IAEA
International Atomic Energy Agency

Interoffice Memorandum

To:	J.K. Park, DIR-NENP	**From:**	I. Khamis, NPTDS
Through:		**Clearance:**	A. Rao, SH-NPTDS
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Subject: Meeting Report on the Technical Meeting on Hydrogen Production using Low and High-Temperature Electrolysis

ATTENDING EXPERTS

Name	**Country/Organization**	**Date**
Mr S. Suppiah	CDN – Chalk River Laboratories	17-19 May
Mr J. Xu	CPR – Tsinghua University, INET	—“—
Mr P. Zhang	CPR – Tsinghua University, INET	—“—
Mr A. Maisseu	FRA – Int. Journal of Nuclear Hydrogen Production and Applications	—“—
Mr P. Ragunathan	IND – Bhabha Atomic Research Centre	—“—
Mr P.P. Prosini	ITA – Agenzia National per le nuove tecnologie, ENEA	—“—
Mr M. Siddiq J.	PAK – Pakistan Nuclear Regulatory Authority, PNRA	—“—
Mr G. Kodochigov	RUS – OKB Mechanical Engineering, OKBM	—“—
Mr V. Golovko	RUS – OKBM	—“—
Mr J.S. Herring	USA – Idaho National Laboratory	—“—
Mr Y. Nemoto	I.O. - OECD	—“—

1. Background

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Hydrogen could be produced from nuclear energy by several means/processes and through different routes in the near-term, mid-term, and long-term. The development and deployment of high efficiency high temperature steam electrolysis and thermo-chemical processes are foreseen to play an important role in the long-term prospect of hydrogen production as they are currently under R&D. Yet, nuclear energy could be used for near and mid-term hydrogen production through various approaches/strategies that involves the use of water and high-temperature steam electrolysis.

Currently there is increasing interest in hydrogen production using conventional water, medium or high temperature steam electrolysis coupled to nuclear energy. Electrolysis of water is a proven technology. However, this process has some advantages and disadvantages related to use of off-peak power and high electrical consumption rates, respectively. Both the reactor operating temperature and the power cycle efficiency will play important roles in the overall economics of hydrogen production using electrolysis..

The IAEA has already organised several technical meetings to exchange information on nuclear hydrogen production. The latest of these meetings was held in October 2009. The meeting was held as a continuation of the previous technical meeting with hydrogen experts on issues concerning hydrogen production, the technical meeting on non electric applications of nuclear energy held in March 2009 in Rep. of Korea, and International Conference on Non-electric Applications of Nuclear Power which was held in Japan April 2007. The meeting which was held during 12-14 Oct 2009 in Mumbai, India helped catalyse recent activities in some Member States and open discussion on advances and challenges to nuclear hydrogen production with emphasis on safety of coupling and future aspects hydrogen economy.

This meeting in Vienna provided a forum for information exchange among Member States and the IAEA ongoing activities especially on the prospects of low and high temperature electrolysis for hydrogen production using nuclear power. The meeting discussed some IAEA activities on nuclear hydrogen production and attempt to formulate, with help of participants, a short and medium term plan on future activities on hydrogen production, especially the newly developed IAEA HEEP software and future related activity.

2. Objectives of the meeting

The objectives of the meeting were to exchange information on:

- Current status of technologies for water, medium and high-temperature steam electrolysis;
- Viability of large-scale production of hydrogen using such technologies;
- Safety aspects of nuclear hydrogen production with emphasis on coupling;
- Use of off-peak electricity for hydrogen production;
- Assessment of economics of hydrogen production based on water, medium and high-temperature steam electrolysis.

3. Agenda

Monday, 17th May 2010

09:00	Inauguration and Welcoming Remarks	**A. Rao, IAEA**
10:00	Introduction of participants and adoption of Agenda	**all participants**
10:10	**IAEA Activities on Nuclear Hydrogen**	**I. Khamis, IAEA**
10:15	**Canadian/AECL Developments in Low and High Temperature Water Electrolysis for Hydrogen Production**	**Sam Suppiah, Canada,**
11:00	*Coffee Break*	
11:30	**Progress of R&D on HTSE in China**	**Ping ZHANG,**

		Jingming XU, Bo YU, China
12:30	*Lunch Break*	
14:00	**Overview of OECD/NEA Information Exchange Meetings on Nuclear Production of Hydrogen**	**Yoshiyuki Nemoto, OECD/NEA France**
14:45	**Porous Nickel Electrodes for Hydrogen by Low Temperature Electrolysis**	**P. Ragunathan, India**
15.30	*Coffee Break*	
16.00	**Medium Temperature Regenerative Molten Carbonate Fuel Cell**	**P. Paolo Prosini, ENEA,Italy**
17:00	*Adjourn of Day 1*	
18:30	*Buffet-dinner outside VIC*	**all participants**

Tuesday, 18th May 2010

09:00	**Safety Aspects and Licensing Strategy for Hydrogen Production using Nuclear Power Plants**	**M.Siddiq Javed, and Kamran Mansoor, Pakistan**
09:45	**Conceptual Studies of Heat Transfer Systems**	**Golovko V.F., Kodochigov G.N., Nizhny Novgorod, Russia**
10.30	*Coffee Break*	
11:00	**Progress in the Development of High Temperature Electrolysis**	**Stephen Herring, USA**
11:45	**XXI° Century: Time for Hydrogen Economy**	**Andre Maisseu, WONUC, France**
12.15	*Lunch Break*	
14:00	**Discussions on future IAEA Activities on Nuclear Hydrogen**	**all participants**
16:00	*Coffee Break*	
14:00	**Recommendations on IAEA future activities**	**all participants**
17:00	*Adjourn of Day 2*	

Wednesday, 19th May 2010

09:00	Panel Discussions **Prospects & Challenges for nuclear hydrogen production and economy**	**all participants**
10:00	*Coffee Break*	
10:15	**Finalization of meeting report**	**all participants**
11:00	**Finalization of meeting report**	**all participants**
12.30	*Lunch Break*	
14:00	*Adjourn of meeting*	

4. Summary of the Work done and results achieved

The IAEA (*Scientific Secretary*): highlighted the meeting with a summary of past IAEA activities on the nuclear production of hydrogen. Efforts now underway and nearing completion include a new TECDOC document on Hydrogen Production using nuclear energy, the development of the Hydrogen Economics Evaluation Program and the publication of a TECDOC on the results of the CRP on Advances in Nuclear Power Process Heat Applications (completed 2009). Expected accomplishment in the near future include the initiation of a new CRP on HEEP Benchmarking and validation (2010), the ICTP Advanced School on “Role of nuclear technology in hydrogen-based energy systems” on one week during June, 2011 and a Technical Report on NPP for cogeneration (including hydrogen).

USA (Mr. *Herring*) presented a summary of recent high-temperature electrolysis experiments at the Idaho National Laboratory, including the operation of the Integrated Laboratory Scale experiment and the 2500-hour test of a ten-cell stack. After discussing the fundamentals of high temperature electrolysis, he discussed the primary technical issues facing the technology – the long-term degradation of electrolytic cells due to inter-diffusion and delamination and the consequent increase in cell resistance.

China (Mr. *Zhang*) The Institute of Nuclear and New Energy Technology (INET) at Tsinghua University in Beijing is developing high temperature electrolysers for use in conjunction with high temperature reactors, such as their HTR-10 experimental reactor. Their main objective is a 200 MW(th) demonstration HTGR. The HTSE development is planned to have a 60 normal litre per hour laboratory scale experiment during 2007-2012, a 5 normal m^3/hour pilot plant in 2013-2017 and a 50 normal m3/hour pilot plant, connected to the HTR in 2017-2020. Dr. Zhang reported on the operation of a single cell using BSCF for the oxygen electrode at 850° C and achieving an Area Specific Resistance of 0.077Ω-cm2. The 5 cm x 5 cm cell showed no signs of degradation in the course of 50 hours of operation with an average hydrogen production rate of 1.02 normal litres per hour at a total current of 800 mA.

OECD/NEA (Mr. *Nemoto*) The Organization for Economic Cooperation and Development Nuclear Energy Agency (OECD/NEA) organized four Information Exchange Meetings on the production of hydrogen using nuclear energy in 2001, 2003, 2005 and 2009. There were no papers on high temperature steam electrolysis in the 2001 meeting, but the number of HTSE papers grew from one to three to eleven in the last three meetings. The reported hydrogen production rate rose from 32 to 115 to 5,000 normal litres of hydrogen per hour in the last three meetings. Mr. Nemoto also discussed potential locations and topics for meetings to succeed the Information Exchange Meetings.

India (Mr. *Raghunathan*) The Bhabha Atomic Research Centre (BARC) in India, where the researchers have been working on advanced alkaline electrolysers incorporating porous nickel electrodes in a zero-gap, bipolar filterpress type cell module design for hydrogen production by water electrolysis at low temperatures. This advanced cell module design is capable of operation at high current densities. Prototype electrolysers producing hydrogen in tens of cubic meter per hour were installed & tested. Technical know-how is available for plants of 30-50 Nm3 H2 / hr. Industrial participation with vendor development activities are underway for establishing the new industrial fabrication techniques and to meet the manufacturing needs for the new electrolyser technology. Recently two 50-cell module units, each with 15 Nm^3/hr H2 generating capacity, have been constructed and are awaiting to be integrated with the process skid structure housing the balance-of-plant.

Italy (Mr. *Prosini)* In 2005 the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) launched an ambitious project called TEPSI (TEcnologie e Processi innovativi per affrontare la transizione e preparare il futuro del Sistema Idrogeno). One of the main objectives of the three years project was to develop the Zero emission integrated hydrogen and electricity production by coal-hydro-gasification.

The ENEA in Italy has used their expertise in the construction and use of molten carbonate fuel cells, which they are now operating as electrolysers at temperatures of 550-650° C. MCFCs use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide (LiAlO2) matrix. Because MCFCs operate at 650°C and above, nonprecious metals can be used as catalysts at the anode and cathode. MCFCs are currently being developed for natural gas and coal-based power plants for electrical utility and MCFC plants are currently being demonstrated in several sites around the world. Focus is mostly on the 200 kW-1 MW range, while scale-up to multi-MW are going to be demonstrated in Europe [11], USA [12] and Japan [13]. The materials typically used for MCFC manufacturing are: nickel-chromium or nickel-aluminium for the anode, lithiated NiO for the cathode, Li2CO3/K2CO3 for the electrolyte, and γ-LiAlO2 for the matrix. One of the most important problems reducing MCFC longevity is the cathode dissolution in the electrolyte. NiO, in fact, reacts with CO2 in the cathode according to the following reaction. [delete last phrase or add reaction]

Pakistan (Mr. *Siddiq*) presented several considerations related to safety and licensing aspects of combined high temperature reactor and a hydrogen production plant, including the location of both nuclear and chemical hazards in the same area,. It was also emphasized that ~~the fact that~~ presently no international industrial codes (like ASME B& PV code) address materials applications above 850 °C and the research needed on nuclear fuels and graphite core materials for future high temperature reactors.

Canada (Mr. *Suppiah*) discussed the role of AECL and of CANDU reactors in the future production of hydrogen. One salient point of his presentation was that hydrogen from low-temperature electrolysers and perhaps also HTSE will not be competitive with steam methane reforming unless the discharge of carbon dioxide into the atmosphere is discouraged through a price on those emissions. He also described the probable role of CANDU reactors and electrolysis in the recovery and refining of the Athabasca Oil Sands. Finally, he presented a combination of a HTSE unit with an ACR-1000 having a steam temperature ~ 278ºC and using electrical resistance heating to increase the temperature to > 800ºC. An optimized flow sheet was developed for integration of HTE with ACR-1000, where about 10% of the steam production from ACR-1000 is used for thermal heating of HTE loop. The overall thermal-to-hydrogen efficiency estimated to be about 33% which is to be compared to ~27% for conventional electrolysis.

WONUC (Mr. *Maisseu*) as the editor of the International Journal of Nuclear Hydrogen Production and Applications – IJNHPA, he described the short term peak in our use of fossil fuels and evolution from using fossil fuels to our present transition to nuclear and renewable energy sources. The I.J.N.H.P.A. is a peer-reviewed journal of research articles, review papers, and technical notes related to the nuclear production of hydrogen and its applications. Topics include technological, regulatory, and policy aspects; risk estimation; and ecological consequences of nuclear-generated hydrogen.

5. Conclusions

1. Nuclear hydrogen from electrolysis is a reality now, and the economics need to be improved.
2. A significant number of countries are involved in research and development on hydrogen production using electrolysis.
3. Materials qualifications and testing for high temperature reactor applications, particularly to define the necessary qualification & testing criteria and to develop a code case for graphite core and high temperature materials.
4. Review of existing technologies for low temperature electrolysis
    a. What is optimal production rate to be expected from existing technology? To review the state of the art of technology and capacity.
    b. Capabilities for dynamic operation of LTE
5. Synergy among the participants, within the limitations of the Agency, for the engagement of civil society
6. Improvement the communication of information about nuclear hydrogen production technologies is important.

6. Recommendations

Some near term recommendations are:

1. Interface with the Gen IV Program Management Boards
    a. Gen IV is specific to the needs of the NGNP
    b. IAEA gathers information and needs for a wider range of applications
    c. The question is how to proceed
    d. Interface with Gen IV, areas of research, status as observers, members in common between IAEA and Gen IV committees
2. Enhance synergy among participants, for instance in the school in Trieste, on the involvement of civil society
3. Establishment of a Technical Working Group on Hydrogen Production
4. A website or a portion of an existing website devoted to the needs for the non-electrical applications of nuclear energy in various countries and document generation on the work being done on those applications. This may be incorporated in PRIS (Power Reactor Information System)
5. Participants to the meetings supported the IAEA on launching a Coordinated Research Program (CRP) on Hydrogen Economic Evaluation Program (HEEP) to include an avenue for information exchange and estimation of future needs in particular applications. The activity may also include:
    a. Distribution of a questionnaire on the future non-electric applications needs, e.g. examples: hydrogen production, desalination, process heat for petroleum refining, petroleum recovery (in extraction of the oil sands)
    b. Consider the economic aspects of the use of the oxygen by-product
6. Thermal integration of several processes to maximize output and minimize the needs for water in both production and cooling to achieve better water management and utilization.
7. The organization of a periodic summer school on nuclear hydrogen production technologies.

The medium term recommendations are:

8. Identify synergies among the various uses of process (>400 C) and waste heat (<150 C) from nuclear reactors
9. Identify role of the IAEA in developing an inventory of the needs for process heat over a spectrum of temperatures.
10. Explore the interface between the nuclear technology and the parameters of the hydrogen production plant and other non-electric uses of nuclear energy
11. Develop a toolkit for hydrogen production cost analysis
12. Identify an inventory of processes that fit within the parameters of various reactors e.g. the temperature and location requirements for the processes as compared with the capabilities for various reactors, and inventory of needs for process heat over a spectrum of temperatures and the rough magnitudes of each need, either by country or worldwide.
13. The safety analysis of the coupling of the nuclear plant and the chemical plant using either a Probabilistic Safety Assessment (PSA) or a Probabilistic Risk Assessment (PRA) should be explored within the IAEA activities. It is also suggested in this regard to use the Phenomena Identification and Ranking Table (PIRT) analysis done in 2008 by DOE and NRC