Subject: Report on 3e[d] 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: 16-18 December 2014

Program code:

Scientific Secretary: Mr I. Khamis

Chairperson: Mr X. Yan (JPN/JAEA)

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 involved presentation of results obtained by CSIs followed by discussion relating to results obtained and suggestions to HEEP upgrade. The presentations also highlighted results of the benchmark generic and technology-based specific case studies based on country specific calculations. 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. Discussion on status of the individual progress towards achieving the CRP objectives, major achievements and potential contributions to the TECDOC were also discussed. At the end, the foreseen IAEA TECDOC table of content was revised and Leads and contributors to each chapter were identified.

The first and second RCMs of this CRP were attended by 10 CSIs representing 10 Member States. This meeting is the 3ed RCM of this CRP, attended by 9 CSIs and 2 CFEs representing 9 Member States.

2. Objectives of the meeting

The purpose of the meeting is to: a) discuss progress made by the Chief Scientific Investigators (CSIs), including results obtained from the generic case studies as well as the results of the individual CSIs; (b) assess potential updates and upgrades to the Hydrogen Economic Evaluation Program (HEEP); (c) discuss the final structure and potential contributions to the IAEA Technical Document to be prepared as a result of this CRP; and (d) finalize and harmonize work plans to align the overall objectives of the CRP.

3. Agenda

See attachment ANNEX A.

4. Summary of the work done and results achieved

The IAEA (Scientific Secretary) presented the current status of the CRP, its objectives, schedule for implementation, and objectives of this 3ed RCM. The agenda of the meeting was unanimously adopted by CSIs. The Scientific Secretary presented some background information on the CRP and a preliminary table of content of such TECDOC was also presented and discussed during the meeting. The following are the summaries of the presentations made by participants:

Canada (Mr Dincer) has successfully completed all the objectives originally stated in the proposal. Furthermore, he mentioned that he will conduct additional studies to cover Mg-Cl cycle and other cycles with CANDU Gen-IV SCWR and compare with Cu-Cl cycles and other S-I and Hy-S cycles. Major achievements include the followings:

- Published over 30 peer-reviewed journal papers
- Trained over 10 graduate students
- Obtained critical NPP data
- Presented the results in over 10 conferences

In regards to the study, the specific achievements are:

- Completed generic studies and compared with other country results
- Studied Cu-Cl (3 step), Cu-Cl (5 step), Hy-S and S-I cycles with CANDU Gen-IV SCWR for hydrogen production cost, cost share (NPP and H2 plant)
- Identified several issues with HEEP
- Proposed several things to improve the content and use of HEEP

China (Mr Zhang) High temperature gas-cooled reactor (HTGR) technology is being developed in China for more than four decades. Currently the commercial demonstration plant program of HTGR, HTR-PM, is being constructed in China. As the most important potential application of the process heat, nuclear hydrogen production technology has been intensively studying in China. Considering the essential of techno-economics evaluation for the future industrial application, INET adopted the Hydrogen Economics Evaluation Program (HEEP) to make the preliminary cost estimation of nuclear hydrogen under the contract of CRP of IAEA. The goal of the CRP is to employ HEEP software to perform economic analysis and benchmarking exercises of nuclear hydrogen production, with acquired data and experiences and Chinese specifications. Almost 90 percent of the works required in the contract has been completed. The benchmarking calculation and analysis for the five generic cases have been done, a new case based on the results of R&D on Chinese HTGR and nuclear hydrogen production was designed, and the cost of hydrogen with this case is calculated. In addition, some facilities for the related experiments were erected and operations were successfully carried out. Some major achievements are:

- A new nuclear hydrogen production case based on Chinese work, HTR-PM-IS, was designed.
- An entire model for the simulation of the iodine sulfur process was built and its reliability was validated. This model can be used to calculation the energy needed for IS process and to estimate the efficiency.
- An integrated lab-scale IS facility with the hydrogen production rate of 100NL/h was erected in INET, and the closed-cycle operation was successfully carried out. The data acquired from the operation supplied technical data for the design of the hydrogen plant, which will be beneficial to the estimation of the capital investment of the hydrogen plant.
- Several papers on nuclear hydrogen production were published in peer-reviewed journal, and a paper on cost estimation of nuclear hydrogen production is under preparation.
- Possible contributions to the TECDOC:

- Progress or status of R&D on nuclear hydrogen production in China, including description on the models, facilities, experimental results, and the R&D plan
- Estimation of H2 cost from nuclear hydrogen production based on Chinese case, i.e., HTR-PM-IS.
- Comparative study of the Chinese case with Japanese and Korean cases.

Germany (K. Verfondern& Sarah Schröders) As a coherent part oft he CRP and within the frame of a bachelor thesis, several nuclear hydrogen production methods were evaluated with the help of the HEEP software. First the hydrogen cost for the IAEA five generic cases (APWR with CE with three different capacities, HTGR with HTSE, HTGR with SI) were calculated using German economical parameters. Thereby the HTGR with HTSE seems to be the cheapest hydrogen production system with hydrogen costs of nearly 3 US$/kg. But in this case, according to the input data, the HTSE was assumed to not need any electricity, so this result cannot be correct. Comparing the German results to previous calculations of China, Korea and India, it shows that the results deviate. Especially the German estimated hydrogen costs for the APWR with CE are much higher. Taking the economical parameters of China instead of the German ones, similar hydrogen costs are calculated. This shows that the economical parameters play a significant role and need further investigation. For this reason the economical parameters were varied while calculating the Japanese (GTHTR300C-IS) and the Chinese (HTR-PM-IS) cases. Taking the Japanese economical parameters, hydrogen costs of 2.46 $/kg were calculated for the GTHTR300C-IS. With the German economical parameters these costs increase to 2.96 $/kg. The same can be observed concerning the HTR-PM-IS with hydrogen costs of 3.78 $/kg with Chinese economical parameters compared to 4.98$/kg with German economical parameters. The most important economical parameter, which is responsible for these deviations, is the calculation rate, which is highly sensitive for hydrogen costs. The calculation rate is derived depending on the fraction of dept to equity from the discount rate and/or the borrowing interest. In order to allow a comparison of different hydrogen production systems, standard economical parameters are necessary. The next step was the calculation of the hydrogen costs for the HTR-Modul coupled to Steam Reforming. In the frame of a parameter variation, the influence of the fraction of internal electricity generation (instead of external electricity purchase) on the hydrogen costs was analyzed. Thereby it turned out that some questionable input parameters were used, that should be replaced in future calculations:

- Electrical efficiency of 20% (to be replaced with 40%)
- Fuel costs of 22937 $/kg
- Electricity price of 123 $/MWh

Due to the low electrical efficiency and high fuel costs, the external electricity purchase turned out to be more cost efficient than the internal electricity generation. This statement needs to be proved with corrected input data. Finally three different hydrogen production methods (steam reforming, high-temperature steam electrolysis and sulphur-iodine cycle) coupled to the HTR-Modul were evaluated. Thereby the steam reforming rendered the cheapest production method with hydrogen costs of 2.46 $/kg (while producing 65% of the required electricity internally).

India (Mr. U. Malshe) Bhabha Atomic Research Centre (BARC), India is contributing to the CRP by participating in an activity "Benchmarking exercises through international collaboration to validate HEEP and establish HEEP database". The main objectives of this activity are to carry out extended benchmarking of the software tool HEEP for its validation and generate database in the form of library of files compatible with HEEP. The work plan for this activity included collection of input

data affecting hydrogen cost for identified cases through support from other participating organisations of this CRP. Compile the information collected in the form of a database compatible with HEEP. In order to validate the HEEP, results of the HEEP shall have to be compared with other available software tools. The needs identification of such software tools, modelling the cases using HEEP and other identified software tool/s and comparing results as well as features of HEEP and identified software. During the first year of the CRP, India contributed in modelling five cases identified during 1st RCM. These five cases were modelled using HEEP as well as another identified software tool H2A. Results of HEEP and H2A were found to be in good agreement with each other. Features of HEEP and H2A were also compared to justify the small difference in the results obtained. In the second year of the CRP, a parametric study was carried out using HEEP to assess the effect of source of energy on hydrogen production cost. In this parametric study, variation in two parameters viz. (a) rate of purchase of electricity from market and (b) thermal efficiency of nuclear power plant , if generating and supply electricity for hydrogen generation was assessed. During the due course of CRP, feedback was received from users of HEEP to incorporate certain modifications in the software to enhance its user-friendliness. Most of the suggestions were incorporated. The information on the parameters affecting hydrogen cost was provided by various participating organisations to this CRP. This information has been compiled in the form of a library of files compatible with HEEP. Based on the achievements, it can be stated around 90% of the work plan is completed. However, considering continuous receipt of feedback received from users, the modification in HEEP will continue till the CRP is declared completed.

Japan (Mr Yan) The scope of the JAEA participation in the IAEA coordinated research program (CRP) on examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software was originally planned for three years. JAEA has completed the work of Years 1 & 2 above. The results within the 2nd year work scope have been presented during the 3rd RCM, including the calculation results using HEEP of the five generic cases provided by IAEA and the benchmark results of this CRP's four selected cases. The future work will be focused on contribution of final reporting to be incorporated in the CRP TECDOC. Major results achieved to date include the followings: development of detailed techno-economic model for high temperature gas cooled reactor for hydrogen production.

Rep of Korea (Mr Kim) The CRP work regarding "Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software" is mainly focused on the benchmark of HEEP results with G4-ECONS program. G4-ECONS (Generation 4 Excel-based Calculation of Nuclear Systems) was developed by the Economic Modelling Working Group (EMWG), and can be used to calculate the unit energy cost from the reactor and unit product cost from the facility using nuclear thermal and/or electric energy. To benchmark HEEP with G4-ECONS we identified the structures, characteristics of the input data of both programs. We have run HEEP program for the 5 generic cases provided by IAEA and made some suggestions to improve its applicability and reliability. As a part of benchmarking work of HEEP with GEN4-ECONS, we have run GEN4-ECONS Program for 5 generic cases and have got the unit electricity cost and unit hydrogen production cost for each case. We also run GEN4-ECONS program to benchmark HEEP for Japanese and China case studies. There will be a benchmarking work for the case studies of Canada and Germany. Contribution to TECDOC will be made in corresponding chapters dealing with "benchmarking of HEEP program with G4-ECONS program.

Rep. of Korea/USA (Mr Revankar) The 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 and (iv) best economic analysis of the optimized SI cycle and couple hydrogen and high temperature reactors system for use with HEEP. The specific outcomes of these studies are (i) process parameters for Bunsen reaction and overall SI cycle and HyS cycle; (ii) simulation results on SI cycle for efficient flow sheet

and process efficiency; (iii) safety and transient analysis results of coupled hydrogen and high temperature nuclear plant, and training of students:

- Graduate Student Thesis Completed directly under this RCP: Parametric Study on Phase Separation and Purification for Bunsen Process in SI Cycle for Nuclear Hydrogen Production, MS Thesis, POSTECH 2013
- One graduate student working Currently at POSTECH
- Two undergraduates worked at Purdue University on SI and HyS Cycles and PBMR reactor models development:
- One visiting research scholar at Purdue University for one year on electrolysis process for HyS cycle.
- One Post-doctoral researcher at POSTECH on BUNSEN process simulation and optimization

Pakistan (Mr Mustafa)

5. Conclusions

- The CRP is near completion as most participants have completed their research. Yet most of them need more time to submit final reports and contributions to the foreseen IAEA TECDOC.

- As a result of this CRP, remarkable achievement have been reported by several participants such as:

    1. Publication of more than 40 peer-reviewed journal papers
    2. Training more over 16 graduate students
    3. Obtained critical NPP data
    4. Presented some results of the CRP in more than 10 conferences
    5. Advancement of science in the area of thermochemical cycle analysis: 5 new cycles have been studied including Cu-Cl (3 step), Cu-Cl (5 step), Hy-S and S-I cycles with CANDU Gen-IV SCWR for hydrogen production cost, cost share (NPP and H2 plant)
    6. Potential release of new version of HEEP due to major suggestions to improve HEEP have been made by participants

- HEEP is a user friendly software to assess feasibility of wide-ranging hydrogen production options

- HEEP result is sensitive to project financing parameters such as discount rate, inflation rate, borrowing cost, etc.

- HEEP calculated hydrogen costs are consistent with JAEA in-house result for HTGR thermochemical cycle (IS-process), and H2A software.

6. Recommendations

- To release the updated version of HEEP ASAP.
- To enhance the HEEP UI and detail User`s Manual to increase the HEEP user friendliness.

- 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) (Yan (L), Revankar)

Ch 2: Techno-economic Aspects of nuclear hydrogen production methods
(Potential technologies, methods, economics, etc.) (Yan (L), Zhang, Revankar, Kim, Verfondern, Dincer, Bohe)

Ch 3: HEEP: Models description
(Models, software description, features, assumptions, examples, comparisons, with other softwares, e.g., Gen4, H2A, ASPEN-plus (Malshe (L), Kim, Revankar)

Ch 4: HEEP Benchmarking
(Description of generic case studies, country case studies, analyses, results, etc.) (Dincer (L), Yan, Zhang, Revankar, Kim, Verfondern, Bohe, Mustafa, Malshe, etc.)

Ch 5: Technology-Based Case Studies
Technologies. Competitiveness and sustainability of nuclear hydrogen production. Comparative assessment of hydrogen production options using available codes. Country case studies, analyses, results, etc. (Verfondern (L), Yan, Zhang, Dincer)

Ch 6: Results and Discussion
(General results, discussion, code capabilities, potential improvement for HEEP, economic results, effects of financial parameters on the economics of hydrogen production, etc.) (Yan (L), Revankar, Zhang, Dincer, Veforndern, Malshe, Kim, Bohe, Mustafa, etc.)

Ch 7: Summary and Conclusions
(Findings, major accomplishments, topics for future CRPs, recommendations, etc.) (Yan (L), Dincer, Verfondern, Malshe)

References (All)
Annexes (All) (final report from each country)
Scientific publications (by each CSI)

- Contributions by all participants including the benchmark result of the updated version of HEEP (to be received for the 4th RCM) to confirm it as final benchmarked software product version of this CRP, and final contributions to the IAEA-TECDOC shall be sent to IAEA by 1 July 2015.
- The meeting will discuss the final draft of the TECDOC.

7. Next RCM Meeting

The next RCM is planned to be held 15-17 Dec 2015.

Agenda
3rd RCM on CRP Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software"
Room MOE05

16-18 December 2014
Vienna, Austria

Tuesday, 16 December 2014

Welcoming remarks		
09:30	Overall status of the CRP & Objectives of this meeting	Mr Khamis, IAEA
10:15	Presentation 1: Results on Examining Techno-Economics of Nuclear Hydrogen Production using HEEP	Mr Khellaf, Algeria
11:00	***Coffee Break***	
11:15	Presentation 2: Results on Techno-economical Feasibility Study on Nuclear Hydrogen Production through Thermochemical Water Splitting Cycles	Ms Bohe, Argentina
12:00	***Lunch***	
13:30	Presentation 3: Results on Contribution to HEEP Software on Cu-Cl Thermochemical Cycle	Mr Dincer, Canada
14:15	Presentation 4: Results on Evaluation of the Techno-Economics of Nuclear Hydrogen Production using HTGR in China	Mr Zhang, China
15:00	***Coffee Break***	
15:15	Presentation 5: Results on Evaluation of Hydrogen Transportation and Distribution Cost in Germany using HEEP	Mr Verfondern, Germany
16:00	***Open Discussion*** on Benchmarking case studies	
17:00	***Wrap up of Day 1***	

Wednesday, 17 December 2014

09:30	Presentation 1: Results on Benchmarking Exercises through International Collaboration to Validate HEEP and establish HEEP Database	Mr Malshe, India
10:15	Presentation 3: Results on Benchmark Analysis of the IAEA HEEP Software for Nuclear Hydrogen Production Plant	Mr Kim, Rep Korea
11:00	***Coffee Break***	
11:30	Presentation 4: Results on Nuclear Hydrogen Generation Technology Development and Analysis of Coupled Hydrogen Production Plant and Nuclear Reactor	Mr Revankar, Rep Korea/USA
12:15	***Lunch Break***	
14:00	Presentation 5: Results on Assessment of Economic Competitiveness of Hydrogen Production in Pakistan	Mr Mustafa, Pakistan
14:45	Presentation 6: Results on Examining the techno-economic aspects of nuclear hydrogen production	Mr Yan, USA/Japan
15:30	***Coffee Break***	
16:00	***Open Discussion*** on TECDOC status	All participants
17:00	***Wrap up of Day 2***	

Thursday, 18 December 2014

09:30	Discussion on: (1) TECDOC (Table of content, Contributions, Leads..)	All participants
10:15	(1) Finalization of 3nd RCM report	All participants
11:00	***Coffee Break***	All participants
11:15	(2) Plan for next year	All participants
12:00	***Lunch Break***	All participants
14:00	(1) Discuss CRP common relating issues	All participants
15:00	***Closing Remarks & End of the Meeting***	