992 reference case estimates of UN Intergovernmental Panel on Climate Change (IPCC), which probably allow for conservative rates of improvement in energy efficiency. The relative geographical shares and the large overall growth in CO_2 emissions predicted under this reference case is subject to unexpected changes in energy prices and policies.

Fossil Energy Resource Distribution and Future Energy Demand

Fossil fuels supply the vast majority of the world's current energy consumption, much of it liquid petroleum for transportation. Hydro and nuclear power are currently the only significant non-fossil commercial sources of energy.[2] While reserves of oil and gas may be adequate for several decades, coal reserves at current production rates are available for hundreds of years.

Petroleum and natural gas are less evenly distributed around the world than coal. The Middle East and the former Soviet republics contain most known oil and gas reserves. Despite propitious developments in recent years, both these regions remain politically and economically unstable. Unlike petroleum and coal, gas frequently faces constraints for distribution and transportation.

Energy consumption and electricity demand are linked with economic growth and development, and many developing countries are growing rapidly especially in the Asia-Pacific region. The current average per capita electricity consumption in developing countries is about one-eighth that of the OECD. Thus, if energy/electricity intensity in many of these countries approaches levels commensurate with industrialized countries, demands on fossil fuels and power generation would be enormous. Long-run global energy models, such as the Edmonds-Reilly model predict that demand for fossil fuels will triple from 2000 to 2100, with the share represented by coal rising to 96%. In terms of coal demand, developing countries will drastically outstrip industrialized countries by 2100, having surpassed them as early as 2025.

Technologies to Improve Conversion Efficiencies

The typical base-load fossil-fuel power plant burns pulverized coal (PC) in a boiler to produce steam for a turbine. With the addition of post-combustion controls to reduce air pollutants (eg, flue-gas desulfurization—FGD) efficiency rates (heat/electricity) are at about 30-35%. A variety of advanced fossil combustion technologies and clean-coal technologies have higher efficiency ratings:

- PC/FGD plants employing supercritical steam, advanced scrubbers, and other improvements have efficiency rates of about 37-42%, which would lower CO_2 emissions by 2-14%.
- Fluidized bed combustion (FBC) burns coal in a bubbling inert medium under either normal (atmospheric—A) or pressurized (P) conditions to generate steam and hot

---

[2] Commercial sources do not include traditional biomass in developing countries (eg, fuelwood and charcoal). If the biomass is allowed to grow back, then overtime such energy sources will generate little or no net CO_2 emissions -- i.e., if the biomass is sustainably consumed and managed. Biomass burning may lead to significant net emissions of other GHGs, however.

exhaust gas for a gas turbine. Combined-cycle-like designs are also integrated with PFBC units. Efficiency rate estimates range from 37% for AFBC units to 48-49% for advanced PFBC units, which compared to conventional PC/FGD units would lower CO_2 emissions by 2-25%.

- Combined-cycle technology combusts natural gas (NGCC) or gasified coal (integrated gasification combined cycle, IGCC) in a gas turbine and uses exhaust heat to produce steam for a second turbine. NGCC units experience efficiency rates of 43-50+%. Conventional IGCC units have been rated at 38% to 43% efficiency, and more advanced designs are anticipated to reach 43-47%, which compared to conventional PC/FGD units would lower CO_2 emissions by 19-23%.

- Fuel cells use either molten carbonate or solid oxide from coal, or hydrogen-rich gas from coal, natural gas or other substances to produce electricity directly from chemical reactions. Efficiency rates are estimated at 45-58%.

- Magnetohydrodynamics (MHD) heats coal or some other fuel to a plasma, from which a magnetic-electric current is derived. 40-53% efficiency rates for coal are anticipated.

- Compared to conventional PC/FGD units, MHD and fuel cells for coal could reduce CO_2 emissions by 20-45%, and advanced technologies using natural gas — i.e., NGCC, fuel cells — could reduce emissions by 58-65%.

The accompanying figure compares some of these technologies against conventional PC/FGD, by graphically depicting relative efficiency improvements and reductions in the annual quantity of CO_2 emissions at a reference 500-megawatt power plant.

NGCC and some FBC designs are increasingly favored in commercial applications. IGCC, advanced PC/FGD and PFBC demonstration units are currently in operation, and wider usage of IGCC awaits refinements in coal gasification technology. Despite promising breakthroughs, MHD and fuel cells are longer-run options on the order of 15 or more years before they may be commercially available.

Cogeneration or combined heat and power (CHP) uses excess heat or steam from a power plant for industrial processes or space heating. Similarly, unused industrial power can be diverted to produce electricity. In either case, efficiency improvements and GHG emission reductions can be tremendous compared to separate, conventional applications. CHP with advanced coal technologies could offer efficiency rates of over 80% and reduce CO_2 emissions by around 60%. CHP is especially suitable for densely populated areas and for FBC technologies because of their generally smaller-scale operation. CHP is increasingly favored in Europe as an energy conservation strategy.

Co-firing of natural gas and coal is also an option to cost-effectively lower CO_2 emissions and provide flexibility in the input of quantities of gas and coal. Similarly, coal gasification has added attractions, because it could be interchanged with natural gas or other gasification applications, depending on technological, operating and supply conditions.

U.S. Research, Development and Demonstration (RD&D) Programs

For several years, the U.S. Department of Energy's Office of Fossil Energy has sponsored a Clean Coal Technology (CCT) program and other RD&D efforts to speed-up the introduction of promising advanced fossil energy technologies. Since 1986, the CCT program has undertaken four phases and is entering a fifth phase of solicitations. 41 cooperative agreements have been signed to demonstrate and further commercialize a vast array of technologies. Cost and technical responsibilities are shared with private sector partners. Between 1986 and 1994, $2.7 billion of federal funds will have been spent on the CCT program. Originally, the CCT program emphasized pre- and post-combustion technologies and especially advances in combustion (in-situ) systems to control pollutants such as NO_x and sulfur dioxide (SO_2). The two most recent rounds (four and five) have targeted energy efficiency (and hence GHG emission reductions) as an important criterion for evaluation.

R&D on Fuel Cells in Japan and Possible Contributions of Fuel Cell to the Global Reduction of CO_2 Emissions

Hiroyasu TAKENAKA
Government Industrial Research Institute, Osaka(GIRIO)
Agency of Industrial Science and Technology(AIST)
Ministry of International Trade and Industry(MITI)
1-8-31, Midorigaoka, Ikeda, Osaka563, Japan

1. Background

Fuel cells can generate electricity equivalent to 40-60% of the energy contained in the fuel consumed, and an overall efficiency as high as 80% is not impossible to achieve through utilization of the exhaust heat. In addition, emissions of pollutants such as NO_x and SO_x from fuel cells are low. Since various reformed gases derived from natural gas, methanol and coal can be used as fuel for fuel cells, the wide range of applications for fuel cells is expected to contribute to the reduction of petroleum dependence in Japan.

2. R&D activities in Japan

An R&D project for Fuel Cell Power Generation Technology is in progress as part of large-scale energy conservation project, the so-called Moonlight Project, founded and sponsored by AIST of MITI. The fuel cell R&D project is being promoted by NEDO(New Energy and Industrial Technology Development Organization) and national institutes of AIST. Over ten companies are taking part in the R&D program under contract with NEDO.

Fuel cells are usually classified according to the kind of electrolytes used. The main types are : alkaline fuel cells(AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells(MCFC), solid oxide fuel cells(SOFC), and polymer electrolyte fuel cells(PEFC).

Recent activities in the Moonlight Project are as follows:

a. AFC

The R&D program for AFC has already been completed, culminating in the development of 1kW class cell stack in FY 1984.

b. PAFC

Two types of 1MW pilot plants for experiments on dispersed power generation, and two types of 200kW systems, one for cogeneration using city gas installed in an urban building and the other for on-site power generation at a isolated island using methanol, were successfully developed in FY1988 and FY1990. 80.2% overall efficiency for the 200kW cogeneration system and 39.7% power generation efficiency for the remote on-site system were obtained, and the accumulative power generation times were 13,000hr for the cogeneration system and 8,449hr for the remote on-site system. After these trial operations of the 200kW systems, the R&D program for PAFC in the Moonlight Project was completed in FY1991. In order to promote the commercialization of PAFC, NEDO started a new program to develop 5MW class and 1MW class systems, starting from FY1991, with financial support from the Agency of Natural Resources and Energy(ANRE) of MITI.

c. MCFC

In FY1992, 100kW class cell stacks were fabricated. In order to develop a 1MW class pilot plant by end of FY1997, two types of cell stacks and the ancillary components, such as fuel reformers and waste heat recovery systems, are being developed. The possibility of an internal reforming-type cell is also being investigated.

d. SOFC

Fundamental research on the manufacture of SOFC was completed in FY1991 and followed by a new program to fabricate a 20-30kW SOFC module.

e. PEFC

A new R&D program for PEFC has just started in FY1992. The goal is to develop PEFC with high power generation efficiency and high power density.

In addition, most of the Japanese electric power and gas companies are independently also carrying out vigorous R&D on fuel cells. Table 1 shows their trial operations of PAFC plants, including those from the Moonlight Project.

3. Current international cooperative activity

AIST and NEDO have cooperated with IEA through the Implementing Agreement for a Program of Research, Development and Demonstration on Advanced Fuel Cells. AIST has also cooperated with the U.S. through the Fuel Cells R&D Coordinating Subcommittee under U.S.DOE/Japan AIST-ANRE Implementing Arrangement in Coal Energy Research and Development, in R&D's on MCFC, SOFC and PEFC. Therefore, the collaborative research with the U.S. on fuel cell technology should be continued under such the existing framework.

As for PAFC, which are expected to be commercialized on a large-scale in the very near future, cooperative activities between private companies in Japan and the U.S. are in progress (see the manufacturers in Table 1).

Table 1 PAFC trials in Japan

Main Organization	Size of cell and Manufacturer
Tokyo Electric Power Co.	4.5MW(U.T.C.),50kW(Toshiba),200kW(IFC),220kW(Sanyo), 200kW(I.F.C.),11MW(Toshiba/I.F.C.)
Kansai E.P.Co.	30kW(Fuji),1MW(Fuji/Mitsubishi)*,50kWX16(Fuji), 200kW(Mitsubishi)
Kansai E.P./Osaka Gas Co.	200kW(Mitsubishi)*,
Chubu E.P.Co.	1MW(Hitachi/Toshiba)*,
Okinawa E.P.Co.	200kW(Fiji)*
Hokaido E.P.Co.	100kW(Mitubishi)
Tohoku E.P.Co.	50kW(Fuji)
Hokuriku E.P.Co.	4kW(Fuji)
Shikoku E.P.Co.	4kW(Fuji)
Tokyo Gas Co.	12.5kWX2(U.T.C.),40kW(U.T.C.),40kW(U.T.C.), 50kW(Fuji),100kW(Hitachi),200kWX10(I.F.C.)
Osaka Gas Co.	12.5kWX2(U.T.C.),40kW(U.T.C.),40kW(U.T.C.), 200kW(I.F.C.),200kWX10(I.F.C.)
Toho Gas Co.	200kW(I.F.C.)
The above 3 Gas Co.'s	50kW,100kW(Fuji)
Other companies	50kW(Fuji),100kW(Fuji),100kW(Sanyo),200kW(I.F.C.)

* projects in the Moonlight Project

4. Future view of collaborative research with U.S. in this workshop

In order to explore the possibility of new collaborative activity with the U.S at this workshop, an alternative view on the impact of fuel cell introduction on the global environmental would be required. For example, the following subjects for collaborative research could be pointed out:

(1) Analysis of effect of fuel cell introduction on global environment

The contribution of fuel cells to the reduction of CO_2 emissions is also now coming to be widely appreciated from the viewpoint of gains of efficiency (38% →40-60%), as compared with thermal power generation. In addition, the applicability of fuels with lower CO_2 emissions than petroleum and coal, such as natural gas and methanol, also will eventually contribute to the reduction of CO_2 emissions. It is politically important that the effect on our society of CO_2 reduction through the introduction of fuel cells can be estimated with higher reliability.

(2) Concentration and separation of CO_2 utilizing MCFC

Electrode reactions in MCFC are as follows;

[Cathode] $CO_2 + 1/2O_2 + 2e^- \rightarrow CO_3^{--}$

[Anode] $H_2 + CO_3^{--} \rightarrow H_2O + CO_2 + 2e^-$, $CO + CO_3^{--} \rightarrow 2CO_2 + 2e^-$

These reactions show that CO_2 in the cathode compartment is transported to the anode compartment. The MCFC is used not only for power generation, but also for concentration or separation of CO_2, as shown in Fig.1. Although the advantages of utilization of MCFC with both functions have been pointed out in a Japanese report, further feasibility studies are required to define the technical and economic problems involved in the application of such MCFC systems to large-scale power generation or cogeneration systems.

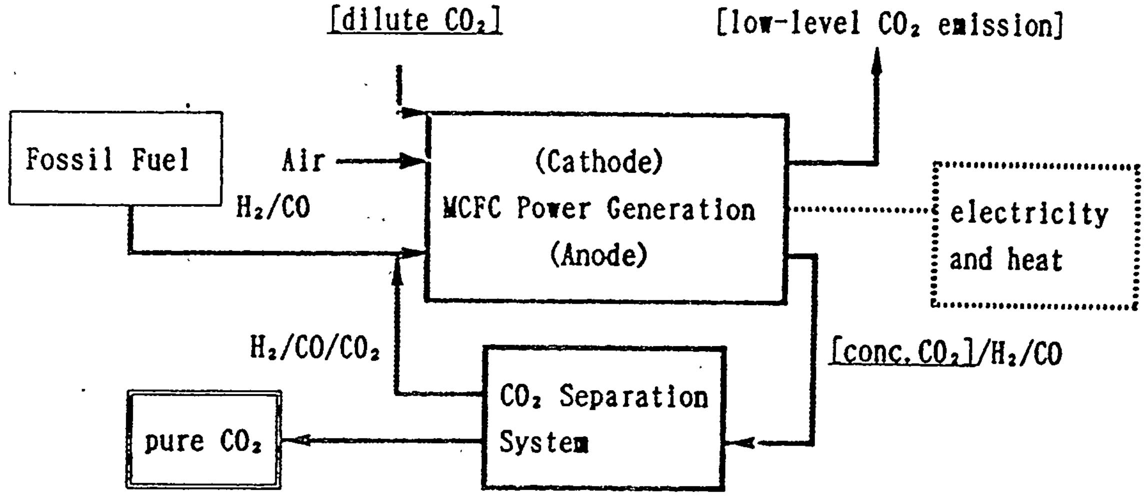


Fig.1 Concentration and separation of CO_2 utilizing MCFC

ENERGY CONVERSION OF BIOMASS IN COPING WITH GLOBAL WARMING

Shin-ya Yokoyama, Tomoko Ogi, and Tomoaki Minowa
Biomass Laboratories,
National Institute for Resources and Environment
16-3, Onogawa, Tsukuba, Ibaraki 305, Japan

1. BACKGROUND

The main purpose of the present paper is to propose energy conversion technologies of biomass in coping with global warming. Among thermochemical conversion, liquid fuel production by high pressure process is mainly introduced.

Biomass is a term used to describe materials of biological origin, either purpose-grown or arising as by-products, residues or wastes from forestry, agriculture and food processing. Such biomass is a renewable energy sources dependent on solar energy. Through photosynthesis, plants converts carbon dioxide into organic materials used in their growth. Energy can be recovered from the plant materials by several processes, the simplest way is burning in air. As far as biomass is used in this way, there is no atmospheric accumulation of carbon dioxide making no effect on the Greenhouse Effect, provided that the cycle of regrowth and burning is sustained.

Of recent an idea that biomass utilization instead of fossil fuel can contribute to carbon dioxide sequestration or reduction in the atmosphere by advanced biomass conversion technology. According to the projections of response strategies working group (RSWG) of the IPCC[1], global carbon dioxide emissions could be reduced to half the 1985 level by 2050 by supplementing the response measures of the RSWG "Scenario B" with biomass energy production sufficient to displace by 2050 5.4Gt per year of carbon from fossil fuels combustion. D.O. Hall reported that this might be achieved by displacing coal with biomass; about one-thirds of which might come from various agricultural and industrial biomass residues and two-thirds from biomass plantations [2]. Such residues are prime candidates for the bioenergy systems.

Toward sustainable biomass production for energy,some 400-600 million hectares will be required by the second quarter of 21st century [1][3]. However, questions are raised by the scenario of afforestation on global size; energy balance sufficiently favorable to justify the effort, sustainability of high biomass yields over wide areas and long periods, and environmental acceptability of plantations. Taking these into account, at this time, utilization of biomass residues and wastes for energy by modern technology such as thermochemical liquefaction is more practical and substantial in terms of technical, economical, and environmental reasons.

2. BIOMASS RESIDUES AND WASTES

Biomass residues from agricultural and forest product industries might be used as fuel for energy. The significance of these markets is suggested by the data[4] which shows that global residue production in selected industries in 1988 was some 56 exajoules. This amount of residues, had it been used to produce power only in IG/ISTIG units, would have been able to produce some 6,600 terawatt-hours (TWh), about as much electricity as was produced by all fossil fuel-fired power plants in the world in 1988 [4]. It can be probably said that this amount is roughly equivalent to 17% of total consumption energy of the world[5]. In other word, it is about one-half of the energy from coal. In addition to these agricultural and forest residues, a great deal of industrial and municipal wastes are generated. The amount of the organic industrial wastes is 300 million tons and municipal wastes is 420 million tons in OECD countries in 1990[6]. It is therefore reasonable to conclude that energy arising from coal can be displaced by biomass residues as pointed out by Hall. Of course, not all these residues could be recovered and used for power generation or other form of energy, but this suggests that residue utilization is worth exploring.

3. ENERGY CONVERSION TECHNOLOGY

Processes for conversion of biomass to heat or to fuels may be divided into three basic categories:direct combustion, thermochemical coversion, and biochemical conversion. Many different technological approaches exist for carrying out the basic conversion process involved. The following will briefly describe the process and some of the technology. Figure 1 shows the energy conversion of biomass.

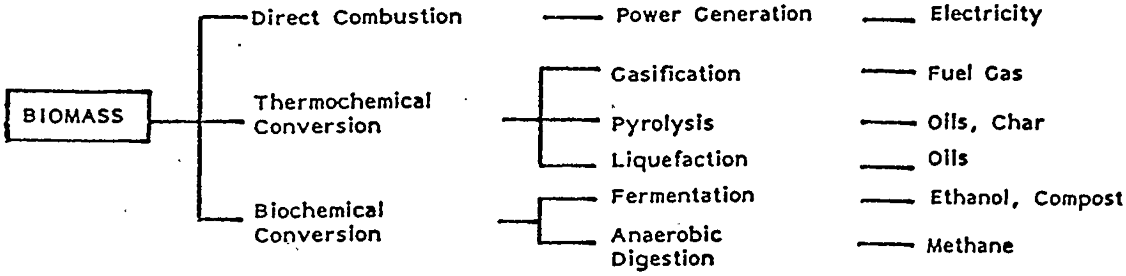


Fig. 1. Energy Conversion of Biomass

3.1 Direct Combustion

Direct combustion is both the oldest and most prevalent contemporary use of biomass. Technology covers a wide range of uses from generation of electricity to industrial production of mechanical energy and furnishing of heat for space heating. Wood is the most common fuel used; however, crop residues, manure, and municipal solid waste are also commonly used. In large systems, cyclone and suspension systems increase efficiency by keeping the fuel suspended. Fluidized bed systems advanced this concept, using a hot fluidized bed of sand, Limestone or other material to incite combustion and provide quick reduction times.

3.2 Pyrolysis

Pyrolysis, or the thermal decomposition of an organic material in the absence of oxygen, traditionally has been to produce charcoal and also may be referred to as retorting, destructive distillation, or carbonization. The slow heating produces roughly equal proportion of gas, liquid and charcoal, but actual output can be varied depending on the feed composition, heating rate, temperature and residence time in the reactor. Higher temperatures and longer residence times promote gas production; while lower temperatures and shorter times produce more liquids and char. A modern process named fast pyrolysis minimizes char production to 10% to 20% and can be tailored to produce high yields of either gas or liquid.

3.3 Gasification

Gasification refers to the partial combustion of solid carbonaceus fuels to produce a gaseous fuel composed principally of carbon monoxide and hydrogen. Biomass feedstocks perform better than coal because they volatize to 70% to 80% gases compared to 20% to 40% for coal. Furthermore, the biomass char is much more reactive with steam and carbon dioxide in its final conversion to an end product.

Gasification with air produces a low energy gas due to the dilution of the product by the nitrogen present in air. If a higher energy-content gas is desired, such as a carbon monoxide and hydrogen rich synthesis gas, pure oxygen can be substituted for air. Another approach transfers heat into the gasifier through its walls, with heat exchangers or hot sand (also called steam gasification or pyrolysis gasification) so that nitrogen is excluded from the final product. To create a pipeline-quality synthetic natural gas, a two or three stage process is required: gasification - shift conversion - synthesis. The shift conversion uses a catalyst to increase the hydrogen content of the gasification product so that methane can be formed. Appropriate processing and catalysts can be used to create ammonia, methanol or hydrogen.

3.4 Liquefaction

A simplified explanation is given by comparing liquefaction with pyrolysis. Both are thermochemical processes in which organic substances are converted to oily material through the action of such factors as temperature, pressure, and catalyst. Among the organic components comprising biomass and waste are crude protein, crude fiber, crude fat, and carbohydrate. In the case of liquefaction, these various giant molecules are decomposed into fractions that are rich in reactive light molecules in the presence of alkali catalyst. At the same time, they can be polymerized into oily material having an appropriate molecular weights while undergoing deoxygenation. With pyrolysis, on the other hand, a catalyst is usually unnecessary, and the light decomposed fractions are converted to an oily material rich in aliphatic compounds through homogeneous reaction in the gas phase.

The differences in operating conditions liquefaction and pyrolysis are presented in Table 1. Temperature is slightly lower for liquefaction and the working pressure is extremely high as compared with that of pyrolysis. Whereas the saturated vapor pressure of the temperature is 50 to 150kg/cm^2 for liquefaction, the pressure is in the normal range for pyrolysis. Considering

Table 1 Comparison of Liquefaction with Pyrolysis

	Temperature	Pyrolysis	Drying
Liquefaction	250 - 350°C	50 - 150 kg/cm^2	no need
Pyrolysis	400 - 600°C	1 kg/cm^2	need

the design for reaction unit, pyrolysis is most advantageous, but in the case of feed materials with high moisture contents, such as sewage sludge, a drying process is essential, so pyrolysis becomes disadvantageous in terms of total energy required. Consequently,for sewage sluged normally containing 70 to 80% moisture, liquefaction is considered to be more suitable. In what follows, the results will be introduced using an autoclave and continuous plant developed on the basis of the basic results together with the balance of energy input and output, etc. [7,8]

Figure 2 shows a flow diagram of a development plant of sewage sludge liquefaction (5 wet ton/day). From the estimation of energy balance in case that oil is used as a heat sources of its own process, it was found that this process is a net energy producer, indicating an excess oil can be obtained from this process. The oil obtained by this process is resembling with petroleum oil in terms of heating value and viscosity. According to the economical evaluation, the disposal cost by this process is competitive with the current disposal cost by other processes such as landfilling near urban areas, anaerobic digestion and incineration. This process is basically applied to not only to organic wastes but to biomass.

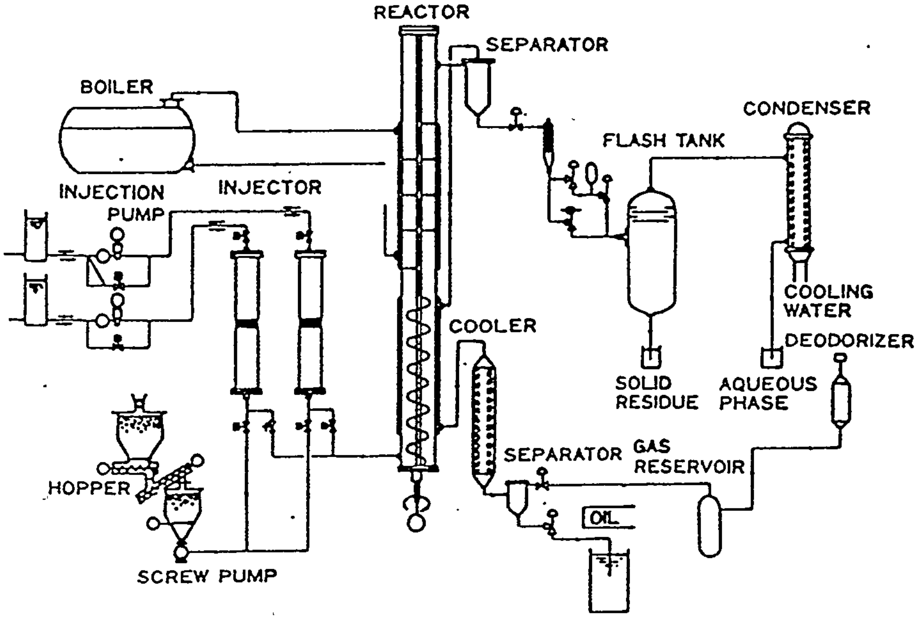


Fig. 2 PDU(5 ton/d) for Sewage Sludge Liquefaction

4. COOPERATIVE ACTIVITY

4.1 Evaluation of Biomass Energy to Global Environment

Regarding biomass energy utilization, two kind of cooperation is basically possible. The first category of cooperation is the theoretical research of biomass for energy. Some studies have shown that the use of biomass could make it the largest single source of fuel in the next century. However it is clear that biomass energy systems including biomass plantation, though it is potentially carbon neutral, are not necessarily totally environmentally neutral. To make these clear, cooperation with institutes and universities is strongly needed. Technological and economical evaluation of biomass plantation must be done including afforestation, irrigation, water supply, prevention of salt damages, etc. Further it is hoped that a new biomass energy system is proposed to supply fuel and chemicals from biomass in coping with global warming.

4.2 Biomass Energy Conversion

In practice the efficiencies of making useful energy will not be the same for biomass and fossil fuels. It is customary to assign much lower efficiencies to biomass. Most biomass used for energy in the world is in the form of fuelwood, crop residues, or cooking char-coal in rural areas in developing countries.

To improve this efficiency, many kinds of modern technologies, for example, power generation by IGCC, fast or rapid pyrolysis, high pressure liquefaction, and gaisfication,have been proposed. High pressure liquefaction of biomass and wastes in making liquid fuel resembling petroleum have been studied for many years in our institute. A demonstration plant for sewage sludge liquefaction has been constructed and at the present time the plant is operating. Cooperation with organizations in which the similar kind conversion technology is being done is expected to exchange information and researchers for collaborative research.

5. OTHER REMARKS

Recently microalgae such as Botryococcus have been attracting attention because it can fix carbon dioxide in the atmosphere and produce hydrocarbon in its body. However separation or extraction of hydrocarbon must be done solvent extraction, leading to economical disadvantages. When the present liquefaction was applied to the green algae, oil was obtained in higher yield than that of original hydrocarbon contained in the algae[9].

Some algae are cultivated on a large scale, the objective of the usage of the algae is still unclear. This method can be a prime candidate for the purpose of oil production.

6. REFERENCES

[1] Intergovernmental Panel on Climate Change Formulation of Response Strategies, Report Prepared for IPCC by Working Group III(WMO and UNEP, Geneva, 1990)

[2] D. O. Hall, H. E. Mynick, and R.H. Williams, Nature, 353, 11 (1991)

[3] P. Elliott and R. Booth, Report Prepared to the World

Renewable Energy Congress (London, 1990)
[4] R. H. Williams and E. D. Larson, Renewable Energy: Sources for Fuels and Electricity, Chapter 17, pp. 729-785, Island Press (1992)
[5] British Petroleum, BP Statistical Review of World Energy,(BP London, 1989) pp. 4, 22, 26, 34
[6] Report of OECD, The State of the Environment, 1991
[7] S. Yokoyama, A. Suzuki, M. Murakami, T. Ogi, K. Koguchi, and E. Nakamura, Fuel, 66, 1150(1987)
[8] S. Itoh, A. Suzuki, T. Nakamura, and S. Yokoyama, Water Sci. Tech., 26, 1175(1992)
[9] Y.Dote, S.Sawayama, S. Yokoyama, Report of 204th ACS National Meeting(Washington, D.C.) 1992

The Role of Renewable Bioenergy in Carbon Dioxide Sequestration

C.M. Kinoshita, Hawaii Natural Energy Institute

Introduction

The use of renewable resources represents a sound approach to producing clean energy and reducing the dependence on diminishing reserves of fossil fuels. Unfortunately, the widespread interest in renewable energy in the 1970s, spurred by escalating fossil fuel prices, subsided with the collapse of energy prices in the mid 1980s. Today, it is largely to reverse alarming environmental trends, particularly the buildup of atmospheric carbon dioxide, rather than to reduce the cost of energy, that renewable energy resources are being pursued.

This discussion focuses on a specific class of renewable energy resources — biomass. Unlike most other classes of renewable energy touted for controlling atmospheric carbon dioxide concentrations , e.g., hydro, direct solar, wind, geothermal, and ocean thermal, which produce usable forms of energy while generating little or no carbon dioxide emissions, bioenergy almost always involves combustion and therefore generates carbon dioxide; however, if used on a sustained basis, bioenergy would not contribute to the build-up of atmospheric carbon dioxide because the amount released in combustion would be balanced by that taken up via photosynthesis. It is in that context, i.e., sustained production of biomass as a modern energy carrier, rather than reforestation for carbon sequestration, that biomass is being discussed here, since biomass can play a much greater role in controlling global warming by displacing fossil fuels than by being used strictly for carbon sequestration (partly because energy crop production can reduce fossil carbon dioxide emissions indefinitely, whereas under the reforestation strategy, carbon dioxide abatement ceases at forest maturity).

Present and Potential Use of Biomass for Energy

In terms of energy resources, biomass ranks fourth in the world, providing up to 14% of the world's energy needs, and is the most important source of energy in developing nations (providing ~35% of their energy), mostly in rural areas where biomass is often the only accessible and affordable source of energy, and where three-quarters of the world's population now lives and 90% of the world will reside by the middle of the twenty first century (McGowan, 1991; Hall, et al., 1992). Bioenergy plays a smaller, but significant, role in developed nations; e.g., in the U.S. and Sweden, about 4% and 13%, respectively, of the energy requirements are met with biomass (Hall, et al., 1992). In these more developed countries, bioenergy, usually in the form of agricultural residues, targets mainly low-grade heating applications in agricultural processing; yet, even in this often lucrative application, the use of biomass-for-energy in developed nations is low in comparison to its potential.

Considering that the annual photosynthetic productivity of biomass is an order of magnitude greater than the world's total energy consumption, that bioenergy can be produced and used in an environmentally sustainable manner, and that promising technological improvements in biomass production and conversion loom ahead, there is little doubt that biomass will have a continuing, and probably increasing, role in the world's future energy mix. However, the extent and rate of increase of its use within the developed world will depend on the perception of biomass as a legitimate energy resource. Presently, biomass is often perceived as a low-quality source of energy that has little place in modern society. Instead, biomass should be viewed as a superior, versatile, renewable replacement for fossil fuels. Indeed, aided by technological advances that are now emerging, biomass can be converted in an environmentally sound manner into alternative transportation fuels such as methanol or ethanol, or into electricity via advanced gas turbines or fuel cells, while producing numerous valuable co-products.

There is a wide array of potential sources for bioenergy: municipal and industrial wastes, forest and crop residues, animal wastes, and energy crops. In the near term, wastes and residues, especially those with tipping fees that often exceed their market value as energy, have the greatest potential for supplying biomass energy. Utilization of such wastes provides the added benefit of eliminating materials that might otherwise generate methane, a potent greenhouse gas, through decay. In the longer term, crops grown specifically for energy will have to be introduced if biomass is to play a more significant role in the world's future energy mix.

Estimates of the extent to which biomass can be tapped to supply useful energy and, in turn, help to stabilize atmospheric carbon dioxide vary, depending on the assumed acreage that can be dedicated to energy crop production, crop yield, conversion efficiency, and the form of energy displaced; however, most investigators agree that biomass could play very significant roles in energy security and environmental protection. Most studies suggest that renewable biomass can sequester as much atmospheric carbon dioxide as deep-ocean containment strategies, and at a cost that is competitive with those projected for deep-ocean containment (Golomb, et al., 1989; Mori, et al., 1992). Under one scenario, Hall, et al. (1991) have projected that by the middle of the next century, carbon dioxide emissions could be reduced to one-half of their current levels by utilizing bioenergy to displace a large portion of the fossil fuels burned, practicing energy efficiency, and reversing deforestation. The bioenergy component could be produced on 600 million hectares (15-40% of the amount of land presently in forests and croplands, respectively), having an average productivity of 12 tonnes (dry-basis) per hectare per year. While such massive conversions of forests and/or croplands into biomass-for-energy production would require major redirections of land and other resources, yield increases comparable to those experienced over the last 50 years in sugarcane and other crops (Kinoshita, 1991) should permit gradual conversions of such magnitudes to occur without causing undue conflict over food versus fuel.

The Path to Greater Bioenergy Utilization

Biomass-for-energy is often considered problematic because it involves so many different issues, such as land use and zoning; forestry and agriculture; animal production and management; energy, environmental, economic, and social issues; as well as competition for resources within many of those areas. There is little question that, managed properly, biomass would have significant positive impacts on the environment, especially in controlling atmospheric carbon dioxide and other more directly harmful fossil fuel emissions while producing less troublesome effluents during feedstock production and conversion than other feedstocks such as coal. However, biomass production and conversion can yield negative impacts as well. Perceived environmental problems associated with large-scale biomass-for-energy production include the use of greater amounts of fertilizers and crop-control chemicals; soil erosion; shift from biodiversification to monocultural cropping; and visual impact. However, most of these problems already are routinely encountered in agribusiness. Through careful planning and sound management, such environmental problems can be addressed satisfactorily and, ultimately, various benefits can accrue to the environment, including the recovery of declining or abandoned agricultural lands, better soil maintenance, water-shed protection, nutrient cycling, and improved hydrological cycling (Rosillo-Calle, et al., 1992).

The future productivity and efficiency of bioenergy will depend on the extent and rate of technological advancements in feedstock productivity and in bioenergy conversion. The systems employed to produce and convert biomass must not be viewed as stagnant with low productivities and efficiencies. There are many opportunities for developing more efficient and sustainable bioenergy systems. Unfortunately, much less public sector funding for energy research and development, critical for achieving key technological advancements, is appropriated for renewable energy than for nuclear energy or fossil fuels. Presently, renewables receive less than 10% of the total R&D budget for energy worldwide (McGowan, 1991); this reflects an overwhelming bias by governments and industry in favor of non-renewable energy resources.

One key area requiring technological improvement to permit biomass to become cost effective as an energy source is the development of more efficient biomass production, harvesting, and feedstock transporting systems. The biomass production and supply system must be environmentally benign and sustainable with respect to the input of resources and the repeated use of the same land or sea area. A sustainable biomass system should include provisions for recycling of nutrients and waste products generated by the biomass conversion facility to enhance biomass production. The economics of dedicated biomass-for-energy production are beginning to look more encouraging; e.g., cost estimates for short-rotation intensive culture energy crops produced in the U.S. are projected to become as low as $2.00 per gigajoule (Bull, 1991), which compares favorably with coal prices projected for the next decade.

The other area that needs considerable research and development, and scale-up, is biomass conversion. The most promising near-term option for increasing the penetration of biomass into the energy mix involves the use of advanced power generation systems (e.g., combined-cycle gas turbines, steam-injected gas turbines, or fuel cells) for generating electricity. Considerable effort is being directed at biomass gasification and pyrolysis for the production of electricity or fuels. Additional research on gas cleanup processes and improved system optimization are needed, particularly on handling feedstocks and wastestreams from such thermochemical conversion processes. Biological conversion processes, e.g., high- and low-solids anaerobic digestion for supplying electricity or fuels, and acid or enzymatic hydrolysis of lignocellulosic materials to produce ethanol for transportation fuels, show much promise. Some investigators have projected that biomass could be converted into methanol thermochemically or ethanol biochemically at costs competitive with gasoline prior to the year 2000 (Bull, 1991).

The strongest argument leveled against bioenergy and most other renewable energy resources is that they are too costly to compete with fossil energy, and therefore would have to be subsidized to survive. Unfortunately, as long as renewables are perceived to be too costly to compete with fossil energy, there will be little incentive to direct funding toward their development. Lack of sufficient R&D funding, in turn, will stall those technological advancements needed for renewables to compete with fossil energy, thus creating a familiar cycle that almost always favors the status quo. Advantages inherent to conventional energy sources in the form of hidden subsidies, coupled with energy pricing policies that often artificially depress the price of electricity and transportation fuels, serve to discourage investment in clean renewables in favor of more environmentally harmful conventional energy sources such as high-sulfur fuel oil and coal.

Externalities must be internalized to more accurately reflect the true economics of energy production and utilization for bioenergy to be able to complete with fossil energy in the foreseeable future. For example, more than 50% of the fossil-based carbon dioxide generated in the U.S. can be sequestered by growing trees at an estimated cost of $27–$48 per tonne carbon, or about $20 billion annually (Rosillo-Calle, et al., 1992). This cost could be internalized by imposing a carbon tax on fossil fuels of $15 per tonne carbon. Considering that the U.S. alone provides subsidies on the order of $100-300 billion annually for energy, mostly from conventional sources (Hubbard, 1991), there clearly is substantial opportunity for bioenergy to become competitive with fossil energy under a more level economic field.

Conclusions

Growing biomass in a sustainable manner to replace fossil fuels can play a much greater role in addressing global warming than growing trees solely for carbon sequestration — under the sustained production/utilization strategy, the contribution of biomass would not be limited to the time scale for forest maturity, and the potential for using biomass as a clean substitute for fossil fuel appears to be much greater, economically, than reforestation just to capture carbon. With an increasing proportion of the world's population residing in developing countries that are striving to improve their living standards, but which usually lack fossil fuels and the means to import such fuels, it is essential that greater effort be placed on producing and converting biomass-for-energy efficiently since biomass represents an indigenous, flexible, and clean substitute for fossil fuels. If biomass resources and conversion processes are managed properly, they could represent an energy strategy that is much more sustainable and environmentally sound than the fossil fuels they replace. However, the advancement, acceptance, and growth of bioenergy faces many barriers — social, economic, and technical. While the future productivity and efficiency of bioenergy clearly will depend on technological improvements in biomass production and conversion, the growth and survival of biomass-for-energy probably will depend more on socioeconomic than on technical factors. The degree to which externalities can be internalized to reflect the true costs of biomass- versus fossil-energy production and utilization will significantly impact the future role of biomass in the world's energy mix.

References

Bull, S.R. 1991. The U.S. Department of Energy biofuels research program. *Energy Sources*. Vol. 13. pp. 433-422.

Golomb, D., H. Herzog, J. Tester, D. White, and S. Zemba. 1989. Feasibility , modeling and economics of sequestering power plant carbon dioxide emissions in the deep ocean. *Massachusetts Institute of Technology Energy Laboratory Report MIT-EL-89-003.*

Hall, D.O., H.E. Mynick, and R.H. Williams. 1991. Cooling the greenhouse with bioenergy. *Nature*. September. Vol. 353. pp. 11-12.

Hall, D.O., F. Rosillo-Calle, and P. de Groot. 1992. Biomass energy — lessons from case studies in developing countries. *Energy Policy*. January. pp. 62-73.

Hubbard, H.M. 1991. The real cost of energy. *Scientific American*. April. Vol. 264, No. 4. pp. 36-42.

Kinoshita, C.M. 1991. Potential for cane energy. *International Conference on Energy from Sugarcane.*

McGowan, F. 1991. Controlling the greenhouse effect — the role of renewables. *Energy Policy*. March. pp. 111-118.

Mori, Y., S.M. Masutani, G.C. Nihous, L.A. Vega, and C.M. Kinoshita. 1992. Pre-combustion removal of carbon dioxide from natural gas power plants and the transition to hydrogen energy systems. *Journal of Energy Resources Technology*. September. Vol. 114. pp. 221-226.

Rosillo-Calle, F., and D.O. Hall. 1992. Biomass energy, forests and global warming. *Energy Policy*. February. pp. 124-136.

RENEWABLE ENERGY, TODAY AND TOMORROW--AN OVERVIEW

Thomas D. Bath

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, CO 80401

The contribution of renewable energy to U.S. energy needs over the next four decades will be driven by the economic and societal attractiveness of technologies to convert renewable resources to useful energy forms and by our success in reducing institutional barriers to the adoption of attractive but novel technology systems. This paper addresses the key factors appropriate to determining the relative attractiveness of these systems--resource characteristics and intensity, conversion-technology performance and reliability, environmental/societal values, and compatibility with demand--and their significance regarding future energy contributions from renewable resources. The institutional factors that bear on broad acceptance of these systems are reviewed and incorporated with system and market factors to provide a basis for assessing future contributions by these technologies to U.S. energy needs. The results of this assessment suggest that as much as 40% of U.S. energy needs can be provided by these resources in 2030. A key factor in attaining this result is progress in technology performance that is expected to occur in the coming decade.

Renewable energy will make increasing contributions to U.S. energy supply over the coming decades. However, it will be necessary to continue progress on the research, development, and deployment (R,D&D) front to assure that these technologies achieve their potential as soon as possible. Greater reliance on RETs can provide a secure domestic supply of energy that can be used with minimal environmental impact. Continued reductions in cost can ensure that the rapid introduction of RETs is accomplished without economic penalty.

The contribution of renewable energy to U.S. energy supply has been growing since 1970 and will continue to grow. In 1970, essentially all renewable energy came from hydroelectric power, used to generate electricity, and wood, used for space heating, industrial processes, and power generation, and represented approximately 6% of the energy supply. In 1990, renewable energy supplied 6.8 quadrillion (10^{15}) Btus (quads) or approximately 8% of the nation's energy needs (see Fig. 1). In contrast to the situation in 1970, in 1990 there were substantial contributions from geothermal power plants, municipal-waste energy plants, wind plants, PV systems, solar thermal devices, and alcohol fuels.

Part of the move to use renewable energy is due to the fact that these technologies are generally considered environmentally benign. Most of the technologies use sunlight, rainwater, or wind as the energy resources and, therefore, do not produce emissions or waste materials (including CO_2 or greenhouse gases) that would have a negative impact on the environment.

For each demand sector--electric power, process and building energy, and transportation fuels--there are several RETs being developed. Thus, if any one RET fails to met the technological and economic goals needed for its demand sector, at least one other RET will be available for that sector. Some of the technologies are already well-established--others require more R,D&D effort before they will become proven commercial commodities.

Wind energy has expanded its role in electricity generation in the past two decades, particularly in California. In the early 1980s, wind equipment capital costs were $2,200/kW, compared to less than $1,000/kW today. O&M costs have dropped from $0.04/kWh to $0.01/kWh over the same period. Wind-turbine availability is now greater than 95% for the roughly 1500 MW installed in the U.S. vs. 50%-60% availability factors in 1980. The cost of wind-generated electricity is $0.07-$0.09 today compared with $0.30/kWh in 1980. The federal government investment of more than $240 million has been matched with more than a $3 billion investment by private industry. Researchers have identified improvements in blade airfoil design which will improve efficiency, allowing greater output of power from better wind sites and also making lower-intensity wind resources economical to develop. In addition, improvements in gear and bearing mechanisms, blade materials, and support structures are expected to reduce costs and increase reliability. As a consequence, the cost of wind-generated electricity is expected to drop from today's level to about $0.03/kWh in 2030, assuming an acceleration of R,D&D efforts.

PV systems are becoming a more significant source of power. Smaller-scale systems are being widely used for powering remote facilities, such as communications and lighting, and for providing power in developing countries. The costs have dropped to the point that utilities (or their customers) can better afford to install PV systems with battery back-up where the alternative would be a long extension (one mile or more) from an existing distribution line. Meanwhile, costs of utility-scale systems have also dropped from $1/kWh in 1980 to $0.25-$0.30/kWh today and are expected to reach the $0.04-$0.05 kWh range by 2030.

Biomass and Biofuels represent perhaps the largest potential commercial energy source among the RETs. Biomass is used in four major ways--direct combustion, electric power generation, conversion to gas for use as a fuel or chemical feedstock, and conversion to liquid fuels. Biomass resources include waste and by-product materials, such as municipal solid waste (MSW) and forest product industry wastes, and materials produced purposely for energy use, such as trees. If costs of producing biomass dedicated to energy use can be reduced to $2/million Btu by 2010 as targeted, dedicated power plants using wood are expected to become more commonplace. Although coal-fired power plants may be more economic in most circumstances (absent major constraints on use of fossil fuels) in the case of smaller, easier to site plants, wood could become an attractive choice.

Liquefaction of biomass for use as transportation fuels is expected to be the largest single potential use of renewable energy. Significant progress is being realized in research in several areas. Today the production of liquid fuels from biomass is primarily via fermentation of corn constituents to produce ethanol, entailing the use of high cost raw materials. The advanced technologies will utilize lower-cost materials--wood or other cellulosic materials--as feedstocks. Ethanol is projected to be available at a cost of $0.60/gal (or $7/million Btu) shortly after 2000 (the timing largely dependent on whether R,D&D is accelerated), using an enzymatic hydrolysis process and an improved fermentation system. Increased yields, reduced residence times, and higher viable concentrations of ethanol in the fermentation reactors are among the key R,D&D targets.

The potential contribution of renewable energy systems is very large, as noted earlier. However, the dispersed nature of the basic solar resources results in competition with other activities for the use of land where the resource is available. Hence the pressures for efficient conversion of solar energy into a usable form are intensified. Land suitable for growing biofuels crops is usually also valuable for food or forest-product production. The scenic areas where wind, hydroelectric, and geothermal resources are abundant calls for difficult choices. The capture of sunlight for power or heat production takes space; many such installations have been mounted on rooftops, allowing multiple use of land. Integrated roofing and power recovery systems are likely to be developed. Efficiency of conversion is therefore an environmental issue as well an economic one.

A recent study, *The Potential of Renewable Energy--An Interlaboratory White Paper* (SERI, 1990), provides an evaluation of the present and projected performance status of RETs and their potential contributions to the nation's energy requirements over the next four decades.

In collaborating to produce the study, the participants saw themselves as representatives of a larger community of scientists and engineers who have worked to improve RETs for more than a decade. Thus, although the study focused on the impacts of federal policy, it did so in the context of a sustained federal/industry partnership. Ultimate success in this area depends on use of RETs in the private sector. The best way to ensure that the developed technology is used is to involve users in its development.

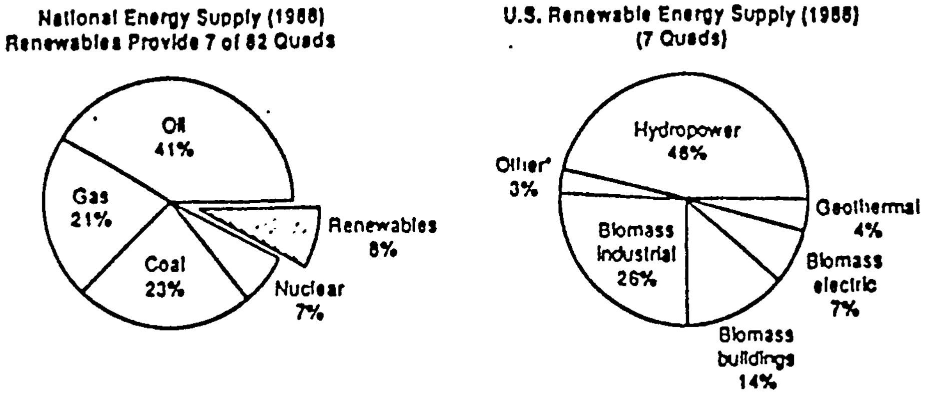
The market penetration potential of RETs was assessed by reviewing expected system performance against demand and market-competition scenarios, which are described in the study. This effort, which considered regionalized energy demand and price projections and took into account competition among the renewable options, was designed to produce mid-range penetration estimates. For simplicity, RET performance and penetration projections were approached from a mid-range point of view over three scenarios of RET deployment. The projections based on those three scenarios are presented in Fig. 2.

The study projects that the contribution of renewable energy to total energy requirements in competition with other energy supply systems should grow over the next four decades, assuming that research and development expenditures continue at present levels, which reflect major reductions from those at the peak of the "oil crisis." In the Business-as Usual (BAU) Scenario, it is projected that by 2030, renewable energy will provide a U.S. domestic contribution of 22.3 quads, or 15% of projected total energy needs. If federal R,D&D expenditures are expanded by a factor of 2 to 3, or to some $3 billion over the next two decades, the projected contribution of renewable energy is nearly double that in the BAU Scenario: 41.1 quads by 2030.

For purposes of comparison, the results of the study under discussion (the *White Paper*) can be contrasted with the results of two recent reports--*The National Energy Strategy, Powerful Ideas for America* (DOE, 1991), and *America's Energy Choices, Investing in a Strong Economy and a Clean Environment* (Union of Concerned Scientists, 1991)--henceforward identified as *NES* and *Choices*, respectively. Because of different assumptions about energy demand and economic growth, this comparison is best drawn by plotting the U.S. renewable contribution (in percent) over the 40-year planning horizon common to all three studies. The results of this comparison are shown in Fig. 3. Estimates from the two *White Paper* policy scenarios are banded by those of the *NES* and *Choices* studies. The estimates of renewables in the reference cases from all three studies are in agreement within the limits of uncertainty for such estimates.

The key to realizing the potential contributions of renewable energy in the near term is to intensify R,D&D activities. If market factors--higher prices or special markets--appear earlier than projected, the industry will respond in force only after the prerequisite R,D&D has been carried out.

Could deployment of these technologies play a significant role in the reduction of greenhouse gases? The answer is clearly yes. According to OTA (199), aggressive CO_2 reduction policies could reduce projected emissions by 50%, only 10% of which would be due to increased renewables. NREL studies (1992) suggest that by 2030 similar reduction could be maintained with a smaller fraction due to demand reduction efforts by employing more aggressive supply-side measures. The key to renewable energy contribution is accelerated technology development followed by policies to remove market barriers.



*Other: wind, alcohol fuels, solar thermal, and PV.

Figure 1: National energy supplies and the renewable contribution.

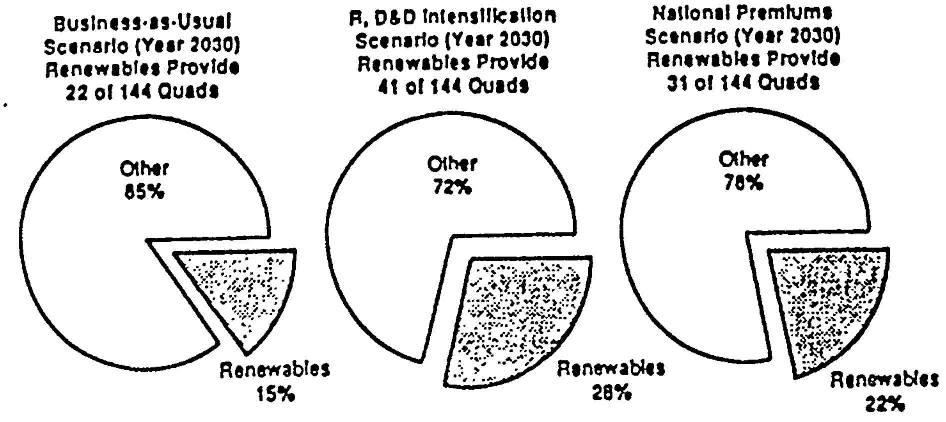


Figure 2: The contribution of renewable energy in 2030, based on the Business-as-Usual Scenario, the R,D&D Intensification Scenario, and the National Premiums Scenario.

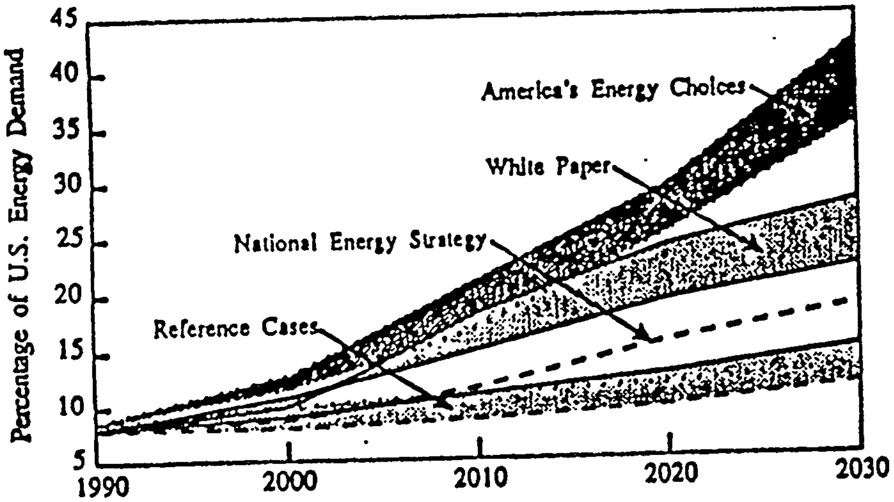


Figure 3: A comparison of projections of the future U.S. renewable energy contribution.

HYDROGEN BASED GLOBAL RENEWABLE ENERGY NETWORK

Makoto AKAI

Energy Engineering Department, Mechanical Engineering Laboratory, AIST, MITI
1-2, Namiki, Tsukuba 305 Japan

1. INTRODUCTION

In the last quarter of this century, global environmental problem has emerged as a major scientific, political and social issue. Specific problems include: depletion of ozone layer by chlorofluorocarbons(CFCs), acid rain, destruction of tropical forests and desertification, pollution of the sea and global warming due to the greenhouse effect by carbon dioxide and others. Among these problems, particular attention of the world has been focused on the global warming because it has direct linkage to energy consumption which our economic development depends on so far.

On the other hand, the future program of *The Sunshine Project* for alternative energy technology R&D, *The Moonlight Project* for energy conservation technology R&D, and *The Global Environmental Technology Program* for environmental problem mitigating technology R&D which are Japan's national projects being promoted by the Agency of Industrial Science and Technology (AIST) in the Ministry of International Trade and Industry (MITI) have been reexamined in view of recent changes in the situations surrounding new energy technology. In this regard, *The New Sunshine Program* will be established by integrating these three activities to accelerate R&D in the field of energy and environmental technologies.

In the reexamination, additional stress has been laid on the contribution to solving global environmental problem through development of clean renewable energies which constitute a major part of the "New Earth 21", a comprehensive, long-term and international cooperative program proposed by MITI. Furthermore, the need for systematic approach for the effective utilization of renewable energies has been also emphasized and a new project named as "International Clean Energy Network Using Hydrogen Conversion(WE-NET)." has been proposed as a core project of The New Sunshine Program.

The present paper discusses the results of feasibility study on hydrogen energy system leading to the concept of WE-NET following a brief summary on R&D status on solar and wind energy in Japan

2. BACKGROUND

Most of renewable energies have its origin in solar radiation onto the earth. This solar radiation can be utilized directly with solar-energy technologies such as photovoltaic or solar-thermal power plant, active solar equipment for water heating and passive solar devices, and indirectly through energy conversion technologies for biomass, wind, hydro and ocean enthalpy difference, and so on. Solar-origin renewable energies have inherent advantages such that resources are supplied form the sun and can be considered as virtually inexhaustible as well as that no carbon dioxide release will occur through energy conversion process, and therefore are expected to be capable of contributing significantly to global warming problem. Moreover there are no Middle East countries for renewable energies and almost every area on the earth enjoy the benefits of either intense sunlight, strong wind, rapid growth of plant, heavy rainfall, geothermal heat and oceanic energies.

Under The Sunshine Project whose primary objective has been to establish an energy supply structure with diversified and stable energy sources, research programs on solar energy technologies have been given higher budgetary priorities over wind, ocean, or biomass energy technology, mainly because of consideration on available amount of domestic resources. Brief summary of R&D activities on solar and wind energy is described below:

Research and development of solar cells have aimed at the manufacturing of highly effective solar cells at a low cost, which produces a large amount of electricity with a high conversion efficiency. The program has the objective of reducing the cost of solar cells to ¥230-390/Wp around 1995 and to ¥100-200/Wp at the beginning of the 2000s. According to these concrete targets, the manufacturing technologies for crystalline and amorphous solar cells have been developed to achieve the results shown in Fig.1. Additionally, a mid-to-long term R&D program to develop ultra-high efficiency solar cells has been initiated to achieve further improvement of the energy supply capacity of solar photovoltaic power generation. For the wide spread of photovoltaic generation system, utilization technologies related to cost reduction of peripheral devices, system technologies including solar-wind hybrid system or water desalination system, etc., and evaluation of grid connection system have been developed.

Solar thermal systems applicable to industrial processes involving a large amount of heat consumption, sophisticated heat management, and various kinds of heat process ranging from low to high temperature, have been developed based on component technologies R&D related to heat collector, heat storage device, heat transfer device, thermal insulation, etc. An example of the solar thermal systems currently under development is a refrigerating system to obtain temperature level less than -20°C using chemical reaction of metal hydride with hydrogen gas. In addition, basic research on passive solar system using innovative passive devices such as transparent thermal insulating material, electrochromic or thermochromic window and so on has started.

Another typical technology using solar energy is wind energy conversion system. In The Sunshine Project, the development of 500 kW class wind turbine has been launched aiming at economic improvement and effective land use. In addition, a comprehensive and systematic measurement of wind characteristics all over Japan has been performed in order to evaluating the potential amount of wind energy in detail as well as to provide information on sites suitable for wind turbine installation.

As mentioned above, renewable energy technologies are expected to be capable of contributing to global warming problem. In general, however, renewable energy sources for electricity generation have major deficiencies such as power interruptions caused by hourly, daily, or seasonal weather changes as well as low energy density for a country with large energy demand. These deficiencies inevitably raise the energy cost as well as make it difficult, under prevailing decision making process based on conventional performance indices, to exploit as a large scale capable of substituting for conventional energy technologies such as fossil or nuclear power.

These problems can be partly resolved by R&D to augment efficiencies of devices and component involved in renewable energy technologies which increase the quantities of available energy per area per hour, and by advanced mass production technologies which lowers the cost of photovoltaic cells, windmills, inverters, batteries, etc., bringing the technologies within a reach of commercial exploitation as well as in a position of actual contributor to solve global warming problem.

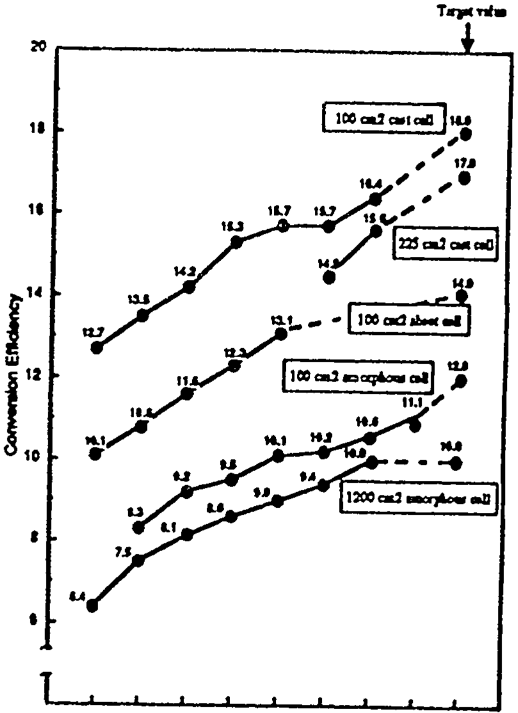


Figure 1. Improvement of solar cell conversion efficiencies

Nevertheless, the intermittent nature of the renewable energy systems might deteriorate quality of electricity when connected to a grid. This problem does not matter while renewable energies contribute only a small proportion of the overall generating capacity on the grid. There is an opinion that when renewable energy becomes a major power source, the various sources can be balanced to supply stable power. Certainly, wind is generally available in night or in rough weather without sunlight, and solar-wind hybrid systems have been constructed and operated. But, how can we realize the balance of two or more renewable energy sources? Are there enough capacity for individual renewables to compensate each other? Can we really manage and rely upon such kind of energy supply system? If possible, this energy supply system apparently requires generating capacity more than twice as large as average capacity we need.

Even more sound way to extract maximum benefit from renewable energy sources is to establish well-organized network throughout the world. One can imagine a worldwide computer network already in function. The network consists of numerous wide and local area networks. Each of the local area networks has a number of nodes, i.e., computers and alike. Wide variety of computers – from PC's to workstations, and further supercomputers – are connected to the network as a server or a client, the role being changed depends on circumstances. These nodes of the network should have functions such as conversion (computing) and storage of information and also perform as a transmitter and receiver of the information. The unit of the information is, actually, a binary number or code which is common in the world.

There is an apparent analogy between the information network and the energy network system – one can substitute energy conversion or storage systems to computers, transport ships to network cable, and energy to information. The similar network has already been established in energy area, that is petroleum network. The present proposal aimed at constructing more integrated and organized network which incorporates not only conventional fossil or nuclear energy sources but also new and clean renewable energy sources. The technological progress and cost reduction due to mass production should follow while renewable energies serve as growing constituents of this network. Meanwhile, the time might come when renewable energies dominate the functioning of the network.

The nodes of the global renewable energy network should have functions such as energy extraction, storage, enrichment or refinement, conversion and end use. Among these functions, the key function should be the energy storage. The establishment of the effective energy storage technology could mitigate major deficiencies of renewable energies, i.e., intermittent character. In this regard, because of its inherent energy storage characteristic, hydropower will be the most promising near term renewable energy source. For this reason, there are some studies to evaluate technical and economical feasibility of long distance transportation of hydropower using hydrogen as an energy medium.

3. GLOBAL RENEWABLE ENERGY NETWORK
– Ongoing Research –

The following discussion on hydrogen based energy transportation system is based on feasibility study conducted under The Sunshine Project Promotion Headquarters and the most of the contents of 3.1 and 3.2 quote Ogimoto1).

3.1 Transportation of Hydroelectric Power

Major undeveloped hydro potentials are located in low and high latitude areas in Asia, Africa, North and South America, and Siberia. On the contrary, most of the bulk energy consuming countries are located far from these energy sources, in middle latitude areas. The situation is applicable to other renewable sources such as solar energy or ocean thermal energy. Accordingly, the electric power from the hydro resources is required to be transported over long distance, sometimes over the sea.

In order to transport electric energy, it is quite usual to utilize a transmission line. As an economy of a country grows, a power transmission network is being established. Moreover, there are some trans-country transmission networks which include many international interconnections as seen in Europe and North America. Some trans-country transmission networks are also growing in developing countries' areas. However, a transmission system has limitations, i.e., when transmission distance increases, its economy and reliability are degraded because of increased construction cost, transmission loss and route trouble such as natural disasters and terrorism. Accordingly, a transmission system is hard to be applied to the transmission by an overhead line, for example, over 1000 km or a submarine cable over several hundred kilometers.

When wired transmission system is not applicable, the electric power generated by hydropower is expected to be transported to bulk energy consuming areas by vessels as in the cases of petroleum or liquefied natural gas. In order to realize such a system, it is necessary to establish the following technologies and processes:

- Conversion of electric power into transportable medium
- Handling (transportation, storage, etc.) of the medium
- Utilization of energy from the media

3.2 Economic Analysis

One of the most efficient conversion process from electric energy to chemical energy is to produce hydrogen through water electrolysis process. Hydrogen is applicable to various kinds of chemical reactions and is capable of producing many derivatives applicable as an energy carrier. Therefore, we decided to search for a renewable energy transportation technology or "clean energy transportation" which begins with water electrolysis. Candidate energy transportation system selected for economic analysis are shown in Table 1.

Table 1. Candidate Energy Transportation Cycle

1. LH_2	a.	H_2			⇒	LH_2 (Liquefaction)		
	b.	LH_2			⇒	H_2 (Evaporation)		
2. CH_3OH/CO_2	a.	$3H_2$	+	CO_2	⇒	CH_3OH	+	H_2O
	b.	CH_3OH	+	H_2O	⇒	$3H_2$	+	CO_2
						CO2 recovery and liquefaction		
3. CH_3OH/CO	a.	$2C$	+	O_2	⇒	$2CO$ (Coal Gasification)		
		$2CO$	+	$4H_2$	⇒	$2CH_3OH$		
	b.	CH_3OH	+	H_2O	⇒	$3H_2$	+	CO_2
4. $CH_3OH/HCOOCH_3$	a.	$2H_2$	+	$HCOOCH_3$	⇒	$2CH_2OH$		
	b.	$2CH_2OH$			⇒	$2H_2$	+	$HCOOCH_3$
5. Ammonia	a.	$3H_2$	+	N_2	⇒	$2NH_3$		
	b.	$2NH_3$			⇒	N_2	+	$3H_2$
6. Cyclohexane	a.	$3H_2$	+	C_6H_6	⇒	C_6H_{12}		
	b.	C_6H_{12}			⇒	$3H_2$	+	C_6H_6

a: Process at supply side
b: Process at demand side

These media and cycle have been selected based on the following criteria:

- to be liquid under the temperature and pressure conditions of transportation and storage
- to have high hydrogen content ratio (for example, more than 5 weight-%)
- if organic, to achieve chemical equilibrium with a low reaction heat and high conversion rate under practical temperature and pressure conditions
- CO_2 generation throughout the whole cycle should be minimum, or less than the existing energy system
- to have high adaptability to the existing energy system.

In the economic analysis, the six candidates shown in Table 1 were compared based on the assumptions presented in Table 2.

Table 2. Assumptions for Economic Analysis

1.	Plant capacity	Supply side electric power input: 1000 and 4000 MWe
2.	Supply side power rate	2 - 5 Yen/kWh (Approx. 15 - 35 mil/kWh)
3.	Transportation mileage	5000 km and 10000 km
4.	Electrolysis efficiency	90 %
5.	Fixed charge rate	25 % for plant facilities 21 % for a vessel

Table 6 compares the technical and cost features of the clean energy transportation cycles for the cases of the power generation of 4000 MW at supply side and the distance of 5000 km.

Table 3. Technical features of energy transportation cycles

S.S.⇒D.S.	LH_2	CH_3OH	CH_3OH	CH_3OH	NH_3	C_6H_{12}
D.S.⇒S.S.		CO_2		$HCOOCH_3$		C_6H_6
H_2 production (1000 Nm^3/h)	800	913	885	932	856	984
Medium production(t/day)	1,714	10,438	15,178	31,945	10,540	29,534
Transported Energy(Gcal/h)	2,370	2,350	3,990	2,380	2,360	2,270
Efficiency	0.70	0.68	0.66	0.69	0.68	0.60
Energy cost(¢/Mcal)						
E=1.5:	9.1	9.8	4.9	8.2	5.4	7.1
E=3.8:	12.8	13.0	7.2	12.0	9.4	11.2

Note Supply side electric power input: 4,000MWe; Transport milage: 5,000km
E: Power rate from renewable energy source at supply side (¢/kWh)
Transported energy: Energy of H_2 or CH_3OH at demand side
Efficiency: Onput energy / Iutput energy; MeOH reformation energy of CH_3OH/CO_2 and CH_3OH/CO cycles, dehydrogenation energy of NH_3, C_6H_{12} and $CH_3OH/HCOOCH_3$ cycles are subtracted from output energy.

The results shown in Table 3 are based on relatively rough assumptions and should b considered as preliminary evaluation. This is because that some of the technologies involved in th system, especially the dehydrogenation processes at the demand side in NH_3 and C_6H_{12} cycle and the hydrogenation process at the supply side in CH_3OH/CO_2 and $CH_3OH/HCOOCH_3$ cycles are not established industrially and the efficiencies for those chemical processes could not b estimated correctly.

3.3 Net Energy Analysis

Net energy analysis is one of the methodologies to evaluate the effectiveness of an energ system in which the values of all commodities are expressed in terms of their energy content. In order to analyze the energy content of a system, energy required for processing raw materials, equipment manufacture, transportation, on site construction, operation and maintenance, etc., should be analyzed based on some database. Based on this analysis, ***net energy ratio R*** can be calculated as follows:

$$R = \frac{e_{out}}{e_{in}}$$

where e_{out} is total energy produced by the system over its entire life time, e_{in} is total energy required for construction, operation and maintenance of the system. The net energy approach can be used for assessment of the effectiveness of a technology to reduce CO_2 emissions.

Evaluated net energy ratios and CO_2 emissions for some transportation cycles based on data in Table 3 are shown in Figures 2 and 3. The calculated values are compared to the estimation for conventional fossil fuel system by Uchiyama & Yamamoto[2)]. In general, the initial energy input which is used for system construction have relatively small portion of the total energy input in these transportation cycles. Therefore the operational energy input such as transportation fuel or energy losses during media conversion process dominate the efficiency of the total system.

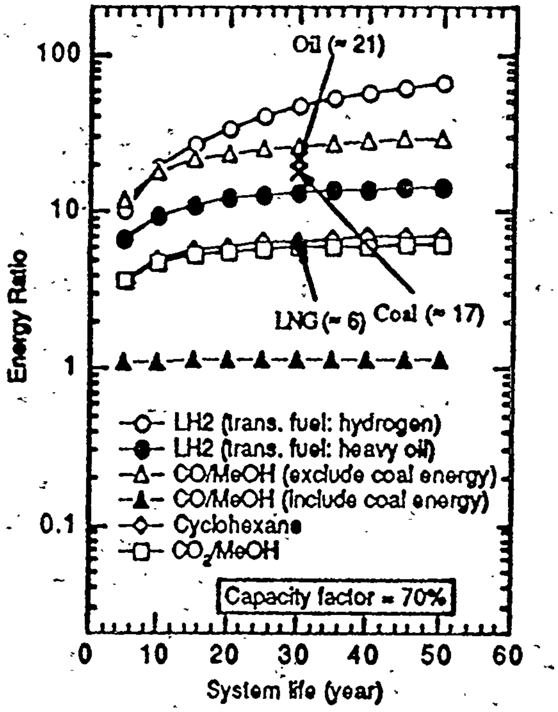


Fig. 2. Energy ratio for candidate cycles

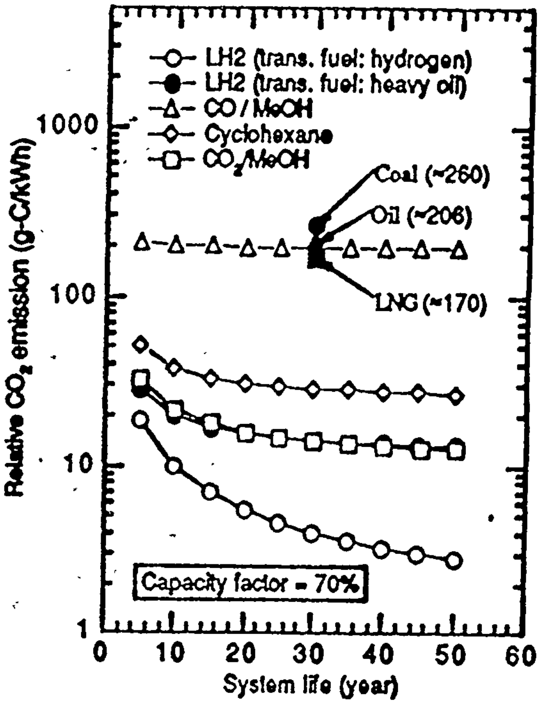


Fig. 3. CO_2 emission for candidate cycles

Although these hydrogen based energy systems are considerably complex one compared to the existing fossil fuel systems, the results shown in these figures has revealed the effectiveness of this system as a future technical option to acquire maximum gain from the renewable energy sources as well as to contributing to reduction of carbon dioxide release to the global environment.

4. FUTURE PLAN FOR COLLABORATIVE RESEARCH

The pre-feasibility study has shown that the clean energy transportation cycle is well within the reach in terms of technology. From the viewpoint of economy, the energy cost is expected to fall within an acceptable range in the age when various kinds of values change including the energy and environmental issues.

The significance of the clean energy transportation scheme is, firstly, one of the energy technology responses to global environmental challenges through the redistribution of energy resources, secondly, the diversification of energy sources at the energy demand side, and, thirdly, the redistribution of income and establishment of infrastructure through energy development and transactions. The scheme is considered to be worth being continuously challenged from various view points aiming at its realization. Accordingly, the concept has been putting into shape as one of the core project of AIST's ***The New Sunshine Program***, which is called "International Clean Energy Network Using Hydrogen Conversion(WE-NET)." The carbon dioxide reduction potential of the project is expected to be 10% at 2030 and 20% at 2050.

The long term R&D program for the project is now being elaborated through discussions in technical committee and internationally open forum. The project will consist of three to four phases from basic research to demonstration. The R&D area includes: (1) high efficiency water electrolysis; (2) media conversion technologies such as hydrogen liquefaction or hydrogenation and dehydrogenation of chemicals, metal hydrides, etc., for effective storage and transportation of hydrogen energy; (3) innovative hydrogen utilization technologies such as high temperature turbine generating system, etc.; (4) safe and reliable hydrogen handling technologies; and (5) optimization of global energy network.

From the social viewpoint, the new energy medium such as H_2 or CH_3OH will largely affect the energy demand-supply structure and social system itself. In the selection of the transportation cycle, various kinds of its influences to society and ecosystem should be studied, including transitional stages' energy supply system.

From the viewpoint of international consensus, the policy of redistribution of energy resources should be discussed, assuming the new energy transportation technology. The discussion should also include the demand-supply balances of each country to identify the reasonable energy surplus of each country.

Of course, the concept would never be realized by one country only, and the international cooperation from the detailed feasibility study phase to the pilot or demonstration phase and beyond should be essential.

REFERENCES

1) Ogimoto, K.: Proc. IEA International Conference on TECHNOLOGY RESPONSES TO GLOBAL ENVIRONMENTAL CHALLENGES, 315 (1991)
2) Uchiyama, Y. and Yamamoto, H.: Central Research Institute of Electric Power Industry, Report No. Y90015 (1991) *in Japanese*

ABSTRACT

ENERGY CONSERVATION TECHNOLOGIES

Henry A. Courtright, P. E.
Customer Systems Division
Electric Power Research Institute
Palo Alto, California

The conservation of energy through the efficiency improvement of existing end-uses and the development of new technologies to replace less efficient systems is an important component of the overall effort to reduce greenhouse gases which may contribute to global climate change. Even though uncertainties exist on the degree and causes of global warming, efficiency improvements in end-use applications remain in the best interest of utilities, their customers and society because efficiency improvements not only reduce environmental exposures but also contribute to industrial productivity, business cost reductions and consumer savings in energy costs.

THE ELECTRIC POWER RESEARCH INSTITUTE

The mission of the Electric Power Research Institute (EPRI) is to discover, develop, and deliver advances in science and technology for the benefit of member utilities, their customers, and society. Funded through annual membership dues from some 700 member utilities, EPRI's work covers a wide range of technologies related to the generation, delivery, and use of electricity, with special attention paid to cost-effectiveness and environmental concerns. More than EPRI 350 scientists and engineers manage over 1600 ongoing projects. EPRI's Customer Systems Division (CSD), manages research and development to help utilities address the "wants and needs" of their customers through electric technologies and services.

Research conducted by EPRI on end-use impacts to global warming is focused in three areas:

1) Efficiency improvements to existing electric applications to reduce kilowatt-hour use.

2) New electrotechnologies with high end-use efficiencies to reduce primary energy use compared to existing electric uses and fossil-fuel applications.

3) Alternative technologies to chlorofluorocarbon (CFC) refrigerants.

EQUIPMENT EFFICIENCY IMPROVEMENTS

Air Source Heat Pumps - EPRI's work to significantly improve heat pump efficiencies resulted in the development of the EPRI-Carrier Hydrotech 2000 heat pump which provided the technology platform for the development of advanced heat pumps by Carrier and other companies. The development of electronically commutated permanent magnet compressors and blower drives has resulted in significant improvement of heating season performance factors (HSPF) and seasonal energy efficiency ratios (SEER), with HSPFs exceeding 9 and SEERs of 14. In addition, the integration of water heating into the heat pump design effectively increases HSPF to 11 and SEER to 20, far exceeding government efficiency objectives. EPRI's present work with Nordyne Corporation has produced a product line designed for residential new construction in homes of moderate price ranges.

Ground Source Heat Pumps - utilizing the ground as a natural heat source increases heat pump efficiency in both the meeting and cooling modes. Ground source makes heat pump applications attractive in northern locations, thus providing a highly efficiency heating source which uses considerably less primary energy than the most-efficient gas-fired pulse combustion furnace. Integrated water heating would also significantly increase overall energy efficiencies.

Heat Pump Water Heaters (HPWH) - EPRI's research has developed a HPWH prototype which is 250% more efficient than resistance water heating and also compares favorably to gas water heating in total primary energy use.

Laundry Use - Advanced versions of the two equipment components of laundries, washers and dryers, are being developed with manufacturers. A high efficiency washer project with Maytag is targeted for a 50% reduction in overall energy use, a 60% reduction water use and a 20% reduction in dryer need through better moisture extraction. A microwave dryer prototype has demonstrated efficiencies in the 76 - 80% range vs. 68% for standard electric dryers while reducing fabric drying time up to 20%.

Super Efficient Refrigerator Program (SERP) - As an associate member of this 25 member utility consortium, EPRI is participating in the development of a residential refrigerator which is 25 - 50% more efficient than 1993 models, is non-CFC, and preempts DOE's 1998 standards. EPRI will be participating in prototype evaluation and conducting field performance evaluations.

Commercial Water Loop Heat Pumps (WLHP) - EPRI research has resulted in the recent introduction of advanced water loop heat pumps which have cooling energy efficient rating (EER) levels of greater than 15 under the Air-Conditioning and Refrigeration Institutes' 320 standard and heating coefficient 4.5. This compares to EERs of 11.5 and COPs of 3.7 for standard WLHP designs. The efficiency improvements are achieved by using thermostatic expansion valves for optimum superheat control, micro-electronic controls integrated to a building energy management system, and advanced compressors, fans, motors and evaporators.

Motors - EPRI's research program is focusing on two key approaches to energy savings in motors. First, efficiencies in motor component design is likely to result in efficiency improvements of 8-12% over the next decade. Second, research into effectively matching motors to the load through adjustable speed drive (ASDs). ASD's offer the best technology for reducing electrical use by motors. The potential for reducing the power requirement of constant speed motor-driven systems range from 20% to 50% thus reducing kilowatt-hour use and emissions. The application of ASD-controlled motors to replace non-electric process drives, such as industrial steam turbines and internal combustion engine drive, could reduce primary energy use and CO_2 emissions through more efficient power generation and overall improved process control.

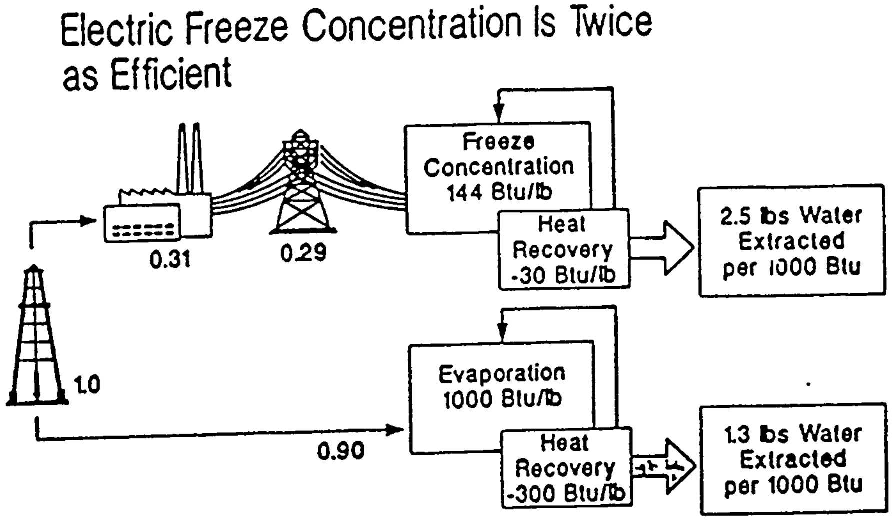
ELECTROTECHNOLOGY DEVELOPMENT

Electricity's efficiency advantage, due to its high controllability and unique abilities at the point of use, has resulted in the development of new technologies which reduce primary energy use compared to existing fossil-fuel applications.

To assure the best use of resources and the most responsible environmental policy, the entire energy-use cycle and its environmental consequences must be considered, from extraction through conversion, delivery, and use. When seen in this comprehensive view, it becomes obvious that many electricity uses are both uniquely valuable to society and the most efficient choices in resource use and environmental protection. The following are examples of primary energy and emission reductions through electrification.

Freeze Concentration - This process is used to separate and remove a liquid -- water, for example -- from a fluid mixture. The technology is already being used worldwide for the concentration of fruit juices and is also being applied in processing beer, wine, vinegar, and coffee. One of the most promising applications for the technology is in the concentration of dairy products. In the process, water is frozen out of milk and the ice crystals are skimmed off, leaving a concentrated milk product that can be packaged directly or used in ice cream production. As shown in Figure 1, freezing requires a total of 144 Btu/lb of water, or 114 Btu/lb with heat recovery, while evaporating or boiling off water requires considerably more energy -- in this case, a net of 700 Btu/lb with heat recovery. As a result, the electric end-use is so energy-efficient that it needs only half as much primary energy, even including the power plant's energy conversion losses. And most important, consumer tests of reconstituted skim milk have indicated consumers prefer the reconstituted product to regular skim milk. This is because the freeze concentration process results in a creamier product, more like whole milk.

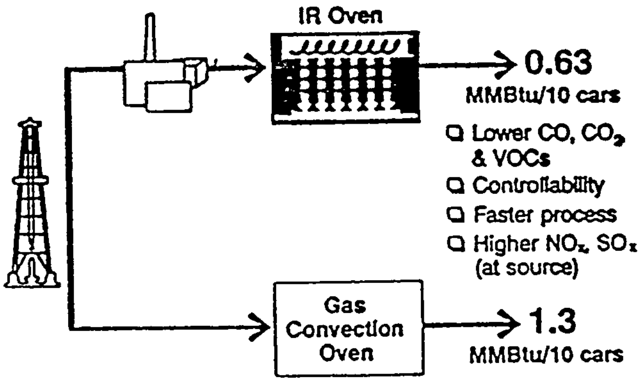
FIGURE 1



Infrared Drying and Curing - This technology is an alternative to conventional gas convection ovens for setting finishes on a wide variety of products such as painted car bodies and home appliances, printed paper, coated steel and aluminum coils, and painted or varnished hardboard, particleboard, and chipboard. IR drying uses only half the total energy resources of the conventional gas-fired convection heating process. IR processing has many other advantages, including faster heating and space savings low maintenance, and adaptability to virtually any heat-treatable coating. IR radiation passes through the coating's surface and dries it from the inside, automatically avoiding the premature surface drying which often can only be eliminated in convection processes by slowing the drying process. IR also lowers CO, CO_2 and VOC's emissions at the factory, although total NO_X and SO_X may be slightly higher at the power plant.

FIGURE 2

INFRARED DRYING & CURING



Transportation - the development of electric vehicles (EV) has been accelerated by the need to reduce tailpipe emissions to solve regional air quality problems, however, EVs can also provide in substantial reductions in primary energy consumption and CO_2 emissions. Present day internal combustion engines vehicles (ICEV) emit 60% to over 100% more CO_2/Km than their EV counterparts. The primary advantage of the EV is gained through drive power systems efficiencies of 90% as compared to ICEV drive train of 13.7% to 15.8%[1]. Figure 3 shows that EVs are more than 60% more energy efficient than an ICEV and the resulting emissions (Table 1) details the emissions reduction from EVs. The benefit of EVs may increase to 2.0 - 2.6 times in favor of EVs as battery capabilities are improved. The development of advanced batteries by the United State Advanced Battery Consortium (USABC), of which EPRI is a member, is a critical component in the success of commercially viable EVs having the performance and range needed by consumers.

FIGURE 3

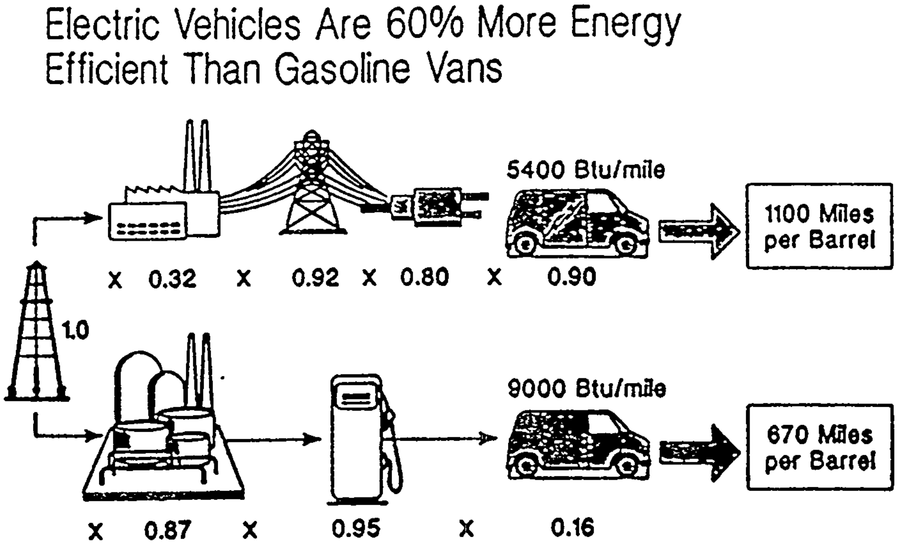

Electric Vehicles Are 60% More Energy Efficient Than Gasoline Vans

Table 1 compares gasoline-powered van emissions based on 1989 U. S. emissions standards with EV emissions under a post 1995 U. S. generation mix scenario. The EV emissions take into account all emissions directly or indirectly associated with electric power production.

TABLE 1
FLEET MINIVAN EMISSIONS
(grams per mile)

	Gasoline Powered Van	Electric Van
VOCs	1.0	0.01
NO_X	1.8	0.3
CO	10.0	0.05
CO_2	690	320

---

[1] The Impact of Electric Vehicles on CO_2 Emissions, Idaho National Engineering Laboratory, Arthur D. Little, May 1992.

CFC REPLACEMENTS

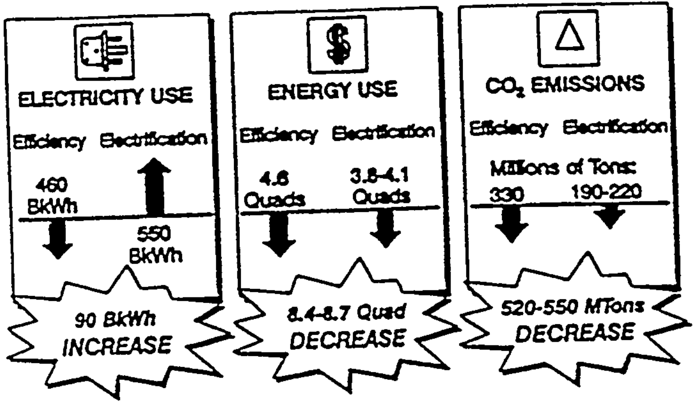
EPRI is conducting research with several organization to identify non-CFC refrigerants with acceptable properties for electric heat pump and chillers. A critical component in the evaluation of CFC phase-out is the trade-off of indirect global warming potential (GWP) from changes in equipment efficiencies compared to direct GWP from CFCs. It is important that efficiency is not significantly reduced in equipment redesign to handle non-CFC refrigerants. Efficiency improvement with new refrigerants is anticipated as well as reduction of refrigerant losses, through improved gaskets and refrigerant recovery techniques. It is expected that electric vapor-compression chillers will continue to provide lower GWP than direct-fired absorption machines when efficiencies are accommodated for impact calculations.

TOTAL BENEFITS

When the estimated benefits of electrification are added to those due to efficiency improvements in existing uses, the results are dramatic. The potential savings in energy and CO_2 emissions are almost as large for new electricity uses as those due to improved existing uses -- so that combining both strategies would almost double the savings.

FIGURE 4

IMPACT OF NEW & EXISTING ELECTROTECHNOLOGIES - 2010.



In addition, development of additional new electrotechnologies during the next twenty years could result in significant reductions in primary energy use as well as enhance the quality of life. Electrification is a crucial part of our nation's energy solutions.

Evaluation of technological measures to cope with climate change

Hiroshi Shimizu and Yuichi Moriguchi

National Institute for Environmental Studies, Environmental Agency
16-2 Onogawa Tsukuba 305 Japan

1. Purpose and background

Because the global warming (climate change) is recognized as a highly probable phenomenon in the next century, the countermeasures to cope with this issue is really important. International discussion is progressing towards the conclusion of the treaty to stabilize global warming.
Therefore, now is the time to take concrete action to reduce the emission to the greenhouse gases (GHG).

To find the way to reduce the emission of the GHG, the procedure as next should be taken.

1) Systematic estimation of GHG emission (GHG analysis),
2) Identification of conventional and innovative technologies,
3) Assessment of individual sectoral technologies,
4) Comprehensive evaluation of countermeasures as a whole.

Both in the U.S.A. and Japan, this kind of research have been made independently.

Among these processes, the standard methodologies should be established on the GHG analysis, the assessment of individual technologies and the comprehensive evaluation.

From such a background, it is important to discuss the way to evaluate technological measures to cope with climate change between the specialist from the U.S.A. and Japan. And still required to search the possibility to establish a joint project between both countries.

2. Ongoing Research and Future Plan

The content of the research process of evaluation is as follows.

1) The methodology of the GHG analysis.
2) Identified conventional and innovative technologies.
   ① Energy conversion technology
   ② Manufacturing technology
   ③ Urban technology
   ④ Transportation technology
   ⑤ Technology applied in Residential and Commercial sectors.
3) The methodology of the assessment of individual technology.
4) The methodology of the assessment on the comprehensive evaluation of countermeasures.

3. Future View for Collaborative Research with U.S.

1) International research activity on the methodology to evaluate the technological measures to cope with climate change.
2) International assembling of the result of the evaluation of the technological measures to cope with climate change.

WORKING GROUP III ABSTRACTS

WORKING GROUP III ABSTRACTS

Takashi Kawanaka	*Research on Countermeasures to Global Environment Change in the Field of Urban Planning*
Kazuo Kontani	*CO_2 from Motor Vehicles - Issue and State of RD in Japan -*
Rowan A. Rowntree	*Atmospheric Carbon Exchange Associate with Vegetation and Soils in Urban and Suburban Land Uses*
Gregg Marland	*Forest Management of Fixing and Sequestering Carbon*
William T. Sommers	*Natural Resources Management in an Era of Global Change*
Takano Fujimori	*Forest Management Techniques for Carbon Dioxide Storage*
Hiroshi Seino	*Adaptation Responses of Crops to Climate Change*
Hugo Rogers Basil Acock	*Rising Atmospheric CO_2 and Crops: Research Methodology and Direct Effects*
John M. Duxbury	*Mitigation Strategies for Methane Emissions from Agricultural Sources*
Haruo Tsuruta	*Strategy for Reduction of Methane Emissions from Rice Paddy Fields*
Thomas Barnwell, Jr. Robert Jackson, IV Lee A. Mulkey	*An Assessment of Alternative Agricultural Management Practice Impacts on Soil Carbon in the Corn Belt*

Research on Countermeasures to Global Environment Change in the Field of Urban Planning

Takashi Kawanaka

Head, Urban Planning Division, Urban Planning Department
Building Research Institute, Ministry of Construction
1 Tatehara, Tsukuba-shi, Ibaraki 305 Japan

1. Purpose and Back Ground / Overview

There are a lot of research themes in the field of urban planning and related fields as mitigation of global environment change. Main theme is reduction method of CO2 gas emission as a countermeasure against global warming.

Some groups research on estimation of CO2 emission caused by construction activities both in building engineering and civil engineering and also on evaluation of countermeasures. They investigate reduction of CO2 emission by fossil fuel combustion and by building materials (cement, steel and so on) production process. But we cannot use data fitted to a spatial scale of urban planning. Many researches are focused on nation wide analysis. We, BRI, make a study of "Research on CO2 Emission in Urban Development and the Control Technologies" as will be seen later at 2.(2).

There are two ways of research to reduce CO2 emission caused by daily activities in urban planning field. One is research on positive utilizing of natural environment in urban areas without depending to energy consuming artificial facilities. There is a research on mitigation of heat island phenomenon for instance. The other ways are research on improvement of energy consumption effect and on reusing of wasted energy in energy consuming type urban space for instance. There is a research on promoting District Heating and Cooling (DHC) and cogeneration.

We think that urban planning is a kind of social planning technology about contents and location of each land use. In this point of view, environmental countermeasures by urban planning is very important. When we think about a simplified city with business function and residential function, location of residential area and business area and condition of transportation facilities relate to energy consumption (CO2 emission) by commuting. There are some discussions about desirable city; someone says that a compact high dense city is desirable and the other says decentralized low dense city (cities) is (are) desirable. We should continue basic discussions on urban structure. By the way, we need to study not only hardware but also software. Some people propose sharing a car for commuting to reduce petroleum energy consumption for instance.

We, urban planners and researchers of urban planning, thought "environment" as spatial scale from local urban space until cities or metropolis, traditionally. In the field of urban planning today, the main proposed countermeasures against global environment change are methods at local scale with effectiveness to improve urban local environment. In other words, we are apt to discuss global environment countermeasures by accumulation of immediate environmental methods. But this approach is not sufficient to build a bridge between global and local spatial scales. We need to continue hierarchical discussions in consideration of different spatial scales. Some people say that it is uncertain to fulfill CO2 emission control without damage to urban activities tied to sustainable economic growth.

In case of quantitative estimation of effect in a field of methods for saving energy or CO2 emission reduction, a result may vary according to accuracy of estimation of dependent components with relation to input countermeasures. If existing data are very limited, estimation may not excel scenario simulation.

We, on the contrary, need to research a long-term strategic way to convert structure of resource and energy consumption in cities. We need not to be particular about accurate estimation. In one research group that the author set up, some members discuss it. One of our plan for collaborative research titled "Research on Adaptation of Energy Conscious Technologies in Mixed Land Use Development in Urban Areas", as will be seen later at 3.(1), relates to this idea.

2. Ongoing Research and Future Plan

In this chapter, firstly, we show you ongoing 2 research programs by the Building Research Institute (BRI).

(1) Research and Development of New Technologies in Building and Planning Field for Sustainable Society (by budget of Ministry of Construction) FY1991-95

Objectives:

1) Development of assessing methods of environmental impacts caused by built environment (buildings and planning)
2) Systematization and integration of environment-oriented technologies in the field of building and urban planning
3) Development of a framework of planning "Ecological Building" and "Ecological City"

Part 1.

Development of assessing methods of environmental impacts* caused by built environment (both of buildings and urban scale)

- Environmental impact may be analyzed from two points of view:
  1) consumption of resource and energy
  2) environmental deterioration

1-1 Environmental impacts in construction process
  1) Survey of resource and energy consumption in construction process
  2) Development of assessing method of resource and energy consumption in construction process
  3) Development of assessing method of environmental deterioration caused by manufacturing of building materials and site construction.

1-2 Environmental impacts in building-operation process
  1) Survey of resource and energy consumption in various scale of built environment.
  2) Development of assessing method of energy consumption in processes of operating or managing built environment.
  3) Development of assessing method of environmental deterioration in processes of operating or managing of built environment.

1-3 Development of total assessing framework (ex. life cycle cost analysis) method for built environment (building and city)

Part 2.
R & D of elemental technologies for environment-oriented design and planning

2-1 Building construction systems
  1) R & D of environment-oriented building system

2-2 Building materials
  1) R & D of environment-oriented building materials
  2) R & D of recycling system of building materials

2-3 Built environment control system
  1) Bioclimatic design in building scale and in urban scale
  2) Energy conscious building service system
  3) Energy conscious urban infrastructure

2-4 Resource and energy conscious urban planning
  1) Land use planning
  2) Heat energy facilities

Part 3.

R & D of design and planning strategy

3-1 Establishment of framework of planning theory for Ecological City

3-2 Application system of integrated energy and resource conscious technologies according to the scale of development

3-3 Case study

This research program is divided into various parts as mentioned above, mainly from a viewpoint of architecture. It will conclude at FY1995.

(2) Research on CO2 Emission in Urban Development and the Control Technologies (by budget of Environment Agency)
FY1990-92

This research aims to estimate the CO2 gas emission amount and to investigate the control technologies to cope with greenhouse effect gas discharged by urban development activities.

We examined estimation method of incentive CO2 emission amount using input-output table(1985) and outlines of results are as follows; 1) conquering methodological problems, 2) accurate estimation stood upon the basic table, 3) estimating the emission amount according to fuel products using material amount table, 3) estimating the emission amount according to fuel products using material amount table, 4) estimating incentive emission amount using inverse matrix, 5) estimating specialized on construction department using input-output table, and 6) estimating details of the emission concerned with urban development in construction department.

We have a plan to evaluate effects of countermeasures against CO2 gas emission. This program will conclude at FY1992.

We, secondarily, show you the contents from research reports of an academic society and industrial associations. We think there are the other reports and proceedings of such bodies and symposia.

The Architectural Institute of Japan (AIJ) issued 2 reports. "Ecological City and Environmental Design"(1991) discussed elementarily under 8 titles: urbanization, water areas, greening, atmosphere, energy, heat island, environmental standards and urban facilities. "Impact on Global Environment by building"(1992) developed basic study on 8 titles: life style, utilization of resources, energy, ecological city, passive designed building, rural planing, urban planning and environmental change.

Civil Engineering Industry Association of Japan and Electric Power Construction Association of Japan issued a report "Relationship between

Global Environment Problem and Construction Industry." It surveyed countermeasures against global environment change implemented by the ministries of Japanese government and estimated environmental load caused by civil engineering works.

(3)Others

There are a lot of research items of the other research programs in the field of urban infrastructures in Japan. Some of them are as follows.

(3-1) Energy consumption
- Control of energy consumption on building materials production
- Control of energy consumption on operation of air conditioner and of the other building equipments
- Utilization of non-used heat energy and waste heat energy
- Utilization of heat energy from a garbage incinerator
- Heat pump etc.

(3-2) Recycling of materials
- Utilization of building scrap (concrete, wood, and so on)
- Utilization of ashes and sludge as building materials etc.

(3-3) Water
- Recycling of water
- Utilization of rain water
- Permeable pavement etc.

(3-4) Green
- Greening of roofs and walls (Energy control of building use)
- CO2 fixation by plants
- Improvement of local climate
- Mitigation of heat island phenomenon etc.

3. Future View for Collaborative Research with U.S.

(1) Research on Adaptation of Energy Conscious Technologies in Mixed Land Use Development in Urban Areas

We think that introducing cogeneration system to mixed land use in energy consuming type central urban districts encourages saving energy by leveling energy consumption peak time. A mixture of office use, commercial use, hotel use and residential use may stabilize management of District Heating and Cooling (DHC) by cogeneration. And a housing complex may reuse waste heat energy from neighboring factories and energy plants. We would like to research such kind of energy conscious urban (re)development method. This research plan also aims to convert some parts of urban infrastructure into energy conscious one.

Urban planners in Japan have paid attention to Mixed Use Development

(MXD) in U.S.A. as an effective restoration method for central urban areas for some time. We think MXD may be effective way to realize energy conscious city too, now.

This theme is related to "2.(1)2-4 Resource and energy conscious urban planning" above-mentioned.

(2) Research on Planning Method and Formation Technique of Green Spaces in and around the Urban Areas which Contribute to the Preservation of Global Environment

This research proposal includes some raw ideas as follows.

The investigation of a method to form urban forests which contribute to CO2 fixation by the utilization of private land through land use control, incentive in taxation system, etc.

The investigation of a method to form "wind passageway" in urban areas through the planning of green spaces location which contribute to the mitigation of heat island phenomenon and contribute to the reduction of electricity consumption for air conditioning in urban areas in summer.

The investigation of the effective timber production technique in such green spaces and a method to cultivate a market for products.

Research for development of a method to select the most desirable species and for development of green spaces, considering the effectiveness of CO2 fixation, the feasibility of recreational use, the efficiency of timber production, the danger degree of making forest fire, etc.

Development of the technique for positive utilization of branches and leaves as energy resources which come out through the maintenance of such green spaces.

(3) Research and Development of New Technologies in Building and Planning Field for Sustainable Society

Please refer to "2.(1) Research and Development of New Technologies in Building and Planning Field for Sustainable Society" above-mentioned. BRI can negotiate collaborative research in some parts of 2.(1) with U.S. side.

4. Other Remarks

We don't discuss urban transportation problem that relates to urban planning, because an author is not a specialist of traffic matters. But people understand that the condition of urban transportation relates to energy consumption and load to global environment. That the energy consumption unit(per person-distance) by a passenger car is greater than by mass transit in case of human trips is well known. There are different opinions on more accurate estimation of energy consumption that covers construction of facilities and maintenance, nevertheless. Some people discuss modal mix or modal shift that mass transit and individual transportation means share roles to consume energy more efficiently. Many people say we need to think better of material transportation by cars. No one knows basic solutions of improvement of transportation energy consumption in a big city as Tokyo, because every existing channel bears maximum load at peak time simultaneously. Some people expect that transportation energy consumption will be controlled well in small local cities rather than big cities, through passengers shift from owned cars to mass transit. In order to mitigate impact on global environment caused by automobile, both urban transportation approach and mechanical technology approach are important.

Some people often introduce policies of former West Germany at discussions of countermeasures to environment problem in the field of urban planning in Japan. They are, for instance, respect to local climate, respect to biotope, ecological housing complex, a policy of traffic change between automobile and electric train (park and ride system), utilization of bicycles, and so on. Those policies may be based on a concept to accumulate as many as immediate countermeasures instead of sticking to accurate quantitative estimation of effect.

The Ministry of Construction implements some institutions in order to conserve global environment as shown in Appendix. In the field of urban planning, "Ecological City Promoting Project" will start at FY1993 as model projects with subsidy institution. But the details are not fixed now.

Appendix

Dealing with the Environmental Problem on a Global Scale

Excerpt from "Striving for a Better Environment - A proposal for providing housing and social infrastructure (social overhead capital) that will create an environment, preserve it, and regenerate it."
April 1992, Ministry of Construction

(1) Dealing with the prevention of global warming

(1-1) Building cities with little carbon dioxide emission

- We are encouraging action such as building of energy-saving houses and other buildings which use heat insulating construction and energy saving and air-conditioning systems(with the assistance and support of the Government Housing Loan Corporation).
- We are planning the introduction of environmentally harmonious public housing which makes full use of recycling, burns less fossil fuel and uses solar energy (supporting the Regional Public Bodies within the framework of the HOPE [HOusing with Proper Environment] Plan for the construction of housing based on regional characteristics).
- We will use untapped energy resources such as rivers and sewers to generate district heating and cooling systems and control public facilities. In addition we will use the heat from treated waste water to melt the snows in areas where there is a large accumulation of snow.
- We will use urban redevelopment plans to put in place integrated regional systems for heating and cooling, re-use of treated waste water and disposal.
- With the promotion of greener cities, we will alleviate the development of heat islands by using the temperature cooling effect of plants, and increase the source of carbon dioxide.
- In road planning, we will make full use of the space under the surface for heating and cooling, sewerage systems, and other public needs and will develop a system so that the heat accumulated in the summer can be used to melt the snow in winter (a test project is currently under way on the Akita Expressway).

(1-2) Building a traffic system with little carbon dioxide emission

Since traffic congestion causes cars to consume more gas than usual, speedy and smooth traffic flow will lead to reduced carbon dioxide emission.

- We are steadily working towards the improvement of roads by building bypasses, ring roads, separation roadways, the improvement of junctions and parking lots and building up a car traffic network that will flow smoothly and save energy.

- We are encouraging greater use of public transport systems by building urban monorails and new transport systems, setting up guideway bus systems, improving station squares, and promoting the park and ride system.
- We are continuing to provide walkways and cycle routes to encourage pedestrians and cyclists.
- We are working towards the development of new distribution systems and the setting up of distribution centers in order to bring about an efficient distribution set-up.

(2) Preventing further depletion of the ozone layer

- We took the decision (in 1989) to stop using fluorocarbons in the installation of air conditioning in government buildings.
- We have prepared a guidance booklet called "Manual for dealing with specific fluorocarbons in cooling equipment" for the building industry (in 1990).
- We have established financing measures for those buildings wishing to change their cooling systems from fluorocarbon-based to non fluorocarbon-based (1990 - Japan Development Bank et al).

(3) Dealing with Deforestation

We have developed the technology and carrying out a pilot study for a way to rationalize the use of plywood frames which incorporate tropical woods.

- We will shift to using prefabricated concrete parts which make frames unnecessary.
- We will shift away from tropical plywood and look at recyclable woods and non-wood materials such as plywood made from evergreens and steel deck plates
- By standardizing wooden material sizes, we will simplify the plywood cutting process and extend the useful life of each frame.

(4) Contributing to solving environmental issues in developing countries

We are implementing the following technical cooperation plans to help solve environmental problems in developing countries.

- By putting together plans, developing technologies, and providing specialized personnel, we transfer technology of sewerage systems, cleaning of rivers and lakes, road planning, traffic control, and development and improvement of the housing environment.

- In keeping with our strategy to preserve the environment over wide areas, we are accumulating all types fo data and have developed an information system to analyze it so that we can develop the technologies that are needed.
- We are researching technologies for the improvement of desert environments.
- Establishing waste water treatment facilities for developing countries suited to each region.

(5) Studying global environmental problems in-depth and developing the technologies needed

- We are measuring sea levels at 23 sites around the country as part of a study of rising sea levels related to global warming.
- We are using a VLBI(Very Long Baseline Interferometer) to measure changes in the earth's crust, and analyzing them in tandem with sea levels to develop a system that will measure accuracy the rise in sea levels which is caused by global warming.
- Using satellite-based remote sensing technology (technology which distinguishes between the types and condition of bodies on the earth's surface as measured by electromagnetic waves), we are developing a way to predict the effects of the rising sea level and the condition and changes in tropical forests.
- By studying the topography of lake bottoms, the material accumulated on lake bottoms and lake dwelling plants, we are putting together a basic blueprint for the prevention of the pollution of lake waters and the improvement in water quality.
- We are studying ways to measure effect of changes in seawater levels and precipitation patterns as a result of global warming and the harm done to plants by acid rain and also studying a strategy for flood control and water utilization.
- We are studying the establishment of a sewage system that will reduce our impact on the environment by making good use of resources such as waste water, solid waste and heat in sewerage systems.
- While clarifying the current state of resource and energy consumption business, we are studying land development technologies such as recycling technology for the efficient use of resource and energy rate.
- We are developing technologies for artificial planting technology in difficult places such as roofs, walls and underground areas.

CO_2 FROM MOTOR VEHICLES
- Issue and State of RD in Japan -

Kazuo Kontani

Mechanical Engineering Laboratory
AIST, Ministry of International Trade and Industry
1-2 Namiki, Tsukuba, 305 Japan

1. Overview

The transportation sector, particularly road transport, is a major cause of growing oil consumption and is, therefore, a dominant source of increasing worldwide atmospheric CO2. It is also a larger source of conventional atmospheric pollutants than any other single human activity. Thus, transportation is obviously given primary concern in global environmental issues. Although the impact of motor vehicles on the environment is often mentioned, it will be helpful to review several basic considerations before starting discussion.

Basic Facts

Oil consumption by transportation sector

The bulk of increasing oil demand in industrialized countries is attributed to the transportation sector. Fig. 1 compares transport oil consumption of regional and overall OECD transportation sector, over the past 15 years, as shares of total final oil consumption. In North America the percentage is almost 80%, with the figure for overall OECD at around 70%. In terms of quantity, the transportation sector and road transport within this sector have both increased their consumption by 2% annually over the past decade. Fig. 2 shows the composition of the transportation sector, through the shares of air, roads, rail and other modes in 1989 OECD. It is seen that roads account for 82% of total transport oil consumption, ie., motor vehicles are by far the major consumer of this resource.

Motor vehicle impacts on the environment

As shown in Fig. 3, all the emissions from motor vehicles are at any rate atmospheric pollutants and have local, regional and global environmental impacts. Locally, they injure health and welfare and regionally cause acidification and tropospheric ozone. Globally, these emissions are directly or indirectly responsible for the greenhouse effect and the depletion of the stratospheric ozone layer. In terms of local pollution, a typical problem in the USA is tropospheric ozone from HC, and in Japan the main challenge is NOx levels in urban areas. Regarding atmospheric pollutants other than CO2, the contribution of motor vehicles is shown in Fig. 4 as a share of overall emissions. Motor vehicles are the greatest single source of conventional pollutant emissions.

CO2 from motor vehicles

As to global environmental impacts, motor vehicles are responsible for emissions of direct and indirect greenhouse effect gases (GHG). Because, as mentioned before, OECD motor vehicle oil consumption accounts for more than 50% of the total oil demand, motor vehicles are also a major source of CO2, second only to power generation.

The well known contributions of gases and their emission sources to global warming is illustrated in Fig. 5. CO2 accounts for 55% of total GHG, and motor vehicles are responsible for around 10% of global warming, 4.7% through CO2 and 5% through CFCs. However, because actions to abandon the use of CFCs have already been started and indirect GHG emissions from motor vehicles are relatively smaller than CO2 and also because discussion about the influence of indirect GHGs is now suspended at IPCC, at the present stage it would be acceptable to limit the vehicular GHGs to CO_2.

Fig. 6 illustrates contributions of countries, sectors in Japan, and modes of transport to CO_2 emission. CO_2 emissions from motor vehicles in Japan account for 17% of the domestic total, and 0.8% of the world total. In the United States, automotive CO_2 emissions is 24% of the U.S. total, and 6% of the world total. Incidentally, those figures are halved when we consider their contribution to global warming, as CO_2 is responsible for 55% of global warming.

Ever rising motor vehicle ownership

Industrialized regions like OECD countries are characterized by massive motor vehicle oil consumption. Future development in the less developed countries will naturally bring about a considerable rise in motor vehicle ownership. Fig. 7 shows past trends in motor vehicle numbers. In the last two decades, world motor vehicle numbers have shown a linear expansion with 2.3% average annual growth. In the past decade, the total has risen around 50%. So what about the future? Fig. 8 projects the future number of world motor vehicles together with population growth. A simple linear extrapolation suggests that the number of vehicles will have jumped another 80% by the year 2020, and another projection, based on the growth of units per capita, rockets the number up to 140%. Thus, motor vehicles will be even more responsible for energy and environmental problems.

Responses to Motor Vehicle CO_2

As in other energy-consuming sectors, the first and best response for CO_2 from motor vehicles is improved fuel economy. The reduction of CO_2 would also lower the emission of conventional pollutants, so the reduction of CO_2 issues hold primary importance in the environmental problem of motor vehicles. The responses can be classified as follows.

Improving fuel economy of conventional vehicles

As shown in Fig. 9, there are four approaches to improve fuel economy in conventional motor vehicles. They are reduction of vehicle weight, reduction of drag, improvement of engine performance and others. But with current technologies there is little scope for further enhancements - perhaps another 20% at most. To achieve further drastic change, we would need to alter the concepts of motor vehicles and, perhaps, of their usage. Incidentally, last month the Japanese government resurrected its fuel consumption standards for motor vehicles as an inclusion in the energy conservation law, which aims for an average fleet improvement of 8.5% by the year 2000.

The development of alternative fuel vehicles

Altering motor fuels to alcohol, natural gas, and other alternative fuels with relatively low C/H ratios, and to electricity is one approach. In this case, it is essential to consider the total energy consumption and emission, covering not only vehicle performance on the roads but also production and distribution of fuels, their feed stocks, vehicles and materials. Fig. 10 features an estimation of GHG emissions from alternatively fueled vehicles, scaling 100 for gasoline-powered vehicles. It is seen that CNG is promising as a short term selection. While diesel is not an alternative vehicle, if only the exhaust problem were overcome, it would be the most advantageous among existing vehicle motors.

Improving driving conditions

No matter how great the enhancements to motor vehicles and their engines, actual driving conditions will greatly affect the final results. Fig. 11 shows actual fuel consumption, ie. mileage, relative to average vehicle speed. If the average speed rises from 20km/h to 40km/h, fuel economy doubles. We should keep in mind, by the way, that the average speed in metropolitan Tokyo is only around 10km/h. There are several ways to improve driving conditions, such as improving road environments, urban restructuring, and developing traffic information and guidance systems.

Social and governmental steps

We can conceive of some other approaches which would be more effective, such as legislation and policy instruments to encourage shifts to alternative modes of transport, vehicle downsizing, and restrictions on use and ownership. But we will not touch on such measures here, because they involve social and economic implications and are predominantly policy matters.

2. Research and Development in Japan

Recent trends in automotive technology

We will have a look at recent trends in the automotive industry, concentrating on engine technologies responding to the call for improved fuel economy in gasoline engines and cleaner emissions in diesel engines.

· Gasoline Engines

Among steady efforts to improve the fuel efficiency of gasoline engines, the following are the prominent trends in the latest engine technologies adopted in vehicles on the market.

- Lean burn engines: They have been put on the market by several makers. They have potential to improve fuel economy by 10%.
- Multi-valve system (4 or 5 valves): The multi-valve system is used in nearly all the latest passenger cars to provide higher power, low fuel consumption and low emissions. The system can be designed with a compact combustion chamber and a center plug to achieve rapid combustion, better intake and exhaust gas exchange, reduced pumping loss and, therefore, high compression ratio and stable combustion.
- Direct ignition: The direct ignition system, having an ignition coil for each cylinder, improves ignition timing accuracy.
- Electronic fuel injection: This has become practically universal. Carburetor systems can hardly be found any more. The use of multi-point injection has spread together with fine control of A/F ratio, and two-hole injectors combined with four-valve engines have begun to be used.
- Reduced friction: Friction is reduced by roller rocker arms and low-friction piston rings: a combination of top ring and second ring into one, and reduced ring tension.
- Variable systems: Variable systems are also typical trends for valve mechanisms, as well as intake and exhaust systems. The systems aim to optimize the torque curve over a wide speed range.

Although still at the concept car stage or under research and development, we are expecting two-stroke engines, variable compression ratio engines and variable cylinder engines.

· Diesel Engines

While diesel engines have high fuel efficiency and superior endurance, they have the disadvantages of particulate and NOx emissions which are not seen with gasoline engines. Generally there is a trade-off relationship between particulate and NOx emissions (and fuel consumption), and that relationship constitutes the main difficulties in diesel engine technology.

In Japan, as well as in the USA, NOx controls have been stringent, and conventional measures based mainly on engine modifications have already been pursued close to the limit. A brief explanation and the present status of other measures to be eventually adopted are given below.

- EGR: This has been used in passenger cars with their rather short life but has not yet been applied to medium and heavy duty vehicles, where longer life and durability are demanded. The problem with EGR is the increased particulate emissions, increased engine wear under heavy load, and the need for suitable fuel (with low sulfur content) and lubricating oil.

- Filter traps (DPF): These have been tackled vigorously in Europe and America, where extensive field tests have been made with city buses. There are plans for these in Japan also, but nothing has yet appeared on the market.

- Oxidation catalyst (Flow-through type catalytic converters): The purpose is to reduce the soluble organic fraction (SOF), and they are not effective against soot. The keys to development are engine compatibility and development of the catalysts. From the aspects of general engine features and cost, they appear to be suitable for small, direct injection engines. Field testing has been extensive in Europe and America, but it has not yet been taken up in Japan.

- Fuel improvement: Sulfur reduction and improved cetane ratings are being looked for. In Japan, the sulfur content for diesel fuel has been set at 0.2% by 1993, and at 0.05% at a later date. There are no moves to increase the cetane rating, since it is already at a high level in Japan.

- High Pressure Injection: Improved combustion through increased fuel injection pressure is the latest focus of attention. Much research involves injection pressures of approximately 100 MPa, but there is a promising attempt to use an ultra high pressure injection, which is being investigated with equipment capable of injecting fuel at pressures up to 300 MPa. It has been observed that the trade-off relationship between NOx and particulate emissions is greatly improved.

- NOx reduction catalysts: It would be ideal if catalysts could be used for diesel NOx in the same way as the three-way catalysts for gasoline engines. Apart from the basic difficulty that diesel exhaust is oxidizing (oxygen rich), problems include the presence of soot and sulfur oxides, and the difficulty in maintaining the catalyst at the desired temperature level, etc. Although success is still a long way off, there is a great deal of recent research, and some possibilities have emerged.

- Hybrid propulsion: The main aim of hybridization based on diesel engines is to lessen the engine burden under high load, which is where the disadvantages of diesel engines are concentrated. A successful example is the HIMR system by Hino Motors which comprises a Diesel-Motor/Generator system.

Research and development on alternative vehicles

Table 3 summarizes R&D activities on alternative fuel vehicles. Currently, no more than 1,300 vehicles on roads in Japan are powered by electricity, methanol, natural gas, and diesel/electric hybrid systems. R&D activities and plans relative to alternative vehicles, however, are being accelerated in recent years. Plans by MITI and the Ministry of Transport project 10,000 methanol vehicles, 200,000 electric vehicles, and a total of 2 million alternative vehicles by the year 2000. In line with this goal, the Eco-Station 2000 plan has been formulated to build 2,000 filling stations nationwide by the year 2000 for those power sources together with conventional fuels.

Work at research laboratories within MITI

Within the Ministry of International Trade and Industry, Including the Mechanical Engineering Laboratory, where the author is employed, several areas are currently under investigation (or have been covered earlier). These areas include control of NOx emission from diesel engines, diesel filter traps, catalysts for NOx, electric vehicles, hydrogen vehicles and hydrogen-oxygen combustion, butane combustion in diesel engines, and methanol and CNG combustion in Otto engines.

Research on hydrogen-powered vehicles was conducted earlier. The main features of the research, as shown in Fig. 12, were the use of metal-hydrides for hydrogen storage and direct injection of low pressure hydrogen gas into cylinders. This approach could solve the twin problems of low suction efficiency with gaseous fuels and the preignition typical to hydrogen fuel. Although the research is now finished, current work focuses on hydrogen-oxygen combustion in gasturbines.

In butane fueling research, we are testing so called dual-fuel combustion, whereby butane gas is supplied premixed in the intake air and ignited by pilot-injected diesel oil. This method suffers the drawbacks of large NOx emissions under high loads and high HC levels under low load conditions, but we are finding a way by the use of de-NOx catalyzers to suppress these tendencies. An experimental result is shown in Fig. 13. We are planning to achieve more diesel-like combustion by directly injecting butane fuel into the cylinder.

3. Proposals for Future Collaboration

Automakers today dominate applied technologies at the product level, leaving little room for external contribution. Accordingly, potential collaborative areas would be as follows.

National projects
RD&D programs on alternative vehicles and advanced engines is a potential area for collaboration. The exchange of related technologies and information and mutual participation, particularly at demonstration stage, would be effective. It is the usual case, however, that those projects are conducted by designated associations under funding and control of national administration, and we research laboratories are not involved in such activities. Therefore we do not have the ability to further discuss collaboration in this area.

Research
Methods similar to those of IEA research cooperation could be implemented to focus on future technologies not currently explored by the manufacturers. The following areas are promising in this respect.

- Diesel engines:
  NOx controls, filter trapping, de-NOx catalysts
- Alternative fuels:
  Hydrogen (for reciprocating engines or turbines), Butane, CNG, batteries (fuel cells)

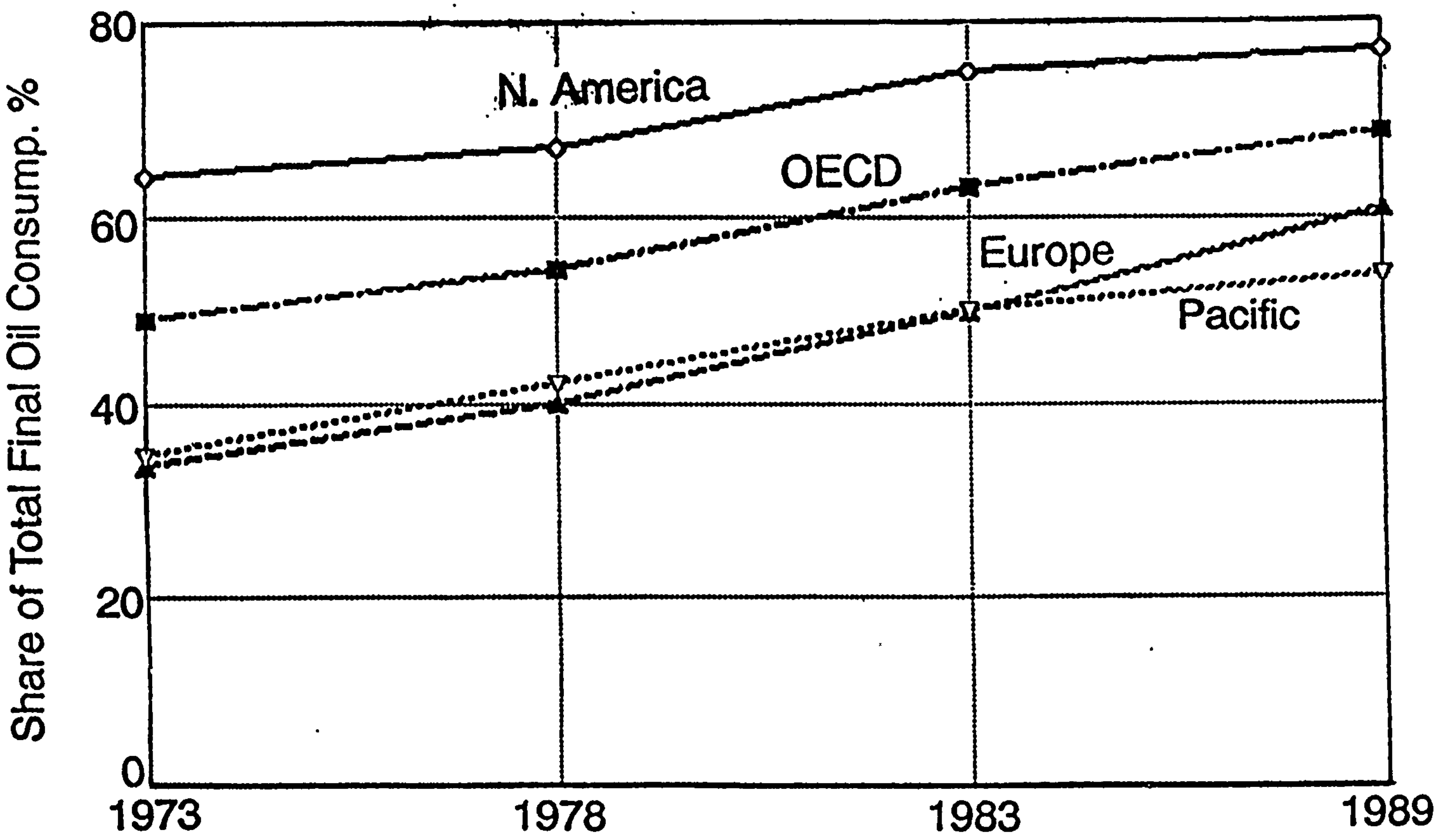
Survey and analysis
Such efforts can encompass surveys, analysis, and projections of the implications of energy, environment, economy, and policy. Many organizations like UN, IEA and OECD already cover such issues through conferences and investigative activities. It would be effective for us also to hold symposiums and operate workshops and to deepen understanding of the issues with wider participation from universities and private research institutes.

4. Concluding Remarks

Motor vehicles are major causes of energy and environmental problems. As motor vehicle ownership is almost proportional to GNP trends, the number of vehicles will probably continue to grow. This is a challenging issue inseparably connected with world economic development. Obviously, technological responses alone are insufficient and strong governmental intervention is crucial.

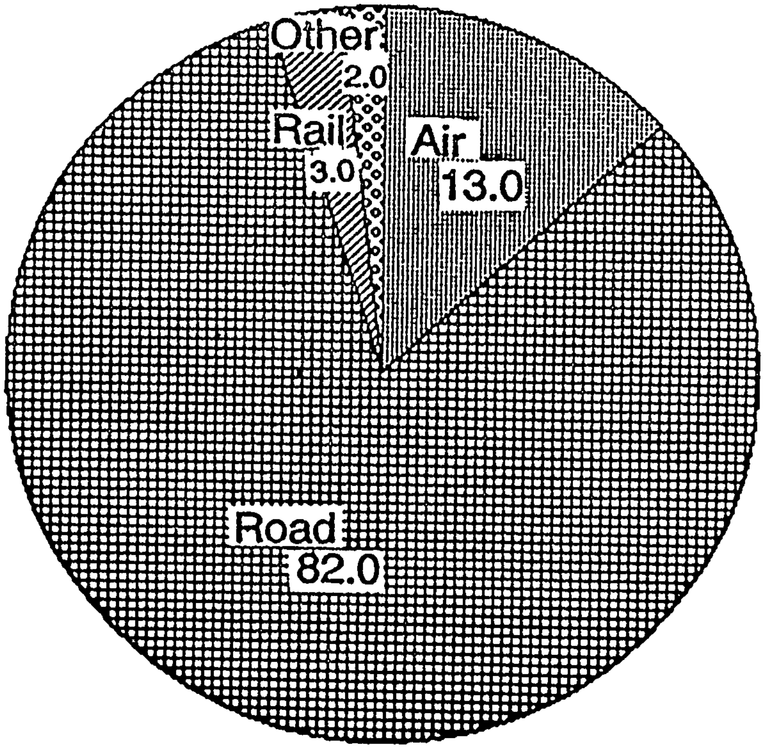
The work of governmental research laboratories, as far as motor vehicle technology is concerned, is limited to basic research into future technologies and "soft" areas related to motor vehicle use. Accordingly, this paper has concentrated mainly on an overview of the environmental issue of motor vehicles and potential responses. While this paper does not present detailed description of any specific research work, we hope that it has helped to understand the issue and present efforts in the field.

Fig.1 Transport Oil Consumption in OECD



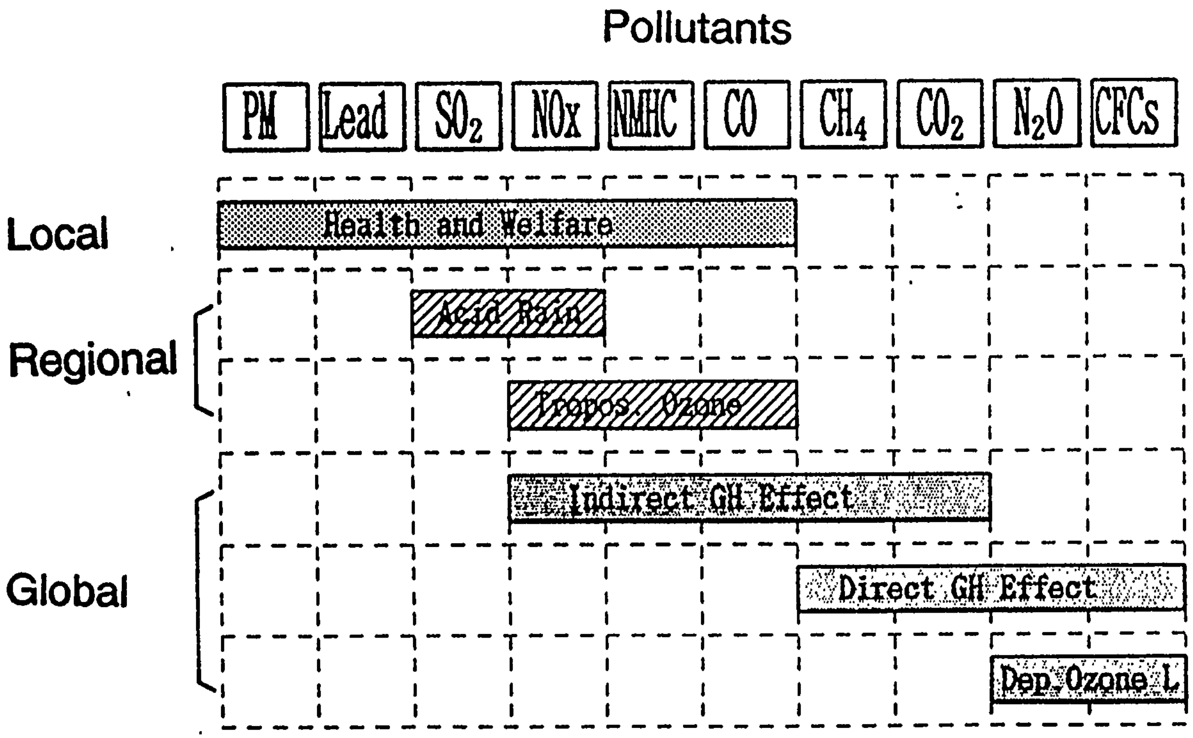
(Source: IEA Energy Balance)

Fig.2 Oil Consump. Share by Transport Mode (OECD 1989)



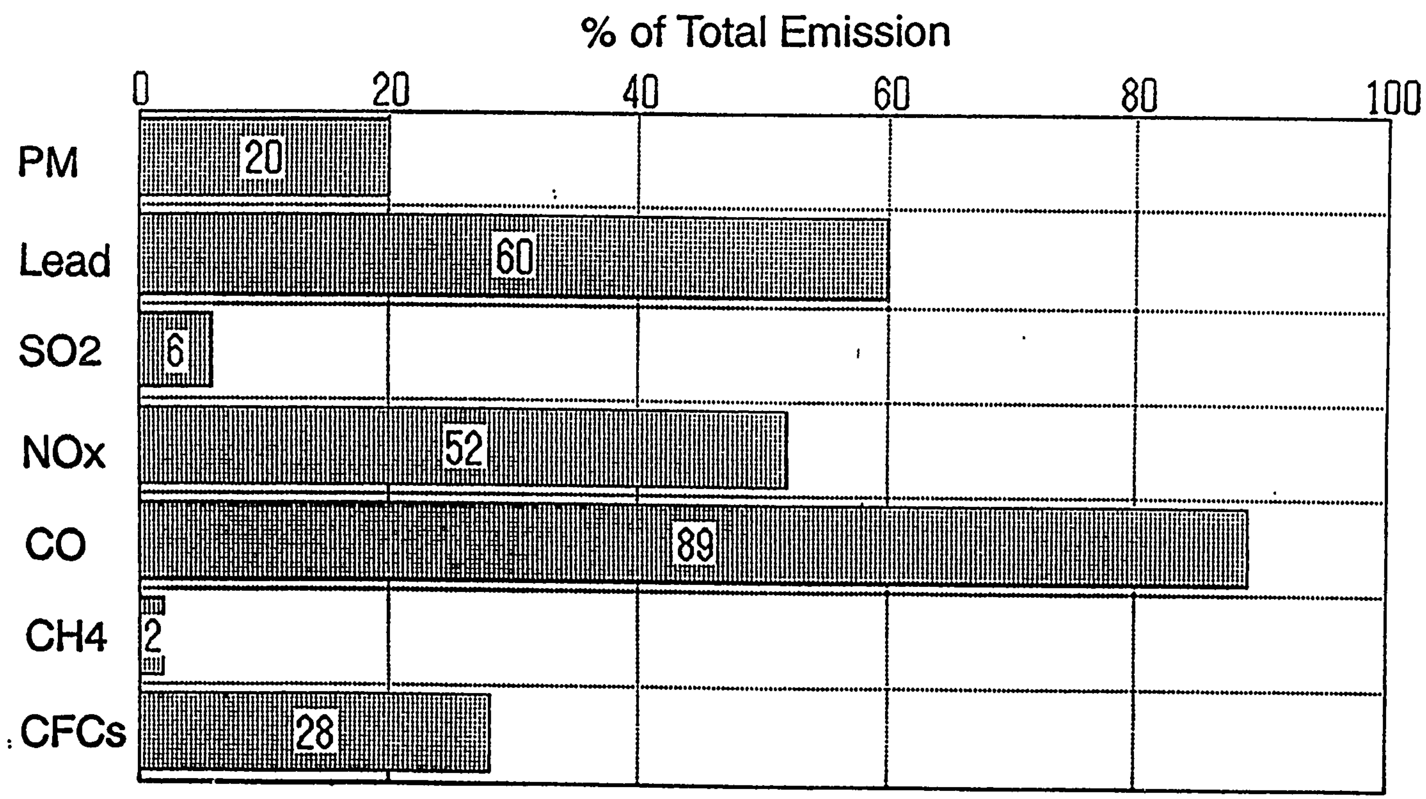
(Source: IEA Energy Balance)

Fig.3 Air Pollution From Transport



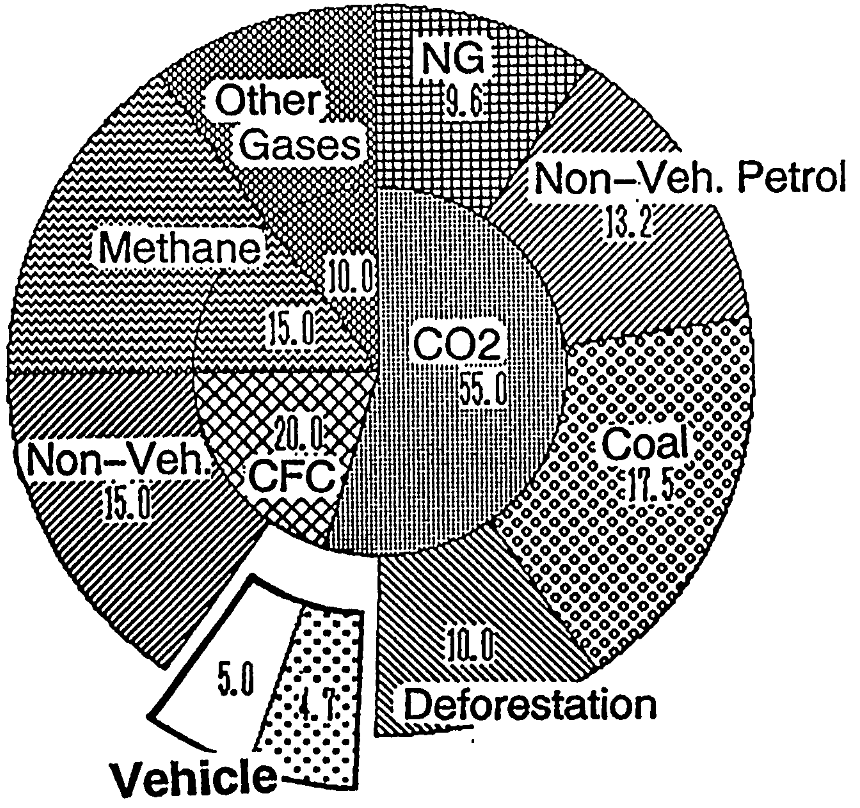
(Source: World Bank)

Fig.4 Non-CO_2 Emissions From Transport (OECD)



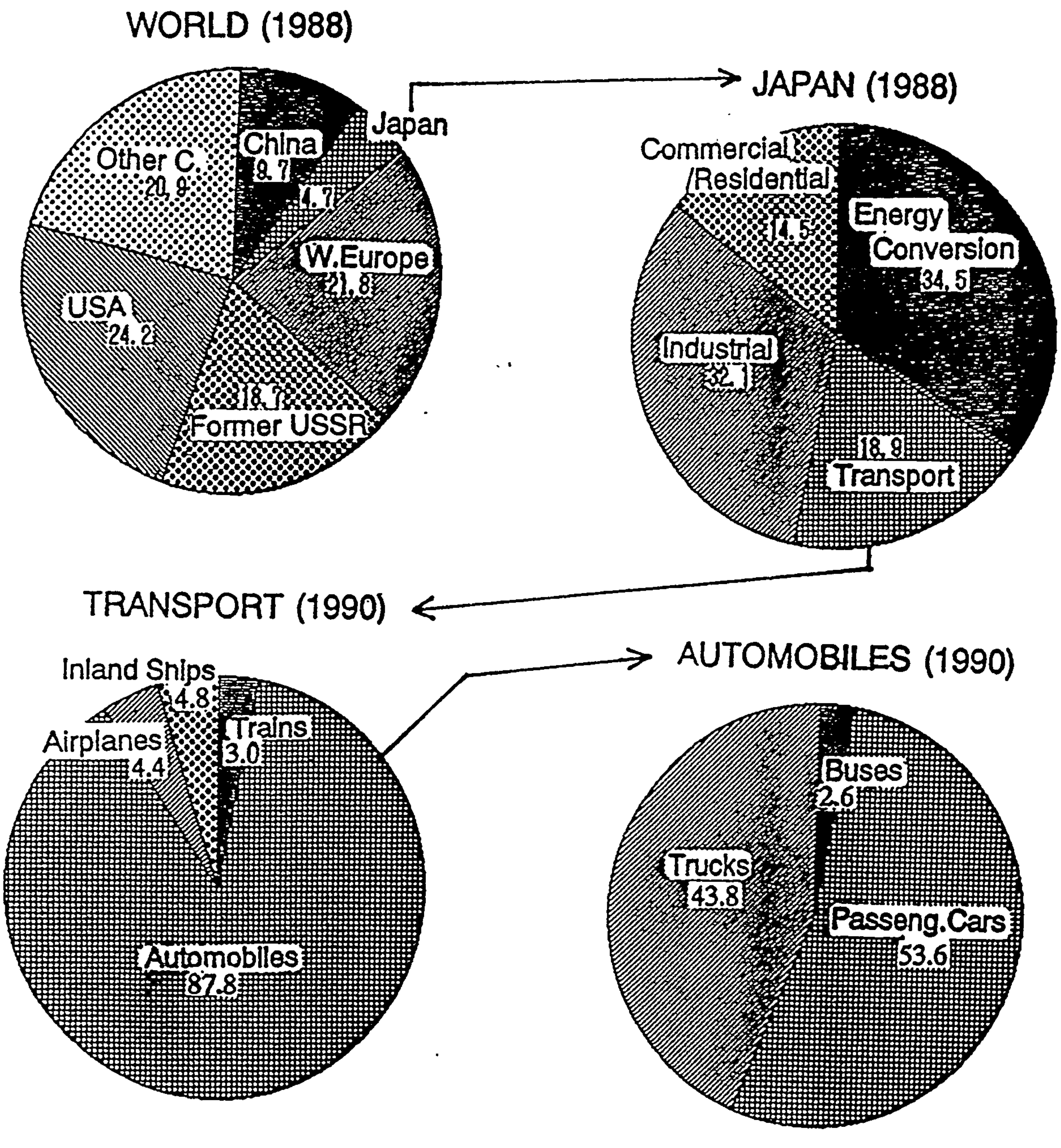
(Source: IEA Draft report)

Fig.5 Worldwide Contributors to Global Warming (1980s)



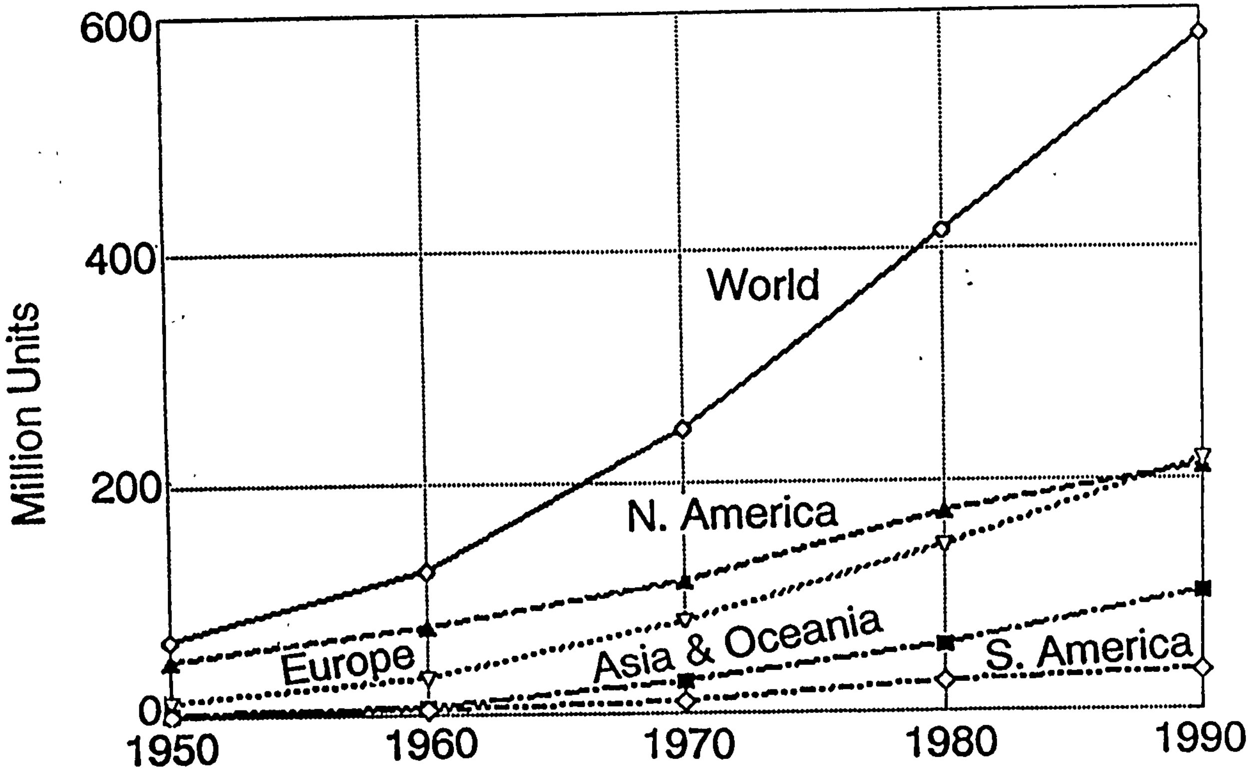
(Sources: IPCC and EPA)

Fig.6 Share of CO_2 Emission
World / Japan / Transport / Automobile



(Sources: Environment Agency,MITI,MOT and IEA Energy Balance)

Fig.7 Increasing Number of World Vehicles



(Source: SMMT)

Fig.8 Future Expansion of Vehicles

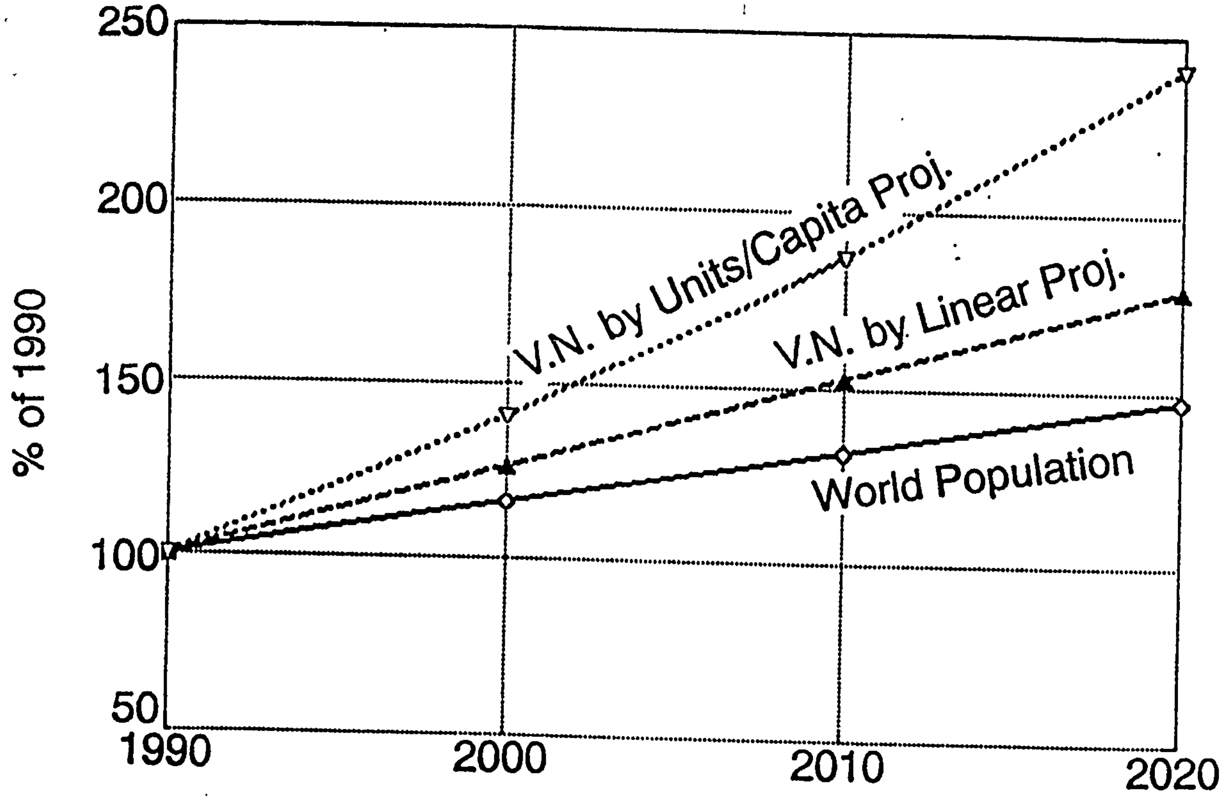


Fig.9 Measures for Improved Fuel Economy

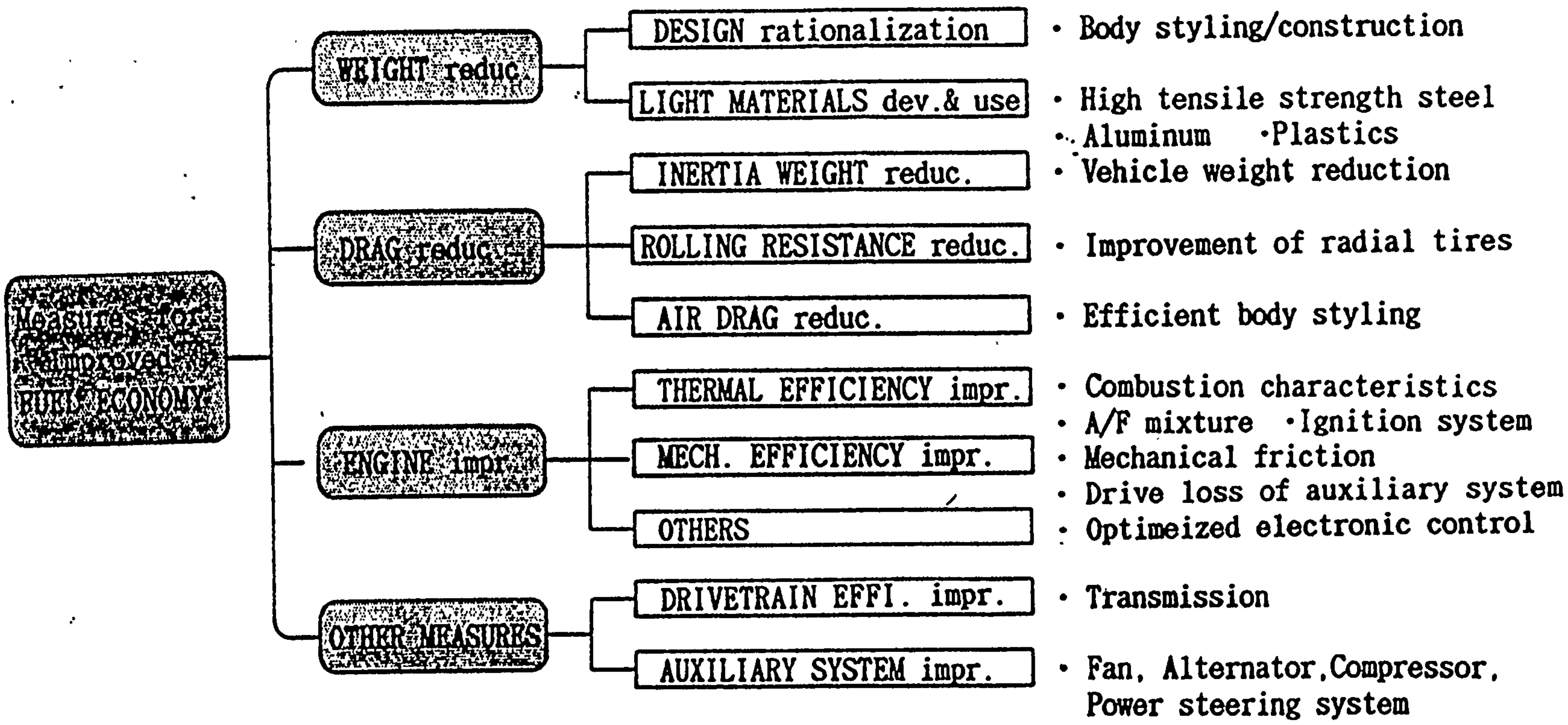
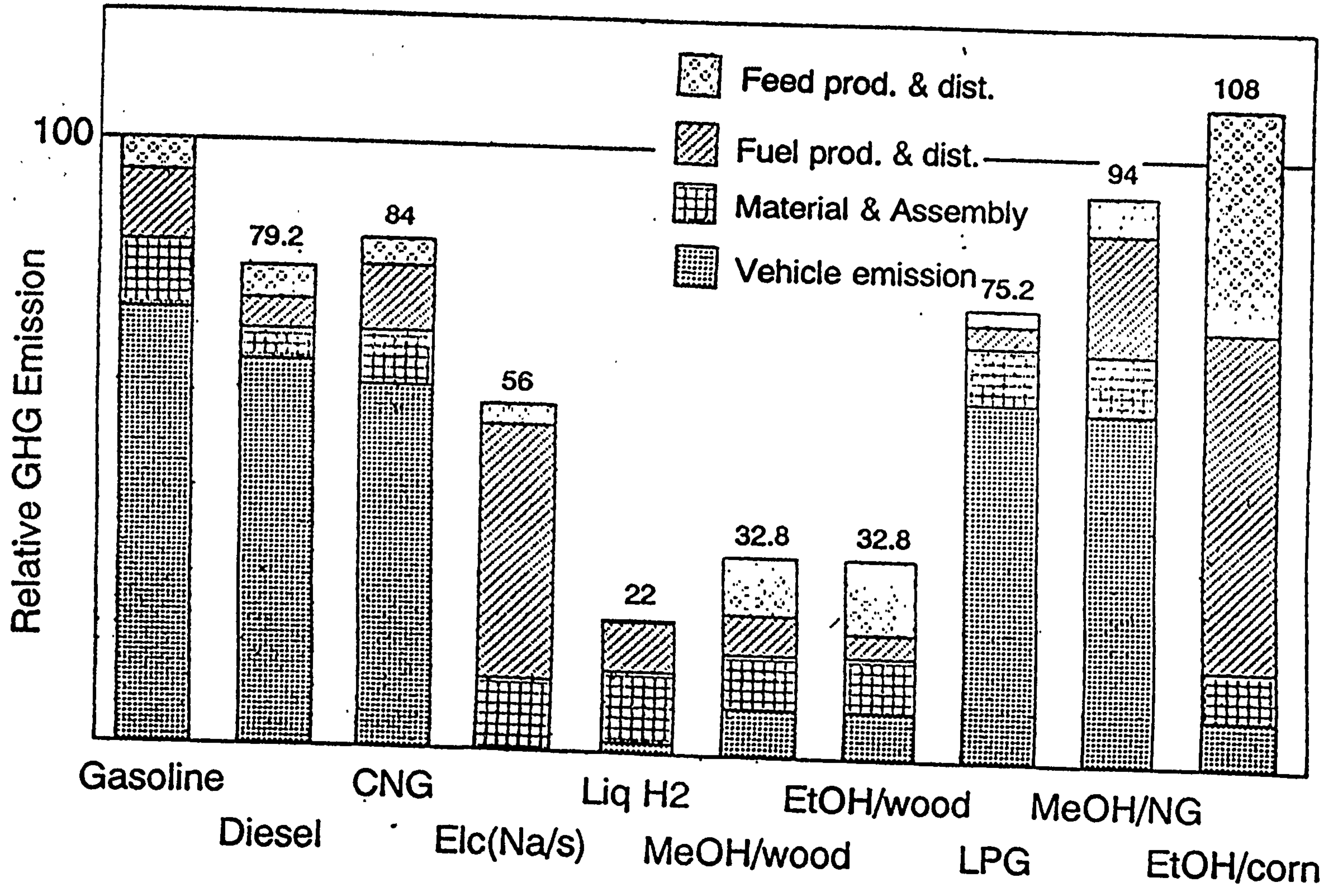
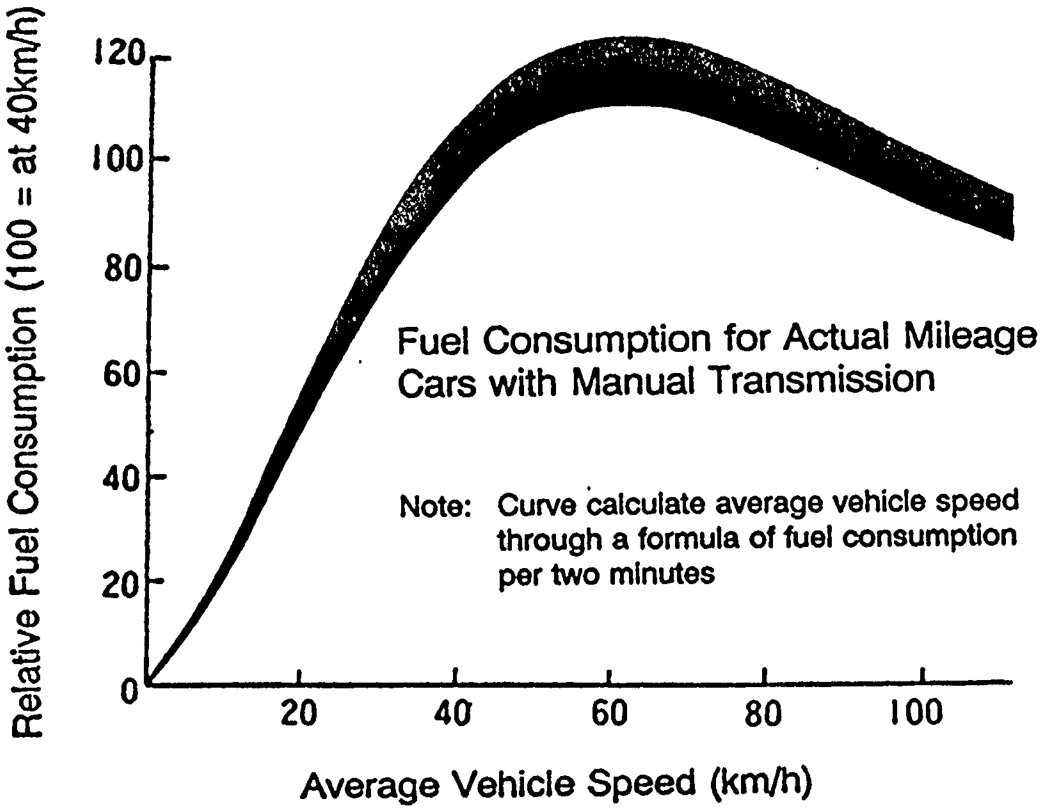


Fig.10 GHG from Alternative Fuel Vehicles



(Source: IEA Draft report)

Fig.11 Average Vehicle Speed and Fuel Consumption



Note: Curve calculate average vehicle speed through a formula of fuel consumption per two minutes

(Source: JAMA)

Tab.1 Trends In Gasoline Engines

• Multi-Valve System	4-5 Valves, Compact Chamber, Rapid Comb.
• Electronic Fuel Injection	Multi-Point, Fine A/F Control, Two Hole Inj.
• Direct Ignition	Ig. Coil for Each Cyl.
• Reduced Friction	Roller Rocker Arms, Low Friction Piston Ring
• Variable System	Valve Mechanism, Intake/Exhaust Sys.
• Lean Burn System	
Others under RD	Two-Stroke E., Catalysts for Lean Burn Variable Comp. Ratio E., Variable Cyl. E.

Tab.2 New Technologies In Diesel Engines

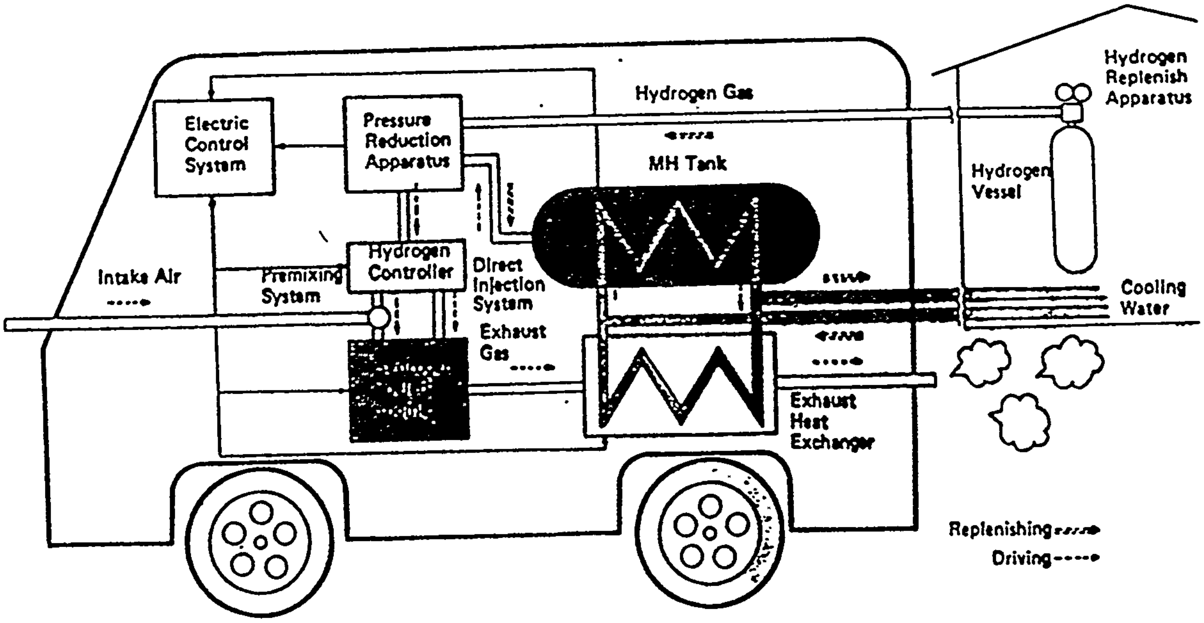
• EGR	Not yet in HD Vehicles
• Filter Trap	
• Oxidation Catalyst	Effective for SOF
• Fuel Improvement	Low Sulfur, Cetane Rating
• High Press. Fuel Injection	~100MPa, ~200Mpa
• NOx Reduction Catalyst	SCR, Copper-Zeolite
• Hybrid Propulsion	Parallel/Serial, Electric/Hydraulic

Tab.3 R&D Activities on Alternative Vehicles

	Conducting body (supporting body)	Stage of RD or Planning
Methanol	(MITI),(MOT)	Fleet test 200 u.
Natural Gas		
CNG	J. Gas Association	Monitoring and own use 50 u.
LNG	JARI	Research
Hydrogen	Musashi Inst. of Tech. Mech.Eng. Lab. Mazda	Research
Electric	Elec. V. Assoc.	On road 1,000 u. Off road 20,000 u.
Hybrid		
DE-Elec	Hino Motors	On road 100 u.(1993)
	Mitsubishi Motors	RD
DE-Hydro	Isuzu Motors	RD
Eco-Station 2000	(MITI)	Construct 2000 fueling stations for Alternativ Veh. by 2000
Plan in 2000	(MITI),(MOT)	Methanol: 10,000 u. Electric: 200,000 u. Total Alternative: 2,000,000 u.

Fig.12 Hydrogen Fueled Vehicle

Hydrogen-Fueled Car with a Low-Pollutant Level Exhaust (Double Over Head Camshafts, 4 cylinder, 16 Valves, 60 HP, Maximum Speed of Over 100km/h and Running Distance of Over 200km)



Work at Research Laboratories within MITI

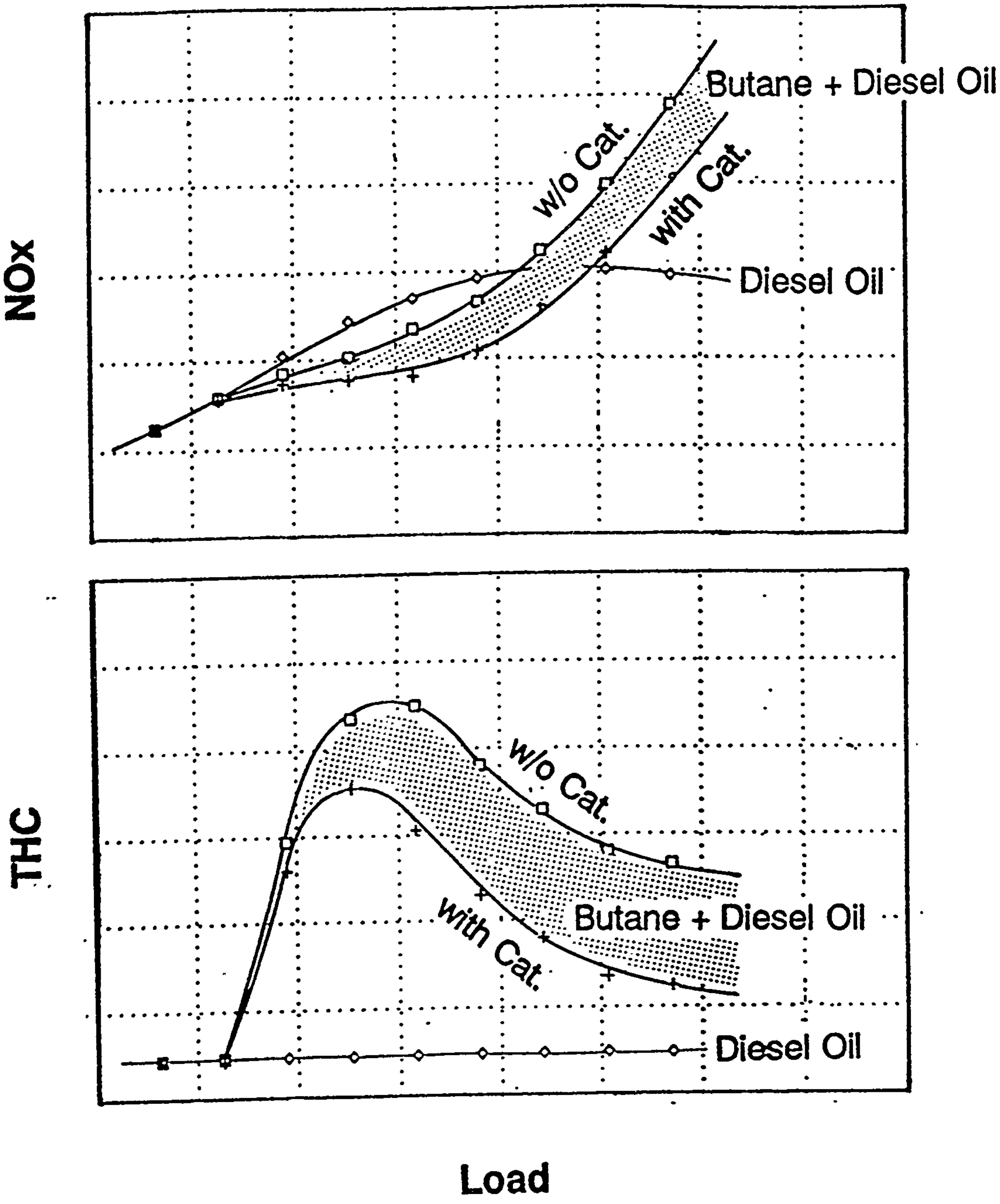
Diesel Engines:

- NOx Control
- Particulate Filter Trap
- de–NOx catalysts
- Butane fuel

Alternative Fuel:

- Electric Vehicle
- Hydrogen Vehicle
- Hydrogen–Oxygen Combustion
- Butane(LPG), CNG, Methanol

Fig.13 Butane Fueled Diesel With de-NOx Catalyzer



Potential Future Collaboration Area

1. National Projects:
    on R&D of Alternative Vehicles

2. Research:
    Diesel Engine Research
        - NOx Control
        - Filter Trapping
        - De–NOx Catalysts
    Alternative Fuel
        - Hydrogen (Otto and gasturbine)
        - LPG, CNG, Alcohol
        - Batteries and Fuel–cells for EV

3. Survey and Analysis:
    Implication of Energy, Environment,
    Economy, Policy and Society

Atmospheric Carbon Exchange Associated with Vegetation and Soils in Urban and Suburban Land Uses

Dr. Rowan A. Rowntree
Northeastern Forest Experiment Station
USDA Forest Service
PO Box 245, Berkeley, CA 94701
510-559-6491

A discussion paper prepared for the Second US/Japan
Workshop on Global Change
Environmental Response Technologies (Mitigation and Adaption)
February 1-3, 1993,
East-West Center, Honolulu, Hawaii

Urban Land Uses and Vegetation

In studies of the global C cycle prior to the 1980s, urban ecosystems were largely ignored, in part because there were inadequate measures of phytomass and soil carbon for the various land uses associated with cities (Bramryd, 1980). In the last decade, progress has been made in gathering urban vegetation data and recently, estimates of urban land use carbon storage and fluxes have been attempted (Rowntree and Nowak, 1992; Adger, et al., 1992; Nowak, 1993). Demographic trends in many countries suggest that urban areas are growing. Thus it is important to discover the appropriate concepts and methods for understanding greenhouse gas fluxes from urban-related vegetation and soils.

Measuring Urban Phytomass

Because urban vegetation ecology and measurement is a relatively unknown field, I will remark first about the status of work on estimating the amounts of vegetation in an urban area. It is useful to divide the metropolitan region into three domains: (1) That built up area having more than about 1000 people per square mile we will call the "urban area," (2) The outskirts of the city with lower population densities called the "suburban area," and (3) That area into which the city will expand, but which is not yet developed, called the "exurban area." To understand vegetation-based carbon fluxes from a metropolitan region, we need to know both the current attributes of trees, shrubs, and herbs in the land use classes of these three domains and the changes these domains are undergoing that might release or sequester more or less carbon. Thus, the purpose of urban vegetation measurement is to generalize about classes of vegetation as they are linked to classes of land uses. Then, if we can understand land use change, we can infer vegetation, phytomass and carbon change as Adger, et al., have tried to do in their study of "Carbon Dynamics of Land Use in Great Britain" (1992).

Geography of Urban Land Uses and Vegetation

At first glance, the diversity of species and forms making up the urban vegetation complex gives the impression of heterogeneity. However, there may be more regularity to urban vegetation patterns than first meets the eye, due to the way land uses are laid out and to the fact that human preferences for urban vegetation do not seem to vary extensively from city to city. We can generalize about the gross geography from studies such as Rowntree, 1984:

1. From above (viewing an air photo) one typically sees about 1/3 tree cover, 1/3rd herbaceous cover (including grass and lawns), and 1/3 artificial surfaces.
2. Residential is the most extensive land use class in most urban areas.
3. Commercial land use loci are often surrounded by residential and/or park land uses.
4. With growth, urban geography is transformed from the traditional form with a "central business district" surrounded by residential land to a "multi-nucleated" city with a more dispersed and fragmented pattern of land use having many important business centers.

How do these four points bear on our discussion of carbon flux? First, with larger cities, precise methods of remote sensing are needed to describe the fragmented geography of land uses and vegetation. Second, the urban climate -- which is important to energy consumption and carbon flux -- can be understand only by knowing about the migration of air parcels from more to less vegetated zones, and vice versa, within the fragmented geography of the modern city.

A more precise picture of the amounts of vegetation would reveal that most of the phytomass is in the residential land use class. Thus, if we understand how vegetation is, or could be, managed in this class to reduce carbon dioxide and other greenhouse gases, we would grasp the principal part of the problem. In a subsequent section, we'll see that actions by residential landowners are increasingly taking into consideration how vegetation on their property affects their use of energy, which in turn dictates the emissions of greenhouse gases from power plants.

It is not the purpose of this paper to describe urban vegetation measurement techniques, but it is noteworthy that good estimates of phytomass can be got by remote sensing, especially air photography at scales of 1:5000 to 1:10,000. Airborne videography is being tested, and we have evaluated most satellite-based sensors and found them wanting for adequate detail.

Estimates of Carbon in Urban Vegetation and Soils

Improving on a model described in Rowntree and Nowak (1991), Nowak (1993; most of the estimates to follow are from this citation) estimates urban tree carbon storage in the U.S at between 350-750 million metric tons (MT), depending on assumptions about the distribution of tree sizes across the U.S. To refine this estimate requires more tree size data from urban tree inventories. For comparison, Birdsey (1990) estimates that non-urban forests in the U.S. contain about 53 billion MT of carbon, but this includes soils and non-tree vegetation.

In these non-urban forests, in fact, the soils contain the majority of the carbon; Birdsey estimates 60%. We do not have estimates of carbon for urban soils. If we included carbon stored in urban soils and the non-tree vegetation, estimates of urban carbon would probably be in the vicinity of 1 billion MT.

Comparisons with U.S. Emissions

In the U.S., there is presently a movement to plant numerous urban trees, mostly in the residential land use class for the purpose, in part, of sequestering and storing carbon as well as for avoiding carbon emissions by reducing energy generation. A mid-range value of 400 million MT stored in U.S. urban trees is equivalent to about 4 months of U.S. carbon dioxide emissions. The annual net addition (about 6 million MT of sequestering) to the U.S. urban tree carbon store is equivalent to about two days of U.S. emissions. A moderate size city in the U.S. stores about 150,000 MT of carbon in its trees, equivalent to the amount of carbon emitted by residents' automobiles in 8 months.

According to Nowak (1993), planting 100 million trees in the U.S. can store and avoid (power plant emissions) up to 363 million MT of carbon over the next 50 years. He estimates this would be less than 1 percent of the amount of carbon estimated to be emitted by the U.S. over the 50 year period.

Carbon Releases from Urban Vegetation Fires

When we consider the role of vegetation in urban, suburban and exurban areas, we must consider episodic carbon exchanges, particularly due to fire. In the western U.S.

forest fires are frequent. In this region of the nation there is a significant migration of people to exurban areas where they settle in a dispersed pattern amongst native forests. This increases the frequency of human-induced fires which are difficult to bring under control because (1) fire fighters must first protect residences, (2) phytomass (fuel) has increased over the decades of fire prevention and suppression, and (3) periods of drought increase flamability. "Urban-wildland" fires constitute a large source of vegetation-related carbon release.

In contrast to urban-wildland fires where the settlement pattern is dispersed, the discrete edge of the urban or suburban areas of many cities join with wildland vegetation that, if ignited, will start a fire that will carry into the urban area. This happened in the city of Oakland, California, in 1991. Ten percent of the city's phytomass existed in the fire area, but the amount of that released as carbon has not been estimated, because many trees were only partially consumed in the fire. If they had been completely burnt, the release of carbon from urban vegetation would have been on the order of 15,000 MT.

Urban Vegetation to Reduce Energy Consumption and Avoid Power Plant Emissions

There are four areas where research has indicated potential energy savings and reduction of power plant emissions of greenhouse gases: (1) Summer shading of residences with trees that allow winter solar access for heating, (2) trees used for winter windbreaks, (3) air cooling by evapotranspiration (ET) of urban vegetation, and (4) the lightening of exterior building surfaces to increase radiation reflection and decrease the need for air conditioning.

Reducing Air Conditioning by Shading Buildings

McPherson and Dougherty (1989) employ a simulation model (from McPherson, et al. 1988) to estimate how much energy savings will occur using different types of trees at various locations around a building depending on climate patterns. This model has been tested in residential buildings. Huang, et al. (1987) have used a different simulation model being tested in residences (Akbari, et al. 1992). It is now believed that the use of appropriate trees for summer shading can reduce residential air conditioning costs by 10-40%.

Trees for Winter Windbreaks

Heisler (1991) uses computer simulation to report that windbreaks around homes in relatively exposed locations in the north central region of the U.S. will save up to 25% of annual heating and cooling costs. The combined effects of trees in residential neighborhoods, planted for shading and air cooling, can have strong windbreak effects (Heisler 1990). This may reduce winter-heating requirements, but also may impair summer breezes that remove heat from buildings, thus eroding the positive effects of shading and ET air cooling.

Trees for Air Cooling

Recent research has focused on testing the hypothesis that increasing urban tree cover reduces air temperatures and the "urban heat-island effect." McPherson, et al. (1989) and Simpson (1991) report on experiments and simulations to determine the most energy- and water-efficient landscaping for urban buildings. Taha, et al. (1991) report on an experiment in an orchard that shows even a small area of tree canopy (150 x 307 m) reduces air temperatures by about 2 degrees C. The extent to which adding trees to cities can cool the urban air mass continues to be of interest to planners and energy analysts, but there have been inadequate field tests to construct a reliable equation. Current work by Simpson and McPherson (1993) in Los Angeles, in cooperation with the Southern California Edison Co., is one of the first scientific field tests in urban landscapes that will measure differences in air temperature among neighborhoods of different tree cover.

Increasing Building Reflectivity

Akbari, et al. (1990) reports from field experiments that there is a significant decrease in building air conditioning demand when the roof and exterior wall colors are lightened. They found that the combined effects of shading, air cooling, and lightening of surfaces (increasing building albedo from 30 to 70%) produced annual air conditioning savings of up to 50%. It is not clear what the effects on vegetation and people will be if the reflectivity of urban buildings is increased. A portion of the ultraviolet (UV) radiation will be reflected and it is expected that human and vegetation UV burdens would increase, but we do not know in what amounts.

In summary of this section, it appears that significant reductions in energy use and associated power plant greenhouse gas emissions can be accomplished with appropriate management of vegetation and building color. With future research, this understanding will be extended to other surfaces and plantings, for example in parking lots which have important influences on urban climate, energy use, and greenhouse gas exchange with the atmosphere. Electric utility companies in the U.S. are joining in research to determine how urban vegetation can be managed throughout their service areas to reduce energy consumption, sequester carbon, and reduce greenhouse gas emissions.

Discussion

I suggest that a useful approach to understanding the role of urban areas, and urbanization as a land conversion process, in global climate change is to view the problem and the possible solutions within a hierarchy of spatial and temporal scales using the ecosystem concept. By doing this, we can understand how the aggregate of individual urban land use actions will be manifested at the regional scale, reverberating throughout the mosaic of coupled ecosystems, and how the consequences of these individual actions will bear on future generations. This approach helps us to see why urban areas, which cover a small proportion of the earth's surface, produce effects that are on a scale to be of interest to global change.

Currently, we are trying to understand the urbanization process as it transforms agricultural, forested, grassland, and wetlands into a landscape of mixed natural and artificial surfaces. Traditional views of the urban-rural dichotomy may have to be discarded as new telecommunications technology allows people and employers to disperse across the landscape. The regional fluxes of energy, water, gases and particulates from these mixed-surface and human-dominated landscapes must be modeled at different scales. The research reported above helps us to construct those models at different scales so that land planning and management policy and decisions can be guided in a coordinated way from residents' actions up the scale to long-term ecoregional policy. An important question is how do we integrate human values and actions into these hierarchical models? If we must manage global landscapes to mitigate climate change, a prime candidate class of landscapes is that influenced largely by present or future urban land use. This is because the consequences of unguided urban development are large and the potential for mitigation is proportional to our ability to work through the people who control landscape function and change.

The ecosystem approach demands that we consider all functions of urban vegetation and soils at different scales, and the interaction of those functions as they influence or respond to climate change. In the text above, I did not discuss the need to know the amount of anthropogenic carbon released in order to plant, maintain and remove various combinations of urban vegetation. The ecosystem approach requires "total carbon accounting" rather than measuring just the carbon sequestered by additional urban trees. Furthermore, as urban land managers consider adding vegetation to reduce energy consumption and greenhouse gases, they must consider what adjacent ecosystems they may be impacting when water is transferred for large tree planting programs.

The course of urbanization transforms the vegetation and soil complexes of large landscapes in obvious and not-so-obvious ways. We are just beginning to understand the range and magnitude of these changes. The opportunity to discuss these in the context of international concern over global climate change is a perfect forum for understanding the interactions between the atmosphere and landscape containing a mix of urban, suburban, and exurban land cover.

Literature Cited

Adger, W.N., Brown, K., Shiel, R.S., and Whitby, C. 1992 Carbon dynamics of land use in Great Britain. J. Environ. Mngt. 36:117-133

Akbari, H., Rosenfeld, A.H., Taha, H. 1990 Summer heat islands, urban trees, and white surfaces. ASHRAE Transactions, Vol. 96, Part 1:AT-90-24-1

Akbari, H., Bretz, S., Hanford, J., Rosenfeld, A., Sailor, D., and Taha, H. 1992 Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District Service Area. Final Report. Energy Analysis Program, Lawrence Berkeley Laboratory, Berkeley, CA.

Bramryd, T. 1980 Fluxes and accumulation of organic carbon in urban ecosystems on a global scale. In: (Eds.) Bornkamm, L. and Seaward, C. Urban Ecology. Blackwell Scientific. pp. 3-12.

Heisler, G.M. 1990 Mean windspeed below building height in residential neighborhoods with different tree densities. In: ASHRAE Transactions, 1990, Vol. 96, Part 1:1389-1396.

Heisler, G.M. 1991. Computer simulation for optimizing windbreak placement to save energy for heating and cooling buildings. In: Third International Windbreaks and Agroforestry Symposium Proceedings. pp. 100-104.

Huang, Y.J., Akbari, H., Taha, H., Rosenfeld, A.H. 1987 The potential of vegetation in reducing summer cooling loads in residential buildings. J. Climate Appl. Meteor. 26:1103-1116

McPherson, E.G., Herrington, L.P., Heisler, G.M. 1988 Impacts of vegetation on residential heating and cooling. Energy and Buildings (12):41-51

McPherson, E.G., Dougherty, E. 1989 Selecting trees for shade in the Southwest. J. Arboriculture (15)2:35-43

McPherson, E.G., Simpson, J.R., Livingston, M. 1989 Effects of three landscape treatments on residential energy and water use in Tucson, Arizona. Energy and Buildings 13:127-138.

Nowak, D.J. 1993 Atmospheric carbon reduction by urban trees. J. Environ. Mngt. (In Press)

Rowntree, R.A. 1984 Forest canopy cover and land use in four eastern United States cities. Urban Ecology 8(1/2):55-68.

Rowntree, R.A., Nowak, D.J. 1992 Quantifying the role of urban forests in removing atmospheric carbon dioxide. J. Arboriculture 17(10):269-275

Simpson, J.R. 1991 Simulating effects of turf landscaping on building energy use. In: (eds.) Vine, E., Crawley, D., Centolella, P. Energy Efficiency and the Environment: Forging the Link. American Council for an Energy Efficient Economy, Washington, DC. pp. 335-347.

Simpson, J.R., McPherson, E.G. 1993 Indirect effects of vegetative cover on urban microclimate and air conditioning energy use in Southern California. Unpubl. Study Plan, USDA-Forest Service, Research Unit NE-4952, Berkeley, CA.

Taha, H., Akbari, H., Rosenfeld, A.H. 1991 Heat island and oasis effects of vegetative canopies: micro-meteorological field measurements. Theor. Appl. Climatol. 44:123-138.

Forest Management for Fixing and Sequestering Carbon

Gregg Marland, Virginia Dale, Robin Graham
Robert Luxmoore, Scott Marland, Samuel McLaughlin,
Richard Norby, W. Mac Post, Timothy Tschaplinski,
Jerry Tuskan, and Lynn Wright

Environmental Sciences Division
Oak Ridge National Laboratory*
Oak Ridge, Tennessee, 37831-6335
U.S.A.

for presentation to the
Second United States/Japan
Workshop on Global Change
1-3 February, 1993
Honolulu, Hawaii, U.S.A.

The concept of planting trees as part of a strategy to confront the possibility of global climate change is now widely accepted. As trees grow they remove CO_2 from the atmosphere and thus slow the atmospheric build-up of CO_2, an important greenhouse gas. Within the global-climate-change context, there are two fundamental problems with managing trees to store carbon. First, the magnitude of fossil-fuel related emissions of CO_2 is so large, 6 billion metric tons of carbon per year, that it takes very large areas of tree planting to make a significant impact. Second, as trees mature their rate of growth, and hence rate of net carbon uptake, declines. The large demand on land area suggests that there is a limit to the fraction of total CO_2 emissions that we might reasonably expect to offset with growing trees. The ultimate maturation of forests suggests that there is a limit on the length of time over which offsets are feasible and that we need to ask what to do as the rate of C uptake declines. Acknowledging that the availability of land will constrain the ability of tree planting to offset industrial emissions of CO_2, we consider how the land which is available can be used most effectively.

Our analysis speculates on how much land might be available for a forest management strategy motivated (at least partially) by concerns about climate change, but our principal focus is on how a given land area can be best used to minimize net emissions of CO_2 and how much might be achieved on a unit of land. We do not suggest that carbon management should be the principal criteria for land management, but we discuss the implications if it

---

* Managed by Martin Marietta Energy Systems, Inc., under contract DE-AC05-84OR21400 with U.S. Department of Energy.

were. Confronting global and local changes in climate will be one of many objectives in land management and we explore for the most effective strategy for pursuing this objective.

Land can be used to plant large areas of trees where there are not now trees and thus to withdraw CO_2 from the atmosphere and store it as carbon in the growing trees. This is what people generally have in mind when they talk about "offsets". A corollary to this strategy is to protect existing forests so that the contained carbon is not released to the atmosphere. However, if our objective is to minimize net CO_2 emissions to the atmosphere, land might be used not as an offset for CO_2 emitted, but in a way so as to prevent its emission in the first place. If we used forest or agricultural land to raise trees to be used as a fuel, an energy crop, we would reduce net CO_2 emissions to the extent that the renewable energy crop replaced fossil fuel use. In essence the carbon would be sequestered in unburned fossil fuels, and the net cumulative CO_2 reduction would continue to increase with every harvest cycle. We should, of course, also inquire whether managing trees under any strategy is the best use of land for confronting climate change. The primary source of anthropogenic emissions of CO_2 to the atmosphere is during the conversion of the chemical energy of fossil fuels to thermal energy to run our machines. If we covered land with a system for producing CO_2-free thermal or electric energy, e.g. with photoelectric cells, we could avoid much of our concern about carbon flows. To contrast this strategy with tree planting involves many aspects which are beyond the scope of this analysis, but we do touch on it by addressing the efficiency with which biomass energy systems can convert solar radiation into useful energy.

The two basic forest management strategies are represented in schematic form in Figure 1. The figure illustrates that a forest managed for carbon storage eventually matures and ceases to be provide a sink for carbon whereas a forest which is harvested regularly to maintain high growth rates, continues to provide a fuel offset indefinitely.

Figure 1 helps us to visualize the difference between using tree planting in a carbon sequestering strategy and in a fossil-fuel-substitution strategy, but it does not provide us with a realistic comparison. It does not show time or land area required. It does not address the productivity of forests, the energy inputs required to operate an energy plantation, or the efficiency with which biomass fuels can substitute for fossil fuels. It does not represent the importance of soil and below ground carbon or of the wide variability in all of the above factors in a real world. This analysis explores the shape of paths C and D in Figure 1 and the factors that define those shapes. It explores the potential of tree plantations managed as energy crops to minimize net emissions of CO_2. It starts by discussing the productivity of forests and how productivity varies in time and space and between natural and managed stands. It then discusses photosynthetic potential and the limits of productivity. With the atmospheric concentration of CO_2 increasing, we consider whether this is likely to accelerate tree growth and carbon uptake in managed and/or natural stands. The role of carbon storage in soils, especially as it relates to intensively managed and harvested stands is discussed. With this insight into potential productivity, the analysis looks at the quantities of land available in the U.S. as a function of productive potential and then at pressures on global forest resources and the prospects for protecting or increasing the areas in forest globally. The next section examines the important issue of fuel-use efficiency and the prospects for biomass fuels to replace fossil fuels. Two final sections consider whether "energy crop" necessarily means trees and whether large-scale changes in earth surface vegetation might have climate-change implications of its own -- through alteration of the terrestrial albedo or hydrologic balance. The paper closes with some speculations on the climatic impacts of energy plantations and some contrasts with carbon sequestering and storage in trees.

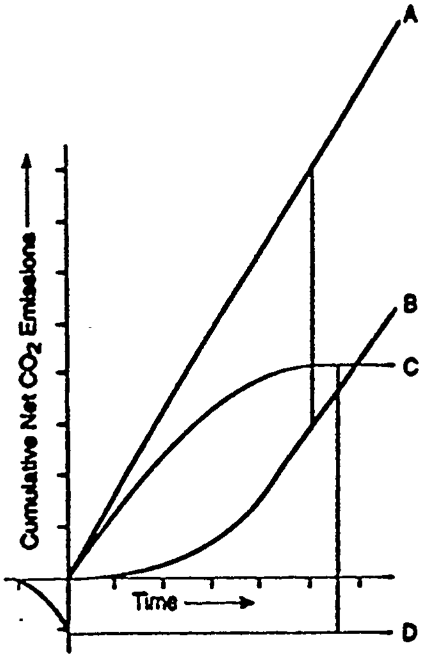


FIGURE 1: Schematic representation of cumulative net emissions of CO_2 as a function of time for various combinations of a coal-fired power plant and forest management strategy. Path A shows the uniform increase of cumulative net CO_2 emissions from the coal-fired power plant. If enough trees were planted so that CO_2 emissions from the power plant were exactly offset by the photosynthetic uptake of C in young, rapidly growing trees; path B would represent the cumulative net emissions for the sum of power plant and tree plantation. The latter part of path B shows net emissions growing parallel to those of path A as the mature forest stand no longer has a net uptake of carbon. Path C represents net CO_2 emissions when a sustained yield energy plantation is established after initial clearing and use of an existing forest stand. Path D represents the emissions from a power plant which burns wood from a sustained-yield energy plantation established on a site which was not previously occupied by forest. The path envisions a tree plantation started some years prior to operation of the power plant so that the plantation can be partially harvested each year to fuel the power plant with no net CO_2 emissions. The distance between paths C and D is related to the amount of carbon which was held in the pre-existing forest.

Figure 2 illustrates the interaction of some of the factors which will define the most effective use of land for minimizing net CO_2 emissions. Lines in the plot cross one another and the optimum solution, that is the solution with the highest average annual rate of net CO_2 sequestering, changes with the interacting factors. Recognizing that plantation management requires some input of resources and emission of CO_2, and that one Mg of C in a forest cannot substitute for one Mg of C in fossil fuel, results in the conclusion that managing trees to store carbon in the forest will be the most effective option on some sites. Managing for on-site storage of carbon will be favored where there is a large initial standing crop and low

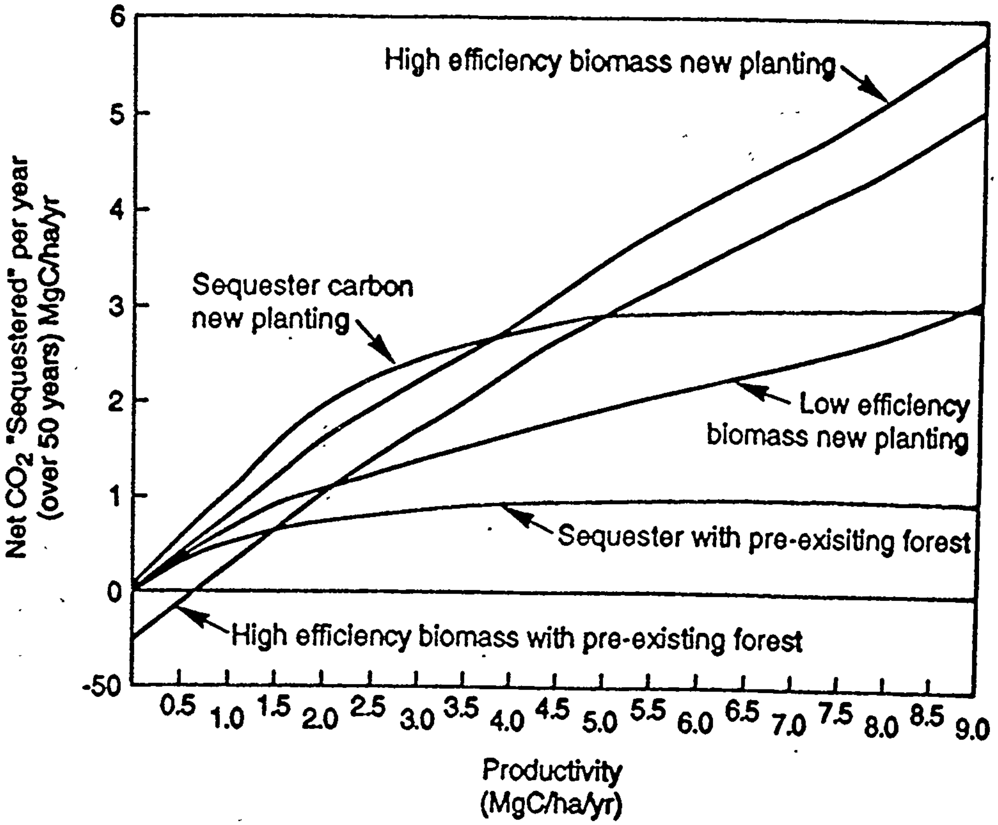


FIGURE 2: Output from a very simple model of carbon balance in a forest system (Marland and Marland, 1992, *Water, Air, and Soil Pollution*, 64:181-195) shows that biomass fuel plantations can, under some circumstances, result in more net "sequestering" of carbon than would simple storage of carbon in standing trees. The advantage of the biomass plantation increases with plantation productivity and the efficiency with which the biomass is produced and used, and depends on how the site was occupied prior to establishment of the plantation. This model run assumes that the maximum standing biomass which can be supported on the site is 150 Mg C/ha and that forest productivity is initially at the rate described on the abscissa but approaches 150 Mg C/ha asymptotically. Carbon "sequestered" includes both the increase in standing biomass and the offset of CO_2 emissions when biomass is substituted for fossil fuels. "High-efficiency" means state-of-the-art efficiency for plantation management and substitution for coal at an electric generating plant. "Low efficiency" is fuel substitution at half this net system efficiency and is near what might be envisioned for a system producing liquid transportation fuel from cellulose. Values for annual carbon sequestering are the average over 50 years. Consideration of longer time intervals would increasingly favor biomass fuels.

productivity and when there is a high energy cost or low efficiency associated with fuel harvest and substitution. Clearly these factors will affect both the carbon balance and the economics of biomass fuels. The questions for land management decisions involve the circumstances under which plantation forestry is the best choice and how much carbon offset is possible.

Taken qualitatively, Figure 2 begins to demonstrate that the optimal solution for land use depends on existing land use and on land productivity. It depends on the efficiency with which wood fuels can be substituted for fossil fuels and on the time period over which we choose to average. Analyses of soil carbon show similarly that the impact of different forest strategies will depend on the specifics of forest management, the initial state of soil carbon, and on the details of the setting. Our more comprehensive analysis is examining the importance of CO_2 fertilization for long-term sequestering, the impact that reforestation is likely to have on climate through changes in albedo and hydrologic regime, and the possible role of biomass crops other than tree species, i.e. herbaceous crops, as a replacement for fossil fuels. Climate change itself adds another level of detail to a complete analysis because any trees planted may be confronted with a changing physical environment and the changing climate could have positive or negative feedback on ecosystem response through its impact on carbon fluxes.

The prevailing view is that many variables will determine the optimal use of any particular parcel of land in terms of its impact on net emissions of CO_2 to the atmosphere. Using growing trees to store carbon on site will be the optimal choice on some low productivity sites but, in general, sites with good productivity will produce a greater reduction in net CO_2 emissions if they are used to produce a harvestable energy crop. The final choice of land use will, of course, have to consider economic factors and a variety of objectives in addition to carbon management.

Abstract

Natural Resources Management in an Era of Global Change

William T. Sommers
USDA Forest Service
Washington, DC

The international science community has issued a series of predictions of global atmospheric change that, if they verify, will have heretofore unexperienced impact on our forests. Convincing the public and their natural resource managers to respond to these effects must be high on the agenda of the science community. Mitigative and adaptive responses we examine and propose, however, should stem from an understanding of the evolving role of the natural resource manager and how that role might be affected by global change.

Three biological systems - croplands, forests, and grasslands (savannahs) - support the world economy and are critical to the global environment. Forests are the most widespread land-based ecosystem on Earth. They play many roles in providing for the economic and environmental well being of human kind. Paleoecological evidence demonstrates that forests have undergone massive changes in association with previous changes in climate.

At their post-glacial peak, forests are estimated to have covered 6.2 billion hectares of the Earth's surface compared with a coverage today of 4.2 billion hectares. In the United States, the retreating glaciers yielded to forests that covered 380 million hectares. About 300 million hectares of the United States is tree covered today, despite large increases in population, industrialization, and urbanization that have occurred in last three and half centuries.

Forest management has its roots in the conservation and manipulation of forest wildlife habitat for hunting purposes and for the protection of timber for its commodity value. Today's forest managers are faced with a much broader array of social, ecological, and economic demands that they must balance while pursuing sustainability of the global forest resource. The linkage of forests and climate combined with prediction of climate change, and other aspects of global change, will place unprecedented pressure on forest managers as they attempt to respond to multiple interacting demands.

Mitigative and adaptive strategies for responding to potential climate change are presented that consider the role of the natural resource manager. Mitigative responses are framed under three strategies -- a "carbon" strategy; an "energy substitution" strategy; and an "energy demand" strategy -- that place the decision burden at the national policy level and could be reasonably implemented by resource managers. Adaptive responses will be need if climate change predictions verify. These responses must be much more localized and specialized to the particular resource condition and social circumstances present. The burden of adaptive strategies will fall on the natural resource manager -- not national policy makers -- and make those individuals pivotal in responding to global change. Six strategies are presented for developing adaptive responses.

Forest Management Techniques for Carbon Dioxide Storage

Takao Fujimori

Forestry and Forest Products Research Institute
Tsukuba, Ibaraki 305, Japan

1. Purpose and Background

In the global ecosystem concerning carbon dioxide content in the atmosphere, the forest ecosystem plays an important role. In effect, the ratio of forest biomass to total terrestrial biomass is about 90%, and the ratio of carbon stored in the forest biomass to that in the atmosphere is two thirds. When soils and detritus of forests are added, there is more C stored in forests than in the atmosphere, about 1.3 times or more. Thus, forests can be regarded as the great holder of C on earth.

If the area of forest land on the earth is constantly maintained and forests are in the climax stage, the uptake of C and the release of C by and from the forests will balance. In this case, forests are neither sinks nor sources of CO_2 although they store a large amount of C. However, when forests are deforested, they become a source of C; through human activities, forests have become a source of C. According to a report by the IPCC, 1.6±1.2 PgC is annually added to the atmosphere by deforestation. According to the FAO (1992), the area of land deforested annually in the tropics from 1981 to 1990 was 16.9 x 10^6 ha. This value is nearlyhalf thearea of Japanese land. The most important thing for the CO_2 environment concerning forests is therefore how to reduce deforestation and to successfully implement aforestation or reforestation.

It is also important when managing forests not to degrade them, that is, it is crucial to maintain the productivity and to preserve the forest soils. Therefore, sustainable management techniques for forests are required.

To raise the capacity of the forest stand, following management techniques are proposed. Firstly, the biomass of the stand should be increased then maintained at a certain high level with gradual and partial regeneration which is done with partial harvesting of old matured trees whose net production has become very small. Secondly, plantations should be established and maintained which have a larger stand biomass.

The restriction of deforestation and aforestation is urgently necessary in tropical regions. However, this requires fundamental political and social countermeasures, for example, guaranteeing the life of the inhabitants and securing the protection of the forests. Forestry techniques such as how to aforestate and how to rebuild degraded forests into valuable ones could be offered. Japan is working on various cooperative projects to establish social forests, environmental forests, and industrial forests in developing countries. Agroforestry is an important compromise system between agriculture and forestry, which has an agricultural base. Cooperation between various disciplines is necessary to protect, preserve, and recover tropical forests. However, in this report, discussion focusses on pure forestry techniques, especially on how to preserve soil quality and raise or maintain stand biomass.

2. On-going research and future plans

Preservation of productivity

Forest productivity is maintained by the forest ecosystem, i.e., through normal turnover of energy and materials such as water, carbon, and minerals. In this ecosystem, the composition and function of the forest soil is especially important as it develops over many years through the accumulation of fallen leaves and branches, the activities of soil fauna and microbes under the shade and mild microclimate created by the forest. Well-developed soils hold much water and air, and contain sufficient minerals and carbon which are the basic conditions for high productivity as well as for storing C and acting as a watershed. Once a forest is clearcut or destroyed, it takes at least several decades for the soil to recover to its condition before the clearcut.

The general pattern of forest development after clearcutting or disturbance is shown in Fig. 1. It takes about 10 years or so until the dominant tree species close the stand, during which time various plant species, both herbaceous and tree species, appear and compete severely. For the first several months, the soil is exposed to the sun, wind, and direct raindrops, which destroy the subtle structure of the soil and the broken fragments are removed by the overland flow or wind. Up to the second year, the stand is covered mainly with grasses. As the years go by, tree species gradually dominate. The stage during which the stand is closed by a few dominant species is referrd to as the stem exclusion stage. Entering this stage most of species which were prevalent in the stand initiation stage are eliminated and new species can seldom invade during the stem exclusion stage because sun light is mostly absorbed and reflected by the closed canopy. Consequently understory vegetation becomes scarce and soil development slows due to direct impact of raindrop on the soil and litter which brings about erosion of the soil. This phenomenon is more pronounced as the inclination of the stand increases. The stem exclusion stage lasts 30 years or so in Japan.

As the age of the stand approaches 40 to 50 years old, the light intensity on the forest floor gradually increases, which allows invading and surviving understory vegetation to exist, although its growth is very small. During this stage, the structure of the forest soil returns to its condition before the disturbance of the forest. This stage is called the understory reinitiation stage. In this stage, the stand biomass still continues to increase although the rate is not as high as in the younger stage (10 to 40 years) (Fig. 2). The understory reinitiation stage lasts 100 years or so in many of the forests of main species in Japan. After the understory reinitiation stage, dominant trees in the overstory gradually die by old age or wind damage, and young trees grow up from the understory to the overstory in the gaps created by the death of old trees. This stage is called the old growth stage or climax. In this stage the biomass of the stand reaches a constant as the amount of growth and death every year in the stand balances. Therefore, the uptake and release of CO_2 by and from the stand balances, with large amount of C stored in the stand.

The dynamics of biomass as the stand develops is schematically shown in Fig. 2. In the stem exclusion stage, the rate of increase of biomass is large, gradually decreasing during the understory reinitiation stage and reaching a biomass maximum in the later part of the stage. Then around the beginning of the old growth stage, the biomass decreases to a certain extent where it remaines constant through the old growth stage. In the clearcutting system, the long rotation system has the merit of pursuing understory reinitiation stage, while the short rotation system pursues that of the stem exclusion stage. The selection system should imitate the old growth stage by harvesting the dominant trees gradually in the understory reinitiation stage before they deteriorate.

The dynamics of the biomass in relation to the silvicultural systems mentioned above are schematically shown in Fig. 3. The biomass in the stand with the selection system maintains a certain high level. The biomass in the stand with a long rotation system has a large range, from zero to the largest biomass in the later part of the rotation. In this rotation system, thinning is usually repeated and the biomass fluctuate a little accordingly, but it was evolved with a single curve. Total amount of biomass over a long time in both stands is simillar for both the selection system and the long rotation system. On the other hand, the total amount of biomass in the stand with a short rotation system is small. Therefore from the view point of C storage, the selection system or long rotation system is desirable. When sustainable management for the soil is also considered, the selection system is probably best.

The most popular rotation interval for the production of saw timber mainly for structural components of buildings in Japan has been 40 to 50 years. This is because the largest number of logs of the right size for standard size square timber can be harvested after a relatively short period which close to the peak of the average annual growth rate. The theory of harvesting at the time of highest average growth rate is reasonable for producing wood for biomass uses like fuel and pulp, but it is not reasonable for producing saw timber, because the quality of wood and harvesting rate of timber from logs increases as stand age increases until the later part of the understory reinitiation stage. Due to the high cost of regeneration including weeding, such short rotations as 40 to 50 years for the production of saw timber has been criticized in Japan: In Japan, weeding must be done 5 to 8 times to regenerate the plantation after clearcutting.

To combine the demands made on forests, that is, the sustainable storage of C and the production of as much timber as possible, systems with a long rotation, harvesting by repeated thinning, regeneration without clearcutting, the selection system, or a mixture of these are desirable. The diversity of species and the watershed function must also be maintained. Such systems have rerely been used for forest management in Japan and in most of the world. However, in Japan these systems have been gradually developed and promoted officially and privately for the last 5 to 10 years. Even so, there are still barriers against it. The main reason is that managers are likely to want a large harvest in a short period (without an overall or long term view) and they want to harvest cheaply. To remove the barriers, it is necessary to improve the laws and subsidies available to meet the current demands of society and the current theories of forestry, as well as to spread awarenes of the theories and techniques of the ideal systems. It must be emphasized that forest management must satisfy the social demand on the forests and contribute to the environment.

The benefit of the long rotation system was emphasized above, but the short rotation system with clearcutting is necessary to produce pulp and fuel wood. To maintain the soil quality, the forests which are kept by this system must be on flat land or only a gentle slope. The species which grow fast and can regenerate by sprouting are required for this system. Regeneration by sprouting is necessary so that the open stand can be closed earlier both for production and the environment. Vigorous sprouting is generally found in young hardwood trees, so sprouting system cannot be adopted for coniferous forests and the long rotation system. Most products of the short rotation system have a short life span, that is, stored C is quickly released to the atmosphere through combustion or decay. Even so, so long as the forests regenerate and maintain the same productivity, the forests are fixing C to at least the same level as is being released from the products. Therefore, provided that products from the forests are used and the forests sustained, CO_2 in the atmosphere does not increase. Thus, how to sustain the productivity of the forest (soil quality) in the short rotation system is very important. Slashes should be left in the stand as far as possible.

Significance of plantations

To increase the amount of C stored in forests, the establishment of plantations is effective. Desired species used for plantations have a high growth rate and the growth which lasts longer, thus accumulating the production matter in a large biomass. Under natural conditions, most species cannot usually establish themselves on their best site mainly due to interspecific competition. So if we plant seedlings of desired species on its most suitable site and control interspecific competition, C storage should increase. In Japan, this can be found typically in sugi (Cryptomeria japonica D. Don) plantations.

Under natural conditions, sugis grow on comparatively dry or poor sites as a result of interspecific competition. The best site for sugi is wet to moderate sites which are generally occupied by broad-leaved species. When we establish sugi plantations on the best sites, the productivity and biomass is far larger than those for natural forests. The growth rate of sugi is high after the first five years or so after germination and it maintains a fast growth longer, then becoming the largest tree and a stand of it on a suitable site will have largest biomass in Japan. As the quality of wood is preferable for saw timber, sugi is the most popular species for plantations in Japan, and adequate management of sugi plantations contributes also to the storage of C.

Japan has 400 year history of plantations, and from the 1950s to 1960s, plantations have been aggressively established officially and privately. The ratio of the area of plantations to the area of whole forest lands is now 40%, and Japan is said to hold 10% of the world plantation area. This is a large figure for the small area of forest land in Japan compared to the world. In the growing stock of plantations, the ratio of conifers is 99%, while in the growing stock of natural forests, the ratio of hardwood is 71%. The ratio of sugi plantation area to whole plantation area is about 40%.

According to a data in the Annual Statistics on Forestry edited by Forest Agency (1992), annual stem volume increment of plantations and natural forests in Japan are 12.5 x 10^6 m^3/yr and 6.1 x 10^6 m^3/yr, respectively. The value of the plantations is thus 2 times as much as natural forests. Since the plantation area is 67% of natural forests, the growth rate of plantations is 3 times as much as natural forests. Much of this must be due to plantations being established on better sites and the average stand age of plantations must be younger than that of natural forests. However, even if such factors are considered, it is clear that the ability of plantations to fix C is far larger than that of natural forests.

The amount of C annually fixed by forests in Japan was estimated from the data in the Annual Forestry Report edited by Forest Agency (1991). Stem volume increments in plantations and natural forests were obtained by averaging the increased volume from 1986 to 1989. Stem volume harvested was obtained by averaging the harvested stem volume from 1986 to 1988. The calculations were made with the following assumptions:

① Total amount of C fixed is the sum of the net production of aboveground and underground biomass and increased organic matter in the soil.
② Net production of climax forest is zero, but most forests in Japan have a positive net production.
③ Carbon stored in leaves becomes C in organic matter in the soil after they fall. The amount of annual litter fall and decomposed organic matter in the soil are constant. So the C in the soil is constant.

Carbon annually fixed by forests in Japan [MgC]
= (Stem volume increment in plantations + stem volume increment in natural forests + Stem volume harvested) [km^3]
x (Biomass increment of Stem + Branch + Leaf + Root/Biomass increment of stem) x specific gravity [Mg/m^3] x ratio of C in the weight of dry matter
= (59,250 + 9,500 + 38,820) [km^3] x (1 + 55/45) x 0.45 [Mg/m^3] x 0.5
= 53.8 TgC/yr

As estimated above, about 54 TgC is being accumulated annually in the forests in Japan. According to the Environment Agency (1992), the average annual amount of C produced by a person in Japan in 1990 was 2.7 MgC. Thus Japanese forests fix C for 20 x 10^6 people every year. The contribution of plantations in this figure can be approximately evaluated. From the accumulated data, in the later part of the understory reinitiation stage, the general stand biomass of a sugi plantation is about 500 Mg/ha or more, while that of natural hardwood forests is below 300 Mg/ha. Therefore, both from the view point of the fixation rate and the storage capacity of C, plantations are very significant.

Plantations play an important role not only for producing goods but also for the high fixation rate and storage of C. However, if the selection of sites is inadequate, the effect is the reverse, and the sites must be properly managed. Widespread plantation degrades both the diversity of species of plants and animals. The distribution of plantations should be done carefully and a mosaic pattern of plantations and natural forests is desirable.

3. Future View for Cooperative Research with the U.S.A.

The following information needs to be exchanged.

① Estimation method of C fixation and storage in a stand in relation to the stand development involving the soil and stand management.
② How to modify the traditional silvicultural systems or establish new ones to maintain high storage of C based on the information from ①.

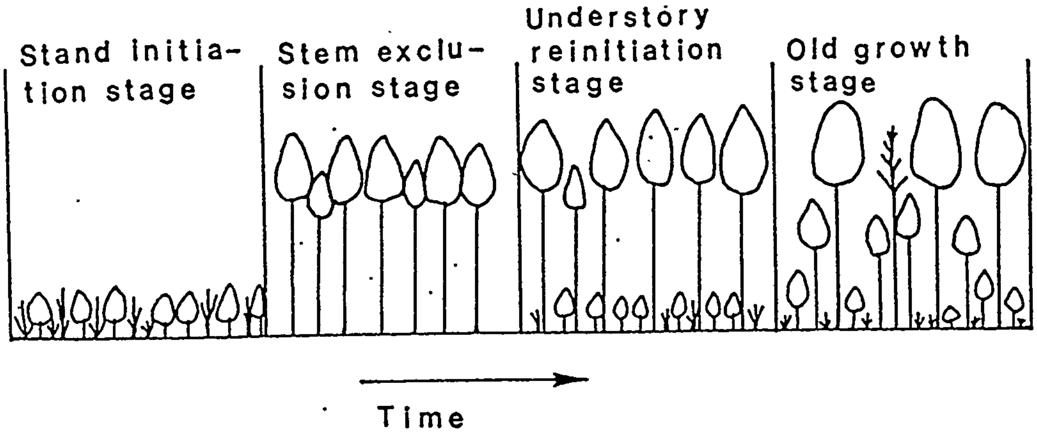


Figure 1 Stand development pattern
Terms of the stage were based on Oliver (1982).

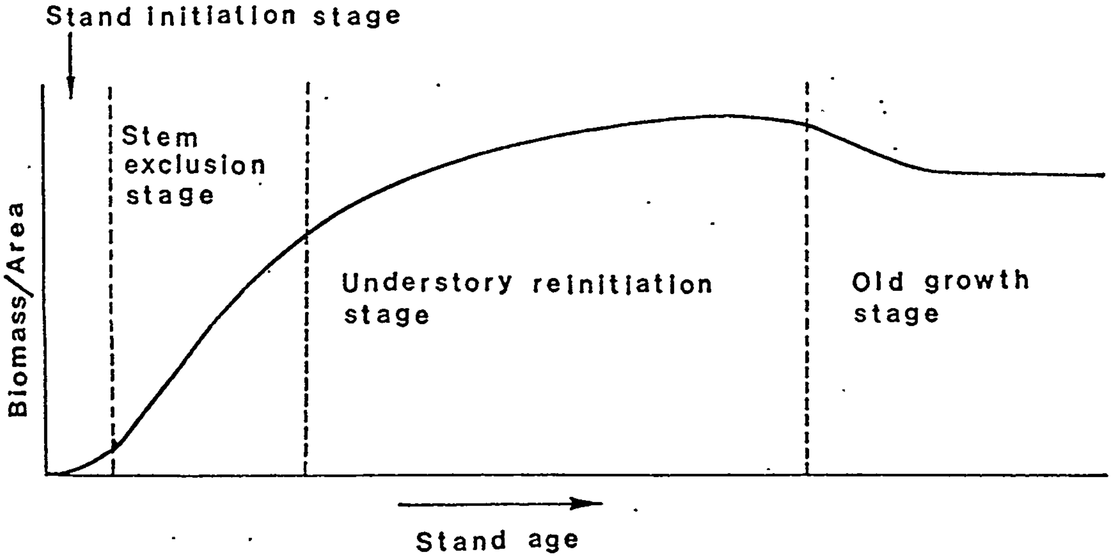


Figure 2 Dynamics of biomass with stand age

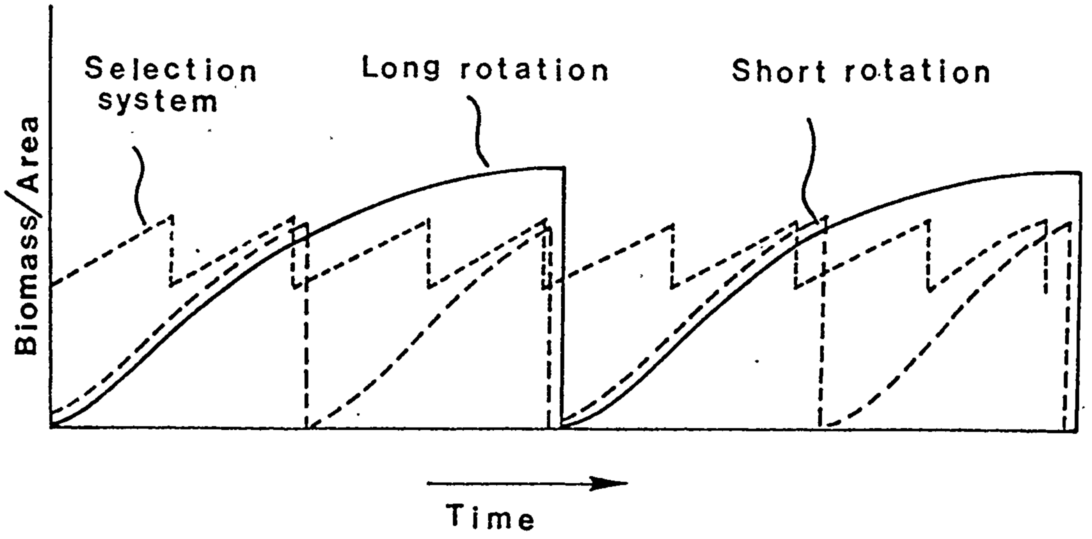


Figure 3 Dynamics of biomass in relation to silvicultural systems

Adaptation Responses of Crops to Climate Change

Hiroshi Seino

National Institute of Agro-Environmental Sciences
Kannon-dai, Tsukuba, Ibaraki 305, Japan

Purpose and Background

Appreciable global climatic responses to increasing levels of atmospheric CO_2 and other trace gases are expected to take place over the next 50 to 80 years. Increasing atmospheric concentrations of carbon dioxide and other greenhouse gases are producing or will produce changes in the climate of the Earth. In particular, numerous efforts of climate modeling project very substantial increase of surface air temperature. In addition to a general warming of the atmosphere, the possibility of increased summer dryness in the continental mid-latitudes has been suggested on the basis of both historical analogues and some General Circulation Model (GCM) studies.

There are three types of effect of climatic change on agriculture: (1) the physiological (direct) effect of elevated levels of atmospheric CO_2 on crop plants and weeds, (2) the effect of changes in parameters of climate (e.g., temperature, precipitation, and solar radiation) on plants and animals, and (3) the effects of climate-related rises in sea-level on land use.

The direct effects of elevated CO_2 are on photosynthesis and respiration and thereby on growth, and there are additional effects of increased CO_2 on development, yield quality and stomatal aperture and water use. A doubling of CO_2 increases the instantaneous photosynthetic rate by 30% to 100%, depending on the other environmental conditions, and reduce water requirements of plants by reducing transpiration (per unit leaf area) through reductions in stomatal aperture. A doubling of CO_2 causes partial stomatal closure on both C_3 and C_4 plants (approximately a 40% decrease in aperture). In many experiments this results in reductions of transpiration of about 23% to 46%. However, there is considerable uncertainty over the magnitude of this in natural conditions.

Agricultural production is one area where consequences of climate variations are felt particularly strongly, therefore agriculture is expected to be especially vulnerable to climatic changes. It has been suggested that a warmer and drier climate in central North America as predicted by GCMs could result in crop yield decreases, and shifts of major cropping areas.

Furthermore, the symptoms can be seen in many places in the form of land degradation and environmental pollution. Climate change has a possibility to accelerate those symptoms.

Our main interests are the quantitative understanding of effects of climatic warming on crop production and of possible adaptation strategies to counteract the negative effects of climate change on crop production.

Ongoing Research and Future Plan

(1) Ongoing research

Uchijima and Seino (1988) described that agroclimatic resources, particularly thermal, and net primary productivity would be very sensitive to the climate changes which might occur by about the middle of the twenty-first century.

Uchijima (1987) showed that the increase in mean temperatures of about 3 degrees C could open up most of the area below about 600 m altitude for rice cultivation and the yield index of present rice varieties may be increased by about 5% in Hokkaido and by about 2% in Tohoku under the 2 x CO_2 GISS scenario.

Horie (1987) showed that the rice yield in Hokkaido could increase by the adjustment of rice production technology to the changed climate, e.g., selecting alternative rice varieties, changing the planting date and procedures, and modifying the management of nutrients and weather, using a simulation model for rice.

Seino (1992) simulated the changes in crop yield under the doubling CO_2 climate using crop models and climate change scenarios projected by general circulation models. The results showed that a temperature increase could have results in crop yield decrease in many regions in Japan under the present management system. While the direct beneficial effects of CO_2 may compensate for the yield decrease in central and northern Japan, they do not compensate for the larger yield decreases in southwestern Japan. Seino also described that early planting and irrigation are possible adaptation strategies for the management systems to climate change.

(2) Future plan

Several adjustment of agricultural practice are anticipated to adapt to changing climate. There are selecting alternative varieties, changing the planting dates and sowing procedures, and modifying the management of nutrients and water. We need to advance the studies on possible adaptation strategies of management systems to climate change. An agroecosystem model is also needed to assess the climate change effects on agriculture, and make possible adaptation strategies. Furthermore, the symptoms can be seen in many places in the form of land degradation and environmental pollution. It is needed to adopt a concept of sustainable agriculture. To advance these studies, the use of systems methodology and of modern information technology is needed.

Future View for Collaborative Research with USA

Simulation model of crop is a useful tool for climate change impact and sustainability assessment. Some simulation models of crop are developed in U.S. and Japan. The model developments for crops are:

1) the addition of new crop models
2) the refinement of existing models of growth, development and yield
3) the development of modules to enable simulation of key pest, weeds and diseases and their effect on the photosynthetic respiratory and reproductive capacity of crops and their final expression as yield loss
4) the assessment of adaptation strategies for new agriculture management under the climate change conditions.

The model developments for soil and water are:

1) refinement of existing models of soil and water process
2) addition of modules dealing with phosphorus, potassium and sulphur dynamics
3) modeling of biological nitrogen fixation process, organic matter turnover, soil erosion, nutrient loss, pesticide movement, and water quality

Rising Atmospheric CO_2 and Crops: Research Methodology and Direct Effects

Hugo Rogers
National Soil Dynamics Laboratory
ARS-USDA
P. O. Box 3439
Auburn, Alabama 36831

Basil Acock
Systems Research Laboratory
ARS-USDA
Bldg. 011A-165C, BARC-West
Beltsville, Maryland 20705

Carbon dioxide is the food of trees and grass. Our relentless pursuit of a better life has taken us down a traffic jammed road, past smoking factories and forests. This pursuit is forcing a rise in the atmospheric CO_2 level, and no one know when and if flood stage will be reached. Some thinkers have suggested that this increase of CO_2 in the atmosphere will cause warming. No matter whether this prediction is realized or not, more CO_2 will directly affect plants. Data from controlled observations have usually, but not always, shown benefits.

Our choices of scientific equipment for gathering CO_2 response data are critical since we must see what is happening through the eye of the instrument. The signals derived from our sensors will ultimately determine the truth of our conclusions, conclusion which will profoundly influence our policy decisions. Experimental gear is selected on the basis of scale of interest and problem to be addressed. Our imaginations and our budgets interact to set bounds on our objectives and approaches. Techniques run the gamut from cellular microprobes through whole-plant controlled environment chambers to field-scale exposure systems. Trade-offs exist among the various CO_2 exposure techniques, and many factors impinge on the choice of a method. All exposure chambers are derivatives of three primary types--batch, plug flow, and continuous stirred tank reactor. Systems for the generation of controlled test atmospheres of CO_2 vary in two basic ways--size and degree of control. Among the newest is free-air CO_2 enrichment which allows tens of square meters of cropland to be studied.

Carbon dioxide is the first molecular link between the atmosphere and the food chain of the entire biosphere. It enters via the photosynthetic mechanism of green plants which are the primary food source for the rest of the planet's living organisms. The carbon from CO_2 not only supports and powers plant life but also regulates its vital functions. As a crucial feedstock to plant productivity, its increase often leads to enhanced crop yields. But because a plant's reaction is species-specific, surplus atmospheric CO_2 could lead to altered plant competition, subsequently resulting in shifts in community structure. Carbon dioxide interacts with other factors that influence the growth of plants and has often been experimentally observed to ameliorate some stresses.

Knowledge gaps dictate priority targets for future research. Our understanding of the effects of increased CO_2 on photosynthesis (especially acclimation), respiration, and water relations should be sharpened. Below ground responses--root growth, rhizosphere microbiology, and soil processes--should be studied. Carbon dioxide's interactions with other physical variables (such as tropospheric O_3 and ultraviolet-B radiation) need further study. Biological interaction including competition in the ecosystem context must also be investigated. Finally, the role of rising CO_2 in the global carbon cycle--flux and storage--has to be elucidated. Our well-being and our economic welfare really depend upon both natural and agricultural plant systems, systems that are tuned to the influx of atmospheric CO_2 and changes in related factors.

Mitigation Strategies for Methane Emissions from Agricultural Sources

John M. Duxbury, Cornell University

Preliminary Abstract for US Japan Workshop

Anthropogenic emissions of CH_4 account for 70% of total global emissions of this greenhouse gas. Current anthropogenic emissions of CH_4 in the US are estimated to be between 24-30 Tg CH_4 or 7-9% of the global anthropogenic total. By comparison the US is responsible for 27% of anthropogenic emissions of CO_2 from fossil fuel use. Table 1 shows that the major anthropogenic sources of CH_4 in the US are landfills (37%), domestic livestock and livestock waste (31%) and the coal mining/natural gas/petroleum industries (28%). On a global basis it is estimated that US landfills contribute 30% to the global landfill total, whereas livestock (including waste) and the coal mining/natural gas/petroleum industries each contribute about 8% to their respective global totals. The US is an insignificant contributor (<1%) to global emissions of CH_4 from rice paddies.

The latest data from the IPCC (Table 1) shows that agriculture is responsible for 46% (or 57% if biomass burning is included in this category) of global anthropogenic emissions of CH_4. The IPCC now estimates that CH_4 emissions associated with livestock are greater than those from rice paddies - 29 and 17%, respectively of the global anthropogenic total; however the rationale for reducing the global estimate of CH_4 emissions from rice paddies is questionable.

Research by US scientists has addressed all agricultural sources of CH_4 and has been directed towards improving knowledge of source strengths and identifying mitigation strategies. Some research has also addressed the impacts of land use change on CH_4

oxidation by soils. US scientists and agencies, especially the Environmental Protection Agency, have been involved in assessment and evaluation activities at the global scale. A primary objective of the US EPA Climate Change Program is to identify and evaluate options for stabilizing or reducing global CH_4 emissions.

Emissions of CH_4 directly from ruminant animals are estimated to account for 22% of the global anthropogenic total and about 70% of these emissions are associated with cattle. The fraction of feed energy converted to CH_4 has long received considerable attention because this reduces the efficiency of feed utilization and hence animal productivity. Methane generation by ruminant animals is dependent upon feed quality being higher with low quality forages. For cattle fed straw, as much as 15% of the digestible energy may be converted to CH_4. It is estimated that 70% of the world's cattle (including buffalo) are in developing countries where feed is usually of poor quality compared to developed countries. Strategies for mitigation of CH_4 emissions from ruminant animals fall into two categories:

(i) reduction of CH_4 emissions from individual animals

(ii) reduction of animal numbers because of the higher efficiency of individual animals and improved herd management.

Improved nutrition of animals fed low quality forages and reduction in methane emissions per unit of weight gain or milk production can be achieved by supplementation with nutrients and by-pass proteins (Leng, 1991). Examples of the impact of supplementation strategies on CH_4 emissions from cattle show a 50% reduction in the generation of CH_4 per unit of digestible energy (Figure 1A) and a six-fold reduction in methane production per unit of live weight gain (Figure 1B). Further reductions in CH_4

emissions from cattle fed straw can be achieved by treatment of straw with ammonia to increase its digestibility (Figure 2). Similar modifications of the diets of native cattle/ buffalo in India decreased CH_4 emissions per liter of milk production by a factor of 3 (Figure 3). Furthermore, improved genetic stock (Friesian-Holstein) performed as well in India when fed tropical forages plus supplements as in the UK with high quality forage/concentrates (Figure 3).

Supplementation strategies also can almost halve the age of first calving and the intercalving interval of cattle fed low quality forages. Under this scenario, the requirement for breeding and dairy cows is reduced by at least 50%, while maintaining the same productivity in terms of replacement meat or draft animals and milk. Reductions in herd size should also be realized leading to further reduction in CH_4 emissions.

Opportunities for reducing CH_4 emissions from intensively managed dairy cows in developed countries and estimated reductions are genetic improvement (10%), use of bovine growth hormone (10%), and improved feed formulations (4%). For beef cattle, pharmaceuticals currently being developed that promote protein gain at the expense of fat could reduce CH_4 emissions by as much as 20% (CAST, 1992). Longer-term biotechnological approaches could be aimed at modification of rumen fermentation to eliminate CH_4 production.

Detailed analyses of global CH_4 emissions from livestock and poultry manures (Figure 4) indicate that this source generates about 28 Tg CH_4/yr; range 20-35 Tg (Safley et al., 1992). About 10 Tg, or 35%, of the CH_4 is derived from liquid/slurry and lagoon storage systems and could potentially be recovered. Mitigation options do not really exist for the remaining wastes. Environmental regulation in developed countries may alter manure handling practices and effects on CH_4 emissions should be considered in development of regulations.

Estimates of global methane emissions from rice paddies are based on relatively few measurements. There is a great need for systematic measurement of CH_4 emissions from representative rice production systems in Asia. New technologies such as tuneable diode laser spectroscopy should allow measurements to be made at larger scales than previously and under real conditions in farmers fields. A number of mitigation strategies have been suggested, including cultivar selection, N source and placement, use of nitrification inhibitors, and alternative water management but this work is still at the research stage (Braatz and Hogan, 1991).

Strategies for reducing CH_4 emissions from rice paddies by making the soil more aerobic, for example by mid-season draining, may stimulate N_2O emissions both during drainage and re-flooding. Tradeoffs between different greenhouse gases should always be evaluated when developing mitigation strategies for a particular greenhouse gas.

Population growth and the associated need for more food will counteract efforts to mitigate CH_4 from agricultural sources and it is uncertain that these will be reduced below present levels in the long-term. It has been estimated that the demand for rice will increase from 480 to 780×10^6 t/yr, a 65% increase in the next 30 years (FAO, quoted in US EPA, 1990). Such an increase will have to be met, at least in part, by increasing yields because of land area limitations to agricultural expansion. There is already concern that high rice (and wheat) yields realized after the "green revolution" are not being sustained. Greater inputs of organic matter (legume green manures, and animal manures where available) may be needed to sustain high rice yields, and organic additions will enhance emissions of CH_4

(see Figure 5). Conflicts between agricultural sustainability, food production, and greenhouse gas emissions will undoubtedly increase in the future. Moreover, because 70% of the agricultural emissions of CH_4 are from developing countries (Figure 6) issues such as infrastructure, economics, and culture are important and will have to be addressed with sensitivity.

REFERENCES

Braatz, B.V. and K.B. Hogan. 1991. Sustainable rice productivity and methane reduction research plan. USEPA, Office of Air and Radiation, Washington, DC.

Council for Agricultural Sciences and Technology (CAST). 1992. Preparing US agriculture for global climate change. Report 119. Ames, Iowa.

US Environmental Protection Agency. 1990. Greenhouse gas emissions from agricultural systems. Vol. 1, Summary report P. 19-24. In. Proc. of IPCC-RSWG workshop, Washington, DC. 12-14 Dec. 1989. USEPA Climate Change Div., Washington, DC.

Intergovernmental Panel on Climate Change (IPCC). 1992. Climate Change 1992. pp. 35-37. J.T. Houghton. B.A. Callender, and S.K. Varney (eds.) Camb. Univ. Press.

Leng, R.A. 1991. Improving ruminant production and reducing methane emissions from ruminants by strategic supplementation. USEPA report 400/1-91/004. Office of Air and Radiation, Washington, DC.

Safley, L.M., M.E. Casada, J.W. Woodbury, and K.F. Roos. 1992. Global methane emissions from livestock and poultry manure. USEPA report 400/1-91/048. Office of Air and Radiation, Washington, DC.

USEPA. 1992. Anthropogenic methane emissions in the US: estimates for 1990. Draft report to Congress, office of Air and Radiation, Washington, DC.

Table 1. Anthropogenic Sources of Methane

	Global[a]		US[a]		
Activity	Tg	%	Tg	%US	%Global
Coal Mining/Nat. Gas/ Petroleum Industries	100	28	7.9	28	8
Ruminant Animals	80	22	5.8	21	7
Animal Waste	25	7	2.7	10	11
Rice Paddies	60	17	0.4	1	<1
Biomass Burning	40	11	NA[b]		
Landfills	30	8	10.0	37	33
Domestic Sewage	25	7	NA[b]		
Total	360		27.9		8

[a] global data from IPCC (1992) and US data from US EPA (1992)

[b] data not available

Figure 1. (from Leng 1991)

(A) The effects of improving the efficiency of rumen fermentative activity on methane production per kg of digestible energy consumed.

(B) The production of methane per kg gain in supplemented cattle [feed conversion efficiency (FCR) 9:1] or unsupplemented cattle (FCR 40:1) fed straw based diets (after Saadullah 1984)

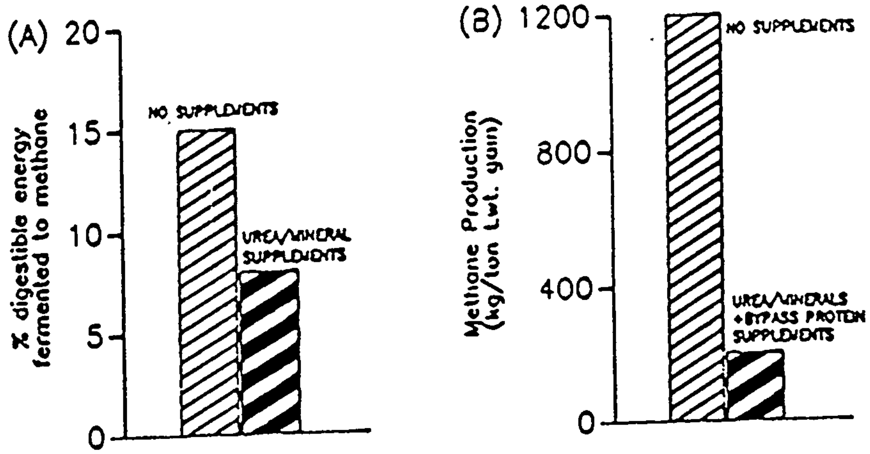


Figure 2. (from Leng 1991)

Effects of supplementation and straw treatment on the kg methane produced for each kg gain in cattle fed straw that was untreated or treated with ammonia to improve its digestibility. The results are from experiments published by Perdok et al. 1988

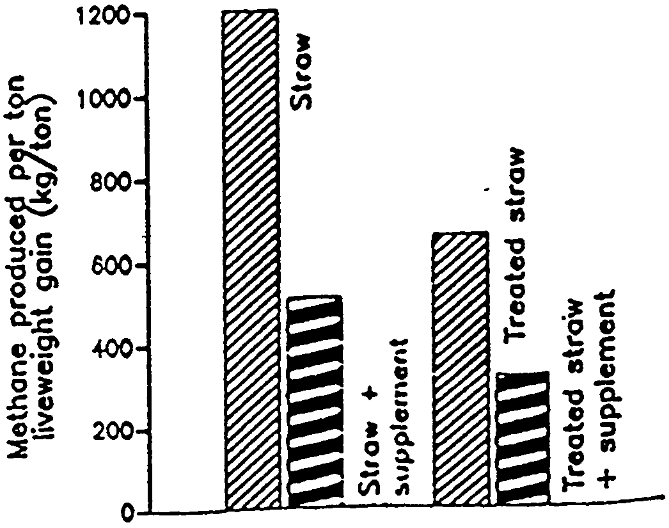
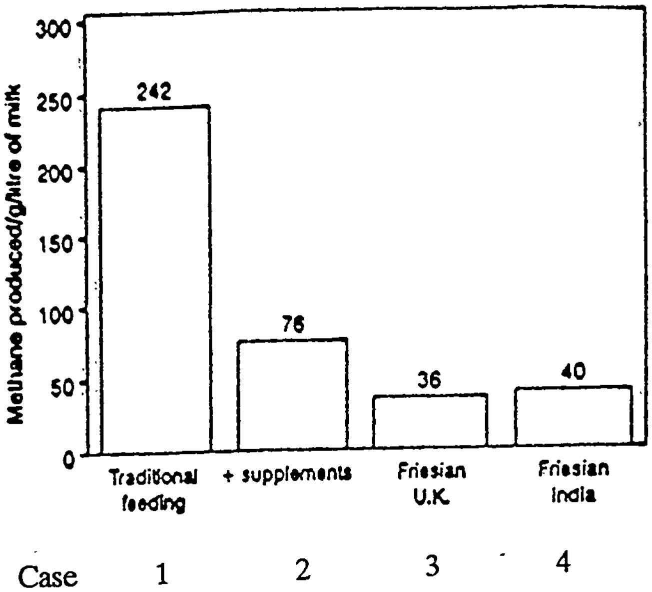


Figure 3. (from Leng 1991)



Case Studies:

1. Traditional feeding with native cattle/buffalo in India.
2. New feeding system using MUB/bypass protein with native buffalo in India.
3. Friesian-Holstein fed high quality forage/concentrate in developed countries.
4. Friesian-Holstein fed tropical forage/MUB/bypass protein in In

Figure 4. (from Safley et al. 1992)

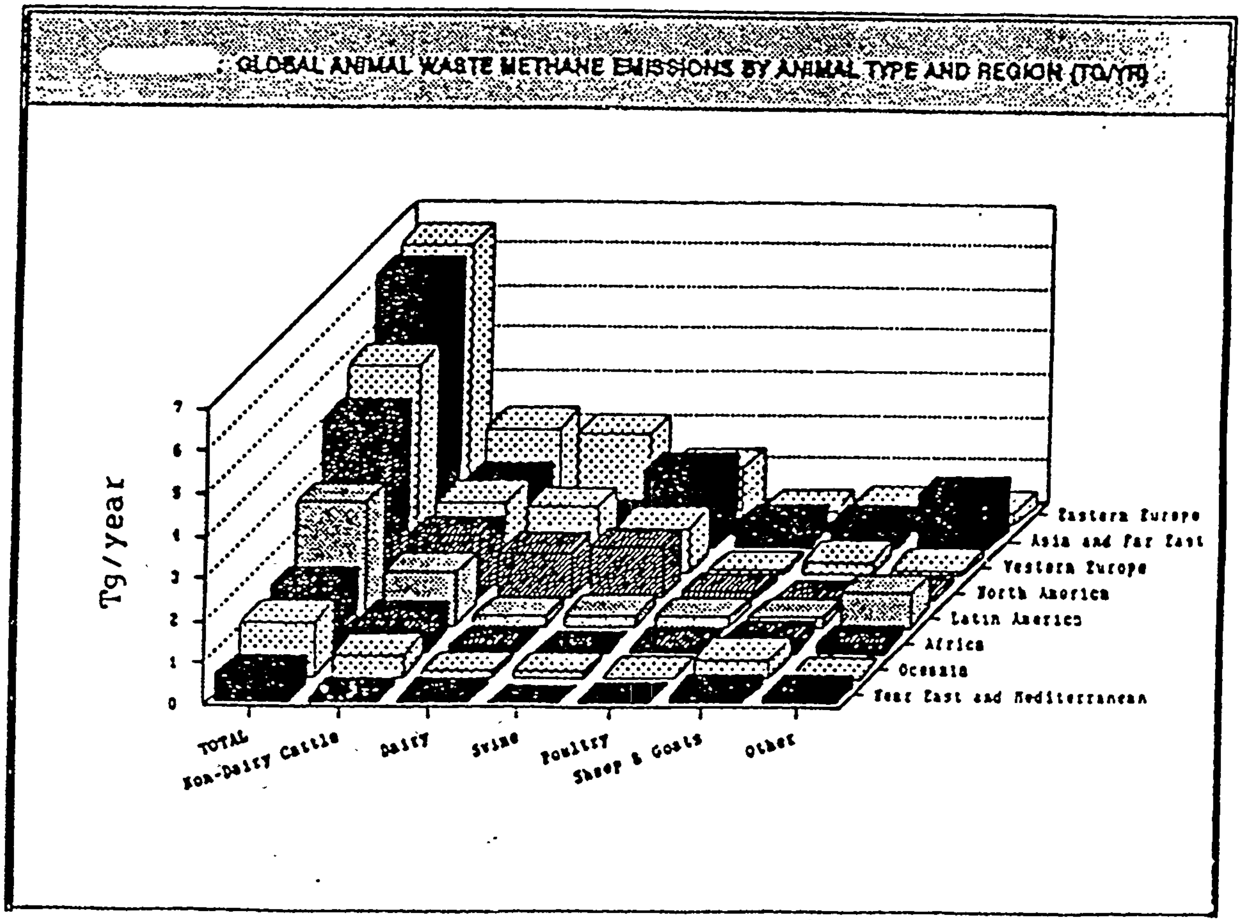


Figure 5. *Effect of green manure additions on CH_4 flux from a California rice paddy* (from Lauren and Duxbury, unpublished)

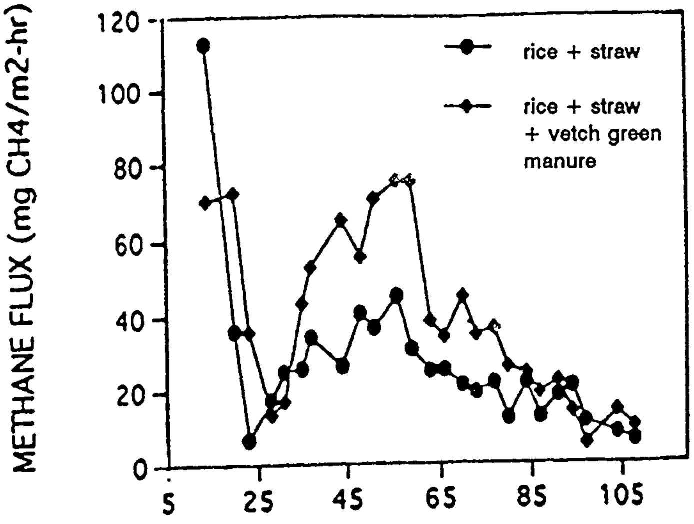
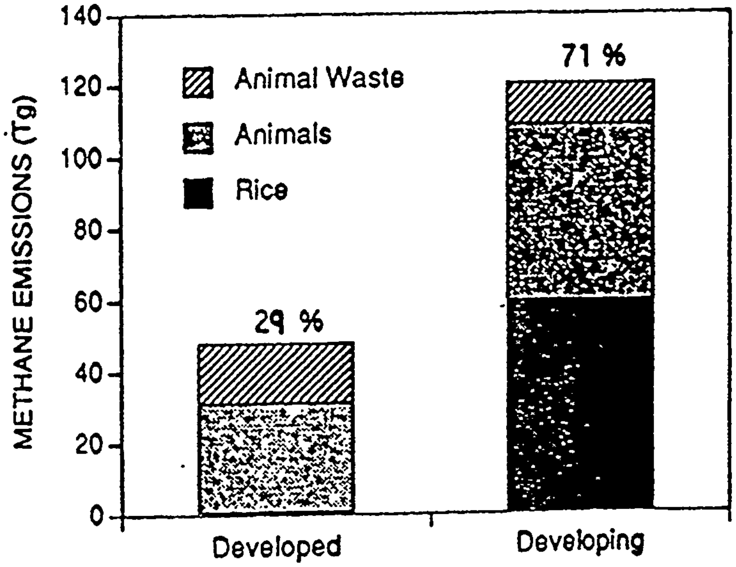


Figure 6. *Methane emissions from developed and developing countries* (based on IPCC 1992 source estimates)



Strategy for reduction of methane emissions from rice paddy fields

Haruo Tsuruta
National Institute of Agro-Environmental Sciences

1. Global estimates of methane emissions from rice paddy fields

Rice paddy field is one of the major sources of methane emissions to the atmosphere. According to the IPCC reports in 1990 and 1992, global estimate of methane emission rate from rice paddy fields has drastically decreased by 55% in these two years. There is, however, still large uncertainty with this estimate.

2. Rice paddy areas in the world

Rice paddy fields are concentrated in Asia because of monsoon climate, and which has 90% of the total rice paddy area in the world. In Asia, about 60% of total area is located in India and China, while Japan has only 2% of the total area.

3. Measurements of methane flux from rice paddy fields

About ten years have past since the first measurement of methane flux from rice paddy fields was carried out in California. The field data now available is, however, not enough in the Asian region.

In Japan, We have measured the methane flux from rice paddy
fields in a agricultural exper ental station located at the
northern part of Tokyo me n area for these four years.
Since we could have tropical and tropical regions
in Asia, we have the methane flux in Thailand
since 1990, unde he Department of Agriculture
in Thailand. T rate during one cultivated
season in Thaila ge of 4 to 75 g/m2. These
values are not so those obtained in temperate
region of norther se two years, several data
have been publishe ndia. Since last year, we have
just started a col ve study on methane flux from Chinese
rice paddy fields between Japan and China.

Nothing to
SCAN
please
cut at 109

4. Controlling factor of methane emission from rice paddy fields

Methane emission rate is determined as a result of methane production, methane oxidation and transport mainly through rice straw. According to the several studies, the major controlling factors of methane emission from rice paddy fields are summarized as follows.

(1) Soil types/soil properties.
(2) Rice varieties.
(3) Plant activities.
(4) Application of nutrient,
(5) Water management.
(6) Solar radiation energy/soil temperature.

IPCC report in 1990 made an overestimate of methane emission because the methane emission in tropical region was calculated by a linear extrapolation of temperature obtained in temperate region, In tropical region, organic carbon can be decomposed faster than in temperate region. The other reason of overestimate was that the difference of soil types could not be taken into consideration. As for India, the area of acid soil in which methane emission is poor, is equal to 50% of the total area in India.

5. Reduction techniques of methane emission

Reduction technology to be developed for methane emission from rice paddies should maintain rice productivity, and should be consistent with sustainable agriculture. Most reliable reduction techniques are summarized as follows.

(1) Improvement of rice varieties.
(2) Water management.
(3) Nutrient management.
(4) Cultivation practice.

We have been studying how the different ~~seniors~~ scenarios of water management can influence on methane emission, and we have got a preliminary result of drastic decrease of methane emission by earlier start of the drainage period. This reduction technique, however, may not be suitable for other countries. Then, each country should develop the best reduction technique available to each country.

It is significantly serious problem that nitrous oxide was emitted when methane emission stopped after drainage. We should take care that a reduction technique for methane emission do not contribute to emission of the other greenhouse gases from agricultural fields.

6. Toward a goal of sustainable agriculture

From agricultural eco-system, many kinds of gaseous species which can influence on the earth's environment are emitted to the atmosphere, in addition to methane.

(1) Nitrous oxide.
(2) Nitric oxide.
(3) Ammonia.
(4) Non-methane hydrocarbon.

We should also develop reduction techniques of these gases toward a goal of sustainable agriculture.

7. Collaborative study in the future

We have many important issues to collaborate with many countries.

(1) Cross check of methane flux measurement by closed chamber method.
(2) Development of new technique for measurement of methane emission in regional scale.
(3) Development of reducing techniques for methane and the other trace gases useful for each country.
(4) Sustainable agriculture.

An Assessment of Alternative Agricultural Management Practice Impacts on Soil Carbon in the Corn Belt

Thomas O. Barnwell, Jr., Robert B. Jackson, IV, Lee A. Mulkey
Environmental Research Laboratory, U.S. EPA, Athens, GA 30613

This impact of alternative management practices on agricultural soil C is estimated by a soil C mass balance modeling study that incorporates policy considerations in the analysis. A literature review of soil C modeling and impacts of management practices has been completed. The models selected for use and/or modification to meet the needs of representing soil C cycles in agroecosystems and impacts of management practices are CENTURY and DNDC. These models share a common ability to examine the impacts of alternative management practices on soil organic C, and are readily accessible.

An important aspect of this effort is the development of the modeling framework and methodology that define the agricultural production systems and scenarios (i.e., crop-soil-climate combinations) to be assessed in terms of national policy, the integration of the model needs with available databases, and the operational mechanics of evaluating C sequestration potential with the integrated model/database system. We are working closely with EPA's Office of Policy and Program Evaluation to define a reasonable set of policy alternatives for this assessment focusing on policy that might be affected through a revised Farm Bill, such as incentives to selectively promote conservation tillage, crop rotations, and/or good stewardship of the conservation reserve. Policy alternatives are translated into basic data for use in soil C models through economic models. These data, including such elements as agricultural practices, fertilization rates, and production levels are used in the soil C models to produce net carbon changes on a per unit area basis. The unit-area emissions are combined with areal-extent data in a GIS to produce an estimate of total carbon and nitrogen changes and thus estimate greenhouse benefits.

While data from long-term field studies has provided much information about the possible rates and directions of change in soil C under various management regimes, our current knowledge base is very fragmented. Most of what we know concerning soil organic matter (SOM) dynamics has been obtained by studying SOM losses; we understand less about SOM accumulation and how it varies across soil types, climatic regions and management regimes. A network of field sites in the Corn and Wheat Belts has been organized through a cooperative agreement with Colorado state University and Michigan State University. Emphasis is on collection, preparation, and evaluation of soil C data. Sites where comparisons of management practices are possible have been given highest priority. Outputs of the studies will be useful in validation of the results of the modeling study as well as providing a better understanding of the response of SOM to management.

Preliminary study results indicate that current agricultural practices and trends will lead to an increase of about 1 Gt C within the Corn Belt by the year 2030 (25 mt/year). This represents a 32% increase over 1990 levels. Nationwide, the increase could be 50% greater as the Corn Belt represents 60 to 70% of total cropland in the United States. A key assumption behind this projection is a continuation of the long-term residue to the soil. Although conservation tillage can increase soil C in some agricultural production systems, the overall impact of Reduced Till and No Till practices was not significant in the Corn Belt as a whole. Cover crops have significant potential to increase soil C where feasible and appropriate. These practices may be particularly important in the southern United States. Conversion to Conservation Reserve Program land leads to an overall increase in soil C, but this increase was on the order of 5 to 10%, and decreases were noted under some scenarios.

Further work indicated by the study includes comparison of projections with data being compiled by Colorado State University and Michigan State University, analysis of methodology sensitivity to alternative crop yield increases, better representation of tillage practices, erosion and nitrogen cycles in models, and further model testing.

WORKING GROUP PROPOSALS

WORKING GROUP I PROPOSALS

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Capture/Transportation
TOPIC:	Purity of CO_2
PROJECT:	CO_2 Purity Requirements
OBJECTIVE:	Determine effects of impurities and degree of drying on pipeline performance

SCIENTIFIC RATIONALE:

Substantial cost savings are possible if SO_x can be handled with CO_2 in pipeline, however the pipeline's ability and dryness must be determined.

PROPOSAL:

Build a subscale pipeline at an oxygen-blown test furnace. Measure long term corrosivity of mixtures of CO_2, SO_x, NO_x, and trace compounds. Study ecological effects if injecting impure CO_2 into disposal sites. Evaluate the integrated capture/transportation system to identify technology problems requiring additional research and development.

PARTICIPANTS:

U.S.:	ANL/ORNL/INTECH
JAPAN:	NIMC

CONTACTS:

U.S.:	A. Wolsky/R. Judkins/B. St. Johns
JAPAN:	T. Hakuta

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Capture

TOPIC: Separation Science

PROJECT: Investigate H_2-$CO_2$4N_2-CO_2 Separations

OBJECTIVE: Learn physical properties of mixtures and methods of separation, particularly membrane separation

SCIENTIFIC RATIONALE:

H_2/CO_2 separation is vital for H_2 production via shift N_2/CO_2 separation is vital for cryogenic sep, pipeline compression, and CO_2-O_2 combustion impurities.

PROPOSAL:

Conduct lab research and analysis to determine properties of N_2/CO_2 mixtures and the possibilities of separating some by membranes. Do same task for H_2/CO_2 mixtures (particularly at high pressure differences). Determine effects of N_2 impurity on O_2-CO_2 combustion.

PARTICIPANTS:

U.S.: ORNL/ANL

JAPAN: NIMC

CONTACTS:

U.S.: R. Judkins/A. Wolsky

JAPAN: T. Hakuta

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Utilization of CO_2 including Natural and Artificial Photosynthesis

TOPIC: Artificial Photosynthesis

PROJECT: H_2 production from H_2O using catalyst system

OBJECTIVE: Construct new hydrogen production systems that use artificial photosynthesis of production of hydrogen from water using these system.

SCIENTIFIC RATIONALE:

The production of economical hydrogen from water is a top-priority objective. Preliminary experiments indicate that this is potentially feasible.

PROPOSAL:

1. Exchange information on both reactions and the catalysts that have been tried in both Japan and U.S.
2. Plan research based on this outcome.

PARTICIPANTS:

U.S.: NREL, OAK Ridge, Battelle

JAPAN: Arakawa (NIMC), Ibuski (NIRE), Asada (NIGH)

CONTACTS:

U.S.: Lipinsky (Battelle)

JAPAN: Ibuski (NIRI), Arakawa (NIMC)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Utilization
TOPIC:	Application of Natural and Artificial Photosynthesis
PROJECT:	Production of organic compounds by photo catalytic and enzymatic processes
OBJECTIVE:	Elucidation of mechanisms to improve rate and efficiency

SCIENTIFIC RATIONALE:

Production of organic materials from CO_2 is a means to stimulate innovation in this area. Preliminary experiments indicate that they are feasible.

PROPOSAL:

1) Exchange information.
2) The research plan based on the outcome.

PARTICIPANTS:

U.S.:	NREL, Oak Ridge, Battelle
JAPAN:	NIRE, NIBH

CONTACTS:

U.S.:	Lipinsky (Battelle)
JAPAN:	Asada (NIBH)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Utilization of CO_2 Using Cyclic Phenomena

TOPIC: Photoconversion to Produce Hydrogen From Water

PROJECT: Space Shuttle Experiment on Conversion of Water to Hydrogen and Oxygen

OBJECTIVE: Investigate Effects of Solar Radiation and Zero Gravity on Photoconversion

SCIENTIFIC RATIONALE:

Large increase in efficiency is needed. Bubble formation and other related phenomena are different at zero gravity. Solar Spectrum outside of atmosphere is different from that of earth.

PROPOSAL:

1. Evaluate prior studies at zero gravity that pertain to this topic.
2. Make go-no go decision.
3. If go is decision, then design and build payload.
4. Conduct experiment in space and analyze results.

PARTICIPANTS:

U.S.: NASA

JAPAN: Arakawa (NIMC), Ibuski (NIRE), Asada (NIBH)

CONTACTS:

U.S.: Brisky (Battelle)

JAPAN: Arakawa (NIMC)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Ocean Disposal

TOPIC: Local Plume Behavior and Environmental Impacts

PROJECT: Pilot CO_2 Disposal Facility

OBJECTIVE: Observe and masure CO_2 plume behavior (e.g. temperature, concentrations, pH fields) for a range of depths (zoom - 3000m); explore interaction with sea floor; test confined mixing chamber concept

SCIENTIFIC RATIONALE:

Theoretical and laboratory results require field validation.

PROPOSAL:

1. Construct pilot scale (e.g., one hour of 1 GW load) CO_2 supply line capable of reaching 3000m;
2. Design/build flexible, instrumented platform suitable for multi-team research. May utilize autonomous underwater vehicles (AUV's) for deployment/measurement;
3. Hold initial workshop to flesh out details.

PARTICIPANTS:

U.S.: MIT, PICHTR, Scripps Inst.-Ocean; Cal Tech

JAPAN: NIMC, MEL, NIRE, UT

CONTACTS:

U.S.: Eric Adams (MIT); Gerard Nihous (PICHTR)

JAPAN: Yuji Shindo, NIMC, (AIST, MITI)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Ocean Disposal

TOPIC: CO_2 Hydrate

PROJECT: Elucidate Kinetics and Mechanisms critical for hydrate formation, hydrate stability, and factors facilitating large scale production of hydrate

OBJECTIVE: Provide a basis for evaluating technical, economic, and environmental aspects of using hydrate for sequestering CO_2

SCIENTIFIC RATIONALE:

We need a much broader understanding of basic and applied science to assess feasibility of using CO_2 hydrate to contain CO_2 over long time periods.

PROPOSAL:

Initiate a workshop between Japanese & U.S. scientists for exchange of information as to the status of hydrate research in both countries. The product of the workshop would be a proposal outlining needed studies that could be conducted cooperatively.

PARTICIPANTS:

U.S.: California Institute of Technology, EPRI

JAPAN: Drs. Watanabe and Uchida (Government Institute at Hokkaido, AIST, MITI)
Dr. Yuji Shndo (NIMC, AIST, MITI)

CONTACTS:

U.S.: W. J. North, J. J. Morgan (Cal Tech)

JAPAN: Yuji Shindo (NIMC)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Land Disposal

TOPIC: CO_2 EOR

PROJECT: Environmental Benefits of CO_2 EOR Workshop

OBJECTIVE: To study CO_2 emission reductions possible through CO_2 flooding

SCIENTIFIC RATIONALE:

PROPOSAL:

EOR has been optimized for oil production benefits. Review the potential for environmental benefits of CO_2 EOR in major oil fields producing oil imported into Japan and U.S.

Sponsor a workshop for cooperation, communication and bilateral info exchange.

PARTICIPANTS:

U.S.: DOE - EOR Specialist

JAPAN: NEDO - EOR Specialist
New Energy & Industrial Technology Development Organization

CONTACTS:

U.S.: R. T. Bailey (AOSTRH)

JAPAN: Dr. S. Tanaka (UT)

WORKING GROUP II PROPOSALS

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Energy Conservation

TOPIC:

PROJECT: Local Energy Supply System

OBJECTIVE: For effective use of thermal energy by an integrated systems.

SCIENTIFIC RATIONALE:

Integration of Technology is most effective way for increasing of total efficiency.

PROPOSAL:

PARTICIPANTS:

U.S.: Lawrence Berkeley Laboratory, Oak Ridge National Laboratory

JAPAN: Mechanical Engineering Laboratory, MITI

CONTACTS:

U.S.: Dr. Art Rosenthal, Roger Carlsmith

JAPAN: Akira Yabe

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Energy Conservation

TOPIC: Development of shared data base

PROJECT: To establish a base of reliable, and consistent information on the efficient use of energy including energy consumption and efficiency by sector in both countries.

OBJECTIVE:

SCIENTIFIC RATIONALE:

Standards for easy comparison of the experience int he two counties are needed as well as a mechanics for easy access to the data.

PROPOSAL:

Convene a working group involving the jurisdictional government agencies, appropriate industry representatives and the research community to develop the concept and approach.

PARTICIPANTS:

U.S.: Energy Information Administration, National Renewable Energy, Electric Power Research Institute Laboratory

JAPAN: Tokyo Institute of Technology, Carbon Recycle Center

CONTACTS:

U.S.: Dr. Tom Bath

JAPAN: Professor Ken Okazaki

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Energy Conservation
TOPIC:	Approaches to improving efficiency of energy use.
PROJECT:	Review the U.S. and Japanese experience in improving energy efficiency and reducing energy use in the residential and business sectors.
OBJECTIVE:	To increase the use energy efficient technology in both domestically, i.e., Japan and the U.S., and also to promote their use in the developing countries.

SCIENTIFIC RATIONALE:

PROPOSAL:

Establish a joint working group to review and discuss the various approaches taken to date in both Japan and the U.S. The successful mechanisms will be identified along with lessons learned and a proactive plan for action developed.

PARTICIPANTS:

U.S.:	National Renewable Energy Laboratory, Oak Ridge National Pacific International Center for High Technology Research
JAPAN:	Mechanical Engineering Laboratory, MITI, Takasago Thermal Energy Company

CONTACTS:

U.S.:	Dr. Tom Bath, Dr. Cary Bloyd, Mr. Roger Carlsmith
JAPAN:	Dr. Haruo Yamada (MITI), Dr. Yoshiyuki Kozawa (Takasago)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Reduction Technologies
TOPIC:	Coal Combustion and Gas Turbines
PROJECT:	Integrated Gasification Combined Cycle (IGCC)
OBJECTIVE:	Advance technology development to achieve higher levels of efficiency at lower cost.

SCIENTIFIC RATIONALE:

Mutual collaboration on technology development will accelerate achievement of objective and thereby minimize future GHG emissions from power generation.

PROPOSAL:

Compile/tabulate research projects; exchange information on state of technology development; arrange site visit/meeting to discuss areas of mutual interest/collaboration -- particularly coal handling, gasifier research, hot gas clean-up, topping cycle, and direct-fired turbines.

PARTICIPANTS:

U.S.:	DOE/ANL
JAPAN:	MITI/NIRE

CONTACTS:

U.S.:	Dr. David South (ANL)
JAPAN:	Dr. H. Moritomi (NIRE)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Reduction Technologies

TOPIC: Coal Combustion and Gas Turbines

PROJECT: Pressurized and Fluidized Bed Combustion (PFBC)

OBJECTIVE: Advance technology development to achieve higher levels of efficiency at lower cost.

SCIENTIFIC RATIONALE:

Mutual collaboration on technology development will accelerate achievement of objective and thereby minimize future GHG emissions from power generation.

PROPOSAL:

Compile/tabulate research projects; exchange information on state of technology development; arrange site visit/meeting to discuss areas of mutual interest/collaboration -- particularly emphasis will be on pressure effect on efficiency and pollutant generation, topping cycle, gas turbine interface, etc.

PARTICIPANTS:

U.S.: DOE/ANL

JAPAN: MITI/NIRE

CONTACTS:

U.S.: Dr. David South (ANL)

JAPAN: Dr. H. Moritomi (NIRE)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Reduction Technologies
TOPIC:	Coal Combustion and Gas Turbines
PROJECT:	Comparative Economics and Market Potential of Advanced Coal Technologies
OBJECTIVE:	Accelerate Technology Diffusion

SCIENTIFIC RATIONALE:

Differences in collating efficiency (MHV vs. LHV) and cost estimation make technology comparisons difficult.

PROPOSAL:

Standardize cost/performance data, identify market/regulatory incentives necessary to overcome technological or market risks/barriers, examine opportunities for coal technologies to meet power demands while minimizing GHG emissions.

PARTICIPANTS:

U.S.:	DOE/ANL
JAPAN:	MITI/NIRE

CONTACTS:

U.S.:	Dr. David South (ANL)
JAPAN:	Dr. H. Moritomi (NIRE)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Fuel Cells

TOPIC: Global CO_2 Reduction Impact of F.C. Commercialization

PROJECT:

OBJECTIVE: Quantify the likely effects left on CO_2 emissions of widespread commercial applications (utility, industrial, commercial sector) of all types of fuel cells.

SCIENTIFIC RATIONALE:

Significant reduction potential in many areas, but full impact is unclear, this study would yield first order approximation.

PROPOSAL:

PARTICIPANTS:

U.S.:

JAPAN:

CONTACTS:

U.S.: D. Kleinschmidt (ADL)

JAPAN: H. Takenaka (GIRI Osaka)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Fuel Cells
TOPIC:	Government Incentives to Foster F.C. Commercialization
PROJECT:	
OBJECTIVE:	To identify practical government incentives to foster early commercialization of F.C. with emphasis on early units capital costs.

SCIENTIFIC RATIONALE:

Early units have above market value capital costs. Government incentives to overcome this barrier could accelerate F.C. implementation.

PROPOSAL:

Review nature and cost effectiveness of Government incentives.

PARTICIPANTS:

U.S.:

JAPAN:

CONTACTS:

U.S.: D. Kleinschmidt (ADL)

JAPAN: H. Takenaka (GIRI Osaka)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Reduction Technologies

TOPIC: Biomass

PROJECT: Bioresource assessments for developing nations

OBJECTIVE: Obtain information needed to facilitate the planting of energy crops.

SCIENTIFIC RATIONALE:

Millions of hectares of energy crops must be planted if bioenergy is to make a significant contribution in CO_2 sequestration. Appropriate sites, mostly in developing nations which have large amounts of arable land, must be identified for the growing of energy crops. Inventories of land best suited for bioenergy production and of biomass and bioresidue resources would facilitate any international effort to grow energy crops.

PROPOSAL:

Assess the availability of bioresources and the potential for production of energy crops on a site-specific basis. Develop geographical information systems to facilitate the assessment using data from the targeted nations and international organizations. Make the database available to investigators worldwide.

PARTICIPANTS:

U.S.: ORNL, NREL, HNEI

JAPAN: MITI, NIRE

CONTACTS:

U.S.: C.M. Kinoshita

JAPAN: S. Yokoyama

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Reduction Technologies

TOPIC: Biomass

PROJECT: General assessment of environmental impact of biomass conversion processes

OBJECTIVE: Obtain information needed to site and permit bioenergy processes

SCIENTIFIC RATIONALE:

Bioenergy generally is perceived to be more environmentally benign than most conventional energy resources. Nevertheless, as with other energy conversion processes, effluent streams and other environmental concerns are inherent to bioenergy conversion processes. An assessment of the impacts of conversion processes, by technology, would facilitate the siting and permitting of precommercial bioenergy conversion projects. The eventual commercialization of the conversion technologies would enhance the bioremediation concept.

PROPOSAL:

Perform a "first-cut" assessment of environmental impacts of alternative thermochemical, biological, ... processes to convert biomass into consumable forms of energy (electricity, fuels, ...).

PARTICIPANTS:

U.S.: NREL, HNEI, PICHTR

JAPAN: MITI, NIRE

CONTACTS:

U.S.: C.M. Kinoshita

JAPAN: S. Yokoyama

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Reduction Technologies

TOPIC: Biomass

PROJECT: High-pressure processing of biomass for energy and co-products

OBJECTIVE: Improve the flow of research information on high-pressure conversion processes.

SCIENTIFIC RATIONALE:

Substantial mutual interest and expertise exists in Japan and the U.S. on high-pressure conversion processes for biomass. Collaboration between the U.S. and Japan in this area would enhance the flow of research information between those two nations and accelerate the commercialization of such processes, and thereby enhance bioremediation efforts and provide co-products to support the primary energy products.

PROPOSAL:

Collaborate on research on high-pressure conversion of biomass.

PARTICIPANTS:

U.S.: HNEI

JAPAN: MITI, NIRE

CONTACTS:

U.S.: M.J. Antal

JAPAN: S. Yokoyama

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

(Individual interest with mutual support)

AREA: Renewable Energy

TOPIC: Hydrogen Handling Technology for WE-NET Project

PROJECT:

OBJECTIVE: To secure safety and reliability in handling large amount of (liquid) hydrogen

SCIENTIFIC RATIONALE:

PROPOSAL:

PARTICIPANTS:

U.S.:

JAPAN: Government Industrial Research Institute, Osaka (GIRIO), MITI
Mechanical Engineering Laboratory (MEL), MITI

CONTACTS:

U.S.:

JAPAN: H. Takenaka (GIRIO)
J. Hama (MEL)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Renewable Energy -- Reduction Technologies

TOPIC: Site-Specific Assessment of Renewable Resources

PROJECT:

OBJECTIVE: To assess potential of renewable energy resources for specific project installation.

SCIENTIFIC RATIONALE:

In order to estimate the energy production from a renewable energy, project, one must be able to characterize resource intensity/availability.

PROPOSAL:

To do research on tools (measurement, analysis, etc.) and modelling techniques for effective assessment of site specific renewable resources in:

1) Local area, such as site for distributed PV system, wind farm, etc.
2) Regional area for Global Energy Network

PARTICIPANTS:

U.S.: NREL

JAPAN: Mechanical Engineering Laboratory (MEL), MITI - Regional; Local (Wind)
Electrotechnical Laboratory (ETL), MITI - Local (Solar)

CONTACTS:

U.S.: Carol Riordan/Dave Ronne, NREL

JAPAN:

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA: Renewable Energy -- Reduction Technologies

TOPIC: Biomass Feedstock Production

PROJECT: Biomass Feedstock Production Technology and Market Development

OBJECTIVE: To improve biomass productivity or dedicated energy use

SCIENTIFIC RATIONALE:

Technologies to convert biomass to useful energy forms are predicted on the availability of reliable, low-cost supplies of biomass feedstock, consistent with environmental constraints.

PROPOSAL:

1) Evaluate technology opportunities to enhance the productivity and reduce the cost of biomass feedstock production in different agricultural environments.

2) Develop a joint definition of "sustainability" for biomass production facilities.

PARTICIPANTS:

U.S.: ORNL/NREL

JAPAN: NIRE, MITI

CONTACTS:

U.S.: Lynn Wright (ORNL)/Ralph Overend (NREL)

JAPAN: S. Yokoyama

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

AREA:	Renewable Energy -- Reduction Technologies
TOPIC:	How do energy decision-making processes influence decisions regarding use of renewable resources?
PROJECT:	Energy Decision-making
OBJECTIVE:	Develop common perspectives on methods for and utility of various aspects of decision-making information

SCIENTIFIC RATIONALE:

Methods to evaluate: risk factors; life-cycle costs; total energy cycle impacts; value of "externalities," etc. Should be consistent between the two parties so that they can operate in freedom to advance the use of renewable energies.

PROPOSAL:

Structure and conduct one (or more) workshops to present and compare tools for informing decision-makers on decisions regarding new/renewable energies vs. conventional supplies.

PARTICIPANTS:

U.S.: DOE/NREL/ORNL

JAPAN: MITI/MEL

CONTACTS:

U.S.: Blair Swezey (NREL), R. L. Sam Martin (DOE) [?]

JAPAN: M. Akai (MEL)

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

Priority 1 of 2

AREA: Transportation - EV

TOPIC: Infrastructure Design

PROJECT: International consortium for Standardization of charging, maintenance and safety

OBJECTIVE: EVs have universal application in any country

SCIENTIFIC RATIONALE:

Market success, improved penetration and lower emissions

PROPOSAL:

Joint working groups with Japan, U.S. and European countries

PARTICIPANTS:

U.S.: EPRI

JAPAN: Central Research Institute for Electric Power

CONTACTS:

U.S.: Larry O'Connell, EPRI

JAPAN: Koshikawa

PROPOSAL FOR JOINT U.S./JAPAN RESEARCH

Priority 2 of 2

AREA:	Transportation
TOPIC:	Efficient Design of Electric Vehicle (EV)
PROJECT:	Total integration of components designed for EV, motor, inverter, drive train, body, tires
OBJECTIVE:	Maximum efficiency

SCIENTIFIC RATIONALE:

Maximum efficiency provides maximum range, increased users, more dispersed infrastructure, reduces total CO_2 and other emissions

PROPOSAL:

Develop a consortium of smaller, specialized manufacturers of electric vehicles and EV components

(NOTE: Proprietary concerns may impede this project.)

PARTICIPANTS:

U.S.:	DOE, EPRI
JAPAN:	MITI, NIES

CONTACTS:

U.S.:	Drs. Henry Courtright (EPRI) and Ed Rindell (EPRI)
JAPAN:	Dr. Hiroshi Shimizo (NIES)

WORKING GROUP III PROPOSALS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Agricultural Methane

PROJECT: Greenhouse gas fluxes (GHG) in rice based cropping Systems

OBJECTIVE:

1. Mass balance analysis of C and N fluxes in rice based cropping systems.
2. Development of management practices for reduction of GHG emissions from rice based cropping systems.

SCIENTIFIC RATIONALE: Rice based cropping systems are a significant source of CH_4 and may directly or indirectly contribute other GHG's. A complete accounting of the impact of these systems on GHG's and the interactions between different GHG's, has not been attempted. This is necessary for the development of successful mitigation strategies.

PROPOSAL: Experimental methodologies and protocols will be developed in the U.S. and Japan but the bulk of the research will be carried out in the major rice producing countries. Measurements will include carbon storage in soils, emissions of CH_4, N_20, NO_x, and NH_3, and the assessment of the impact of volatized NH_3 on GHG production in other environments. System/environment based mitigation strategies will be developed for CH_4 and other GHG's where appropriate, and will consider tradeoffs between different GHG's.

PARTICIPANTS:

JAPAN: J. TSURUTA, K. MINAMI, K. YAGI
USA: J. DUXBURY (Cornell), A. MOSIER (USDA-ARS, Ft. Collins)

CONTACTS:
JAPAN: H. TSURUTA
USA: G. EVANS, L. MULKEY, J. DUXBURY

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Global environmental change and agro-ecosystems - effects of multiple environmental factors on crop systems

PROJECT: Response of crops to CO_2, O_3, and UV-B radiation

OBJECTIVE: To assess the reaction of crop plants to the simultaneous impact of CO_2, O_3, and UV-B

SCIENTIFIC RATIONALE: The rise of CO_2 in earth's atmosphere is well-known, as are problems of high levels of the common air pollutant 0_3 and UV-B. These may well interact to influence crop growth. There already exist some limited data on the physical interactions, which may be used to guide experimental design.

PROPOSAL: To establish field studies, preferably generating test atmospheres of CO_2 and O_3 via free-air CO_2 enrichment (FACE) techniques and UV-B test environments with lamps (after Caldwell), of selected species (to include rice, corn, sorghum, and soybean).

PARTICIPANTS:

JAPAN:	H. SEINO
USA:	H. ROGERS

CONTACTS:

JAPAN:	H. SEINO
USA:	G. EVANS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: The influence of elevated atmospheric CO_2 on the below ground process in agro-ecosystems

PROJECT: Response of crop root systems, the rhizosphere, and soil to elevated atmospheric CO_2 concentrations

OBJECTIVE: To determine root structure and function, rhizosphere (dynamics and population), and soil responses to rising CO_2

SCIENTIFIC RATIONALE: Well-known rises in the CO_2 level of the atmosphere are known to appreciably affect crop growth and development, usually positively. A development of how below ground components respond is needed, since most research work has dealt with canopies.

PROPOSAL: Selected major crop species will be exposed to known concentrations of CO_2. Root system form and function will be assessed along with rhizosphere microbiology and soil physical/chemical properties.

PARTICIPANTS:

JAPAN:	H. SEINO
USA:	H. ROGERS

CONTACTS:

JAPAN:	H. SEINO
USA:	G. EVANS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Urban infrastructure

PROJECT: Research on planning method and formation technique of green spaces in and around the urban areas which contribute to the preservation of global environment

OBJECTIVE: CO_2 fixation, mitigation of heat island phenomenon, saving, etc.

SCIENTIFIC RATIONALE:

PROPOSAL: (p. 6 of T. Kawanaka paper and R. Rowntree's paper)

PARTICIPANTS:

JAPAN:	BUILDING RESEARCH INSTITUTE AND A RESEARCH GROUP
USA:	USDA FOREST SERVICE

CONTACTS:

JAPAN:	UNKNOWN
USA:	R. ROWNTREE

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Forest management - carbon storage

PROJECT: Estimation method of carbon fixation and storage in a stand in relation to stand development involving soil and stand managers

OBJECTIVE: Better estimation of carbon flux related to forest management options

SCIENTIFIC RATIONALE: Central issue to mitigation/adaptation options as they relate to carbon sequestration.

PROPOSAL: Select matched forests in each country and develop prioritized research proposals for carbon fixation estimation methods.

PARTICIPANTS:

JAPAN:
USA:

CONTACTS:

JAPAN: T. FUJIMORI
USA: W. SOMMERS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Urban Infrastructure

PROJECT: Research on adaptation of energy conscious technologies in mixed land use development in urban areas

OBJECTIVE: To level the peak time of energy load through mixed land use

SCIENTIFIC RATIONALE: Technologies of DHC (district heating and cooling) with cogeneration and urban planning systems in Japan and US cities.

PROPOSAL:

1. Introduce cogeneration system to mixed land use in energy consuming type central urban districts to encourage saving energy by leveling energy consumption peak time. Convert some parts of urban infrastructure into an energy conscious one.

2. Research and development of new technologies in building and planning field a for sustainable society

PARTICIPANTS:

JAPAN: BUILDING RESEARCH INSTITUTE AND A RESEARCH GROUP
USA: UNKNOWN

CONTACTS:

JAPAN: T. KAWANAKA
USA: UNKNOWN

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Agricultural CH_4

PROJECT: Reduction techniques of CH_4 and N_20

OBJECTIVE: Workshop in regional and global scale

SCIENTIFIC RATIONALE: CH_4 and N_20 are greenhouse gases from a variety of sources. Their reduction techniques are now under development in each country

PROPOSAL:

1. To exchange the information about the reduction techniques of CH_4 and N_20.

2. To get common consensus of mitigation and adaptation technology of CH_4 and N_20 from anthropogenic sources.

PARTICIPANTS:

JAPAN: H. TSURUTA
USA: J. DUXBURY

CONTACTS:

JAPAN: H. TSURUTA, K. MINAMI
USA: (G. EVANS), (J. DUXBURY), L. MULKEY

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Influence of CO_2 concentrations and temperature on plant agriculture

PROJECT: Below ground responses of crop roots to CO_2 and temperature

OBJECTIVE: To determine how CO_2 and temperature simultaneously influence the growth of crop roots

SCIENTIFIC RATIONALE: Carbon dioxide is increasing the global atmosphere. It has been predicted that the continued rise will increase temperature. Carbon dioxide enrichment most often enhances crop growth. A much neglected aspect is root system response. Therefore, a study of CO_2 and temperature effects on roots is proposed.

PROPOSAL: It is proposed that open top chambers be used to study the influence of CO_2 and temperature of field-grown crops, with primary focus on root structure and physiology. Detailed studies in controlling growth chambers will also be carried out. This will provide new data in a little-studied area.

PARTICIPANTS:

JAPAN:	H. SEINO
USA:	H. ROGERS

CONTACTS:

JAPAN:	H. SEINO
USA:	G. EVANS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Soils Management - Assessment

PROJECT: Assessment methods for soil management to mitigate and adapt to climate change

OBJECTIVE: Develop, test, and apply local, regional, and national assessments to identify, rank, and promote mitigation and adaptation technologies for soil management.

SCIENTIFIC RATIONALE: Sustainable development requires management of soil systems to reduce greenhouse gas emissions, adapt to climate change, and meet food and fiber needs. As new experiments increase our basic understanding and as new technologies emerge, the problem remains to assess the applicability and widespread effectiveness as climate changes over relatively large areas. The need is urgent in the tropics where population pressures are high and data bases are limited. Assessment methods that are scientifically sound and integrate regional data and technologies are needed to guide initiation and implementation of long-term solutions.

PROPOSAL: This proposal has three parts:

1. Review and evaluate existing data assessment methods and models for soils management to mitigate and adapt to climate change in tropical and temperate zones.

2. A bilateral workshop to review ongoing assessments and discuss alternative approaches, data bases, models, and procedures. This workshop will lead to refinements in existing approaches and initiation of bilateral assessment and research needs for assessment methods and models.

3. Joint research projects on assessment methods and joint implementation of assessment projects for US, Japan, and selected tropical countries/regions.

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Agricultural Methane

PROJECT: Methane emissions from ruminant animals

OBJECTIVE: Reduce CH_4 emissions from ruminant animals and animal waste

SCIENTIFIC RATIONALE: Ruminant animals and animal waste are currently considered to be the major agricultural source of CH_4. Technologies for CH_4 reduction need to be developed/implemented in both developed and developing countries.

PROPOSAL: To be developed by appropriate U.S. and Japanese scientists

PARTICIPANTS:

JAPAN: M. SHIBUTA, K. MINAMI, H. TSURUTA
USA: L. BALDWIN (UC Davis), L. SAFLEY (NC State), (USDA scientists)

CONTACTS:

JAPAN: H. TSURUTA, M. SHIBUTA
USA: G. EVANS

PARTICIPANTS:

JAPAN:	NIAES and NIARS
USA:	EPA - GCRP - Office of Research and Development USDA-ARS-FS

CONTACTS:

JAPAN:	H. TSURUTA, H. SEINO
USA:	L. MULKEY, G. EVANS

PROPOSAL FOR JOINT U.S. / JAPAN RESEARCH

AREA: Working Group III

TOPIC: Urban infrastructure adaptation

PROJECT:

OBJECTIVE:

SCIENTIFIC RATIONALE: Analysis of the impacts of global change tends to focus on agricultural systems and natural ecosystems, We tend not to look at the demands that climate change will place on urban systems.

PROPOSAL: The U.S. and Japan are two very urbanized societies and we need to consider how resilient urban areas are to changes in climate. Water supply, waste disposal, run-off, storm frequency and intensity are obvious areas in which climate change will affect urban areas.

PARTICIPANTS:

JAPAN:
USA:

CONTACTS:

JAPAN:
USA:

APPENDIX A

East-West Center

Program on Resources: Energy and Minerals

1777 East-West Road
Honolulu, Hawaii 96848

Phone: (808) 944-7555
Cable: EASWESCEN

Telex: 989171
Facsimile: (808) 944-7559

SECOND U.S./JAPAN WORKSHOP ON GLOBAL CHANGE:

ENVIRONMENTAL RESPONSE TECHNOLOGIES (MITIGATION AND ADAPTATION)

February 1-3, 1993
East-West Center
Honolulu, Hawaii

AGENDA

Monday (February 1, 1993)
Plenary Session
9:00 am - 12:00 noon (Simultaneous translation)
East-West Center, Asia Room

9:00am - 9:05am	Welcome and Introductions, Allen Clark, Program on Resources, Assistant Director
9:05am - 9:20am	Welcoming remarks, Dr. Michel Oksenberg, East-West Center President
9:20am - 10:00am	Keynote address, Frederick M. Bernthal, Chairman, U.S. Committee on Earth and Environmental Sciences (CEES)
10:00am - 10:30 am	Break
10:30am - 11:00am	Workshop Views, Dr. Osayuki Yokoyama, National Institute for Resources and Environment (NIRE)
11:00am - 11:30am	Workshop Views, Dr. Robert Simon, U.S. Department of Energy (DOE)
11:30am - 11:40am	Introduction of Working Group Chairs from Japan - Dr. Tataki Mizuno, NIRE
11:40am - 12:00	Introduction of Working Group Chairs from U.S. and Announcements - Dr. Sylvia Edgerton, CEES
12:00 - 1:30pm	Catered Lunch - Luncheon speaker - Dr. Haruo Tsuruta, National Institute of Agro-Environmental Sciences (NIAES)

Center for Cultural and Technical Interchange Between East and West, Inc.
A national educational institution established by the United States Congress and incorporated by the State of Hawaii—An Equal Opportunity Employer

Working Group Sessions

1:30pm - 5:30pm (Working language is English)

1:30pm - 5:00pm Concurrent sessions of Working Groups I, II, and III

5:00pm - 5:30pm Reconvene in Plenary Session for Working Group reports, Robert Simon, DOE

U.S. - Hosted Dinner for Workshop Participants

7:00pm Willows Restaurant in Honolulu
Welcome, Dr. Michel Oksenberg, East-West Center
Dinner Speaker: Honorable George Ariyoshi, Former Governor of Hawaii

Tuesday, (February 2, 1993)
East-West Center
Working Group Sessions (Working language is English)

9:00am - 12:00 Concurrent sessions in Working Groups I, II, and III

12:00 - 1:30pm Lunch - Luncheon speakers:
-Dr. Toufiq Siddiqi, East-West Center
-Dr. Kuninori Otsubo, National Institute of Environmental Sciences (NIES)

Working Group Sessions (Translations available in each Working Group)

1:30pm - 5:00pm Concurrent sessions of Working Groups I, II, and III and development of joint proposals

5:00pm - 5:30pm Reconvene for Working Group reports in Plenary Session, Dr. Osayuki Yokoyama, NIRE

Wednesday (February 3, 1992)
East-West Center

9:00am - 12:00 Meeting of Working Group Chairs to draft Working Group Reports (Translation available)

12:00 - 1:30pm Lunch

1:30pm - 3:00pm	Meeting of Working Chairs and Working Group Chairs to review and finalize Working Group Reports and prepare Workshop communique (Translations available)

Plenary Session (simultaneous translation)

3:00pm - 3:20pm	Working Group I Report
3:20pm - 3:40pm	Working Group II Report
3:40pm - 4:30pm	Working Group III Report
4:30pm - 5:00pm	Workshop Summary, Closing Comments, and signing of Workshop Communique, Gary Evans, U.S. Department of Agriculture

APPENDIX B

SECOND U.S./JAPAN WORKSHOP ON GLOBAL CHANGE: ENVIRONMENTAL RESPONSE TECHNOLOGIES (MITIGATION AND ADAPTATION)

February 1-3, 1993

U.S. PARTICIPANTS

Dr. E. Eric Adams
Massachusetts Institute of Technology
Room 48-325
Cambridge, MA 02139
Tel. 617/253-6595
FAX. 617/258-8850

Mr. Roger Bailey
Alberta Oil Sands Technology & Research Authority
18th Floor - McFarlane Tower
700 Fourth Avenue, S.W.
Calgary, Alberta,
CANADA T2P 3J4
Tel. 403/297-3380
FAX. 403/297-3638

Dr. John Bardach
Research Associate
Program on Environment
East-West Center
1777 East-West Road
Honolulu, HI 96848
Tel. 808/944-7285
FAX. 808/944-7298

Dr. Tom Bath
Director
Analytical Studies Division
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393
Tel. 303/231-7306
FAX. 303/231-7811

Dr. Frederick M. Bernthal
Deputy Director
National Science Foundation
1800 G Street, N.W., Room 520
Washington, D.C. 20550
Tel. 202/357-9427
FAX. 202/357-9725

Dr. Cary Bloyd
Program Manager
Argonne National Laboratory/PICHTR
East-West Center
1777 East-West Road
Honolulu, HI 96848
Tel. 808/944-7249
FAX. 808/944-7298

Mr. Roger Carlsmith
Director, Conservation and Renewable Energy Program
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831-6188
Tel. 615/574-5204
FAX. 615/576-7572

Dr. Allen Clark
Assistant Director
Program on Resources
East-West Center
1777 East-West Center
Honolulu, HI 96848
Tel. 808/944-7509
FAX. 808/944-7298

Mr. Henry A. Courtright
Director, Customer Systems
Division
Electric Power Research
Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303
Tel. 415/855-8757
FAX. 415/855-2954

Dr. John Duxbury
Professor
Dept. of Soil, Crop, and
Atmospheric Sciences
Cornell University
Ithaca, NY 14853
Tel. 607/255-1732
FAX. 607/255-2644

Dr. Sylvia A. Edgerton
Senior Science Associate
Committee on Earth and
Environmental Sciences
National Science Foundation
1800 G Street, N.W., Room 305
Washington, DC 20550
Tel. 202/357-7353
FAX. 202/357-7830

Dr. Jerry W. Elwood
Department of Energy
Office of Energy Research
ER-74
Washington, DC 20545
Tel. 301/903-4583
FAX. 301/903-8519

Dr. Gary Evans
Global Change Program Office
U.S. Department of Agriculture
1621 N. Kent St., Room 60-LL
Rossyln, VA 22209
Tel. 703/235-9018
FAX. 703/235-9046

Ms. Linda Greczy
Global Change Program Office
U.S. Department of Agriculture
1621 N. Kent St., Room 60-LL
Rossyln, VA 22209
Tel. 703/235-9018
FAX. 703/235-9046

Mr. Howard J. Herzog
Research Engineer
Massachusetts Institute of
Technology
Energy Laboratory
Room E40-489
Cambridge, MA 02139
Tel. 617/253-0688
FAX. 617/253-8013

Dr. Harold M. Hubbard
President
The Pacific International Center for
High Technology Research
711 Kapiolani Blvd., Suite 200
Honolulu, HI 96818-5249
Tel. 808/539-3900
FAX. 808/538-0345

Dr. Roddie R. Judkins
Fossil Energy Program
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831-6084
Tel. 615/574-4572
FAX. 615/574-7721

Dr. Robert Kane
Office of Fossil Energy
Department of Energy, FE-4
Washington, DC 20585
Tel. 202/586-4753
FAX. 202/586-1188

Dr. David Kleinschmidt
Manager, Advanced Power Systems
Arthur D. Little, Inc.
20 Acorn Park, Room 20/434
Cambridge, MA 02140
Tel. 617/498-6090
FAX. 617/498-7007

Dr. Charles Kinoshita
Hawaii Natural Energy
Institute
University of Hawaii at Manoa
2540 Dole Street
Honolulu, HI 96822
Tel. 808/956-2346
FAX. 808/956-2335

Mr. Ed Lipinsky
Research Leader
Battelle Columbus
505 King Avenue
Columbus, OH 43201-2693
Tel. 614/424-6526
FAX. 614/424-3903

Dr. Gregg Marland
Oak Ridge National Laboratory
U.S. Department of Energy
Bldg. 1000, Mail Stop 6335
Oak Ridge, TN 37831
Tel. 615/574-0390
FAX. 615/574-2232

Dr. Lee A. Mulkey
Director for National Program
Environmental Research
Laboratory
U.S. Environmental Protection
Agency
960 College Station Road
Athens, GA 30605-2720
Tel. 706/546-3129
FAX. 706/546-2018

Dr. Gerard Nihous
Pacific International Center for
High Technology Research
2800 Woodlawn Drive, Suite 290
Honolulu, HI 96822
Tel. 808/539-3870
FAX. 808/538-0345

Ms. Judy Nishioka
Program on Environment
East-West Center/Argonne Nat'l Lab.
1777 East-West Road
Honolulu, HI 96848
Tel. 808/944-7224
FAX. 808/944-7298

Dr. Wheeler North
Professor of Environmental Science
Emeritus
Kerckhoff Marine Laboratory
California Institute of Technology
101 Dahlia Avenue
Corona del Mar, CA 92625
Tel. 714/673-9894
FAX. 714/675-1837

Dr. Michel Oksenberg
President
East-West Center
1777 East-West Road
Honolulu, HI 96845
Tel. 808/944-7103
FAX. 808/944-7106

Dr. Hugo H. Rogers
Plant Physiologist & Professor
National Soil Dynamics Laboratory
Agricultural Research Service
U.S. Department of Agriculture
P. O. Box 3439
Auburn, AL 36831-3439
Tel. 205/887-8596
FAX. 205/887-8597

Dr. Kazuo Kontani
Head, Combustion Engineering
Division
Energy Engineering Department
Mechanical Engineering Lab.
AIST, MITI
1-2 Namiki Tsukuba 305, Japan
Tel. 0298-58-708
FAX. 0298-58-7275

Dr. Tateki Mizuno
Chief Senior Researcher,
National Institute for
Resources and Environment
AIST, MITI
16-3 Onogawa Tsukuba 305,
Japan
Tel. 0298-58-8104
FAX. 0298-58-8118

Dr. Hiroshi Moritomi
Senior Researcher
Advanced Combustion System
Division
Thermal Energy and Combustion
Engineering Department
National Institute for
Resources and Environment
AIST, MITI
16-3 Onogwa Tsukuka 305, Japan
Tel. 0298-58-8224
FAX. 0298-58-8208

Dr. Kuninori Otsubo
Research Program Manager,
Center for Global
Environmental Research
National Institute for
Environmental Studies
16-2 Onogawa Tsukuba 305,
Japan
Tel. 0298-51-6111, Ext. 378
FAX. 0298-58-2645

Dr. Hiroshi Seino
Head, Climate Resources Lab.
Agrometeorology Division
National Institute of Agro-
Environmental Sciences
Kannon-dai Tsukuba Ibaraki
305, Japan
Tel. 0298-38-8148
FAX. 0298-38-8199

Dr. Hiroshi Shimizu
Head, Traffic Pollution Control Researc
Team,
National Institute for
Environmental Studies,
Environmental Agency
16-2 Onogawa Tsukuba 305, Japan
Tel. 0298-51-6111
FAX. 0298-51-4732

Dr. Yuji Shindo
Senior Research Scientist
Separation Engineering Lab.
Dept. of Chemical Systems
National Institute of
Materials and Chemical
Research, AIST, MITI
Higashi Tsukuba 305, Japan
Tel. 0298-54-4760
FAX. 0298-54-4487

Dr. Kazuo Suzuki
Senior Researcher
Engine Division
National Aerospace Laboratory
7-441 Jindaiji Higashi-machi
Chyofu-shi, Tokyo, Japan
Tel. 0422-47-5911
FAX. 0422-44-5446

Dr. Hiroyasu Takenaka
Head, Electrochemical Process
Section
Material Chemistry Department
Government Industrial Research
Institute, Osaka, AIST, MITI
1-8-31 Midorigaoka Ikeda Osaka, 563
Japan
Tel. 0727-51-8351
FAX. 0727-54-1934

Dr. Shoichi Tanaka
Professor
Dept. of Mineral Development
Engineering
Faculty of Engineering
The University of Tokyo
Hongo Bunkyo-ku Tokyo 113, Japan
Tel. 03-3812-2111, Ext. 7059
FAX. 03-3818-7492

Dr. Haruo Tsuruta
Head, Laboratory of
Environmental Impact
Assessment
Environmental Planning Dept.
National Institute of Agro-
Environmental Sciences
Kannon-dai Tsukuba Ibaraki
305, Japan
Tel. 0298-38-8276
FAX. 0298-38-8199

Dr. Osayuki Yokoyama
Director-General
National Institute for
Resources and Environment,
AIST, MITI
16-3 Onogawa Tsukuba 305,
Japan
Tel. 0298-58-8101
FAX. 0298-58-8118

Dr. Shin-ya Yokoyama
Head, Biomass Division
Global Warming Control Dept.
National Institute for
Resources and Environment
AIST, MITI
16-3 Onogawa Tsukuba 305,
Japan
Tel. 0298-58-8180
FAX. 0298-58-8158