IEA/H2/AR-95

IEA AGREEMENT ON THE PRODUCTION AND UTILIZATION OF HYDROGEN

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1995 ANNUAL REPORT

Edited by

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OVERVIEW OF THE HYDROGEN IMPLEMENTING AGREEMENT

The IEA Hydrogen Implementing Agreement was established in 1977. The Program was initially comprised of three annexes. Two of these annexes dealt with the production of hydrogen from water using a high temperature source. The third was a broad study of potential future markets for hydrogen. In 1979, three more annexes on production were initiated, introducing electrolysis into the program.

The first non-production annex dealing with storage, combustion and safety (Annex 7) was formed in 1983. In 1986 a decision was made to perform a technical and economic assessment study of hydrogen. In 1989, all of the production activities (Annexes 1,4 and 6) were combined into a single annex (Annex 9). It was comprised of subtasks on Thermochemical, Electrolytic, and Photocatalytic Hydrogen Production. The Annex 9 activities were completed in 1994. The final report was provided in the 1994 Annual Report.

At the March 1993 meeting, the Executive Committee decided to take important steps to re-vitalize the IEA Hydrogen Implementing Agreement. This involved changing the nature of the Programme from one of information exchange and periodic workshops to task-shared collaborative Research & Development projects. Three topics were selected, lead countries were identified, and planning of the following new Tasks was initiated:

Task 10: Photoproduction of Hydrogen (Operating Agent: Norway)

Task 11: Integrated Systems (Operating Agent: United States)

Task 12: Metal Hydrides for Hydrogen Storage (Operating Agent: United States)

During 1995, Programmes of Work were developed for all three of the tasks. The Executive Committee approved the Programme of Work for Task 10 at the Spring Meeting. The Programmes of Work for Task 11 and 12 were approved at the 1995 Fall Executive Committee Meeting.

The signatories to the Hydrogen Implementing Agreement are as follows:

Canada
European Union
Germany
Italy
Japan
The Netherlands
Norway
Sweden
Switzerland
Turkey
United Kingdom
United States
Spain

The IEA Hydrogen annexes and their duration are summarized in the following table:

Current and Completed Annexes of the IEA Hydrogen Implementing Agreement

Annex 1	Thermochemical Production	1977-88
Annex 2	High Temperature Reactors	1977-79
Annex 3	Assessment of Potential Future Markets	1977-80
Annex 4	Electrolytic Production	1979-88
Annex 5	Solid Oxide Water Electrolysis	1979-83
Annex 6	Photocatalytic Water Electrolysis	1979-88
Annex 7	Storage, Conversion and Safety	1983-92
Annex 8	Technical and Economic Assessment of Hydrogen	1986-90
Annex 9	Hydrogen Production	1988-93
Annex 10	Photoproduction of Hydrogen	1995-
Annex 11	Integrated Systems	1995-
Annex 12	Metal Hydrides for Hydrogen Storage	1995-

REPORT OF THE CHAIRMAN

Mr. Neil P. Rossmeissl
U.S. Department of Energy

Introduction

This report summarizes the IEA co-operative activities within the Hydrogen Implementing Agreement during 1995. In addition, this year's report features two articles, an Executive Committee funded article on the Technology Status of Hydrogen Road Vehicles, and an overview of the Energy Conference held in Tokyo, Japan. The former was prepared by Mr. Thomas Doyle, Technology Consultant of Italy, and the latter by the National Renewable Energy Laboratory, Golden, Colorado.

The Hydrogen Implementing Agreement was established in 1977 and has under-gone many changes in priorities and projects. Nine Annexes were initiated and completed during this period, covering production, storage, potential markets and economics. I am pleased to report the Executive Committee has unanimously approved all three of the Annexes and work is underway. The major developments and activities for the Annexes are summarized in this report.

Membership

At present there are eleven members of the Hydrogen Agreement: Canada, the European Union, Germany, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, Turkey, and the United States. The United Kingdom has renewed its interest in the Agreement and has assigned their responsibilities to a new agent, Kings College, London England.

Potential New Members

Turkey has participated as an observer in 1994 and has declared its intention by signing the Hydrogen Implementing Agreement. Additionally, Spain is partici-pating as an observer and hosted the last Executive Committee meeting in November 1995. Austria, Finland, France and Korea are also considering participation. We welcome the participation of Turkey and Spain and look forward to the possibility of several other new members.

Hydrogen Driven Vehicles

In May 1995, the Executive Committee decided to launch a review of the state-of-the-art of technologies for hydrogen fueled vehicles for road transport. The review is intended to identify a valid point of departure for Task 11 - Integrated Systems. An abbreviated summary of the draft review is contained in this report. The final review will be available in 1996.

Coordination with other Organizations

Coordination and exchange of information continues to take place with the IEA Advanced Fuel Cell, Solar PACES, and the Greenhouse Gas R&D Agreements. The Committee is also kept informed of ISO activities in the hydrogen area.

Changes in the Secretariat

Ms. Baker announced that she would be leaving the National Renewable Energy Laboratory (NREL) and subsequently the post of secretary to the Executive Committee at the end of 1995. She has been replaced by Carolyn Elam, also of the NREL.

Mr. Tetsuo Ishii will be returning to Japan at the end of February 1996. Mr. Takashi Okano will be assuming the responsibilities of IEA Secretariat (Paris) for the Hydrogen Implementing Agreement upon Mr. Ishii's departure.

Summary

In summary, 1995 was an exciting year for the Hydrogen Agreement. Collaborations were strengthened, significant progress was made in the three tasks, and a new operating agent, Ms. Gregoire Padró was appointed to support Annex 11, Integrated Systems, losing no time in organizing the team members and accelerating the work. It is anticipated new collaborations will be

integrated into the tasks through the United States Hydrogen Program and the Japanese WeNet Program in the areas of Photobiology and utilization.

I extend my gratitude and thanks to all of the Operating Agents, Executive Committee members and a warm welcome to Ms. Carolyn Elam, secretary to the Executive Committee.

TASK 10 - PHOTOPRODUCTION OF HYDROGEN

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Interim Operating Agent for the
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Task Description

The objective of the Task is to investigate and develop processes and equipment for the production of hydrogen by direct conversion of solar energy. These processes should have the potential to be efficient, economically competitive and environmentally benign. Photoelectro-chemical and photobiological processes are studied in this Task, which is divided into the following subtasks:

Subtask A: Photoelectrochemical hydrogen production

This includes two main activities:

! Development of innovative concepts for water splitting (involving evolution of hydrogen and oxygen).

! Evaluation of non-oxygen-evolving systems, emphasizing the potential of combining hydrogen production with waste degradation.

Subtask B: Photobiological hydrogen production

This involves the metabolic production of hydrogen by micro-organisms (algae or bacteria) using light as an energy source. The subtask includes efforts to enhance the hydrogen-producing capability of micro-organisms by screening and breeding, as well as the development of processes and reactors for industrial systems.

Subtask C: Standardization of methods for measurements, calculation and reporting of efficiencies

The purpose of this subtask was to derive and recommend methods for consistent measurement and reporting of efficiencies of photoconversion processes. Because of past ambiguity in this area, it was felt that some guidelines were needed for researchers, including those participating in Subtasks A and B.

Task 10 started on March 1, 1995 and will continue until the end of February 1998.

Participation

The following countries participate in Task 10: Japan, Norway, Sweden, Switzerland, Turkey, the United States, and the United Kingdom. Their contributions add up to some forty person-years for the Task.

Activities and Progress during 1995

An experts meeting was held in Geneva on February 13-14. This was considered as the "kick-off" meeting for Task 10, and a Programme of Work was drafted. The official starting date was March 1. The Work Programme and the Annex Document were approved by the Executive Committee in their meeting in Ottawa in May. A special Subtask C meeting was held in Ottawa on May 3.

A technical workshop was arranged in Honolulu on September 25-26. Fifteen experts and five observers participated in this meeting. Status reports were presented by the experts, and the Programme of Work was discussed and revised. The revised version, including detailed work plans for the next year, was presented to the Executive Committee at their fall meeting in Seville.

The work is carried out on a task-sharing basis, and collaborative activities were started and pursued during 1995. Some of the progress made in the different subtasks is summarized below.

Subtask A - At the Honolulu meeting, the following six projects for cooperation were specified:

- Electrochemical characterization of semi-conductor/water interfaces (mainly SiC/H_2O);

- Conductive and/or catalytic transparent layers;

- Modelling of process design for water splitting systems;

- Photodegradation of organic water pollutants;

- Oxygen evolution by photo-electrochemical process; and

- Semiconductor particle suspensions for water splitting and water depollution.

Some of these activities started early in the year or were already underway, others will take more time to become fully operational. The following institutions are participating in the various collaborations: the University of Hawaii and NREL (National Renewable Energy Laboratory), Colorado, USA; NIRE (National Institute for Resources and Environment), Tsukuba,

Japan; Geneva University, Bern University and the Federal Polytechnic School of Lausanne, Switzerland; and Marmara Research Centre, Turkey.

Stable high-activity catalysts with properties optimized for specific photoelectrode configurations are being developed at the University of Hawaii. Emphasis is being placed on transparent oxygen-producing catalysts providing corrosion protection of the semiconductor. Thin catalyst layers (NiO_x, mixed oxides) are deposited by a sputtering technique. PECVD (plasma enhanced chemical vapor deposition) is used for depositing dense SiC:H films. With photoelectrodes fabricated from high-efficiency, triple-junction α-Si, a conversion efficiency of 7.5% was demonstrated. The University of Hawaii is also in charge of the modelling activities which are aimed at the screening and selection of promising systems for photoelectrochemical hydrogen production.

The NREL emphasis has also switched to α-Si devices. Good results (greater than 10% efficiency) were obtained earlier with III-V type semiconductors (like $GaInP_2$), but due to their high cost the cheaper α-Si systems are now being developed. Multiple-junction cells covered with α-SiC coatings are being investigated, and splitting of water has been demonstrated.

At NIRE in Tsukuba, a sol-gel method for the preparation of thin film TiO_2 photo-catalysts was developed. Film thicknesses of about 0.8 μm were measured by SEM, the films consist of aggregated TiO_2 particles of about 20 nm in diameter. The photocatalytic activity of the thin film catalyst was evaluated from photo-degradation of acetaldehyde. The rate of degradation is shown in Figure 1. Also shown is a comparison of the thin film catalyst to the commercial TiO_2 catalyst P25. As the thin film becomes transparent, it is expected to result in new photo-chemical devices for water splitting and degradation of pollutants.

The research group at the Swiss universities is developing a tandem photo-electrochemical device for water splitting. It consists of a water electrolyser connected in series with a liquid-junction photovoltaic cell ("Grätzel cell"), the purpose of the latter being to provide the bias (0.75-0.8 V) required to decompose water. Several types of photo-anodes were studied, including WO_3 anodes, silver-charged zeolites and large surface AgCl films. With a photo-electrochemically activated WO_3 anode, a water splitting efficiency of 2.6 % was achieved. The photoelectrolysis cell has also been applied to photo-degradation of organic pollutants with promising results.

In the Marmara Institute in Turkey, the necessary infrastructure for work with transparent conductive and catalytic films was established during the fall. In conclusion, the first year of collaboration has shown that the efforts in the participating countries are to a large extent complementary, and that the researchers are ready to benefit from this in the task-sharing activities.

Subtask B - This Subtask comprises two main activities:

- B1 - Increasing the hydrogen-producing capabilities of micro-organisms

- B2 - Development of photobioreactors for hydrogen production.

The following institutions participate: the University of Hawaii and ORNL (Oak Ridge National Laboratory), USA; NIBH (National Institute of Bioscience and Human Technology), Tsukuba, Japan; Kings College London, United Kingdom; NIVA (Norwegian Institute for Water Research), Oslo, Norway; and the University of Uppsala, Sweden.

Some of the progress made in the task-sharing activities is summarized below.

Activity B1 - Increasing the hydrogen-producing capabilities of microorganisms:

B1a - Screening and characterization of hydrogen-producing microorganisms:

Screening of microorganisms is a base for microbiological studies and is carried out more or less in the participating laboratories. The Norwegian group has been active in microalgae and cyanobacteria screening, not only for hydrogen production but also for other purposes such as waste treatment or production of valuable products.

The ORNL group recently discovered that a PSI (photosystem I, non oxygen-evolving photosystem) - deficient mutant of green alga was able to fix carbon dioxide and evolve molecular hydrogen. They proposed not only antithesis against usual mechanisms on photosynthesis, but also a theoretical probability of doubling the light energy conversion efficiency.

B1b - Breeding of microorganisms for enhancing their hydrogen-producing-capabilities:

The Japanese group has been developing genetic engineering systems for cyanobacteria and photosynthetic bacteria. A few of the genetically-engineered strains are now being characterized.

The Swedish group has been characterizing the hydrogenases (hydrogen-metabolizing enzymes) and cloning the gene from *Anabaena* sp. Their basic studies are and will be quite important and useful for genetic or physiological control of the hydrogen producing activity of cyanobacteria.

The British group has also been interested in selective, molecular breeding of cyanobacteria, especially genetic modifications of hydrogenase.

B1c - Data bank for hydrogen-producing microorganisms:

The Norwegian group has been isolating, collecting and characterizing eukaryotic algae and cyanobacteria to establish culture collections. Their collections have been growing. The Japanese group has been collecting literature concerning hydrogen producing microorganisms.

Activity B2 - Development of photobioreactors for hydrogen production

B2a - Basic studies for R & D of photobioreactors, and B2b - Optimization of photobioreactors:

The British group has been a pioneer in this field. Their main effort has focused on the basis and development of photobioreactors. They devised a hollow fiber reactor where cyanobacteria are immobilized. Once the conditions were optimized, they succeeded in long-term (a year) hydrogen production. The Japanese group has also been studying the basis of photobioreactors with photosynthetic bacteria, including the optimization of light intensity and the effects of light source and wavelength, etc.

B2c - Several (photo)bioreactors in combination for multi-purposes:

The Norwegian group has been working on the multiple utilization of microorganisms, not only for hydrogen or energy production, but also for waste water recycling or production of useful materials such as food, feed or second metabolites. In order to make the basis for multi-purpose reactors, they evaluated the high productivity of outdoor algae cultures in low-temperature areas including northern Europe.

Besides the activities by participants themselves (briefly reviewed above), the following accomplishments are a result of IEA network activities.

1. Databank and culture collections for hydrogen-evolving microorganisms have been growing mainly by the efforts of the Norwegian group. One of USA groups will join the activity. This could offer a common base to screen potent hydrogen-producing microorganisms. The mutant of green alga lacking Photosystem I also could be a new objective for hydrogen-production research.

2. Basic studies on hydrogenases in cyanobacteria assisted to design breeding strategies to enhance hydrogen-producing capabilities. Hydrogenase-mediated hydrogen production and uptake in cyano-bacteria is still unclear. The up-to-date information on hydrogen-metabolism and its enzymes has been quite helpful for the strategy of genetic engineering.

3. The Japanese group and the British group have been intimately exchanging information on photobioreactor research. The Japanese group has not precisely studied photobioreactors with cyanobacteria or algae. The experiences of the British group have proved helpful, especially for the basic studies on photobioreactors by Japan.

4. IEA activities seem to activate technological trends of biological hydrogen in the world.

Subtask C - The work in this subtask was finished in 1995. In the meeting in Ottawa in May, it was agreed that the objective of this subtask could best be accomplished by revising Professor James Bolton's Position Paper on the photoproduction of hydrogen, prepared for the IEA Hydrogen Programme in 1994. Professor Bolton was asked to make the revisions, emphasizing the efficiency aspects and recommending standards for efficiency measurements. The re-drafted paper was thoroughly discussed in the Honolulu workshop and some critical comments were put forward. After incorporating these comments, Professor Bolton presented a final version of his paper. This was approved by the Executive Committee in November, and is being issued as an IEA Technical Report.

Work Planned for 1996

The first experts' meeting is scheduled for around June 20, in Stuttgart, Germany, in conjunction with the 11th World Hydrogen Energy Conference (WHEC). The fall experts' meeting will be held in the October-November timeframe, in Japan. Presentations of Task 10 will be given at the 11th WHEC. Participants will also present IEA-related work at the 7th International Conference of the International Association of Applied Algology in South Africa in April, at the IPS-11 in India in July, and possibly at other international conferences.

 # Subtask A activities

! Electrochemical characterization of semiconductor/water interface: Doped layers on various substrates will be produced and characterized, problems assessed and strategies will be developed.
! Conductive and/or catalytic transparent layers: Surveys of the current materials will be performed, promising new materials will be identified and tested.
! Modelling of process design: Possible designs proposed by participants will be evaluated, existing modelling tools will be surveyed and evaluated.
! Photodegradation of organic water pollutants: Several important pollutants will be investigated and products will be determined. Economic appraisal will be performed by November.
! Oxygen evolution by photoelectro-chemical process: Reversibility of Ag reduction will be investigated. WO_2 photoanodes will be further improved for better light adaption.
! Semiconductor particles suspensions: Feasibility of depollution and water splitting will be assessed.

 # Subtask B activities

! Screening and characterization of H_2-producing micro-organisms: Ongoing work will be monitored, coordinated, and reported at experts' meetings.
! Breeding of micro-organisms for enhancing H_2-production: Strategies for enhancing H_2-producing capabilities will be planned in accordance with scientific developments. Discussions of strategies till take place in the fall experts' meeting.
! Databank for H_2-producing micro-organisms: Contacts will be established with relevant culture collections. Literature will be surveyed.

- Basic studies for R&D on photobio-reactors: Ongoing work will be coordinated, specific tasks will be assigned to participants.

- Optimization of photobioreactors: Design of a conceptual photobioreactor for water splitting will be started, progress will be reported at the fall experts' meeting.

Meeting Schedule for 1995 and 1996

February 13-14, 1995: "Kick-off" meeting, Geneva, Switzerland.

May 3, 1995: Subtask C meeting, Ottawa, Canada.

September 25-26, 1995: Technical workshop, Honolulu, USA.

June 27-28, 1996: Experts' meeting, Stuttgart, Germany

October/November 1996: Experts' meeting, Tokyo, Japan

Publications

James R. Bolton: Solar Photoproduction of Hydrogen. IEA Technical Report (in preparation).

Task 10: Photoproduction of Hydrogen. Proceedings from the Workshop in Honolulu, September 25-26, 1995 (internal report).

Miyake M, Yamada J, Aoyama K, Uemura I, Hoshino T, Miyake J and Asada Y (1996), Strong expression of foreign proteins in *Synechococcus* PCC7942. J. Marine Biotechnol. (in press).

Namada E, Nishikata S, Asada Y and Miyake J (1996) Hydrogen production by gelimmobilized cells of *Rhodobacter sphaeroides* - Distribution of cells, pigments and hydrogen evolution - J. Marine Biotechnol. (in press).

Nagamina Y, Kawasugi K, Miyake M, Asada Y and Miyake J (1996) Characterization of a photosynthetic bacterium *Rhodobacter sphaeroides* RV for hydrogen production - J. Marine Biotechnol. (in press).

Oxefelt F, Tamagnini P, Salema R and Lindblad P (1996) Hydrogen uptake in *Nostoc* strain PCC7102: Effects of nickel, hydrogen, carbon and nitrogen. Plant Physiology and Biochemistry, vol. 33, (in press).

TASK 11 - INTEGRATED SYSTEMS

Catherine E. Gregoire Padró
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U.S. Department of Energy

Task Description

The objective of this effort is to develop a tool to assist in the design and evaluation of potential hydrogen demonstration projects and in the optimization of existing hydrogen demonstration projects. Emphasis will be placed on integrated systems covering all components, from input energy to end use. The activities will be focused on near- and middle-term applications, with consideration of the transition to sustainable hydrogen energy systems.

Systems under consideration include stand-alone and grid-connected hydrogen production and hydrogenation systems; hydrogen and oxygen transport and storage systems; conversion devices including fuel cells, turbines, combustors, and hydrogen-tion units; electric load leveling systems; and general characteristics of mobile applications.

The task participants will undertake research within the framework of three highly coordinated subtasks. This work will be carried out in cooperation with other IEA Implementation Agreements, where appropriate.

Subtask A: Case Studies

Hydrogen energy systems will be critically evaluated and compared, with measurement of systems performance as the central focus. Safety and regulatory issues will be considered where appropriate. For

this subtask, a list of pilot and demonstration projects that are available for evaluation will be compiled. Although it is not expected that this list will be exhaustive, it is anticipated that the participating countries will provide extensive lists of demonstration projects in their respective countries. Some additional contributions from non-participating countries may also be made available. A limited number of projects will be selected from the compiled list for detailed evaluation.

Data requirements will be established for the development of a detailed questionnaire. This questionnaire will be distributed to the appropriate contact points for the selected projects, and detailed information and data (performance, operating conditions, start-up, costs, etc.) on the selected projects will be collected and organized. It is anticipated that the data base will be updated and extended to include new projects and additional data according to requirements of Subtasks B and C. A case study report will be produced to document the hydrogen energy systems.

Subtask B: Analysis Tools

Subtask B will focus on simulation activities that build on existing modeling efforts. Early in Task 11 efforts, a number of commercially available simulation tools were evaluated (Badin, 1995), and a common integrating platform was selected. On the basis of information gathered in

Subtask A, the components to be modeled will be identified. Using data collected in Subtask A, these component models will be validated. If necessary, additional data will be requested from Subtask A, to complete validation.

The component models will then be adapted into the integrating platform, and parametric studies will be conducted to identify promising strategies for improving the performance of selected components. A report describing the models will be produced and the component models will be organized into a library that will be made available to the participating countries.

Subtask C: Design Guidelines

A set of guidelines will be developed to assist in the design of future demonstration plants to meet operating and user requirements, and to facilitate the systematic integration of hydrogen into the energy system. These guidelines will be the result of analysis of integrated hydrogen energy systems.

Baseline application requirements of conventional energy systems that should be met by hydrogen energy systems will be identified. The projects selected in Subtask A will be compared to the requirements list. Systems that can meet energy services that are currently not covered by the set of projects selected in Subtask A will be catalogued, and the most promising hydrogen energy systems that have not been demonstrated will be identified. Requests will be made for additional project data (Subtask A) and component models (Subtask B).

System models will be built in the integrating platform, on the basis of component models developed in Subtask B. Base case validation runs will be conducted and the results compared to data collected in Subtask A. These base case results will also be compared to the application requirements.

Following validation of the integrated models, optimization runs will be performed, and variances identified that require component model modification (Subtask B) or additional data (Subtask A). A report will be prepared that includes recommendations for the optimization of existing hydrogen systems and design guidelines for new, promising, and desirable hydrogen systems.

Duration

The Task was formally begun on August 1, 1995 and will continue until July 31, 1998.

Expected Results

The collaborative efforts of Task 11 will result in the following outputs:

- Case study report to document the selected hydrogen energy systems;
- Report describing the component models, including the required inputs and the expected outputs, and limitations and capabilities of the models;
- Library of component models for use in the common integrating platform; and
- Report of recommendations for optimizing existing hydrogen energy systems and the set of design guidelines for planning future integrated hydrogen energy systems.

Participation

The following countries are participating in Task 11: Canada (Subtasks A and B); Italy (Subtasks A and C); Japan (Subtasks A, B, and C); the Netherlands (Subtasks B and C); Spain (Subtasks A, B, and C); Switzerland (Subtasks A and B); and the U.S.A. (Subtasks A, B, and C).

The Lead Countries for Subtasks A, B, and C are Switzerland, the USA, and the Netherlands, respectively.

Activities and Progress during 1995

Activities during 1995 were focused on Task definition and planning, and initiation of Subtask efforts.

The Subtask Leaders and the Operating Agent met in Denver, Colorado on July 17-18, 1995 to develop the Programme of Work and the Annex 11 text. Dr. Thomas H. Schucan (Paul Scherrer Institut, Switzerland), Mr. Hajo Ribberink (ECN, Netherlands), and Mr. Joseph Badin (Energetics, Inc., USA) met with the Operating Agent (Ms. Catherine E. Gregoire Padró, NREL, USA) to complete the development of the subtasks. Based on the results of the meeting, the revised Annex and Programme of Work were developed. The revised texts were distributed to the participating countries and to the members of the Executive Committee for comments. In addition, National Participation Commitment Letters were received from all participating countries. Modifications were minor in nature, and, on September 20, 1995, the Chairman of the Executive Committee authorized the start of work, contingent on approval by the full Committee at the November meeting. Official, unanimous approval by the Executive Committee was obtained on November 22, 1995.

Subtask A - Case Studies began its work with the distribution of a questionnaire to the subtask participants for information on hydrogen pilot and demonstration projects. The requested information included identifying data such as location and project leader; project goals, status, whether computer models had been developed; and characteristics of the project (production technology, storage method, and end use). Participants were asked to complete the questionnaire for each relevant project in their country. From this list, the first selection of systems was made, and a first draft of the physical and technical boundary conditions was developed. Projects include hydrogen as off-peak power storage; hydrogen vehicles; cogeneration systems; solar/electrolysis systems with low and high pressure storage; and integrated renewable hydrogen production, storage, and use for small utility vehicles.

Subtask B - Analysis Tools began its work using the results of early Subtask A activities. A questionnaire was developed to obtain information on simulation models. The requested information included simulation or mathematical modeling activities, software used, availability, validation efforts, and inputs and outputs. Existing computer simulations will be used to the extent possible, and a preliminary list of components that require modeling will be developed. Processes or systems that have been modeled include production by steam reforming, biomass gasification, biomass pyrolysis, and small scale partial oxidation; storage using metal hydrides, compression, liquid, and carbon systems; transport in pipelines and truck; and utilization in fuel cells, internal combustion engines, and burners.

Subtask C - Design Guidelines began its work making an overview of the conventional energy system and of hydrogen alternatives for parts of this energy system in the form of energy chains, as described by D.S. Scott (1994). Participants were asked to review the draft chains and comment as necessary. In addition, baseline application requirements were collected for conventional energy systems that have hydrogen alternatives. These requirements included efficiency, emissions, availability, variability (start up time, load following behavior), lifetime, production costs, investment costs, and safety regulations. The list of existing pilot and demonstration projects produced in Subtask A was compared to the list of conventional and alternative hydrogen systems generated in this subtask.

Work Planned for 1996

Collection and analysis of information continues in all subtasks. The work plan is following the schedule developed in 1995. An Experts Meeting is scheduled for March 28-29, 1996 in Alexandria, Virginia, USA. The meeting is expected to be attended by more than 20 experts in process design and analysis. The Subtask Leaders will moderate the presentation, discussion and modification of the list of systems and the identification of the components to be modeled. Initial assignments for component modeling will be made, in addition to identification of additional projects and requests for supplemental data and models.

Scheduled activities for 1996 by subtask are:

Subtask A:

- Establish data requirements
- Obtain detailed information and data
- Organize collected data

Subtask B:

- Identify components to be modeled
- Begin validation of component models
- Request additional data
- Begin adaptation of models to integrating platform
- Begin parametric studies

Subtask C:

- Complete identification of baseline application requirements
- Identify systems that have not been demonstrated
- Make initial requests for additional project data and component models
- Begin building integrated system models

Meeting Schedule for 1996 and 1997

March 28-29, 1996	Experts Meeting, USA
Fall, 1996	Task Meeting, TBD
Spring, 1997	Experts Meeting, TBD
Fall, 1997	Task Meeting, TBD

References

J. S. Badin, 1995, "An Overview of Hydrogen Energy Demonstration Projects, Process Simulation Tools and Design Guidelines," IEA Agreement of the Production and Utilization of Hydrogen 1994 Annual Report, IEA/H2/AR-94.

D.S. Scott, 1994, "The Energy System," International Journal of Hydrogen Energy, Vol. 19, No. 6, pp. 485-490.

TASK 12 - Hydrogen Storage in Metal Hydrides

William Hoagland
W. Hoagland and Associates, Inc.
Interim Operating Agent for the
U.S. Department of Energy

Description of Task

Metal hydrides have been actively researched for the storage of hydrogen because they are safe and provide the capability for long-term storage of hydrogen at high volumetric density. This task has two specific objectives:

- to develop new hydride materials suitable for on-board storage for vehicles; and

- to develop new hydride surface treatments for a new generation of electrochemical applications.

The activities of the task involve laboratory research to develop new preparation methods and new materials to reversibly store hydrogen as a fuel for vehicular transportation. The work will be divided into two parts: (1) novel preparation techniques that will allow for the synthesis of new hydrogen storage materials that do not now exist in that form, and (2) material surface engineering to improve the gaseous and electrochemical charge/discharge processes of known materials.

Participation

The following countries are participating in Task 12: Japan, Norway, Sweden, Switzerland, and the United States.

Activities and Progress During 1995

This is a new task and much of the efforts during the past year were aimed at developing a work plan and annex description to obtain approval of the executive committee to begin work. This approval was obtained in November 1995 and work will begin in early 1996.

Two experts meetings were held during the past year. An informal planning meeting was held July 17-18 in conjunction with the *Gordon Research Conference on Metal Hydrogen Systems* in Henniker, New Hampshire (USA). The purpose of the meeting was to review changes to the work plan as a result of the discussion at the Executive Committee meeting in May 1995. A task initiation workshop was held on September 27-28, 1995 at the Institute for Energy Technology, Kjeller, Norway. The experts reviewed the task work plan and began to schedule the first year activities and agree on a management plan and methodology for synthesizing and evaluation of the first hydrides. A number of hydrides were identified for development and some samples will be available to the collaborative effort early in 1996.

The work is organized into four Projects.

Summary of Work Planned for 1996

Project A: Synthesis Techniques - The development of techniques for synthesizing new materials and surfaces for hydrogen storage.

! **Synthesis of intermetallic hydrides based on transition metal - hydrogen complexes**. For the first year, 3 to 5 new intermetallic hydrides are expected to be synthesized.

! **Synthesis of metal hydrides -** For this task, techniques such as rapid solidifications, mechanical alloying and thick film synthesis will be employed to produce alloys which have the desired properties of pressure, temperature, kinetics, particle size, etc. During the first year, thick films (10-50 micro-meters) of Mg alloys will be produced and characterized. Also, 2 to 4 mechanically alloyed materials will be studied and compared to existing alloys.

! **Search for new metal hydrides comprised of light and cheap metals -**

It is known that some intermetallic compounds consisting of light and cheap elements, such as Ca and Al, have a hydrogen absorption capability, but slow kinetics. Attempts to increase their hydrogen absorption capacities will be performed by partial substitution of additive elements. Effects of the substitution on the crystal structure, hydriding and dehydriding characteristics, and thermal stability will be examined by XRD, DTA and PCT measurements.

- **Rapid solidification -** Rapid solidification (10^5deg/sec) techniques will be used to make alloys of compositions not obtainable by normal melting techniques or to control microcrystallinity. The resulting alloys may be single or multi phase, amorphous or crystalline or both. The alloys will be produced in vacuum or an inert atmosphere to prevent oxidation. The spin melting technique will be used and sample sizes to 50g may be used to produce thin ribbons (50µ). Magnesium based alloys may be made by this technique. Up to 50 different compositions are anticipated to be made per year.

- **Surface engineering -** Alloy surfaces will be modified by chemical, metallurgical and physical methods in order to encapsulate the bulk materials. The chemical method includes chemical etching and chemical modification on the surface. The metallurgical method includes precipitate formation on the grain boundaries. The physical method includes electrochemical and chemical coating and mechanical mixing with additives.

Project B: Characterization of New Materials and Surfaces - Each of the new materials produced under this task will be characterized using available techniques with participants' facilities. The results of this effort will be compared with hydrogen storage properties to correlate physical properties with operating performance.

- **Structure determination -** Neutron diffraction analysis is the only definitive method for determining the complete structure since hydrogen cannot be "seen" by x-rays in the presence of heavy atoms. Selected samples which show promise will be subjected to complete structure analysis to include neutron diffraction analysis. This technique will be used only after careful consideration, since only 5 to 6 samples can be done in the first year.

- **Pressure-Composition-Temperature measure of hydrides -** Gas-phase measurements will be made of the pressure, composition and temperature (PCT) relationship of synthesized hydrides to complete a quick survey of synthesized samples. These measurements will yield values of hydrogen composition, as well as the kinetic behavior and equilibrium pressure as a function of temperature. The effect of impurities and cycling on hydride behavior will also be determined. Since these measurements are relatively time-consuming, only more promising alloy candidates will be measured in detail. Approximately six samples could be fully characterized in the first year.

- **Microstructural Analysis -** Typically, hydride alloys can have complex microstructures that need to be characterized in order to understand hydriding behavior and possible material modification for improving hydride performance. A number of the participating laboratories have extensive analytical capabilities which will be applied during this task. These techniques include metallography, electron microprobe analysis (EMPA), scanning electron microscopy (SEM) and x-ray fluorescence (XRF).

- **Surface analysis, surface treatments, new surfaces** - Metal hydrides for reversible energy storage are used in a high surface area shape, typically 10 micron powders, and eventually ribbons or films. They are handled in air or dry gases and thus covered naturally with oxide layers. The properties of these layers are crucial in view of passivation and activation of the hydrogen storage material. Catalytic sites for H_2 dissociation and for charge transfer are needed in these surface layers for gas phase and cathodic charging, respectively. Various surface treatments (wet chemical etching and deposition, thermal treatment) will be used to improve the surface properties for selective applications. Surface sensitive analytical techniques will be used at Kogakuin University (Japan) and Fribourg University (Switzerland). X-ray photoelectron spectroscopy (XPS, ESCA) and Auger electron spectroscopy (AES) as well as scanning tunneling microscopy (STM) in an electrochemical environment will be used to characterize sample surfaces before and after treatment and as a function of cycle life. Depth profiles will be measured using Argon ion sputtering. The results will be correlated with materials performance in gas phase and electrochemical cycling.

- **Electrode Evaluation and P-C-T -** Developed alloys, new microstructures and new surfaces will be evaluated as a metal hydride electrode. Electrode performance such as activation, electrical capacity, charge and discharge efficiency, cycle life and temperature dependencies will be examined in order to check the effectiveness. New electrode preparation methods will also be developed to suit the nature of the new materials.

Project C: Evaluation of Manufacturing Technology - In the end, the new materials developed in this subtask must be amenable to practical and economic large scale production. Input and evaluation on proposed manufacturing techniques will be provided on a continual basis, as needed. It is expected that the main study of this area will be made in the second and third years of the effort, that is, after some initial success in identifying promising new materials and techniques during the first year. Total effort for the first year should be about a 0.2 person years.

Project D: Applicability Analysis of Hydrogen Storage Materials - Although the task is directed toward improved hydrogen storage materials for transportation and electrochemical applications, the new materials developed may very well have other uses. Each of these applications will have its own set of preferred properties. The purpose of this project is to try to identify possible "spin-off" applications for hydrides developed by this task. Next year's effort will be directed at a detailed analysis of hydride applications such as stationary storage systems, thermal compression, separation, liquid hydrogen, batteries and others. Particular emphasis will be on stationary storage systems. The main objective will be to determine the target chemical and physical properties required of ideal hydrogen storage materials for each application to be commercially successful. Existing barriers and difficulties will be identified and the competition identified.

Reports Published During 1995:
None

Reports to be Published During 1996

- Comprehensive Review of Metal Hydrides - May 1996

- Published Report of Technical Workshop - November 1996

Task Meetings Held in 1995

- An informal planning meeting was held July 17-18 in conjunction with the *Gordon Research Conference on Metal Hydrogen Systems* in Henniker, New Hampshire (US).

- A task initiation workshop was held on September 27-28, 1995 at the Institute for Energy Technology, Kjeller, Norway.

Task Meetings to be Held in 1996

Two technical meetings will be held in 1996:

- A Technical Workshop to be held in conjunction with the 11th World Hydrogen Conference in Stuttgart (June)

- A technical coordination meeting to be held in conjunction with the International Symposium on Metal Hydride Systems in Switzerland (August).

16th Annual World Energy Congress - Tokyo, October 1995

A Report to the IEA - Hydrogen Implementing Agreement
by David Hicks, National Renewable Energy Laboratory

World Energy Congress Convenes in Fast-Growing Asia Pacific Heartland

When the Sixteenth World Energy Congress began on October 8, 1995, it was clear that its sponsor, the World Energy Council, has become the leading non-governmental multi-energy organization. The addresses, round tables, and sessions held during the six days of the Congress reflected the work of hundreds of authors. Five thousand participants attended from 84 countries, and an associated World Energy Fair attracted 62,000 visitors.

The setting of the Congress in Tokyo, at the heart of the fast-growing Asian Pacific region, reflected global interest in and concerns about the energy needs, challenges, and opportunities of this vital part of the world. The Congress emphasized that global cooperation and interaction are needed to respond wisely to two main international energy challenges: (1) The need to provide energy access to the more than 2 billion impoverished people in developing countries so that they can improve living standards with minimum environmental damage, and (2) The long-term need to achieve global sustainable development.

Despite current abundant supplies of fossil fuels that encourage complacency toward energy issues, the World Energy Congress exhorted all parties involved to intensify the pursuit of energy efficiency and global partnerships to facilitate capital and technology transfer. Energy prices should reflect full costs, educational programs must heighten awareness and change perceptions, technological development must accelerate, and the risks of climate change must be minimized. Simultaneously, the 40% of the world deprived of adequate energy supplies will require investment, cooperation, and development.

The Congress answered the question posed as its theme: "Energy for our Common World-What will the future ask of us?" with a number of valuable recommendations. Keynote speakers in particular stressed market-based solutions that encourage investment, global cooperation and diversity, and discourage subsidies, monopolization, and narrow views. The next two to three decades represent a key period of opportunity, the Congress concluded, and, if not seized soon, returning to the path may become difficult and costly in the long run.

The Fundamental Relationship Between Energy and Economic Development

A study of the world's new Economic Order led the discussion as addressed by keynote speaker Dr. Kim Chulsu, Deputy Director General of the World Trade Organization. The collapse of bipolar political systems has signaled a global rise in economic issues, including market-based policies such as privatization, deregulation, liberalization, and internationalization. This "paradigm revolution" will require the world's peoples to "be more intelligent in our use of energy," Dr. Chulsu pointed out. He called for greater accountability for the external effects of energy use and production and greater emphasis on renewable energy options.

Another challenge resides in the view of commercial energy development as a necessary prerequisite for modernization. "This pattern has also been accompanied by rapid depletion of resource reserves and rising environmental deterioration," Dr. Chulsu said. To combat this trap, greater emphasis should be placed on energy efficiency improvement and conservation through both market and regulatory approaches. Minimum standards, labeling, and aggressive policies to encourage investment in new technologies and practices are all needed, he asserted.

The preference for convenient, inexpensive and abundant oil and coal will need to be surmounted by greater reliance on natural gas and other cleaner fuels, said Dr. Chulsu. Finally, reforms are needed to open developing countries to new technology and domestic and foreign investment. In areas of Eastern Europe, particularly, rehabilitation, energy efficiency improvements, and adoption of new technologies and practices will take place during the coming transition years.

Many countries are realizing that the scope of environmental problems calls for international cooperation. Developed countries bear responsibility for their lion's share of greenhouse gas emissions, while developing nations should also accept their responsibilities. Transfer and exchange of energy efficient technologies should be preferred over "conservation measures which restrict world trade, and hence reduce global welfare," Dr. Chulsu advised.

With more than 25% of the world's population, Northeast Asia is emerging with significant concerns regarding future energy demands, the need for development of untapped resources, and the construction of integrated energy transport systems. Dr. Chulsu called for multilateral, intra-regional cooperation to develop a framework for accomplishing the area's energy goals without unduly compromising the environment. "Energy and environment cooperation in Northeast Asia will be one of the most urgent needs we face," he concluded.

Future Sustainable Energy Supplies

Development of new energy sources and advances in fossil fuel development and use will complement each other, as "the world will need as many energy options as possible," declared keynote speaker John S. Jennings, Chairman of Shell Transport and Trading and Vice Chairman of Royal Dutch Shell Group's Managing Director Committee.

He championed an energy policy focusing on diversity and flexibility to meet world energy demand, which he estimated could grow by as much as 70% over the next 30 years. In this respect, the role of government should be to foster inventiveness, competition, and productivity. All parties should be involved in a debate that resolves policy dilemmas; is calm, rational, and open; and is based in sound scientific principles.

The energy industry is currently grappling with an excess capacity situation. In the last decade, the industry has come to terms with lower oil prices, slashing production costs and instituting new exploration techniques and production technologies. Other energy technologies, such as renewables, are becoming more competitive. Mr. Jennings concluded, "There is little reason to believe that the price of energy in oil equivalent terms need ever go much over say $25. . . ."

Mr. Jennings also shared Shell's current scenario planning results, in which a 'high growth' scenario would lead to the greatest energy demand. Excess capacity would disappear early in the next century, but demand would continue to be met by fossil fuels with massive annual investment for the next 30 years. Ultimately, production costs would continue to decrease, recovery ratios would rise, associated gases would be utilized, higher cost resources would begin to be developed, and gas would be transported over increasing distances. Fuel conversion and coal gasification would also play roles.

In the second quarter of the coming century, alternative energy sources would emerge, especially for heat and power generation, expanding first into niche markets. If renewables development is successful, these technologies will become cheaply and widely available, contributing significantly to world energy supply.

Another scenario involves enhanced productivity, perhaps combined with lifestyle changes such as telecommuting. Shell scenario planners anticipate that energy use will still grow at about 1.3% annually for 30 years, with 2% annual improvement in energy intensity. Both scenarios project a peak in CO_2 emissions from fossil fuels at 10 gigatonnes annually until mid-century, followed by a decline to less than half that amount by the century's end. Mr. Jennings recommended following the "principle of prudence" and avoiding precipitate action regarding CO_2 emissions, as well as encouraging competitive technologies. "The trend to deregulate energy markets is a strong enabler of these important transitions," he asserted.

Efficiency Gains in Energy Use

The large appliance industry is an example of what can be achieved through constant

focus on greater productivity, according to keynote speaker Mr. Paolo Fresco, Vice Chairman of the Board and Executive Officer of the General Electric Company. Appliances such as refrigerators often sell for less than their price 75 years ago, with more features, higher reliability, and up to half the energy use of models from just a decade ago. Calculations show that "every one of GE's global businesses would be out of business. . . losing money. . . in less than five years with no productivity gain," he said. "Productivity. . . is the lifeblood of our competitiveness in a global marketplace that will be dominated by low-cost, high-value producers of goods and services."

Availability of electricity correlates closely with growth in domestic product, Mr. Fresco maintained, citing Indonesia, Malaysia, and Korea as examples of note. In contrast, India's slower growth in high technology power generation plants constrains that nation's gross domestic product growth to about 4% per year. It is globally true that "electrical energy infrastructure can be an engine driving...productivity and competitiveness or an anchor dragging on it," he asserted.

The Energy, Environment, and Economic "Trilemma"

In his keynote address, Mr. Shou Nasu, Chairman of the Board of Tokyo Electric Power Company, discussed the problem of reconciling growing energy use with deepening environmental problems. He described the vicious circle of economic growth, energy use, and environmental degradation that is often termed a "trilemma," and called for a change of perspective.

Today's environmental problems are difficult to solve because they arise unavoidably from daily need satisfaction and economic activities, pose serious harm unless they are soon remedied, and can only be solved through unified, global efforts. The challenge of simultaneously protecting the Earth's environment, while giving full consideration to the right of developing countries to pursue rapid economic growth, offers a new role to the global energy industry, Mr. Nasu declared.

Prosperity often brings a tendency to waste resources and lose interest in recycling, but this must be replaced with *mottainai*, or caring, thankful treatment of everything, Mr. Nasu warned. Also, environmental problems are exacerbated by and intertwined with modern social systems and lifestyles, requiring behavioral changes and rebuilding of whole systems. "We need to devise new standards . . . that can't be measured according to existing economic indices, . . . such measures as spiritual fulfillment of harmony with nature," he advised.

A slowdown in energy conservation has coincided with widespread low energy prices, Mr. Nasu pointed out. "When energy prices are held down for policy reasons, consumption will be unnecessarily high," he said. Thus, prices should be dictated by market forces. He concluded that a good mix and variety of energy sources, including nuclear fuels, will serve coming generations best.

A Commitment to Action

Taking to heart the messages of the speakers at the Congress, the attendees concluded by committing themselves to creating a strategic and integrated vision of long-term global energy needs and how best to meet them. Through education, communication, and the building of awareness, the Congress vowed to push for the establishment of sound policies, decision-making and action, rather than protracted debate, for the greatest benefit of all.

SUMMARY: TECHNOLOGICAL STATUS OF HYDROGEN ROAD VEHICLES

A Report to the IEA - Hydrogen Implementation Agreement
by Thomas Doyle, Technology Consultant

This report is intended to be a state-of-the-art summary of hydrogen-fuelled vehicles for road transport. The draft version runs to some 60 pages, but will undoubtedly be modified and enlarged after national representatives have provided additional information and comments.

It is not based on deep insider knowledge, but is rather a distillation of some 150 publications on the matter in the past 5 years.

A rigorous comparison of the technical merits and weaknesses of individual projects underway is neither intended nor possible at the present time. The need is rather to identify a valid point of departure for the new Task 11 - Integrated Systems under the Hydrogen Implementation Agreement. A survey is therefore made in the report of the important sub-systems which have a strong bearing on vehicle architecture and layout, and the most important ones - hydrogen on-board storage; safety measures; power units, both internal combustion engines and fuel cells; and drives are analyzed in some detail. The demonstration vehicles being operated or firmly planned worldwide are illustrate in two tables.

Three technical appendices on safety questions, internal combustion engines and fuel cells are intended to help those coming to hydrogen vehicles for the first time.

The principal conclusion which can be advanced at present are:

! In the absence of adequate gaseous hydrogen (GH_2) pipelines, small fleets can be satisfactorily furnished with liquid hydrogen (LH_2) from large tankers which are already in regular highway use for the electronics, space and other industries.

! On-board storage for adequate daily ranges can be provided by GH_2 or LH_2 tanks and the safety implications have been clarified to the extent that they are no greater, and possibly even less, than those deriving from conventional transport fuels; all fuels have some dangers, and safety must be engineered into the vehicle.

! A heightened awareness of safety in design and operation must accompany hydrogen vehicles, first because of certain accident situations (especially leakage to confined spaces) and then also because the public is probably less tolerant of fuels with unfamiliar and exaggerated dangers.

! The familiar internal combustion engine can be made, albeit with some difficulty, to operate on H_2; if only low-to-medium pressure GH_2 is available, it can be injected on the inlet stoke but care must be exercised to purge the inlet ports of H_2 to prevent backfire and turbocharging is needed to avoid power loss from low-density H_2 displacing too much air; cryogenic temperatures of LH_2 are helpful because more air enters the cylinder, backfire tendency is cooled, and turbocharging gives similar outputs to gasoline engines; better still is to inject LH_2 at high pressure (over 100 bar) near top dead center, but high precision is required of the difficult injectors and ignition devices, and high-pressure LH_2 pumps need much development to overcome severe cavitation and friction problems.

! The improvement in emissions is dramatic: NO_x can be below 10% of future standards and carbon monoxide, carbon dioxide and hydrocarbons (all from lubricating oil) are practically zero; they cannot however reach the zero levels of standards being advanced in the USA for turn-of-the-century vehicles, whose overall regional effects when storage batteries are used outstrip those of H_2 engines.

- The fuel cell, which combines H_2 and oxygen (usually from air), in docile electrochemical reactions which can provide sufficient electrical power and energy at low temperatures for road vehicles, with no emissions except water and no noise except that o the drive train, would seem to be ideal if it can be brought to acceptable levels of cost and reliability; the proton exchange membrane fuel cell has made great strides in the past few years, and is becoming the favorite world-wide for transport applications; the problems are above all cost (platinum electrodes contain ten times as much of this precious metal as a catalytic converter), and power density.

- A so-called hybrid solution is emerging to ease the H_2 combustion (for ICE) and cost (for FC) problems: the prime mover, ICE or FC, is sized only for average load and speed, while energy storage devices -usually batteries- provide peak power and absorb braking energy; demonstration versions are running, and promise is high.

- While generalizations are difficult, it can be said that in Europe and Japan at present the internal combustion engine projects with operating vehicles outnumber the fuel cell ones, while the reverse is true in the USA; furthermore the trend is accelerating in the USA with many fuel cell projects announced for completion in the coming years, and few internal combustion engine ones - and Europe as well as Japan have yet to announce more than one or two projects between them.

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