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# Interoffice Memorandum

**To:** D. Hahn,
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**From:** I.Khamis
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**Through:**

**Clearance:** S. Monti
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**Reference:** 622-I35004-CR-4

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**Subject: Fourth Research Coordination Meeting on 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: 14-16 December 2015

Program code: 1000155 2014.02 I35004 RBF-MP1-2015 613224-NHR-TRV-Non Staff
RCS NENP-Nuclear Power Technology Development Section

Scientific Secretary: Mr Ibrahim Khamis

Chairperson: Mr Yan Xinglong (JAEA)

## ATTENDING EXPERTS

| Name | Country/Organization | Date |
|---|---|---|
| Ms Rafika Boudries | Algeria/ Centre de développement des energies renouvelables (CDER) | 14-16 Dec |
| Ms Ana Ester Bohe | Argentina/ Comisión Nacional de Energía Atómica (CNEA) | 14-16 Dec |
| Mr Ibrahim Dincer | Canada/ University of Ontario Institute of Technology (UOIT)) | 14-16 Dec |
| Mr Zhang Ping | China/ Tsinghua University Institute of Nuclear and New Energy Technology (INET) | 14-16 Dec |
| Mr Karl Verfondern | Germany/ Institute for Energy and Climate Research (IEK) | 14-16 Dec |

cc:
M. Chudakov
de Grosbrois
NENP All staff
ARMS

File

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| Name | Country/Organization | Date |
|---|---|---|
| Mr Anil Antony | India/ Bhabha Atomic Research Centre (BARC) | 14-16 Dec |
| Ms Erlan Dewita | Indonesia/ National Nuclear Energy Agency (BATAN) | 14-16 Dec |
| Mr Yan Xinglong | Japan/ Japan Atomic Energy Agency (JAEA) | 14-16 Dec |
| Mr Ghulam Mustafa | Pakistan/ Atomic Energy Commission (PAEC) | 14-16 Dec |
| Mr Kim Jong Ho | Korea/ Korea Atomic Energy Research Institute (KAERI) | 14-16 Dec |
| Mr Shripad Revankar | Korea/Pohang University of Science and Technology | 14-16 Dec |

## 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 analysing various options for a future hydrogen economy. Being the first-of-a kind, HEEP needs to be benchmarked for various scenarios of nuclear hydrogen production, storage and transportation. The CRP has been planned based on extensive feedback from many participants in technical meetings on nuclear hydrogen production, and conducted by the Nuclear Power Technology Development Section.

The 1st and 2nd RCMs of this CRP were attended by 10 CSIs representing 10 Member States. The 3rd RCM was attended by 9 CSIs and 2 CFEs representing 9 Member States. This meeting is the 4th and the final RCM of this CRP. It was attended by 11 CSIs representing 10 Member States.

## 2. Objectives of the meeting

The purpose of the meeting is to discuss:

- Progress made by the Chief Scientific Investigator (CSIs) for the planned IAEA technical document;
- Final outline and additional contributions to the IAEA technical document; and
- Future activities as a result of the outcome of this CRP.

## 3. Outcome of the meeting

**The IAEA (Scientific Secretary)** presented the current status of the CRP, its main objectives, and the specific objectives of this 4th CRM. The meeting agenda was unanimously adopted by CSIs. The Scientific Secretary presented background information on the CRP and emphasised the importance of providing the individual contributions of the countries' progress reports. He also discussed the current status of the TECDOC to be produced as a result of this CRP and the status of obtained results by CSIs to be added to the TECDOC. He encouraged the meeting's participants to provide and discuss their vision on future activities related to nuclear hydrogen production and the potential improvements to be implemented into HEEP software. The following are the summaries of the presentations made by participants:

**Algeria (Ms Boudries)** Interest in Algeria in nuclear based techniques is growing. Steps are going to be taken to investigate the possibility of carrying out activities in this field in collaboration with COMENA. Small scale experiments are being carried out. Techno-economic studies have been carried out through extensive modelling and simulation using "homemade" programs. Demonstration and eventually small scale hydrogen production facilities are under consideration. Our contribution to the CRP has been two-fold: first it has been on nuclear hydrogen production cost estimation, and then it has been on solar hydrogen cost estimation. She presented and discussed nuclear-based hydrogen production cost results during CRP meetings. She also presented and discussed comparison of the nuclear-based hydrogen costs to those obtained using environment friendly hydrogen production techniques such as solar-based techniques. Important results in Reports sent to the secretary of the CRP are summarized and contribution to IAEA TECDOC was elaborated. Several benefits have been received through participating in the CRP. These can be listed as follows:

- Opportunity to discuss and exchange information with experts in the field of hydrogen as an energy carrier. This could lead to networking and long lasting collaboration in the field.
- Possibility in contribution in improving HEEP capability by expanding HEEP capabilities to include cost evaluation of hydrogen production based on other environmental friendly techniques, such as solar-based techniques.
- Interest and train students on hydrogen as an energy carrier.
- Publication of journal papers and communication on the issues of hydrogen production using HEEP.

**Argentina (Ms Bohe)** emphasised that even many types of thermochemical processes were developed, their interest continue to be concentrated on chlorine cycles which is one of the leading long-term methods: vanadium-chlorine cycles, rare earth-chlorine cycles and mixed chlorine cycles. A lot of studies have been performed in the past on these methods, but the kinetics and mechanisms of reactions are not completely understood yet and this project will go on contributing to a better understanding of the critical problems identified for each cycle. Also it enables to obtain the parameters that permits the best results in the production of hydrogen as much as the highest efficiency as the economic advantages. Furthermore, a new process for obtaining Fluorine for the Argentina Enrichment Plant by liquid salts electrolysis produces hydrogen as a by-product; this plant begun to work this year and it would be another driving force for nuclear hydrogen economy in our country.

This CRP contributed significantly in this mainstream through a well-designed theoretical and experimental and economic program. During this project one doctoral thesis was finished and another has begun last year. Some publications in papers and meetings were done and further publication will be presented with the thesis results. It is expected that the results of this research would give impulse to the growing of H2 economy, which is associated with a cleaner technology and a sustainable energy source all through the world. But especially throughout the remote desert regions of our country like the vast Patagonia extended at the south and the highest Norther Puna.

**Canada (Mr Dincer)** Clean Energy Research Laboratory at the University of Ontario Institute of Technology (UOIT), in Oshawa, Ontario, in collaboration with Atomic Energy of Canada Limited (AECL) and other universities and institutes, 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 research group 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. They have successfully completed all the objectives originally stated in the proposal. The major achievements include the following under Cu-Cl cycle and HEEP package:

- 10 peer-reviewed journal publications, 1 book chapters and 6 conference papers, specifically related to Cu-Cl cycle and HEEP and HEEP use.
- Trained 3 graduate students (2 PhD students and 1 MASc student).
- Obtained critical NPP data from various Canadian organizations to incorporate into the modeling studies and HEEP analyses.
- Presented the modeling and HEEP analysis results in 6 international conferences

In regards to the completed CRP study, the following specific tasks have been achieved:

- Completed generic case studies and compared with the results provided by other countries.
- 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), etc.
- Studied heat upgrade options for the CANDU reactors to increase the temperature to the desired cycle temperatures for thermochemical/hybrid cycles.
- Identified several issues with HEEP.
- Proposed several things to improve the content and use of HEEP.

**China (Mr Zhang)** As for the nuclear hydrogen production, INET developed both IS process and HTSE. By the end of the year 2013, INET complete the construction and test of the IS facility. The closed cycle experiment of IS process on the facility was successfully carried out with the rate of hydrogen 60NL/h. Meanwhile, a lab-scaled facility and 10-cell SOEC stack were developed, 100h electrolysis experiment to test the performance. Several benefits have been gained by participating in this CRP. This includes: enhancing the capability of techno-economics evaluation for nuclear hydrogen production, preliminary economic data of nuclear hydrogen was obtained, which will be used as a basic reference for introduction to the public as well as the policy-maker. Also, a lecture was given to the student to introduce HEEP, and a paper on the economics of the hydrogen production is under preparation. The main contributions to the HEEP benchmarking and assessment include:

- Benchmarking exercise results were obtained for comparison, sensitivity analysis was made.
- A new nuclear hydrogen production case based on Chinese work, HTR-PM-IS, was designed and offered to the members. Estimation of H2 cost from nuclear hydrogen production
- 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.
- 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.
- Final report will be given, which presents the progress of R&D on nuclear hydrogen production in China, including description on the models, facilities, experimental results, and the R&D plan.

**Germany (Mr Verfondern)** Germany has gained in the past a broad experience on the development of high temperature reactors which also covered the operation of the test reactor AVR and the prototype commercial reactor THTR-300. The HTGR program also included the development of process heat reactors for non-electricity applications. Current reference design is the Siemens concept of the 200 MW(th) HTR-Modul as electricity producing baseline concept, and a 170 MW(th) variant

with higher coolant outlet temperatures for process heat applications such as steam reforming of natural gas or coal gasification. Depending on the reforming conditions and downstream processes, the main product will be synthetic natural gas, synthesis gas, hydrogen, or other liquid fuels. Through the contribution of this CRP, several persons learned to handle the HEEP software, accumulated experience, conducted studies with the code, and gave recommendations on how to further improve the model. This IAEA tool has presented itself as a valuable means for the comparison of different primary energy sources (nuclear, solar, and conventional), of different hydrogen production technologies, and different sets of economic parameters.

Main results achieved were two comprehensive studies conducted by bachelor students. Apart from the two benchmark exercises conducted within the frame of the HEEP CRP (generic cases, technology-based cases), additional cases were investigated. One study treated a comparison of conventional hydrogen production methods with those that are assisted by nuclear heat and power. The comparison is still in favour of the conventional method. This even holds if the capture and storage of CO2 during the production process is taken into account showing that under current conditions, this is an inefficient regulation tool. A comparison was also made with regard to solar primary energy.

**India (Mr Antony)** The primary objective of this activity was to validate models used in the HEEP through extended benchmarking exercise. Other objectives were (a) to enhance robustness and user-friendliness of the HEEP, and (b) to generate database in the form of library of files compatible with HEEP. The work included (i) collection of input data affecting hydrogen cost for identified cases through support from other participating organisations of this CRP, (ii) estimating hydrogen cost using HEEP for identified cases (iii) compile the information collected in the form of a database compatible with HEEP for identified cases, (iii) identify other similar software tools for estimation of hydrogen cost (iv) estimate hydrogen cost using these software tools and compare results, (v) obtain feedback from HEEP users, and (iv) incorporate modifications in HEEP to enhance robustness and user-friendliness. 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 excellent agreement with each other. Features of HEEP and H2A were also compared to justify the small difference in the results obtained. This exercise not only validated mathematical models used in HEEP but also demonstrated various features of HEEP. Feedback was received from users of HEEP to incorporate certain modifications in the software to enhance its robustness and user-friendliness. Most of the suggestions have been 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. 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.

**Indonesia (Ms Dewita)** Hydrogen production activities in Indonesia have focused on two methods, (i) SI cycle and (ii) Steam Methane Reforming. Actually, in Indonesia Steam Methane Reforming Methods has already commercially implemented in the fertilizer industry. However, for nuclear hydrogen, both of those methods are still in laboratory activities. Result of this study concluded that Steam Methane Reforming Method is one of hydrogen production process that commercially used at fertilizer industry in Indonesia and it was one of hydrogen production process which can be coupled with a HTGR type reactor. In order to coupling a HTGR with hydrogen production installation,

several components are needed, such as : IHX (Intermediate Heat Exchanger, the main component), ACS (Auxiliary Cooling System), purity helium and volume control system, several cooling system and compressor, temperature and pressure control system, helium flow control system and additional safety requirements for hydrogen production with nuclear heat. Pre-design is based on hydrogen production 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) and by natural gas feed rate of 67.5 kg/sec). The benefits received from contributing in the CRP include: improvement of knowledge and skill of human resources of Indonesia in use of HEEP programme, especially in our group, sharing information and experience among the researcher in the Member State, and improvement of the capacity building of our institution.

**Japan (Mr Yan)** presented the status of the nuclear hydrogen production development in Japan. JAEA has developed and is operating the currently largest high temperature gas reactor in the world. The 30 MWt HTTR achieved the initial criticality in 1998 and has since performed various technology demonstration tests including 950oC-coolant, full-power operations. The technologies verified on the HTTR are applied to designing the commercial reactor GTHTR300C for hydrogen cogeneration based on the iodine sulfur thermochemical process. The basic design including cost estimation has been concluded for the GTHTR300C. To prepare for the licensing and to validate the system performance, a model test plant for the GTHTR300C is being developed for operation with the HTTR. This will provide for the first nuclear hydrogen production based on the IS process. These development efforts are made to pave for the lead commercial plant construction around 2025. The main benefits received from participation in this CRP can be concluded as follows:

- Developed a network with the experts in other MSs
- Improved the capability and usability of the HEEP as a tool for in-house research.
- Developed a journal paper on the economics of hydrogen production through collaborative research in the CRP and using the HEEP as an analytical tool.

**Rep of Korea (Mr Kim)** HEEP generic cases have been studies and discussed with other participants about HEEP improvement based on the HEEP run experience. He also highlighted the impact of the financial parameters, especially discount rate and inflation rate on the hydrogen production cost. G4-ECONS which is developed by GEN4 EMWG (Economic Modelling Working Group) is introduced as another economic evaluation program for nuclear systems. Comparative analysis is performed using the 5 generic cases provided by IAEA and three country specific cases, using HEEP and GEN4-ECONS. These analyses confirmed the reliability of HEEP program by showing 1) the results from two programs are within tolerable error bound of 2~9% for all generic cases and 2) the results are within tolerable error bound of 2~12% for the country specific cases.

**Rep of Korea/USA (Mr Revankar)** Nuclear hydrogen production activities in USA have focused on three methods, (i) SI cycle and (ii) HyS cycle based thermochemical water splitting and (iii) high temperature electrolysis using solid oxide electrolyser. Small scale test facilities have been built and each of these processes are demonstrated through experiment and extensive modelling and simulations at General Atomics, Sandia National Lab, Savanna River National Lab, Idaho national lab and various academic institutions including Purdue University. The SI cycle is also studied in South Korea through small scale experiments and simulations at national labs like KAERI, KEIR, RIST and academic institutions including POSTECH. At POSTECH and Purdue University, SI cycle has been simulated with ASPEN PLUS simulation code where detailed flowsheets have been developed, Bunsen process analysis is performed for optimized operation, and models for coupled SI plant and PBMR nuclear plant have been studied for various transients.

**Pakistan (Mr Mustafa)** The country produced around one million tonnes of hydrogen in 2013 with fertilizer sector being the major consumer of the hydrogen for production of ammonia based fertilizer. The country's annual demand of hydrogen is projected to exceed 2.5 million tonnes per year by 2030 and 6.0 million tonnes per year by 2050. Hydrogen is being produced mainly from natural gas by SMR process. The production of natural gas in the country is insufficient to meet its growing demand. As a result, natural gas consumers in all sectors; industry, power, household, commercial and transports suffer shortage of supply round the year. Therefore, there is immense need to assess the alternative economical processes to meet the hydrogen demand of the country. At present, the country is operating two PWRs and a PHWR reactor while four PWR plants of 2,900 MWe capacity are under construction. Future plans envisage additional generation capacity. The main benefits of this CRP can be concluded as:

- The HEEP benchmarking exercise provided opportunity to learn and use the HEEP software which improved confidence in the in-house software being used for techno economic analyses of energy projects.
- The HEEP is a valuable tool that improves our analytical capabilities in techno-economics of co-production of hydrogen and electricity using nuclear energy. This enabled us conducting the country case study to assess techno-economics of nuclear hydrogen production in the country.
- The CRP provided opportunities to present and discuss results of the country case study with experts of other IAEA member states. Feedback from these experts was valuable in refining the techno-economic analysis of nuclear hydrogen production. The study results provide important information to support policy decisions regarding nuclear energy planning in the country.

## 4. Agenda

Annex 1 attached.

## 5. Conclusions

- The CRP has successfully been completed. Discussions were conducted on the status of the individual progress towards the contributions of the participants to the TECDOC chapters. The final shape and format of the TECDOC table of contents, chapters, and annexes are agreed after being discussed thoroughly. The participants proposed certain items to be considered for further improvement of HEEP software for future updates.
- The CRP provided opportunities to present and discuss results of all country case studies. The studies, in forms of feedback was valuable in refining the techno-economic analysis of nuclear hydrogen production results, provide important information to support policy decisions regarding nuclear energy planning in the country.
- HEEP has been used by all participants to the CRP and proved to be a valuable tool that improves analytical capabilities in techno-economics of co-production of hydrogen and electricity using nuclear energy. HEEP is now eyed by many CSIs as the tool for conducting country-specific case studies to assess techno-economics of nuclear hydrogen production.

## 6. Recommendations

- HEEP and its user's manual should be updated to include all the features suggested throughout the CRP.
- A new CRP should be initiated. The new CRP could well address challenging issues to the up-scale of nuclear hydrogen production including the formulations of milestone

recommendations to the MSs considering development and deployment of nuclear hydrogen production. The CRP could also address in-depth the other outstanding feasibility issues relating to nuclear hydrogen production including user requirements, application selection, demand modelling, safety and utilities regulations by seeking input of users and regulators of both production side (manufacturing) and application side (car makers, oil refiners, steel makers). Furthermore, the CRP could also tackle the socio-economic, public acceptance and environmental aspects of nuclear hydrogen production, and could in part focus on adaptation of low temperature reactors for hydrogen production integration using innovative ideas like chemical heat pumps for heat upgrade.

ANNEX 1

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# 4th RCM on CRP Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software"

**14-16 December 2015**
**Vienna, Austria**

**Room MOE79**

## Meeting Agenda

**Monday, 14 December 2015**

| | | |
|---|---|---|
| **Welcoming remarks** | | |
| 09:30 | **Overall status of the CRP & Objectives of this meeting** | Mr Khamis, IAEA |
| 10:15 | **Overall Status of the TECDOC & Ch 1: Introduction** | Mr Yan, USA/Japan |
| 11:00 | *Coffee Break* | |
| 11:15 | **Ch 2: Techno-economic Aspects of nuclear hydrogen production methods** | Mr Yan, USA/Japan |
| 12:00 | *Lunch* | |
| 13:30 | **Ch 3: HEEP: Models description** | Mr Antony, India |
| 14:15 | **Ch 4: HEEP Benchmarking** | Mr Dincer, Canada<br>Mr Zhang, China |
| 15:00 | *Coffee Break* | |
| 15:15 | **Ch 5: Technology-Based Case Studies** | Mr Verfondern, Germany |
| 16:00 | *Open Discussion* on Ch 1-5 | |
| 17:00 | *Wrap up of Day 1* | |
| 17:15 | *Reception* | |

## Tuesday, 15 December 2015

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|---|---|---|
| **Opening Session** | | |
| 09:30 | **Ch 6: Results and Discussion** | Mr Yan, USA/Japan |
| 10:15 | **Ch 7: Summary and Conclusions** | Mr Yan, USA/Japan |
| 11:00 | *Coffee Break* | |
| 11:15 | Status of final contributions by CSIs to the TECDOC | All participants |
| 12:00 | *Lunch Break* | |
| 13:30 | Status of final contributions by CSIs to the TECDOC | All participants |
| 14:15 | Status of final contributions by CSIs to the TECDOC | All participants |
| 15:00 | *Coffee Break* | |
| 15:15 | ***Open Discussion*** on new ideas for future CRP relating to nuclear hydrogen production | All participants |
| 16:00 | ***Open Discussion*** on new ideas for future HEEP relating activities | All participants |
| 17:00 | *Wrap up of Day 2* | |

## Wednesday, 16 December 2015

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|---|---|---|
| 09:30 | ***Open Discussion*** on the preliminary draft of TECDOC:<br>• **Annexes** (All) (final report from each country)<br>• **Scientific publications** (by each CSI) | All participants |
| 11:00 | *Coffee Break* | All participants |
| 11:15 | Finalization of the 4th RCM report | All participants |
| 12:00 | *Closing Remarks & End of the Meeting* | |