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Interoffice Memorandum

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Subject: Meeting Report on the Technical Meeting to Assess the Prospects of Coupling Non-Electric Applications to High Temperature Nuclear Reactors

Place of Meeting:	IAEA Headquarters, Vienna
Date of Meeting:	19 – 21 November 2018
PTAEO Code:	1000155.2018.06.RBF-MP1-2018.613222.NENP-NPTDS
Scientific Secretary:	Mr I. Khamis
Chairperson:	Mr J. Kupitz, Germany

ATTENDING EXPERTS

Name	**Country/Organization**
Mr G. Zhao	China/Tsinghua University
Mr J. Kupitz	Germany/Private
Mr T. Setiadipura	Indonesia/BATAN
Mr T. Sainati	Italy/University of Leeds
Mr T.H. Lee	Korea, Rep/KAERI
Ms F. Ghangir	Libya/Libyan Atomic Energy Establishment
Mr G. Mustafa	Pakistan/PAEC

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Name	Country/Organization
Mr M. Dabrowski	Poland/National Atomic Energy Agency
Mr K. Kowal	Poland/NCBJ
Mr A. Nasr	Tunisia/STEG
Mr H. Özcan	Turkey/Karabuk University
Mr R. Faibish	USA/General Atomics

1. Background

There has been increasing interest in high temperature reactor (HTR) technology in Member States, especially its use for non-electric applications. Prominent ongoing programmes include the already commissioned HTR-10 and the proposed HTR-PM in China, already commissioned high temperature engineering test reactor (HTTR) in Japan, the pebble bed modular reactor (PBMR) programme in South Africa, and developments in the Next Generation Nuclear Plant (NGNP) project in the United States of America. The main potential non-electric application of HTR technology is hydrogen production. Other potential applications include seawater desalination, based on the recovery of waste heat from HTRs, high temperature process heat for industrial applications, oil sand production, steam assisted methane reforming, coal gasification, etc.

The use of nuclear reactors for low temperature process heat has already been demonstrated. Even for high temperature applications, several potential applications have been identified that have major benefits, including support for climate change mitigation through the reduction of greenhouse gas emissions, the preservation of fossil fuels for more valuable applications, support for energy security and curbing the volatility of fossil fuel prices. Yet, there are challenges to such high temperature applications, especially for hydrogen production. Some of these challenges include the overall safety of a cogeneration plant, economics related to the cost structure of nuclear projects, nuclear cogeneration plant licensing, selecting a suitable business model for management, the misalignment of planning horizons and public safety perceptions regarding co-location.

In support of its Member States, the International Atomic Energy Agency (IAEA) has developed the Hydrogen Economic Evaluation Programme (HEEP) to provide support in analysing the economic aspects of hydrogen production using nuclear energy. This meeting will discuss further steps towards the realization of nuclear hydrogen production using HTRs and summarize potential strategies to align nuclear reactors with hydrogen production plants to lower entry barriers.

2. Objectives of the meeting

The purpose of this event is to: 1) exchange up-to-date information on types of foreseen potential high temperature reactors suitable for hydrogen production; 2) consider near term commercial technologies available for hydrogen production; 3) address socioeconomics and environmental considerations associated with nuclear hydrogen production; 4) assess market potential, economics and other related challenges, including potential upscaling of current research and development and other technologies involved in nuclear hydrogen production; and 5) draw a clear picture of the role of nuclear hydrogen production as a player in the future hydrogen economy.

3. Agenda (see Annex 1.)

4. Summary of the Work done and results achieved

The participants to the meeting were introduced to activities of the IAEA on non-electric applications, and the scope of such applications and the use of nuclear energy for cogeneration applications with focus on high temperature reactors. In addition, they also contributed effectively and interacted

positively in the fruitful discussions for exchange of experience and information. Below is the summary of the delivered presentations, work done, and discussions during the meeting:

Mr Khamis (IAEA Scientific Secretary) delivered an introductory presentation on the objectives and expected outcomes of the meeting, and encouraged the participants to actively contribute to the discussion sessions on the different topics related to the scope and objectives of the meeting. In addition, he introduced the status of the table of contents of the foreseen technical document on user and vendor requirements and considerations in nuclear cogeneration projects and invited the interested participants to contribute to the document.

In the following, the input of participating Member States is presented:

China (Mr G. Zhao) delivered a presentation on the potential of nuclear hydrogen and industry application couples with HTGR in China. He stated that modular HTGR, with good inherent safety, high outlet temperature; could provide process heat for industry application, and is the most suitable clean energy for large-scale hydrogen production in the future. Replacing coke with hydrogen reduction iron can solve the problem of CO_2 emission in steelmaking industry, and has a good prospect. So Nuclear hydrogen production is a clean way for steelmaking industry. Further research about nuclear hydrogen and steelmaking industry application is undergoing in China. He also added that a nuclear hydrogen steelmaking demonstration project is expected to start soon in China.

Germany (Mr J. Kupitz) In Germany substantial programmes on the development of the High Temperature Reactor (HTR) and its application for process heat production and electricity generation have been performed from the 1950's until the 1990's. This includes the construction and operation of the Arbeitsgemeinschaft Versuchsreaktor (AVR) close to the Research Center Juelich in the State North Rhine Westfalia (NRW) of Germany. It was an experimental pebble bed reactor with an electrical output of 15 MWe. The AVR was in operation from 1969 until 1988 and served as a test bed for materials irradiation, in particular for various types of pebble bed fuel elements and for the demonstration of the production of high temperature heat up to 950 °C, which is needed for coal gasification. NRW is a coal rich area and coal gasification and liquefaction were at that time considered as promising options. In 1983 the Thorium High Temperature Reactor (THTR) was put into operation in Hamm/Schmehausen in NRW. It was a prototype pebble bed reactor for electricity generation using a steam turbine with an output of 300 MWe. The THTR had a prestressed concrete reactor pressure vessel and its fuel elements contained high enriched Uranium- and Thorium-Oxide. The maximal helium temperature in the reactor was 750°C. The reactor was shut down in 1989 after several disturbances during its operation and a lack of interest from utilities for its continuous financial support. The German programme on the HTR and its applications was a cooperative effort between Industries, Research Centers and Technical Universities with substantial Governmental support. Besides the construction and operation of 2 HTRs several large experimental loops were built for the application of HTRs for electricity generation with direct cycle Helium turbines using the Brayton Cycle and for high temperature process heat applications for coal gasification and nuclear long-distance energy transport, where hydrogen is used as the energy carrier for the transportation of heat in a closed cycle without any emission of CO2. Due to an increasing critical attitude of the public towards nuclear energy in the1980ies the HTR development programmes were continuously reduced and finally discontinued.

Indonesia (Mr T. Setiadipura) present the current progress of the Indonesian Reaktor Daya Eksperimental (RDE) Program including the design development in which they are currently working to develop the detail design of RDE, also for the licensing status in which currently the Design Approval phase is already started since 27 August 2018. He emphasised that non-electric application can play a role to increase the rational of building the RDE by broadening the stakeholder and potentially improve the economic benefit of high temperature reactor which represented by RDE.

Italy (Mr T. Sainati) presented on the techno-economic feasibility of cogeneration for hight temperature Small Modular Reactors. Mr Sainati focused on load following applications for cogeneration assuming the use of high-temperature steam and electricity for cogeneration applications

during the night assuming law prices of electricity for periods equal to 8 to 12 hours. He also presented a "backward" economic appraisal identifying the target capital costs that would make these technologies competitive given the actual market conditions, and he focused on electricity and hydrogen prices, which are deemed to be some of the most significant drivers according to a sensitivity analysis. The techno-economic appraisal shown that the (3) sulfur-iodine thermochemical cycle is the most competitive co-generation technology for Hight temperature SMRs. The target capital cost is technically achievable as long as the electricity prices stay relatively low for daily periods longer than 8 hours (0.02- 0.04 €/kWh(e)), and the cost of hydrogen equal to 0.45 €/Nm^3. Under these conditions, the target CAPEX for (3) sulfur-iodine thermochemical cycle would be in the order of 6-14.2 k€/(Nm^3/h), which is deemed to be feasible by most manufacturers interviewed.

Korea Rep. of (Mr T. Lee) delivered a presentation about energy policies in Korea and cogeneration analysis results based on 350MW(th) HTGR. In Korea, new government announced new policies such as "Renewable energy 3020", "Industry innovation 2020 platform" and "Renewable energy complex plan". Especially, "Renewable energy 3020" implementation plan declared that it will increase renewable energy's share of the energy mix from its current level of 7% to 20% by 2030 by providing 48.7GW in new generating capacity. At the Korea Atomic Energy Research Institute (KAERI), a number of efforts are currently under way to develop a cogeneration system coupled to a HTGR including hydrogen production using steam methane reforming, high-temperature steam electrolysis, and sulfur–iodine processes in conjunction with helium Brayton and/or reheat Rankine systems in the 350 MW(th) HTGR at core outlet temperature of 750oC to 950oC. He also presented that hydrogen production rates were estimated to be between 92,566 Nm3/h and 143,812 Nm3/h; 92,566 Nm3/h and 143,812 Nm3/h; and 16,072 Nm3/h to 22,240 Nm3/h for the three technologies, respectively.

Libya (Ms F. Ghangir) presented on considering HTGR for hydrogen production in Libya. She detailed the current situation on various considerations of high temperature reactor designs suitable for cogeneration, nuclear hydrogen production, and infrastructure development taking place in Libya following the guidelines and IAEA publications in relevant areas. She also discussed the adopted technology assessment and selection process for the reactor design in Libya.

Pakistan (Mr G. Mustafa) delivered a presentation on economic assessment of hydrogen production using high temperature reactor in Pakistan. The presentation described Pakistan's energy needs, prospective energy supply options and status & prospects of nuclear power in the country. National plan for deployment of nuclear power by 2030 exists and assessments regarding use of nuclear energy for large scale non-electric applications including desalination are underway. The presentation also highlighted the role of IAEA software for nuclear power planning in the country. HEEP software has been used for the assessment of hydrogen production cost of the sulfur iodine system, high temperature steam electrolysis and steam methane reformer coupled with high temperature reactor. Cost of hydrogen production using the conventional steam methane reforming, coal gasification, and low temperature electrolysis using wind and solar electricity has also been assessed. The assessment shows that high temperature reactors can economically supplement natural gas for hydrogen production, conserving the resource.

Poland (Mr K. Kowal and Mr M. Dabrowski) In 2017 Polish Ministry of Energy has published the report on possibilities for deployment of High Temperature Reactors (HTR) in Poland. This work has been driven by the desire of the domestic industry (mostly chemical and energy companies) to be provided with the heat source of predictable costs, resistant to changes in fuel prices and independent from the price of CO2 emission allowances. Implementation of the new nuclear reactor technology within the country encounters, however, new challenges, among others the framework for the licensing and risk assessment of the joint HTR-based nuclear-chemical facilities. These processes must be carried out with respect to all specific features of the nuclear reactors and the related chemical installations. Moreover, the bidirectional nuclear-chemical interactions should be considered. This prompts the adoption of an integrated approach to the risk analysis, which leads, however, to greater complexity and uncertainty of the models being developed. The Probabilistic Risk Assessment for the newly designed HTRs is a challenge, due to the novel technological concepts for which neither the damage states, safety goals nor risk measures are clearly defined. Thus, there is a need for

reconsideration of the traditional PRA framework in the terms of its applicability for such installations. In this presentation some new risk metrics have been proposed and the new approach for risk models' development has been discussed in the context of the Polish HTR program.

Turkey (Mr H. Ozcan) presented on the hybrid thermochemical cycles for hydrogen production, mainly focusing on CuCl and MgCl cycles. Their operations require next generation reactors to provide higher temperature thermal energy, mainly from super critical water reactor and molten salt reactors. Hybrid cycles enable decreased maximum temperature requirement while consuming electricity at least at one step of the cycle. Economic assessment results depicted that Nuclear based CuCl cycle shows lowest hydrogen costs while solar based HTSE has the highest cost. Environmental assessment also indicates superiority of nuclear based hybrid cycles over conventional methods. Use of HTRs for generation of hydrogen via thermochemical cycles are inevitable. Cost aspects and technology development are two main issues for decision makers. IAEA HEEP software is a developed tool for evaluation of many nuclear based hydrogen methods for addressing the economic aspects of nuclear hydrogen generation. HTRs could be suitable for energizing high temperature energy requirement of energy dependent countries, internally. Environmental benefits of nuclear based heat use for industrial processes should not be ignored for countries suffering from intensive emissions.

USA (Mr R. Faibish) presented on the US perspectives on high temperature nuclear heat applications. He stated that USA has been leading R&D into non-electrical applications of nuclear power for decades now. The first two commercial gas-cooled reactors operated in the US from the 60s through the 80s (Peach Bottom and Ft. Saint Vrain) and were designed and engineered by General Atomics. Though these were used solely for electricity generation, future advanced high-temperatures reactors (HTRs) that are being designed and proposed in the US (e.g., GA's EM2 and X-Energy's Xe-100) could readily support non-electrical heat applications, such as industrial heat, hydrogen production, district heat, and water desalination. Temperatures ranging from 500 to 850°C would be readily available from existing advanced nuclear concepts once deployed and ideal for a range of the above-mentioned applications. In the US, utilities working closely with national labs, universities, industry partners, and the Department of Energy are actively considering lower grade heat utilization (of around 300°C) from the existing fleet of LWRs for low-temperature hydrogen production processes as well as low-grade industrial heat applications. These latter activities and related projects would help demonstrate the feasibility of coupling nuclear heat with various end-uses, gain relevant and useful experience, and help set the stage for the coupling future non-LWRs (HTRs and others).

5. Conclusions

The meeting highlighted the large potential for industrial high temperature process heat applications using low-carbon heat generation with nuclear power. Main conclusions are:

1. Information exchange was a crucial element and very useful to form a path forward towards more understanding and better communication between technology providers and interested users, and effectively understanding the specific country/user regulations and requirements, especially on hydrogen production and industrial heat using HTRs.
2. Existing light water nuclear power plants in USA are considering plans to use heat for various industrial applications, including hydrogen generation. This experience could assist in assessing coupling of future advanced HTRs to various heat applications.
3. Non-electric application can enhance the public acceptance and broadening stakeholders.
4. One of the most demanding challenges for the newcomers (like Poland) is the licencing process and safety demonstration of the coupled nuclear-chemical facilities with the High Temperature Reactors. There are some countries like China and Japan, where these issues have been already addressed. Many technical aspects we can also learn from private sector (e.g. General Atomics) and from scientific institutions. Thus, it would be much more beneficial to learn from these experiences more detailed knowledge instead of reinventing the wheel.

6. Recommendations

Participants to the meeting recommend the Agency to:

1. Better coordinate various activities relative to non-electric applications across the Agency.
2. Organize one or more future activities to discuss advanced nuclear systems especially the ones that utilize heat for hydrogen and industrial applications.
3. Address in-depth the economics and business models for high temperature nuclear cogeneration systems.
4. Publish a report on safety standards/requirements for nuclear cogeneration plants with focus on high temperature reactors and on the interface between nuclear and industrial safety.
5. Organize a workshop devoted to the safety aspects of the HTRs for nuclear cogeneration. The goal of the workshop could be to develop a general guidance on how to perform safety studies for this type of installations.

Annex 1.

Technical Meeting to
Assess the Prospects of Coupling Non-Electric Applications to High Temperature Nuclear Reactors

Vienna, Austria

Meeting Agenda

	Monday, 19 November 2018	**Room: M5**
09:30	Welcoming and opening remarks	Mr. I. Khamis, IAEA
09:35	Introduction of participants, Selection of chairperson and adoption of the Agenda	All participants
09:45	Overview and objectives of the meeting	Mr. I. Khamis, IAEA
10:00	High Temperature Heat Applications Using an Innovative High Temperature Gas-Cooled Fast Reactor	Mr. R. Faibish USA
10:30	*Coffee Break*	
11:00	High-Temperature SMRs and Cogeneration – A Techno-Economic Analysis	Mr. T. Sainati Italy
11:30	**Discussion on** the promising scenarios for coupling and upscaling of non-electric applications and the role of involved stakeholders	All Participants
12:30	*Lunch Break*	
14:00	The Use of HTRs for Cogeneration	Mr. H. Paillere OECD/NEA
14:30	**Discussion on** the responsibilities of vendors and users involved in nuclear cogeneration projects	All participants
16:00	*Coffee Break*	
16:30	**Discussion on** business models and potential market towards deployment of nuclear cogeneration projects	All Participants
17:30	**End of Day 1**	

Tuesday, 20 November 2018		Room: M0E18
09:00	HTR Project in Poland	Mr. M. Dabrowski Poland
09:30	An Integrated Risk Assessment of HTR-Based Nuclear-Chemical Facilities	Mr. K. Kowal Poland
10:00	Considering the High Temperature Nuclear Reactors for Non-Electric Applications in Libya	Ms. F. Ghangir Libya
10:30	*Coffee Break*	
11:00	Nuclear Hydrogen Production in Tunisia: Opportunities and Challenges	Mr. A. Nasr Tunisia
11:30	Synergetic Approach to Assessing the Role of Non-Electrical Applications of HTR in Nuclear Power Structure	Mr. V. Nevinitsa Russia
12:00	Potential of Nuclear Hydrogen and Industry Application Coupled with High Temperature Gas Cooled Reactor in China	Mr. G. Zhao China
12:30	*Lunch Break*	
14:00	Status of Non-Electric Application Study Related to Indonesian Reactor Daya Eksperimental (RDE)	Mr. T. Setiadipura Indonesia
14:30	The Use of High Temperature Reactors for Thermochemical Hydrogen Production	Mr. H. Özcan Turkey
15:00	Economics of Nuclear and Renewable Hydrogen Production in Pakistan	Mr. G. Mustafa Pakistan
15:30	*Coffee Break*	
16:00	Performance assessment of cogeneration systems based on 350 MWth HTGR	Mr. T.H. Lee Korea, Rep. of
16:30	**Open Discussion**	All Participants
17:00	**End of Day 2**	

Wednesday, 21 November 2018		Room: M0E18
09:00	Collecting Feedback and Summary of the Meeting	All participants
10:00	Conclusions and Recommendations	All participants
10:30	*Coffee Break*	
11:00	Finalizing meeting report	All participants
13:00	**Closing Remarks**	