IAEA
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Interoffice Memorandum

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Subject: Report on the Technical Meeting to Examine the Role of Nuclear Hydrogen Production in the Context of the Hydrogen Economy

Place of Meeting:	VIC, Vienna, Austria
Date of Meeting:	17–19 July 2017
PTAEO code:	1000155.2016.04.RBF-MP1-2017.613222.NENP-Nuclear Power Technology Development Section
Chairperson:	Ms R. Boudries, Algeria
Scientific Secretary:	Mr Ibrahim Khamis

1. Participants

Name	Country/Organization	E-Mail Address
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Mr J. Wang	China/ Chinese Academy of Sciences	wangjianqiang@sinap.ac.cn
Ms E. Dewita	Indonesia/ National Nuclear Energy Agency of Indonesia	darmawan_p3tir@batan.go.id
Mr J. Takegami	Japan/ Japan Atomic Energy Agency	takegami.hiroaki@jaea.go.jp
Mr T. H. Lee	Korea/ KAERI	leeth@kaeri.re.kr
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2. Background

Hydrogen is becoming an attractive source of clean next-generation fuel that can help Member States to meet their requirements under the Paris Agreement adopted at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in December 2015, in particular by serving as an alternative energy carrier for transport applications. There are several pathways for hydrogen production, including water splitting and electrolysis. Currently the global 'hydrogen economy' is mainly based on hydrogen generated by steam reforming i.e. use of fossil fuel. Nuclear and renewable energies can also be seen as alternative carbon-free energy sources for the production of hydrogen. However, each technology pathway has its advantages and disadvantages. Hence, it is essential that various aspects, including the environmental, social and economic impacts of hydrogen production, be clarified.

Nuclear energy can make a large contribution to the hydrogen economy, meeting the globally growing demand for hydrogen without carbon emissions, when used as the primary thermal energy source to produce hydrogen. Conventional water electrolysis coupled to a light water reactor-type nuclear power plant is the only nuclear technology option available for hydrogen production at present, but it is costly in terms of both energy efficiency and economy. The nuclear-heated steam methane reforming (NH-SMR) method can be considered for deployment in the near future due to the maturity of existing steam methane reforming (SMR) processes for hydrogen production and the partially demonstrated coupling of nuclear reactor technologies to these processes. However, the NH–SMR methods still involves carbon dioxide (CO2) emissions due to the nature of SMR and can be subject to environmental taxes or penalties, which add to the uncertainties in future cost estimates. For hydrogen production, there are several processes which can be integrated with advanced reactor technologies, such as high temperature steam electrolysis (HSTE) and high temperature thermochemical, or hybrid water splitting processes. These are the most promising technologies for long term nuclear-driven large-scale hydrogen production plants. With the right high-temperature nuclear technology integrated into the relevant hydrogen production process, both thermochemical and electrolysis-based production of hydrogen have a promising future. One of the potentially more energy efficient systems is the coupling of a direct cycle advanced gas cooled reactor and a supercritical CO2 power conversion system to the HTSE process, where the medium temperature range is of the order of 550–750°C.

In support of its Member States, the International Atomic Energy Agency (IAEA) has developed the Hydrogen Economic Evaluation Programme (HEEP) to provide support in analysing the feasibility of hydrogen production using nuclear energy. HEEP can be used for performing economic assessment for various scenarios of hydrogen production including conventional and nuclear options. It can also be used for comparative studies between various nuclear and conventional energy sources.

3. Objectives of the meeting

The purpose of this meeting is to: (a) exchange up-to-date information on commercial technologies for nuclear hydrogen production that are foreseen to be available for near-term deployment, as well as on related socio-economic and environmental considerations; (b) assess the market potential, economics and other related challenges (including potential upscaling) of technologies that are currently used or are being investigated and/or developed for nuclear hydrogen production; and (c) draw a clear picture of the role of nuclear hydrogen production as a player in the future hydrogen economy.

4. Agenda

See Annex 1 attached

5. Summary of the work done and results achieved

IAEA: Mr I. Khamis (IAEA Scientific Secretary) presented the background, objectives, and expected outcomes of the meeting. In addition, he delivered a presentation on IAEA Activities on Nuclear Hydrogen Production, and an overview of the new CRP on entitled Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment. **Mr El-Emam** also presented on Introduction and Demonstration of HEEP and on Benchmarking of HEEP: Results of the completed CRP.

Algeria (Ms Boudries) presented on techniques for hydrogen production at high temperature. Economic study on nuclear and solar hydrogen production at high temperature has been presented. The study has shown that nuclear-based hydrogen production is economically competitive; in combination with solar energy, nuclear offers better opportunities for hydrogen economy development; and that solar -nuclear hybrid energy system offers the opportunity for a better use of nuclear and solar energy resources intended as a flexible energy system that is more reliable and more efficient. Ms Boudries also stated that there are numerous configurations of the hybrid system. That depends on the technical specifications, the economic constraints and on the local resources. She added that a solar nuclear hybrid energy system offers the opportunities not only for the production of clean energy and the increase in energy conversion efficiency but also the optimal use of equipment and the optimization of the system reliability, and that it also brings stability to the energy supply to the electrolyzer and fast solar energy market penetration.

Argentina (Mr Fouga) presented on nuclear hydrogen production by steam coal gasification in Argentina.The presentation gave description on laboratory scale two-step reaction process (gasification and pyrolysis) of natural solid fuels which are potentially applicable to hydrogen production. These processes are proposed in order to obtain a syngas composed by hydrogen and carbon monoxide. He also showed basic concepts of the two-step reaction process, the development of experimental facilities and some experimental results. The presentation included the characterization of three solid Argentine fuels (sub-bituminous coal and two types of asphaltites). Experimental results of the pyrolysis and gasification reactions of three Argentinean solid fuels using a Fixed Bed Reactor and Batch Fluidized Bed Reactor were shown.

China (Mr Wang) presented on the nuclear hydrogen production research activities at the Shanghai Institute of Applied Physics, which started the research on HTSE system in 2011 within the project of the Thorium Molten Salt Reactor Nuclear Energy System (TMSR), under the support of Chinese Academy of Sciences. He stated that in 2013, a 1 kW HTSE was established and operated at 800°C for 500h with a hydrogen production rate of 170 Nl/h and a degradation rate of 3.25%/100h; in 2015, a 5 kW HTSE was established and operated at 750°C for 1000 h with a hydrogen production rate of 1.37 Nm^3/h and a degradation rate of 2.25%/1000h; and in 2016, another 20 kW and 100kW HTSE demo systems are in designing and will be installed in next several years. In his presentation, he mentioned that the commercialization of HTSE technology for large scale hydrogen production still faces some technological challenges including: the degradation of SOEC stack during long-term operation; and the lack of mature integration technology for large-scale HTSE system, which bears great influence on the overall efficiency and stability of the system. He also added that the commercially available HTSE system is below 100kW, far below the MW scale requirement for large scale hydrogen production coupled with nuclear energies, and there is still lack of proofs for the commercial viability.

Indonesia (Ms Dewita) presented on the prospects of the nuclear-heated steam methane reforming (NH-SMR) Method for Fertilizers Industry in Indonesia. She showed that natural gas is used for both as raw material and fuel in hydrogen production by using steam methane reforming; and that introducing nuclear heat for hydrogen production is considered beneficial because natural gas (which is about 60% as fuel for hydrogen production) can be replaced by heat from HTGR type reactor. She also added that the National Nuclear Energy Agency of Indonesia (BATAN) plans to build the experimental Power Reactor in 2020 with one of the objectives is to conduct experiments for hydrogen production. Ms Dewita stated that she plans to use the IAEA HEEP to evaluate the hydrogen production cost in her national project, while the government is managed to regulate the price ranging USD 8-10/MMBTU.

Japan (Mr Takegami) presented the current R&D progress of Iodine-Sulfur process for high temperature gas-cooled reactor in HTTR project in Japan Atomic Energy Agency (JAEA) including: the completion of constructing hydrogen test facility of 0.1 Nm^3/h-scale in 2014, which is currently under operation to verify integrity of process components and stability of hydrogen production; success in the 1st stage test of 0.01 Nm^3/h, 8 hours to continue hydrogen production with integration of 3 section (H_2SO_4 decomposition section, Bunsen reaction section, and HI decomposition section) in February 2016; successful completion of second continuous hydrogen production tests (0.02 Nm^3/h, 31 h) in October. He presented the next step where JAEA has launched R&D for Iodine-Sulfur process to be coupled with the HTTR. Mr Takegami added that, currently, demonstration of hydrogen production by Iodine-Sulfur process and HTTR in JAEA is under consideration, and that the obtained results will be utilized for demonstration of hydrogen production using HTTR.

Korea, Republic of (Mr Lee) presented the current status of nuclear hydrogen development program in Korea and its related economic analysis. Korea's domestic policies related to hydrogen were presented, and that hydrogen demand will dramatically increase in Korea due to demand from administration policies such as new energy industry 2030 program, fuel cell vehicle promotion policy and fuel cell power policy based on 7th basic power supply plan. He also introduced the R&D program to develop VHTR technology, showing that the national R&D plan for VHTR and nuclear hydrogen consists of two tracks: one is for key technology development project and the other is nuclear hydrogen development and demonstration project; and that KAERI is mainly focus on key technology improvement project. He added that the key technology areas for the hydrogen production using a VHTR are design & analysis code system, high temperature experiment and components, high temperature materials, and coated particle fuel. In addition, the NHDD (demonstration) project is under discussion with government and industrial companies. Finally, preliminary economic analysis result including construction ripple effect was presented, based on 350MWt- 4 units and economically feasible.

Pakistan (Mr Khan) presented on nuclear hydrogen production processes and the national line of action. His presentation discussed the current energy mix in the electricity generation of the country, and added that the thermal energy contribution is 64 % in the energy mix and is mostly met by natural gas followed by other fossil fuels. Stationery power plants, domestic consumers, general industry, fertilizer and transport are being the main of natural gas consuming sectors. He added that the future energy scenario in the country identifies transport, fertilizer, hydrogen peroxide and ammonia plants are key sectors where the nuclear hydrogen can be employed as substitute to fossil fuel. In addition, he discussed the current hydrogen production processes in the country and the future prospective hydrogen production processes based on nuclear energy. He concluded that cheap and surplus electricity and HTGR Technology can pave a way for nuclear hydrogen production in the future. Further, he recommended development of an integrated plan for research, development and demonstration of the nuclear hydrogen production technologies in the country.

Russian Federation (Mr Balanin) presented on high temperature reactors from position of the hydrogen economy, showing that high temperature nuclear technologies provide high temperature potential required for hydrogen production, as well as high safety level necessary for co-location of facilities, in case of HTGR; its power line and modular design match well with demands of hydrogen production. In his presentation, Mr Balanin said that the MHR-100 nuclear power plant with two options for hydrogen production is the most near-term commercial Russian (OKBM Afrikantov) design that can play a role in hydrogen economy, especially in case of MHR-100 SMR option using steam methane reforming, because it is actually the most mature and effective method to produce hydrogen in a large scale; and that MHR-100 SE option designed for hydrogen production by the electrolysis method will be more desirable at the next stages of the hydrogen economy development. He added that for the comparative assessment and to examine role of different nuclear hydrogen production technologies it is proposed to carry out of multi-criteria analysis, considering different criteria such as economy, safety, reliability, ecology, social acceptability, infrastructure, independence, maturity, and prospect; and that economic criterion can be comprehensively evaluated by HEEP.

Saudi Arabia (Mr AlZahrani) presented on the future and Future and opportunities of nuclear hydrogen production in Saudi Arabia to meet the increasing energy demand that is derived mainly by the country's residential cooling and water desalination sectors. He introduced the energy challenges and the distribution of the current electricity demand. Furthermore, he discussed the Saudi nuclear plans to reach 17 GWe by 2040 in the context of recent international agreements and cooperation programs that have been announced by King Abdullah City for Science and Technology (K.A.CARE). To address the technical potential of nuclear hydrogen production, Mr AlZahrani presented a preliminary assessment of the efficiencies of SMART reactors-powered low-temperature electrolyzers for hydrogen and desalinated water production in the near-term deployment. Finally, the economic aspects of nuclear hydrogen production through electrolysis technologies were evaluated; the results show the significant dependence of the cost of nuclear-electrolysis hydrogen on the price of the electricity. He concluded that at current actual electricity prices, nuclear-electrolysis hydrogen is not competitive with steam methane reforming, however; in future, considering the daily electricity price fluctuating hydrogen production can be a promising solution to store surplus energy during off-peak hours, for commercial and storage options.

Turkey (Mr Özcan) presented the recent advances on nuclear energy in Turkey and upcoming projected plans for nuclear power plants and economics of possible nuclear hydrogen production options. An economic feasibility assessment was performed for nuclear hydrogen production using suitable reactors for conventional electrolysis, HyS, Cu-Cl, and Mg-Cl. IAEA's HEEP software was utilized for economic analysis of all considered nuclear hydrogen options with transportation via pipeline, where it is then to be mixed with the blue stream natural gas pipeline in Turkey. Advantages and disadvantages of hydrogen – natural gas mixtures were discussed. For nuclear electrolysis of hydrogen, only electricity was utilized, while nuclear heat was also used for hybrid cycles, as well as possible cost of chemical heat pump use was considered for high temperature heat requiring thermochemical cycles. Mr. Özcan presented the results by depicting on increased price of the gas supplied when hydrogen is mixed with the natural gas when the base price of natural gas is USD 0.30/Nm^3. However, fluctuating price and possible global and regional instabilities might make the hydrogen – natural gas mixture option a more economically feasible one, where Cu-Cl based nuclear hydrogen production showed the lowest hydrogen cost. It was also depicted that internal production of hydrogen by only utilizing one reactor of the upcoming Sinop nuclear plant can compensate more than 2% of Turkey's natural gas energy consumption.

OECD/NEA (Mr Paillère) mentioned that the NEA was finalising a report on the role and economics of nuclear cogeneration in a low carbon future. This report includes discussion on hydrogen production from nuclear systems, as well as benchmarking results provided by Canada and Japan. The NEA had published in the period 2005-2010 proceedings of workshops related to nuclear hydrogen production. But of course, the economics have changed to the disadvantage of nuclear with the decrease of gas prices brought by non-conventional gas production – and the absence of strong carbon pricing. However, with the signature of the Paris treaty, there is now new emphasis on decarbonising not only the electricity sector but also the heat and the transport sectors. The International Energy Agency has recently published its 2017 edition of Energy Technology Perspectives which includes for the first time a discussion on the potential of nuclear cogeneration applications, including hydrogen production. Finally, Mr Paillere mentioned that the NEA, as Technical Secretariat for the Generation IV International Forum, supported the work of the "Hydrogen Production" Project under the Very High Temperature Reactor (VHTR) System Arrangement – which investigates various hydrogen production technologies from thermo-chemical cycles to high temperature steam electrolysis. The level of activity of this project has decreased in recent years, but with the recent revival of interest for hydrogen as a low carbon energy carrier, the level of activity may hopefully increase again.

6. Conclusions

- Nuclear energy is an attractive source for future hydrogen production and could play an essential role in the global hydrogen economy.
- Coordinated activities on nuclear hydrogen production should be strengthened further among Member States.
- Very high temperature nuclear reactors will provide, when available, an economic advantage for nuclear hydrogen production. However, the lengthy expected licensing process for such new reactors will delay the near-term deployment of nuclear hydrogen production facilities.
- The development of high temperature steam electrolysis HTSE is rapidly progressing and many breakthroughs on technology development have been reported. Hence, HTSE commercial plants can be expected in the market within 10 years.
- Hydrogen production based on nuclear assisted steam methane reforming systems could be the alternative choice for meeting the increased demand of hydrogen for the near-term future.
- Hybrid systems (consisting of nuclear and renewable energies like solar) could also be seen as a mid-term strategy for hydrogen production at competitive cost.
- The new IAEA initiated CRP is an important step towards meaningful assessment of the nuclear hydrogen potential.
- The latest version of the IAEA HEEP meets lots of the user's expectations. However, the software can be further improved by incorporating additional features including: Capability to perform optimization and sensitivity analysis; expanded user's manual; perform efficiency calculations for nuclear energy, hydrogen generation along with overall efficiency and display as one the result; cost estimation credit for the by-products of hydrogen production; and process results in excel sheet format.

7. Recommendations

- Challenges and prospects for large scale hydrogen production, and the techno-economic aspects of promising technologies for nuclear (or hybrid) hydrogen production should thoroughly be examined based on gained experience by Member States and foreseen evolvement of hydrogen economy.
- Update HEEP to include some of the above features.
- Inform participants on the official initiation of the new CRP to allow sufficient time for participation.
- Consider the impact of licensing of nuclear hydrogen production on the overall economics of produced hydrogen, and the interlinked influence of safety aspects from nuclear plant (impact of nuclear safety) to hydrogen production plant (impact of industrial safety) and vice versa; to be examined as part of the upcoming CRP and/or other activities on nuclear hydrogen production.
- Share, when available, the TECDOC produced from the recently concluded CRP on nuclear hydrogen production with the participants of the meeting.

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Technical Meeting to

Examine the Role of Nuclear Hydrogen Production in the Context of the Hydrogen Economy

Room: M0E79, VIC, Vienna, Austria

Meeting Agenda

Monday, 17 July 2017		
09:30	Welcoming and opening remarks	Mr. Khamis, IAEA Mr. Monti, IAEA
09:35	Introduction of participants, Selection of Chairperson and Adoption of the Agenda	All participants
09:45	Overview and objectives of the meeting	Mr. Khamis, IAEA
09:50	IAEA Activities on Nuclear Hydrogen Production	Mr. Khamis, IAEA
10:10	Nuclear Hydrogen Production Research in TMSR	Mr. Wang China
10:30	*Coffee Break*	
11:00	Current R&D Status of Hydrogen Production Technologies for HTGR Heat Application System in Japan Atomic Energy Agency	Mr. Takegami Japan
11:20	**Brainstorming Session:** • Challenges facing near term deployment of Nuclear Hydrogen Production projects in Member States • Socio-economic and Environmental consideration associated with deployment of Nuclear Hydrogen Production Plants	All Participants
12:30	*Lunch Break*	
14:00	Techniques for Hydrogen Production at High Temperature	Ms. Boudries Algeria
14:20	Studies on Nuclear Hydrogen Production by Steam Coal Gasification in Argentina	Mr. Fouga Argentina
14:40	Prospects of the Nuclear-Heated Steam Methane Reforming (NH-SMR) Method for Fertilizers Industry in Indonesia	Ms. Dewita Indonesia
15:00	*Coffee Break*	
15:30	Introduction and Demonstration of HEEP	Mr. El-Emam, IAEA
16:30	**Open Discussion on HEEP**	All Participants
17:00	**End of Day 1**	

Tuesday, 18 July 2017		
09:00	Current Status of Nuclear Hydrogen Development Program in Korea and its Economic Analysis	Mr. Lee Korea, Republic of
09:20	Nuclear Hydrogen Production Processes and the National line of action	Mr. Khan Pakistan
09:40	Feasibility of Nuclear Hydrogen Transportation via Blue Stream Pipeline in Turkey	Mr. Özcan Turkey
10:00	High Temperature Reactors in the Nuclear Energy System from Position of the Hydrogen Economy	Mr. Balanin Russian Fed.
10:30	*Coffee Break*	
11:00	Nuclear Hydrogen Production in Saudi Arabia: Future and Opportunities	Mr. AlZahrani Saudi Arabia
11:20	Benchmarking of HEEP: Results of the completed CRP	Mr. El-Emam, IAEA
12:30	*Lunch Break*	
14:00	**Brainstorming Session:** • Upscaling of current technologies for large scale Hydrogen Production • Market Potential and Economics of large scale Nuclear Hydrogen Production	All Participants
15:30	*Coffee Break*	
16:00	**Introduction to the IAEA New CRP:** Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment	Mr. Khamis, IAEA
17:00	**End of Day 2**	
Wednesday, 19 July 2017		
09:00	Conclusions and recommendations	All participants
10:30	*Coffee Break*	
11:30	Summary of the meeting	All participants
12:30	Finalizing meeting report	All participants
13:30	**Closing Remarks**	