IAEA
International Atomic Energy Agency

Interoffice Memorandum

To: J.K. Park, DIR-NENP

From: I. Khamis, NPTDS

Through:

Clearance: T. Koshy, for SH-NPTDS 1/30/14

Reference: 622-I35004-CR-2

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Subject: Report on 2nd RCM on CRP Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software

Place of Meeting:	IAEA Headquarters, Vienna
Date of Meeting:	17-19 December 2013
Program code:	1000026/2012.03.08/RBF-MP1-2013/613224-\NHR-\TRV-Non Staff RCS/NENP-NPTDS
Scientific Secretary:	Mr Ibrahim Khamis
Chairperson:	Mr Xing Yan

ATTENDING EXPERTS

Name	Country/Organization	Date
Mr I. Dincer	CAN/UOIT	17-19 Dec
Mr K. Verfondern	GFR/FZJ	"-"
E. Dewita	INS/BATAN	"-"
X. Yan	JPN/JAEA	"-"
J-H Kim	ROK/KAERI	"-"
S. Revankar	ROK/Pohang University of Science & T.	"-"
Mr A. Khellaf	ALG/CDER	"-"
Mr P. Zhang	CPR/INET	"-"
Mr U. Malshe	IND/DAE	"-"
Mr G. Mustafa	PAK/PAEC	"-"

1. Background

The potential of hydrogen production using nuclear energy has lead the IAEA to carry out an active programme on the subject including meetings for information exchange on the status of nuclear hydrogen production, on future challenges to nuclear hydrogen production with emphasis on safety of coupling and on future aspects of hydrogen economy. The IAEA has developed the Hydrogen Economic Evaluation Programme HEEP, which is computer software that allows analyzing various options for a future hydrogen economy. Being the first-of-a kind, HEEP needs to be benchmarked for various scenarios of hydrogen production and distribution. The CRP has been planned based on extensive feedback from many participants in technical meetings on hydrogen production, and will be conducted by the Nuclear Power Technology Development Section.

The meeting was run smoothly with time allocated for discussion on each of the CRP progress presented. The work completed, results obtained and next year projects plans were discussed during the presentations. The presentations highlighted: (i) The results of the benchmark problems varied one user to another and the results depended on some key parameters such interest rate, discount factors and tax rates. (ii) There were presentations on estimation of hydrogen generation cost from participants which utilized domestic conditions such as interest rate and debt to capital ratio –the result of these presentation indicated that there would be variation of hydrogen cost depending on the models, methods and parameters used in calculations. (iii) The discussion following presentations resulted in identification of four exercise cases that used combination of different nuclear power plants (such as modular pebble bed and prismatic gas cooled reactor, supercritical water reactor) and hydrogen generation methods (SI cycle, Cu-Cl cycle, steam methane reformation and high temperature steam electrolysis). These cases will compare the hydrogen cost based on HEEP versus the participants methodology. (v) The participant presentations contained ideas and plans for developing modules for nuclear power plant and hydrogen generation systems that can be added to the HEEP platform. These efforts are being pursued in the next year project tasks and are expected to enhance the value and versatility of the HEEP software.

The first RCM of this CRP was attended by 10 CSIs representing 10 Member States. This meeting is the 2nd RCM of this CRP, attended by 10 CSIs representing 10 Member States..

2. Objectives of the meeting

The purpose of the meeting is to:

- Review mid-term achievements (strength & weaknesses);
- Review progress made by participants towards reaching the CRP stated objectives;
- Modify/adjust individual and overall work plans, if required;
- Draft Table of content for the expected IAEA publication documenting the CRP results.

3. Agenda

See attachment ANNEX A.

4. Summary of the work done and results achieved

The IAEA (Scientific Secretary) presented the status of the CRP. The agenda of the meeting was unanimously adopted by CSIs. The Scientific Secretary, presented background information of the CRP and discussed aspects of progress reports presented by CSIs with emphasis on collaborative approach and pointed out that about the work plans are well consolidated and serve to achieve the overall objective of the CRP. He also emphasised the importance of providing timely progress reports and results obtained by the CSIs as these will be the basis for the foreseen TECDOC to be produced as a

result of the CRP. A preliminary table of content of such TECDOC was prepared by the Scientific Secretary and was discussed during the meeting. The Scientific Secretary highlighted the current development of the IAEA toolkit on nuclear hydrogen production as well as other major foreseen activities on nuclear hydrogen production. The following are the summaries of the presentations made by participants:

Algeria (Ms Khallaf) The aim of the present work is to propose a techno-economic model for solar hydrogen production. This permits not only the enhancement of HEEP but also to provide a mean of comparison between the nuclear hydrogen production process and the solar hydrogen production process. Algeria is working on CPV –electrolyzer system. It considered the case of the conventional but advanced one-junction cell then we considered the case of high efficiency multi-junction cell. Different factors, such as the temperature, the cell efficiency and the concentration are considered. For low to medium concentration and with advanced one-junction cell, results indicate that the cost of production is of the order of the cost of production using nuclear means. However, as solar concentration and temperature are increased and multi-junction used, the results show that the solar production cost drops drastically. The upcoming workplan will include the followings:

- Participate in the benchmarking of HEEP using first five generic cases then the proposed four nuclear case studies. The four cases are the case of GTHTR +IS (Japan), PBMR+IS (China), SCWR +CuCl (Canada) and HTR module + steam reforming (Germany).
- Extend our work on solar. The aim is to contribute to the enhancement of HEEP by proposing solar models that can complement the nuclear one. To this end:
- Different CSP technologies will be investigated.
- Models to be included in HEEP will be presented.
- A comparison with the four studied cases will be carried out.

Canada (Mr Dincer) In collaboration with Atomic Energy of Canada Limited (AECL) and other universities and institutes, the University of Ontario Institute of Technology (UOIT), in Oshawa, Ontario UOIT-led team is developing the world's first integrated copper-chlorine (Cu-Cl) cycle for nuclear hydrogen production. This proposal aimed to contribute to a new version of hydrogen economic evaluation program (HEEP) software based on the Cu-Cl thermochemical cycle. The University of Ontario Institute of Technology (UOIT) has actively been working on Cu-Cl cycle for hydrogen as part of a large-scale project on the development and commercialization of this cycle. The following objectives have been achieved:

- To comprehensively model a Cu-Cl hydrogen production plant including detailed analyses based on thermodynamic, energy, exergy and exergoeconomic analyses, and life cycle assessments (considering the conventional and exergetic based approaches).
- To study the integration of the developed 3-step, 4-step and 5-step cycles with NPPs
- To integrate the Cu-Cl based systems with renewables, such as solar, wind, geothermal, etc. and study them thermodynamically.
- To examine and compare the Cu-Cl cycle with other methods such as high temperature steam electrolysis, conventional electrolysis and steam reforming, and other potential thermochemical cycles.

The proposed research would expand the capabilities of the pre-processing module to provide a user-friendly interface to enter technical details, chronological inputs and cost components of each of the execution modules for nuclear energy generation, hydrogen generation and storage, and hydrogen transportation. The new version of HEEP will include calculations of levelized cost in these three areas. To accomplishment the extended features in HEEP based on the use of parameters reported in previous publications. The preliminary benchmarking of HEEP is expected to reveal that HEEP can be used with reliable accuracy compared to published data. To be consistent with previously applied methods in the Beta version of HEEP, the program estimates "Levelized Cost of Hydrogen Generation" by bringing down all cost components over the period of a life cycle at one level using the method of discounting. Subsequently, the post-processing module is expected to present results as components of levelized cost of hydrogen generation in various optional graphical formats. There

would be a capability to view the information in tabular form also. The post-processing module can be designed to generate a report in "html" and "PDF" formats.

China (Mr Zhang) Pointed out that high temperature gas-cooled reactor (HTGR) technology is developing in China for more than 40 years, based on the accumulated experiences and R&D results on the developed 10MW test reactor, HTR-10. The first commercial demonstration plant, HTR-PM, was approved and financially supported by the central government and industrial sector. Now the HTR-PM is being constructed, and the key R&D items, including manufacturing of reactor pressure vessel, helium loop, digital control system, simulator, etc., are on the track. With this strong background of HTGR, China has been conducting the R&D on nuclear hydrogen production, both iodine sulfur (IS) thermochemical process and high temperature steam electrolysis (HTSE) were selected as the potential candidates of hydrogen production technology for coupling to HTR at the institute of nuclear and new energy technology (INET) of China. The hydrogen economic evaluation program, HEEP, was used by INET under the contract of CRP for cost estimation of nuclear hydrogen. Currently, the Lab-scaled and bench-scaled facilities of IS process and HTSE have been erected and the experiments are going on. Meanwhile, models for simulation of IS process were built, which can be used for process simulation, flowsheet design, efficiency evaluation, etc. the results of these activities will support technical support for the techno-economics evaluation of nuclear hydrogen. Based on the offered data by IAEA, the cost of H2 from five generic nuclear hydrogen production cases were estimated, the contributions of the various parts, such as capital cost, O&M cost, decommissioning cost of NPP and HGP to the cost of H2 were estimated and compared. The works for next year include collecting and analyzing the available financial and technical data for cost estimation, concept design of a commercial nuclear hydrogen production plant, nuclear hydrogen production cost estimation, as well as case study and sensitivity analysis.

Germany (K. Verfondern) Pointed out that within the frame of a bachelor thesis, the HEEP software tool has been taken to conduct an analytical and comparative study on the levelized cost of hydrogen generation using different conventional and nuclear-assisted production methods. A further aim of the study was to identify the sensitivity of various input parameters on the price of hydrogen and improvement potential for refinement of the HEEP model. The conventional cases selected were the presently most widely applied production method, i.e., steam reforming of natural gas, as case 1; the same technology, but additionally assuming the capture and storage of the CO2 generated (CCS) as case 2; and finally a kind of future projection of case 2 assuming technology progress (reduced capital cost), but higher energy and raw material cost as the case 3. Based on cost input data derived from US-DOE and EU sources, the calculated specific hydrogen generation cost were 2.72 Euro per kg-H2 for case 1 to be compared with 2.92 Euro/kg-H2 if including CCS (higher capital cost and higher energy consumption) and with 3.43 Euro/kg-H2 for the future scenario.
The nuclear-assisted scenarios selected were all based on a 4-module H2-MHR nuclear reactor system with 600 MW of thermal power per module to be connected with hydrogen production using high temperature steam electrolysis (case 4), using the sulfur-iodine thermochemical cycle (case 5), and, as a scenario for the future, again HTSE, but assuming higher capital cost, lower operation cost due to technology progress (case 6). With most input data taken from General Atomics reports, calculations resulted in specific hydrogen generation cost of 2.34 Euro/kg-H2 for the HTSE case 4 to be compared with 2.59 Euro/kg-H2 for the future scenario case 6, and with 3.38 Euro/kg-H2 for the alternative sulfur-iodine method of case 5. The high price of S-I produced H2 is mainly due to the large electric power demand of 812 MW(e) assumed to be bought from the external grid.

Finding out the cost-pushing input parameters by deriving so-called sensitivity factors defined as the ratio of cost change over variation interval, the discount rate was discovered to be highly sensitive for both the conventional and nuclear case. A large influence has furthermore the gas price on the conventional side and the capital cost on the nuclear side. Recommendations for improvements of the HEEP model are seen in introducing a time dependence of fuel cost, load factor, availability, financing parameters and also in taking account of market fluctuations due to economic situation or lack of demand. Further calculational studies with HEEP are planned by introducing the process heat variant of the SIEMENS HTR-Modul concept.

Indonesia (Ms Dewita) steam reforming of natural gas is the most common method of producing hydrogen used in the fertilizer plant. The reforming reaction is strongly endothermic, it supply by combustion of natural gas. Until now, in fertilizer industries still using natural gas as raw material and fuel. Ratio of natural gas used as raw material and fuel is 40%: 60%. HTGR type reactor is a potential for cogeneration process, especially to supply heat for high temperature process, such as hydrogen production. Therefore, coupling of HTGR type reactor with hydrogen production plant cause utilization of natural gas as fuel can be replaced by nuclear (reactor) heat, so the natural gas can be totally used for raw material in Steam Methane Reforming process. According to the work plan has been submitted, until now our team has done the reviewing some references on Steam Methane Reforming (SMR) hydrogen plant to identify the process technology for hydrogen production from natural gas, developing schema of nuclear heat supply system for hydrogen plant, preliminary design of hydrogen production plant including the economic and technology aspects using steam reforming method. The preliminary design of the nuclear heat supply scheme for hydrogen production includes mass balance and heat balance and process flow chart that comes with the operating conditions in accordance with the licensing process of Haldor Topsoe. Hydrogen plant has a designed production capacity of 150,000 tons / year (purity: 99.99%) in which the process heat needs is supplied by 193 MWth HTGR nuclear type with a capacity of 600 MWth (3 x 200 MWth). Besides that, it takes HP steam (110 bar, 475 ° C) as much as 92,000 kg / hour, MP steam (38 bar, 375 ° C) of 207 871 kg / hour, saturated steam (1.26 bar) of 190 820 kg / hour, water cooling as much as 107,959 kg / hour, the water as much as 95,288 kg / hour, 0.86 MW electricity demand, and compressed air as much as 184.8 m3/hour. It has been done also economic analysis by using 'PROFITABILITY ANALYSIS -1.1. Xls "compiled by Holger Nickkich (2003). In order to conduct the economic analysis, we used several assumption, such as : hydrogen and natural gas prices, the hydrogen production plant will be operated continuously for 330 days / year, feed ratio of natural gas and oksigen etc. The results are BEP : 37.8%, profitability Index : 3.8, benefit cost ratio : 5.62We and ROI : 54.3%. Its will be compared by economic analysis using HEEP software and It is also intended to benchmarking of HEEP softeware.

Japan (Mr Yan) discussed how nuclear energy is recognized as an important and economical source of energy essentially free of CO2 emission and is being developed in Japan for a range of non-electric applications such as through the use of high temperature gas cooled reactor for mass production of hydrogen to be widely utilized in industries such as steelmaking and transportation sector through the planned market launch of hydrogen fuel cell vehicles from 2015. International collaboration efforts prove to be an effective means to accelerate this development. One current such effort is participation by Japan Atomic Energy Agency in the IAEA coordinated research program (CRP) on Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software. During the 2nd RCM of the CRP held on December 17-19, 2013 in IAEA, Vienna, Austria, JAEA presented the results of the work completed during the past 1st year of the CRP. These results include review and compilation of the GTHTR300 nuclear reactor plant design and cost data, the thermochemical IS process plant design and cost data, and the conventional and nuclear steam methane reforming process design and cost data. All participants at the meeting identified the integration of GTHTR300C+IS system with 950oC reactor coolant temperature as one of the four benchmark cases for nuclear hydrogen production to be investigated by all participants during the 2nd year work of the CRP. JAEA agrees to prepare a template of the system input data and cooperate by providing additional design and cost information necessary to assist other participants in their benchmark studies of this integrated system. According to the original work plan, JAEA will complete techno-economic analysis using the HEEP of the five generic cases of nuclear hydrogen production and plan to present the results at the planned user technical meeting in March 2014. Finally, according to the work plan, JAEA will perform the benchmark studies using the HEEP of the four selected system cases with respect to the deployment conditions specific to Japan and discuss the findings at the next RCM of the CRP.

Rep of Korea (Mr Kim) discussed the preliminary structure of G4-ECONS program which was surveyed as part of the CRP. He pointed out that they have already defined the input data needed to calculate the levelized unit electricity cost (LUEC where LUEC=(Annualized TCIC+ Annualized O&M Cost+ Annualized Fuel Cycle Cost + Annualized D&D Cost) / Annual Electricity Production

Rate) and levelized unit hydrogen cost(LUHC = (Annualized TCIC + Annualized O&M Cost + Annualized Thermal Energy Cost + annualized Capital Replacement/Upgrades Cost) / Annual Hydrogen Production Rate)). As a result, they have selected four 600-MWth VHTR modules with 4 SI processes as their case model. Results obtained include the followings:

- The LUEC calculated by the above formula was 40.36 $/MWh.
- The LUHC calculated by the above formula was 0.232 $/m3 H2.

The workplan for next year includes the benchmarking of HEEP compared to G4-ECONS program based on the new generic cases suggested in this CRP and has been identified during the meeting.

Rep. of Korea/USA (Mr Revankar) pointed out that the technology of nuclear hydrogen generation with thermo-chemical processes, sulfur iodine cycle (SI) and hybrid sulfur cycles and the high temperature electrolysis is investigated using the state of the art developments in each technology. Economic analysis of these hydrogen generation methods is carried out using HEEP software. Specific research work is focused on (i) optimization and enhancing efficiency of SI cycle, (ii) simulation of Bunsen reaction, and (iii) simulation of coupled hydrogen plant and high temperature nuclear plants for transient analysis and safety assessment. The results of these studies are used in assessing the technological advantage and economic assessment in nuclear hydrogen production. The following tasks have been completed:

- Bunsen reaction simulation model in ASPEN PLUS was developed for full flow sheet
- Bench mark exercise analysis with HEEP software was carried out and key sensitive parameters that affect the cost of hydrogen were identified.
- Models for coupled Pebble bed modular reactor coupled to hydrogen plant based on SI cycle or Hybrid sulfur cycle for coupled system

The workplan for the upcoming year will include the followings:

- Perform 5 example cases for training and comparing existing HEEP capability with a template and key input parameter
- Perform 4 exercise cases studied using ASPEN supported cost analysis and compare with HEEP based results.
- Develop base economic models for SI cycle, Hy-S cycle and High Temperature Electrolysis (HTE) using ASPEN Economic Evaluation Software for and perform comparative study with HEEP.
- Development of safety and control system for couple (N-plant and H2 plant) cost estimation module for HEEP

In addition, as part of the collaborative work with other CRP members, the workplan will include as well the followings:

- Development of cost models for of solar PV based H2 generation through electrolysis
- Development of nuclear plant based on components cost estimation model
- Optimized SI cycles cost model

Pakistan (Mr Mustafa) Discussed that within the CRP they have completed hydrogen demand projections for the country from 2012- 2050. The energy resources available, potential use and hydrogen production technologies/processes for the country have been identified. A set of three cases for hydrogen production i.e., HTR nuclear reactor coupled with the Sulphur-Iodine cycle, conventional Steam Methane Reforming (SMR) of natural gas and coal gasification, have been investigated using the HEEP model. The techno-economic data required for economic evaluation of the three cases has been obtained from literature. The data has been normalized for escalation, unit size, country setting etc. After normalizing the data, we transformed the data into HEEP input format. The results have been compiled and an interim report submitted to the IAEA. The progress report also includes some comments on HEEP model based on its use in economic evaluation of the case studies. Refinement of techno-economic data for this study is underway. The future work regarding the CRP:

- Comparison of the results with a locally developed spreadsheet based economic and financial modeling tool using the Case Studies to be provided by the IAEA.
- Refinement of the data for improved techno-economic assessment of the hydrogen production options studied.

- Investigation of some additional cases i.e., nuclear reactor coupled SMR process, HTSE and other candidate hydrogen production processes envisioned to be deployed in near future.
- Economic evaluation of hydrogen storage and transportation in the country
- Sensitivity analysis

5. Conclusions

- No modification to any workplan as all CSIs agreed to perform in addition to their case studies, the five benchmark generic cases using HEEP or any other available software and to enhance collaborative work.
- Participants welcomed the IAEA activity on HEEP Group Users to be held in 25-26 March 2014, where they could have results discussed.
- CSIs from Canada, China, Germany and Japan agreed to prepare templates for four more generic case studies (see table) and share among all participants. Templates will be completed and shared by mid February 2014.
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Generic Benchmark Case 1	Generic Benchmark Case 2	Generic Benchmark Case 3	Generic Benchmark Case 4
Canada	**China**	**Germany**	**Japan**
Involves the use of thermochemical cycle Cu-Cl and the SCWR	Involves the use of thermochemical cycle S-I and the HTR-PM	Involves the use of SMR and the HTR-Module	Involves the use of thermochemical cycle S-I and the GTHTR300C

6. Recommendations

- Participants recommend to continue the development of the IAEA toolkit on nuclear hydrogen and expected release in early 2014.
- The foreseen TECDOC shall cover the following Table of content:
    - Ch 1: Introduction, highlight of CRP, Objectives of the report/study, overview of the subject
    - Ch 2: Advances in nuclear hydrogen production, Potential technologies, and Economics. (Canada, China, Germany, USA/Korea, Japan)
    - Ch 3: Methods for nuclear hydrogen production (Canada, USA/Korea, India)
    - Ch 4: Software description and assumptions: HEEP, Gen4, H2A, ASPEN-plus (India, Korea, USA/Korea, Algeria)
    - Ch 5: Results of HEEP and Benchmarking (All):
    - Ch 6: Analysis of results: (All)
        - Competitiveness and sustainability of nuclear hydrogen production. (..)
        - Comparative assessment of hydrogen production options using available codes. (..)
    - Ch 7: Analysis of HEEP results/code capabilities/improvements (All)
    - Ch 8: Analysis and findings from selected national studies (All)
    - Ch 9: Summary and Conclusions (All)
    - References (All)
    - Annexes (All)
        - Contributions of MS participating in CRP (All)
        - Scientific publications

7. Next RCM Meeting

The next RCM is planned to be held Istanbul/Turkey or Bali/Indonesia 17-19 Dec 2014 or 11-13 May 2015.

Agenda for IAEA's 2nd RCM of the Coordinated Research Project on "Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software"

Vienna, Austria

ROOM F 0817

17-19 Dec 2013

Tuesday, 17 December 2013

09:30	Welcoming and opening remarks	I. Khamis, IAEA
09:35	Election of Chairperson and adoption of Agenda	All participants/Chairperson
09:45	Status of the CRP and objectives of the 2ed RCM	I. Khamis, IAEA
10:15		Algeria
11:00	*Coffee Break*	
11:15		Canada
12:00	*Invited Lunch*	
14:00		China
14:45		Germany
15:30	*Coffee Break*	
16:00		India
16:45	Discussion	All
17:00	*Adjourn Day 1*	

Wednesday, 18 December 2013

09:15		Indonesia
10:00		Japan/USA
10:45	*Coffee Break*	
11:15		Pakistan
12:00	*Lunch break*	
14:00		Rep of Korea
14:45		Rep of Korea/USA
15:30	*Coffee Break*	
16:00	Discussion on Benchmarking case studies	All
17:00	*Adjourn Day 2*	

Thursday, 19 December 2013

09:15	Discussion on: (1) TECDOC (Table of content, Contributions, Leads..) (2) Plan for next year	All participants
10:15	(1) Finalization of 2nd RCM report	All participants
11:00	*Coffee Break*	All participants
11:15	(1) Discuss CRP common relating issues	All participants
12:30	*Lunch Break*	
14:00	(1) Discuss CRP common relating issues	All participants
15:00	**Adjourn Day 2**	All participants