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Interoffice Memorandum

To: J.K. Park, DIR-NENP

From: I. Khamis, NPTDS

Through:

Clearance: T. Koshy, SH-NPTDS

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Subject: Report on Technical Meeting for "Users of the Hydrogen Economic Evaluation Program (HEEP)"

Place of Meeting:	IAEA Headquarters, Vienna
Date of Meeting:	25 – 26 March 201413
Program code:	1000155/2014.03/RBF-MP1-2014/613222-\NHR-TRV-Non Staff Other/NENP-NPTDS
Scientific Secretary:	Mr Ibrahim Khamis
Chairperson:	Mr X. Yan (JAEC/USA)

ATTENDING EXPERTS

Name	Country/Organization	Date
Ms R. Boudries	ALG/CDER	25-26.3.
Mr H.R. Corti	ARG/CNEA	-“-
Mr I. Dincer	CAN/UOIT	-“-
Mr P. Zhang	CPR/INET	“-“
Mr U. Malshe	IND/DAE	“-“
J-H Kim	ROK/KAERI	“-“
Ms Fernandez-Valverde	MEX/ININ	“-“
Mr J. Nisar	PAK/PAEC	“-“
Mr G. Kodochigov	RUS/OKBM	“-“
X. Yan	USA/JAEA-JPN	“-“

1. Background

The IAEA Hydrogen Economic Evaluation Program (HEEP) is a tool which could be used to analyse the economics of hydrogen production using conventional and nuclear power. It employs the four most promising processes for hydrogen production: high and low temperature electrolysis, thermochemical processes including S-I process, conventional electrolysis and steam reforming. HEEP software is suitable for comparative studies not only between nuclear and fossil energy sources for hydrogen production but also for solely hydrogen production or cogeneration with electricity. The HEEP models are based on some economic and technical data, and on cost modelling which include various aspects of hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users. The beta-version of HEEP was first released in November 2009. Subsequently, this beta version was modified and updated in November 2012 to the present version. In 2012, the IAEA launched new coordinated research project aiming at the techno-economic evaluation of nuclear hydrogen production and benchmark analysis of HEEP. Being still under development, this HEEP user's group meeting is the first platform for HEEP users to exchange information on various aspects of HEEP functionality, results and usefulness and provide feedback for future update.

2. Objectives of the meeting

The purpose of the meeting is to: 1) provide a forum for the exchange of information on the utilization and robustness of the IAEA-developed Hydrogen Economic Evaluation Program (HEEP), in particular on how to make this tool more user-friendly; 2) disseminate the results of the latest research and development activities relating to the hydrogen production processes embedded in the HEEP software; and 3) evaluate the results achieved by various HEEP users in order to develop a number of case studies as well as to support the necessary updating of the HEEP software.

3. Agenda

The complete agenda of the meeting is included as ANNEX I of this report

4. Summary of the work done and results achieved

The Technical Meeting was opened officially by the Scientific Secretary, Mr Ibrahim Khamis of NPTDS. After an introductory of the objectives of the background and expectations for the work throughout the meeting, he presented on the IAEA activities relating to nuclear hydrogen production. The meeting programme was agreed by the participants and Mr X. Yan was appointed as Chairman. The first and second sessions were devoted to the presentations of the participants. Highlights of each presentation are presented below:

Algeria (Ms. R. Boudries) presented on the techno-economic model that is used not only to enhance HEEP capabilities but also to provide a mean of comparison between the nuclear hydrogen production process and the solar hydrogen production process. In the present study, aim is to carry out HEEP benchmark exercise analysis. This is done first by using generic case for hydrogen production using high temperature electrolysis and thermochemical cycles as the techniques of hydrogen production. Then four cases are treated. The four cases are those presented by the four CSIs from Canada, China, Germany and Japan. The work is going to be based on the data provided by these CSIs. Three cases are based on thermochemical cycle technique for hydrogen production while the last one is based on the steam reforming technique. The case, proposed by Canada, involves the use of thermochemical cycle Cu-Cl and the SCWR. The case, proposed by China, involves the use of thermochemical cycle S-I and the HTR-PM. The case proposed by Japan involves the use of thermochemical cycle S-I and the GTHTR300C. Finally, the case proposed by Germany involves the use of SMR and the HTR-Module. These cases are used to check HEEP software capabilities for each type of process and energy source. A sensitivity analysis is also carried. The results are to be used for the introduction of the solar hydrogen production model cost.

Argentina (Mr H. Corti) as water electrolysis is an environmental friendly and versatile process for hydrogen production from nuclear and non-fossil fuel primary energy sources, water electrolysis technologies include high-temperature steam electrolysis, proton exchange membrane electrolysis (PEME), anion exchange membrane electrolysis (AEME) and liquid alkaline electrolysis (LAE). AEME and LAE represent the most inexpensive alternatives, owing to the fact that relatively low-cost non-precious metals materials are employed as electrodes. Zero gap electrolysers employing hydroxide conducting polymer membrane electrolyte, and Ni-based electrodes represent highly promising approach. However, in spite of its advantages, water electrolysis has to become more energy efficient and inexpensive in order to gain massive acceptance, as a technology suitable as one of the energy conversion step in the hydrogen economy. Our group is developing membranes for PEME and AEME based on polybenzimidazole (PBI) polymers. ABPBI (poly(2,5-benzimidazole), prepared by condensation of 3,4-diaminobenzoic acid (DABA) monomer in polyphosphoric acid (PPA), is a neutral polymer than can be doped with acid (H_3PO_4) or alkali (KOH) to become a proton or an anion exchange material with excellent thermal and mechanical stability. This procedure yields a low cost polymer as compare to Nafion (for PEME) and quaternized anion exchange membranes (for AEME). The performance of ABPBI membranes in the laboratory alkaline water electrolyzer, feed with a 15 wt% KOH aqueous solution, was found to be superior to that exhibited by commercial membranes based in Dowex marathon a functional polymer crosslinked to a polyethylene matrix. The observed behaviour of the alkaline ABPBI membranes is probably related to the higher conductivity of these membranes as a consequence of their higher KOH solution uptake.

Canada (Mr I. Dincer) presented a comprehensive case study by the HEEP to cover cost assessment of some selected nuclear hydrogen production processes, including S-I cycle, with the options of hydrogen storage and transportation was presented. Three different types of reactors (HTRK, PBR and PMR) are selected for 2 case studies for HTRK with 4 units and 6 units, 1 case study for PBR and 1 case study for PMR. Cost estimation for capital, fuel, decommissioning, O&M, and consumables are calculated and evaluated in addition with the thermal energy and electricity cost details. The overall cost estimation is performed by adding hydrogen storage and transportation options. Hydrogen storage options are mainly compression, liquefaction and metal-hydrate storage and available in the database. Pipeline or vehicle transportation costs can also be additionally considered for cost estimation. He noted that the HEEP software is a user friendly software package with a convenient way to estimate hydrogen cost from various plant configurations. Enhancing the nuclear- and renewable-based hydrogen generation plant options is necessary which will bring a more comprehensive study, comparison and interpretation for hydrogen cost calculations.

China (Mr P. Xhang) discussed how high temperature gas-cooled reactor (HTGR) technology has been developing in China for more than four decades. Currently the only commercial demonstration plant program, high temperature reactor-pebble module (HTR-PM), is being constructed, and the related key R&D items, including manufacturing of reactor pressure vessel, helium loop, digital control system, simulator, etc., are on the track. With this background of HTGR, China has been conducting the R&D on nuclear hydrogen production since 2005 in the institute of nuclear and new energy technology (INET), Tsinghua university of China. Considering the essential of techno-economics evaluation for the industrial use, INET adopted the Hydrogen Economics Evaluation Program (HEEP) to make the preliminary cost estimation of nuclear hydrogen under the contract of

CRP. The related R&D in the field of nuclear hydrogen production will provide technical data for the estimation. The cost of H2 from five generic nuclear hydrogen production cases offered by IAEA were estimated, the cost break of hydrogen, including capital cost, O&M cost, decommissioning cost of NPP and HGP to the cost of H2 were presented. A new case partially based on the Chinese HTR-PM was designed, and the hydrogen cost of it was evaluated using HEEP.

India (Mr. U. Malshe) India has been contributing in developing of IAEA tool HEEP for economic assessment of hydrogen generation using nuclear power as source of energy. The presentation identified the following important features of HEEP:

- Possibility of modelling different options and different combinations available for energy source, hydrogen generation process and its distribution using library files or fresh inputs.
- Feature to expand database as and when information on developing technologies would be available.
- Feature to model effect of location of nuclear power plant and facilities associated with hydrogen production and its distribution.
- Feature to model nuclear power plant supplying electricity along with heat

Important ideas behind the incorporation of various features in the tool were also presented. Preliminary benchmarking and subsequent case studies carried out during first year of CRP on "Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software" have demonstrated accuracy of underlying mathematical models of the HEEP programming and flexibility to analyse economics of hydrogen generation scenario.

Republic of Korea (Mr. J. H. Kim) presented on how the Hydrogen Economic Evaluation Program (HEEP) is a software tool developed by IAEA to estimate hydrogen cost in a comprehensive manner, which comprises its production, storage and transportation cost. We have test-run the HEEP software for the sample cases to see how it works. The sample cases are provided by IAEA for the purpose of benchmarking. After the test-run for sample cases, we have some comments on using HEEP software. The units of some input data are ambiguous, which needs to be more clearly clarified. For example, one of the input data for hydrogen plant, "capital cost (USD/kg of H2)", needs to be corrected as "capital cost (USD)". The "capital cost (USD/kg of H2)" falls into one digit number for all sample cases. When the HEEP was run with these input data, it produced a nonsense result. Our test run was done with "capital cost (USD)" instead of "capital cost (USD/kg of H2)". The test-run results are presented. In HEEP software, the "O&M cost" and "D&D cost" for both plants are advised to be input as a "% of capital cost" corresponding to each plant. In calculating "% of capital cost" for these "O&M cost" and "D&D cost", we are a little confused, because the units for capital cost(USD) and O&M cost($M/yr) are different. Unless this issue clarified, the resultant hydrogen cost (USD/ kg of H2) will be changing depending on the individual user's interpretation.

Mexico (Ms. S. M. Fernandez) highlighted on the rapid development of hydrogen energy for vehicles and other application is growing. In 2008 the hydrogen market was evaluated about $ 300 billion/year, growing at 10% year, doubling to 20% by 2010, doubling again by 2020. In this context Mexico needs to increases the hydrogen production from alternative energies as nuclear in order to face the needs of new fuel cells cars coming soon to the market. Pemex the only oil company in Mexico produces hydrogen mostly from methane to use it in gasoline process. A preliminary evaluation was performed for the hydrogen cogeneration with alkaline electrolizers using the excess heat of the laguna verde BWR nuclear reactors. The obtained results will be presented and discussed. Also a general panorama of the electricity cost in Mexico and the off peaks periods of two regions will be presented.

Pakistan (Mr. J. Nisar) The search for clean and renewable energy has received great attention due to the depletion of fossil fuel resources and increasing serious environmental problems with their combustion. Hydrogen is one of the most abundant elements on earth and promising energy carrier, which may meet the future world-wide energy demands. Mass energy density of hydrogen economy as promising energy resource is three times higher than the current fossil fuel. Development of efficient materials for hydrogen production, storage and fuel cell are facing many scientific challenges. Pure hydrogen gas is not found in nature because mostly it is combined in water and organic molecules. So generation of hydrogen is one of the exciting issues for renewable energy search. Solar energy is to be a major primary energy source; it can be utilized for hydrogen production from the water splitting. Other way to generate hydrogen is the water splitting from the surface reactivity nanostructured materials.

Cost of hydrogen via nuclear power energy can be evaluated using the HEEP software. HEEP is the software for estimating the cost of hydrogen and compare it with different methodologies. HEEP software cover a most of the parameters for hydrogen production using nuclear power plants and it produce realistic results. This software perform excellent for hydrogen production using nuclear thermal or electric energy but It is not user friendly for other process like reforming of methane or solar electrolysis like CPV or solar light driven photocatalysis. It is because parameters which are involved in other hydrogen production methods are not accommodated properly. Software developer should take the input from the other established hydrogen generation methodology and improve the cost estimation of hydrogen via renewable resources. It is also suggested that OPTION of methodology should be involved, Is hydrogen produced via water splitting or other ways. If hydrogen is generated via water splitting then we have to consider the production of oxygen as byproduct, off course it will reduce the cost of hydrogen. In Pakistan, inflation is more than 10%, but if we put inflation rate 10 or more than 10, this software produce error "Run time error '6' ", please check it. It is concluded that HEEP software is designed for hydrogen economy using energy from nuclear power plants and performing very well.

Russian Federation (Mr. G. Kodochigov)

An observer without presentation or material

United States (Mr X. L. Yan) presented on the GTHTR300C-IS as a commercial scale hydrogen cogeneration plant designed by JAEA. It combines an iodine sulfur thermochemical process hydrogen production plant with a prismatic HTGR. JAEA has accumulated a significant experience in the construction and operation of the HTGR reactor through its HTTR test reactor program. The HTTR has been successfully operated at full power of30MWt and outlet temperatures of 850~ 950oC. Based on the HTTR knowhow, the GTHTR300C-IS cogeneration plant is being developed since 2001 and its basic design has been completed including engineering and manufacturing of large-scale gas turbine equipment and integrated IS-process plant. Figure 1 shows the design of the GTHTR300C-IS reactor plant and Figure 2 shows the layout of the IS-process hydrogen plant. The reactor is rated at 600MWt thermal power and 950oC outlet coolant temperature. The intermediate heat exchanger (IHX) used to deliver 900oC helium as nuclear heat source for the hydrogen process is designed based on the technology of helical tube and shell heat exchanger installed in the HTTR. The IHX is rated at 170MWt. The GTHTR300C-IS co-produces 202 MWe electricity and 25,000 Nm3/h (2250 kg/h) hydrogen. Electricity of 23 MWe used by the hydrogen plant is supplied by the nuclear reactor power plant. The overall efficiency of the hydrogen plant is 43.6%, taking into account of the IS-process thermochemical efficiency (45% HHV), the IS process electric utility (pumps and electrolyzer), and the helium gas circulation power consumption of the secondary helium transport loop. A case file has been created of the GTHTR300C-IS for the HEEP. The case file includes the detailed industrial cost database developed for the reactor plant components and for the IS-process plant (note that no option is given by HEEP to enter component cost data of hydrogen production plant) of the GTHTR300C-IS. The hydrogen cost estimated from using HEEP is US$2.27/kg-H2. Various difficulties such corrupted case files and frequent crashes of code execution have been encountered in the use of HEEP. This technical meeting for the HEEP users offers an opportunity to address these difficulties.

1. Conclusions

- The TM was very useful to discuss and find solutions to various issues related to HEEP by HEEP users.
- HEEP is a user friendly software to assess feasibility of range of hydrogen production options
- Further improvement on HEEP can make it more powerful

2. Recommendations

- Update HEEP based on the following suggested technical recommendations

1. Help functions are not implemented completely. It should also be content sensitive and detailed.
2. HEEP should take into account of distribution and transmission energy loss/cost of electricity and heat for isolated H2 plant cases
3. How to treat coupling system cost of co-located nuclear plant with H2 plant
4. The units of both input and output for nuclear plant and H2 plant cost unit needs correction.
5. Technical documentation of methodologies should be expanded, well made with simple sample cases and illustration to demonstrate the use of the methodologies employed in the HEEP. The methodologies should come from reliable sources. References should be clearly given.
6. How to modify nuclear plant input box to accommodate solar CPV-electrolyzer, non-conventional energy sources as suggested from Ms. Boudris
7. Modify output to echo input as mechanism to validate calculation/input values.
8. Clarification of capital cost/construction cost in nuclear plant and H2 plant input windows
9. Update with correction in "HTGR and SI", one of the 5 generic case files of HEEP as distributed in the 1st RCM, correcting 428MWe to 42.8MWe for "non-process electricity required".
10. Make a standard data sheet for providing input related to various plants and facilities to be considered in HEEP
11. Minimizing/resize HEEP in front window
12. Cost input and functionality of how to calculate the specific cost with HEEP with respect to hydrogen purification from Mr. Horacio Corti
13. Hydrogen transportation and storage data are currently from information of 2000 and shall be updated from present level of information.
14. Distribute table file of 5 generic case systems of HEEP plus new case files from China and Japan
15. To accommodate cost of byproducts consideration in HEEP

- Convene similar activity on a periodic basis.
- Release the updated version of HEEP ASAP.
- Indian participant to the meeting would like to consider hosting the upcoming TM in India.

ANNEX I

Agenda for the technical meeting "Technical Meeting for Users of the Hydrogen Economic Evaluation Program"

ROOM M0E100

25-26 March 2014, Vienna, Austria

Tuesday, 25 March 2014

09:00	Welcoming and opening remarks	I. Khamis, T. Koshy, IAEA
09:05	Election of Chairperson and adoption of Agenda	All participants/Chairperson
09:15	Objectives of the meeting & IAEA activities	I. Khamis, IAEA
09:30	Hydrogen production and benchmark analysis of IAEA-HEEP software	Ms Boudris, Algeria
10:00	Ion exchange membranes for hydrogen production by acid or alkaline water electrolysis	Mr Corti, Argentina
10:30	*Coffee Break*	
11:00		Mr Nisar, Pakistan
11:30	Techno-economics evaluation of nuclear hydrogen production using HEEP based on HTGR program in China	Mr Zhang, China
12:30	*Lunch*	
14:00	Case studies using HEEP to highlight important features	Mr Malshe, India
14:30		Ms Dewita, Indonesia
15:00	Experiences of using HEEP for calculating hydrogen cost	Mr Kim, Rep. of Korea
15:30	*Coffee Break*	
16:00	Preliminary Evaluation of Hydrogen Production Costs with Alkaline Electrolysers Coupled to Laguna Verde Reactors	Ms Fernandez, Mexico
16:30	Cost Assessment of Nuclear Based Hydrogen Production Systems using HEEP	Mr Dincer, Canada
17:00	Generic case study using HEEP of HTGR and thermochemical IS cycle - GTHTR300C-IS	Mr Yan, USA
17:30	*Adjourn Day 1*	
18:00	*Invited Dinner*	

Wednesday, 26 March 2014

09:00	*Discussion:* • On presented case studies. • HEEP Evaluation (utilization and robustness)	All participants
11:00	*Coffee Break*	All participants
11:30	Conclusions and recommendations	All participants
12:30	*Lunch Break*	
14:00	Conclusions and recommendations-continue	All participants
16:00	**Adjourn Day 2**	All participants