GIF VHTR Hydrogen Production Project Management Board
Mr. Sam Suppiah, CNL, Canada

Berta Oates
Patricia Paviet is the group leader of the Radiological Materials Group at the Pacific Northwest National Laboratory. She is also the chair of the GEN IV International Forum Education and Training Work Group. Patricia.

Patricia Paviet
Yes, good morning, thank you so much Berta, and good morning everybody. I hope you are doing well during this COVID-19 crisis. And like Berta said, we are very happy to have Sam Suppiah with us today. He is currently the manager of the chemical engineering branch and the Facility Authority for Tritium Facility Operations at the Canadian Nuclear Laboratories in Chalk River, Ontario. He received his chemical engineering degree and his Ph.D. from the University of Birmingham in the UK and worked for a contracting company and British Gas Corporation in the UK before joining CNL. He is a professional engineer in Ontario, and a certified Project Management Professional. He has more than 35 years of expertise in different areas where he has been leading collaborations with industry, institutes, and universities. His current focus at CNL in the area of hydrogen production is in the development of the hybrid copper-chlorine cycle. This development is approaching lab-scale continuous operation demonstration in 2021.

He is the Canadian delegate for and the current Chair of the GEN IV Very High Temperature Reactor Hydrogen Production Project Management Board. He is also a board member of the Canadian Hydrogen and Fuel Cell Association. He has been a regular presenter at IAEA's technical meetings and other national and international meetings on hydrogen production. Again thank you so much, Sam, for delivering this webinar today, and without any delay I give you the floor. Thank you Sam.

Sam Suppiah
Thank you Patricia. Dear colleagues, good morning, good afternoon, or good evening to all of you, depending on where you are in the world. I hope everyone is healthy and hopeful under the current environment, and helpful too. My presentation is on the activities of the Generation IV forums, Very High Temperature Reactor Hydrogen Production Project Management Board, a really mouthful. In short it is really Hydrogen PMB. I would refer to it as Hydrogen PMB.

My presentation will give a quick outline of the Hydrogen PMB board itself, the current hydrogen production technologies and advanced technologies that our member countries are working on and their current progress.

This slide shows a GIF Governance Structure basically and how the project management board here fits into the structure through a steering committee to the policy group. Essentially, the PMB is established by the signatories of each project arrangement in order to plan and oversee project activities. Their main goal basically is to establish the viability and performance of the relevant Generation IV system in their technical area.

The flags in this slide show the current members of the board, France, US, Canada, EU, Japan, South Korea, and China are the current members. These are the individuals who officially are part of the current board, the Hydrogen PMB board.

This slide shows the Chairs and Co-Chairs of the board since the project arrangement was approved in 2008 for the first 10-year period. The project arrangement is now extended for another 10 years until 2028. Normally, the Chairmanship of the Board is for 2 years, and the member countries take turn on a rotation basis. At the beginning, we needed three face-to-face meetings a year to establish and implement the project plan, but with time we have learned to be more efficient and have come down to a maximum of two meetings per year, and sometimes only one.

We also rotate the country that hosts the meeting. The graph shows here how many times the meetings were hosted by the different countries. The last meeting was held in Shanghai in November last year, just before all the COVID issues came up. These were the chairs over the years. Currently Canada is chairing the board, that is me, and Korea is holding the Vice Chair position. China, as you can see, China is still an observer, not a full member, but with the current finalization of the project plan their exertion is imminent.

The VHTR Hydrogen production program basically aims at developing and optimizing high temperature thermal chemical and electrolysis water splitting processes as well as defining and validating technologies for coupling any Gen IV Hydrogen Nuclear Reactor system to such Hydrogen production plans processes.

This slide shows the evolution of the different reactor systems over the last several decades, from Generation I to Generation IV. The current Generation IV reactor systems included in the GIF are shown on the slide. Although the Hydrogen PMB is under the VHTR system, hydrogen production processes that are better suited for the other reactor systems that are shown here are also included in this PMB to make it more inclusive for the benefit of GIF.

I am sure all of you are aware that hydrogen basically is a critical energy carrier for now and future because of its high specific energy, seen in this first top graph here. As the graph shows, for a unit weight it really packs in the highest amount of energy compared to all other fossil fuels. That is, it has the highest gravimetric energy density of any known field, about three times. This is about three times that of the gasoline that you see here. However, because it is a light gas at ambient conditions, its energy density per unit volume can be only decent if it is contained at a high pressure, as shown here for example. Here the hydrogen is something like 100 megapascal pressure conditions.

For automobiles, for example, it needs to be compressed to something like 700 bar, that is about 70 megapascal, to cover a distance similar to a gasoline-fueled car with a full tank of fuel. The demand for hydrogen, as you can see over the years, has been growing with the expanding population of the world. Because it is a raw material used to produce fertilizers and various other materials, its demand is growing and is only expected to grow even faster. With increasing living standards for example, of the developing world, the demand for hydrogen is forecast to grow, as I said, very rapidly.

In the future, to minimize the greenhouse gas emissions from heavy duty vehicles, it's very likely a shift will have to be made to hydrogen fuel. This slide shows some of the current available hydrogen production processes. Currently, something like 80% to 90% of the hydrogen is produced from fossil fuels through what's called the SMR, Steam Methane Reforming process, and partial oxidation process, and a few other processes. These pictures show the two main processes. For example, every ton of hydrogen produced this way would throw something like 10 tons of CO2 into the atmosphere.

Yes there are cleaner methods available, conventional electrolysis of water alkaline, or PEM type using basically electricity. However, the electricity has to come from a clean source of production. The other issue is that electricity is not cheap, and the current electricity producing technologies are not as efficient as they should be or could be.

Generation IV reactor systems can produce electricity more efficiently and therefore should be beneficial even for these low temperature electrolysis for hydrogen production.

However, when you convert the heat produced by fossil, by fission, by nuclear reactor, by any reactor systems to electricity, the current systems or future systems, you lose a significant amount of the energy as waste heat and hence reduce the efficiency. The heat to electricity conversion, efficiency of the current commercial reactor systems is about something like 33%. And the advanced reactor systems can be something like in the mid-40 region, still significant waste of energy on the conversion of heat to electricity.

What if there is a way of using the heat directly, heat produced by these sources directly to produce hydrogen so that you do not have to lose the efficiency of the conversion of heat to electricity. Yes there are hydrogen production processes that can utilize mostly heat to deliver hydrogen. However, as you will see soon, these hydrogen production processes require high temperature heat. I would say, this is one of the main reasons why many clever people in the past decided that producing hydrogen using advanced nuclear energy systems that can deliver heat at high temperatures is a good idea for large scale hydrogen production.

Why are high temperature processes better for hydrogen production? Using the first and second law of thermodynamics, one can derive an efficiency term for the splitting of water shown here. As the efficiency equation shows here, the higher the temperature, the TH is the temperature at which the splitting process takes place, and TL is the outlet temperature or the ambient conditions. As this equation shows that, for example, if TH is high, this term will be small, hence the efficiency will be large. So in a sense, with increasing temperature of the process, your efficiency would increase.

As part of an early energy research initiative called NERI a study sponsored by the US Department DOE, a general atomics team supported by Sandia National Lab, SNL, and the University of Kentucky sort of looked at something like 115 different thermochemical cycles that produced hydrogen. Out of all these processes, the 4 processes shown in this slide have been receiving most attention over the last decade or two.

And these are the processes with the hydrogen PMB, member countries are mainly focused on. The SI, the sulfur-iodine process, and sometimes it's called iodine sulfur process but I call it as SI process, is a close cycle based on three main steps. One exothermic step called, this the middle one, the Bunsen reaction, producing sulfuric acid and HI at around 120 degrees Celsius.

Another endothermic step decomposing the hydrogen iodide produced from the Bunsen reaction into hydrogen, the product that we want, and iodine, to recycle for the Bunsen reaction. And the other endothermic step, the sulfuric acid decomposition into oxygen, the other product of the process, and SO2 for recycling to go back into the Bunsen reaction. And this step takes place around 850 degrees Celsius, hence the need for a high temperature source, heat source to accomplish this step.

A somewhat close relative of this sulfur-iodine process is the hybrid sulfur process which utilizes the sulfuric acid decomposition step, similar to the sulfur-iodine process but uses what's called SO2 depolarizing electrolyzer, basically to produce the hydrogen and the sulfuric acid to recycle. The copper-chlorine cycle, hybrid cycle utilizes three main steps: the electrolysis, hydrolysis, and thermolysis, with an addition of step of separation process, separation step. Basically an aqueous acid solution CUCL is electrolyzed to produce hydrogen and CUCL. More details will follow in the slides coming soon.

There is one step, for example this step here was called the thermolysis decomposition step, requires something like 530 degrees Celsius, hence it is better suited for this whole cycle, that is the highest temperature requirement of this cycle, suited for moderate temperature nuclear systems such as supercritical water or molten salt reactor systems, or solar energy. Since electrolysis is involved in these two processes, the CUCL and hybrid sulfur process, they are called hybrid sulfur processes.

The fourth one is high temperature electrolyzer of steam, this one here, a reverse of the solid oxide fuel cell technology. Generally, the electrolyzer functions very efficiently at around 800 degrees Celsius, but also can function at temperatures as low as 700 degrees Celsius.

This slide basically captures the kind of work being done in the sulfur-iodine process under its own work package. So, as part of the hydrogen PMB, each member state does its work in the various cycles and provide the input to the work package that is created as part of the Hydrogen PMB in the various cycles. So, this one, the sulfur-iodine process has its own work package where the process engineering aspects, materials and their mechanical strength and corrosion resistance properties, catalysts used for the decomposition of hydrogen iodide, sulfuric acid, their purification, bench-scale testing, pilot-scale testing, the lifetime studies etcetera, these kinds of work all reported in this work package.

These are all critical aspects of the process development and they are covered in here. This slide shows that the work done in the high temperature steam electrolysis. Again, it involves process evaluation, development of advanced materials for electrodes, electrolytes, interconnections, stack designs, lab-scale and pilot-scale demonstrations are covered here. One interesting area, a growing area is the CO2 co-electrolysis. Basically, you feed CO2 with steam into the electrolyzer to produce syngas, synthetic fuel. So, what you get is carbon monoxide and hydrogen, which as you would know, can be used to produce various chemicals. And this is a growing area that many countries are interested in.

This slide shows the development of the copper-chlorine cycle, the work package that covers the development of the copper-chlorine cycle, and other sort of cycles such as hybrid sulfur and also any other cycles that might come onstream as time passes by. This work package covers the hydrogen production and nuclear reactor coupling. And again, it sort of looks at various aspects. This work package covers basically development methodologies and safety standards for individual processes and their coupling to nuclear reactors. Economic evaluations are also included in this work package.

To give some more details on the various hydrogen production processes, so this slide shows some details of the sulfur-iodine process. As I mentioned before, there are three main steps in the process within the overall process, and these are fairly sophisticated operations that these individual steps require. For example, in the HI process section, there are many operations so the HIx solution that comes in here, needs to be purified, then it needs to be concentrated using a technology called EED, electro-dialysis method and then it goes through a distillation system, and then decomposition reactor, separators etcetera before the hydrogen is separated and provided, and the other materials are recycled, are sent back to the Bunsen reaction.

Similarly the sulfuric acid section has purification operations, concentration, the decomposition, which basically the sulfuric acid gets decomposed to SO3 and then SO3 gets decomposed to SO2 and oxygen, and oxygen is a product. In the Bunsen reaction, the reactor itself, it is a complex reactor system. Then there are separators of the liquid and gas phases. It is truly a complex chemical process, but it has the potential to offer major benefits of high efficiency in the hydrogen production capabilities.

Actually, many countries have been interested in developing this process, US and France collaborated on the development of what was called an integrated laboratory scale experiment in sort of 2006-2009 period. Much of their experience and the results have been captured by the Hydrogen PMB, in kind of as background IP reports. Unfortunately, further development of this process by US and France was abandoned to basically enable focusing their effort on the high temperature steam electrolysis process development, in both countries. That sort of followed a down-selecting exercise that was conducted towards the end of the first decade in 2000. However, Japan, Korea, and China have continued the development of this process very successfully, I should say.

So, this slide shows Japan’s progress under JAEA’s support or work. Starting in fact with this lab-scale testing in the 90s, they demonstrated that you can produce hydrogen using this process. In fact, they operated this system for 48 hours to produce hydrogen continuously as something like 1 liter per hydrogen rate.

And that sort of demonstration, the successful demonstration encouraged them to move on to the next phase, which was a bench-scale testing, bench-scale system which was operated continuously for about a week, about 175 hours, to produce hydrogen at about 30 liters per hour rate.

And then this demonstration was sort of followed by R&D activities over the next several years that focused on various issues that they uncovered or discovered in the operation of these facilities, mainly materials related.

The above focus in fact contributed to their next phase of their development of this system here which is 100 liters per hour capacity, built with more engineered components. So, this slide summarizes Japan's efforts since 2010, efforts focused on integrity tests of these various components to both liquids and gases, there are both liquids and gases in the system; exposures to components over 150 hours at a hydrogen production rate of 30 liters per hour. And actually, that work really showed that some of the materials that they had selected and used had a decent behavior under these conditions. Their current focus is underway to acquire more materials related data on long term testing and basically the exposure of materials to these processed fluids and gases.

This slide shows basically the demand for hydrogen that Japanese expect over the next several decades and how Japan is going to sort of satisfy such a demand, at least partially, using their high temperature gas-cooled reactor technology that they are developing, integrating it with the hydrogen production process. This slide also shows the high temperature gas-cooled reactor core generation capabilities, that is to produce heat as well as the electrical power produce the kind of hydrogen production rate that they have shown here.

This slide basically summarizes what I have just mentioned.

China has been very actively involved in the sulfur-iodine process. This slide shows their progress from fundamental studies in the early 2000 through system integration, key component studies, and then the ambition to couple the hydrogen production process to the HTR10 nuclear high temperature reactor system that's there now.

The HTR is a 10-megawatt thermal power unit. In 2009, they carried out proof of concept development, that was called the IS10 system which was sort of 10 liter per hour hydrogen production capacity unit. And later on in the 2014 period, they moved on to what's called IS100 system that was capable of producing 100 liters per hour, shown here in this picture. It ran for something like 86 hours, producing hydrogen out of those 86 hours, 60 hours continuously, at something like 60 liters per hour. They are also looking at materials currently in larger scale demonstration in the future.

This slide shows their current and future activities in the area. One of the important contributions of Japan and China to the development of the sulfur-iodine process is the HI concentration technology, which is the EED, electrodialysis system where the HI is concentrated to overcome basically the azeotropic issues that they see. Again, they are looking at the different sections of the whole process, simulations, and coupling of the hydrogen reaction process to the HDR system.

This slide shows actually, this picture is their original concept demonstrations unit. And this sulfuric acid decomposer catalyst tests results shown here are from the original studies. The various catalysts were tested, as you can see, and I think this copper-chromite catalyst was the one that they settled on for the work with the IS100 system. These results are from the IS100 system, where they planned continuously for 60 hours producing hydrogen, as 60 liters per hour rate.

This slide is on the Korean activities. Korea earlier on focused very heavily on the sulfur-iodine process development. They were one of the main players. The current focus however is on sort of investigating the integration of the iodine production processes to the HTR system, as shown here. They are looking at high temperature steam electrolysis integration, sulfur-iodine process integration to the VHTR, and also steam methane reformers to the VHTR. The coupling of these SMRs, the steam methane reformers to VHTR does reduce the greenhouse gas emissions significantly, through a reduction in the use of methane, that's conventionally used to produce heat in the SMR process.

Moving on to the high temperature steam electrolysis, as mentioned earlier HTSE is the reverse of the solid oxide electrolysis technology. However, the performance and the efficiency of the cells are quite different under these different operating conditions. The efficiency under the fuel cell mode is less compared to the electrolysis mode. There are various reasons for the different behaviors under these conditions as shown in this slide here.

Originally, the original high temperature steam electrolysis had separate layers for the cell, electrolyte cathode layer which is a nickel-cermet electrode, the anode layer, these were all separate layers in the old technologies where they were put together to produce a cell and a stack. The latest technologies involve electrode supporter cells in which the anode and/or the cathode electrode materials are coated on to the sides of the electrolyte here, as shown in white.

Actually all countries, US, France, EU, China etcetera have invested quite substantially in the development of the HTSE technology over the last little while. This slide shows the holistic approach that CEA in France has taken on the development of HTSE and they are extremely focused on their item which is steam electrolysis.

As I said, it's a holistic approach and they look at base materials, various components, development and production of the components, preparation processes, system integration, and various demonstrations, including high performances, to show high performance, durability and cost efficiency. This slide shows their sort of progress over the last 10 years that the Hydrogen PMB has covered.

Phenomenal cost reduction, as you can see here, 80% cost reduction through various things that I just mentioned, and good lifetime achievements have been demonstrated. A prototype integrated system is also a great achievement over the last decade. The specific developments on module and systems are shown in this slide as a timeline. In 2014 their first 5 kilowatts high temperature steam electrolysis system started. Then 2018, a reversible system. As I said, the electrolyzer can be operated as a fuel cell or an electrolyzer, so that was 2018, their first reversible system. It was delivered to ENGIE and some details you can see here.

And then in 2020, again multi-stack reversible system delivered to Italian installation. And then current activities, which is supposed to progress until 2022 is called GrInHy which is a Green Industrial Hydrogen 2.0 project to produce hydrogen for a steel mill to reduce steel.

This slide basically just shows some interesting results on a 6 kilowatt electrical unit. Although the results are shown here for a short period of operation, interesting to see how you only just need to heat the electrical power requirement initially to get the temperature up and then you basically shut down the heating part of it, and the internal resistant heating from the power supply to the unit keeps the temperature high and you can produce hydrogen at reasonably steady conditions without that electrical power for heating.

This slide basically shows some estimation of the cost of hydrogen produced by High Temperature Steam Electrolysis carried out by CEA. And it basically shows as a function of the scale of production and manufacture of these cells, and the cost of electricity etcetera. The forecast is for something like €1-€1.5 per kilogram. However, I should caution that some significant assumptions are made on the lifetime of these cells, capital costs, etcetera.

This slide shows the US activities, and US has continued quite strongly in the development and demonstration of the HTSE technology high temperature steam electrolysis technology. This slide shows the nuclear hybrid energy concepts that they are looking at, what's called DETAIL Lab, that's the acronym for Dynamic Energy Transport and Integration Laboratory, and that includes the 25 kilowatts electrolyzer as part of this system.

Here the effort is focused on advancing the state-of-the-art high temperature electrolysis technology, while demonstrating grid and thermal energy integration and dynamic performance characteristics. The effort is focused on these activities. The facility has been – this is the electrolyzer system – has been commissioned and initial testing at a 5 kilowatts scale has been carried out. Actually, US over a period of time was very heavily involved in the development of the high temperature steam electrolyzer components, and this slide shows that. They worked with several manufacturers and suppliers of various components for the electrolyzer, and they tested them and worked with these suppliers. The suppliers are the manufacturers identified in this slide, Ceramatec, MSRI, Versa Power, St. Gobain, Rolls Royce, etcetera. So there was lot of work that went in the development of various components at INL, Idaho National Lab.

And this slide shows some of their initial work at the MSRI unit, a 5-cell solid oxide electrolysis stack used for these tests. They demonstrated fairly good degradation behaviors of the cell, and they ran it for something like 1200 hours, as this figure shows. Actually, recent advancements around the world have demonstrated even lot better lifetime performance of these cell designs.

As I think I pointed out really, I'm not sure, various countries in Europe are actively pursuing the High Temperature Steam Electrolysis development. However, many of these developments are really linked to solar power rather than nuclear power. That is fine as long as the basic HTSE technology is developed for application with different energy sources. This slide shows the solar stimulator providing the heat to the boiler here, the steam generator. And then the actual high pressure electrolyzer that they used to look at. It's something like 7 liters per minute hydrogen production experiment.

Moving on to the Canadian focus on the copper-chlorine cycle, Canada has focused on the development of the moderate temperature, we call it moderate temperature because the temperature requirements are less severe, it's about 530 degrees Celsius. As I pointed out before, there are 3 main steps involved here, electrolysis, hydrolysis, and decomposition. The electrolysis, basically involves copper-chloride, HCL aqueous solution getting electrolyzed to produce hydrogen, and then CUCL gets oxidized to get CUCL2, and there's a separation step here where the heat is provided and then you basically produce CUCL2 for the next step where it is hydrolyzed with reaction or exposure to steam at around 380 degrees Celsius, to produce an intermediate product called copper oxychloride which is then passed to the decomposition step where it is decomposed to produce oxygen and the CUCL required to complete the cycle. As I said, the maximum temperature is 530 degrees Celsius for the decomposition step, hence you can use moderate temperature, nuclear reactors, renewables, and even industrial waste heat.

The attractiveness of the CUCL cycle, as compared to sulfur-iodine etcetera, you could have seen from what I have shown already, it's somewhat of a simpler process. The chemicals involved are not that bad, though the HCL concentrations that we use, there are significant limitations with materials etcetera, but it's somewhat an easier process, and it does have high efficiency and better economics at large scale. As I said, low temperature we can use different reactor systems ideally suited for coupling with heat sources, small module reactors. It's an area that this copper-chlorine cycle can be coupled easily.

As I said materials of construction is not too bad. And the raw materials are inexpensive and there are no requirements for catalysts in any of these steps, except the electrolyzer does have a catalyst on the electrode but it is a well-established catalyst technology.

However, there is a requirement for solid handling, that's the caveat here that requires special considerations. This slide basically just shows a simplified, integrated copper-chlorine cycle of the different steps that I talked about. This slide shows a MATLAB Model that we sort of started with to look at the heat and mass balances, and now we've moved on to ASPEN modeling for more detailed process engineering work, and also cost estimation, and also to look at optimization of the heat balances. Heat requirement for this process is an important aspect that needs to be looked at very carefully and we are using models to look at the best ways to optimize these, the heat requirements of the process.

This slide shows the electrolysis step, and this step was considered to be a very difficult challenge in the past, but now it's a well-developed and well understood step. Lab systems shown here is capable of producing hydrogen at 50 liters per hour or more, and long-term operation of the cell has already been demonstrated over 1600-hour period.

This slide, slide 43, shows the separation of the various species. And it is not a technically challenging step but it can be challenging from an energy requirement point of view. It is an energy-intensive step. As I mentioned before the current focus is on process simplification, minimization of energy requirements and recovery of heat as much as possible.

This step, the slide 44 is the hydrolysis step. It's basically you are hydrolyzing the CUCL2 with steam. It's been the most challenging step for continuous operation of the overall process or to develop a continuous process. Progress is achieved though a bit slow, but it is the current efforts are basically to make it more efficient and more amenable for integrating within the complete system. There is also a collaborative development project underway with the Ontario Tech University in Ontario Canada.

This slide shows the decomposition step involved. This is basically the copper oxichloride is decomposed to CUCL for recycling and oxygen is produced here. This step is well-developed at Chalk River at CNL. The unit shown in the picture can easily provide the required capacity for integration in the cycle to produce 50 liters per hour. Current focus is on optimization of the step for thermal efficiency and good gas solid contact in the decomposer.

In Canada, CNL is sort of spearheading a plan to demonstrate this technology for industrial application. The current plan is by 2021 to put together this lab-scale system, to produce something like 50 liters per hour of hydrogen, using this process. Following that, the technology, the plans are to pilot plant demonstration with commercial partners and then further implementation for industrial applications.

I didn’t talk much about the hybrid-sulfur cycle. The development of this technology has been limited. In the early part of the first 10-year project arrangement of the Hydrogen PMB, it was around 2008, there was a considerable interest on this technology in the US, and some good advancements were happening. Unfortunately, because of the down selecting that happened, this process also got skipped. But EU institutions have resumed development of this cycle for solar energy applications. Currently INET in China is starting experiment to work on the development of the electrolyzer used for this process.

In summary, I would say there has been very good progress demonstrated by the member countries, and these are captured by the hydrogen production management board. The operation of the integrated sulfur-iodine process has been demonstrated, so it’s not really theoretical. However, there are issues. There are materials related issues that require a solution for industrial demonstration.

High Temperature Steam Electrolysis Technology actually is a reasonably matured technology. However, degradation of cell components requires continuing advances and also still the costs related, the CapEx, capital cost needs advancement, so a reduction in capital cost etcetera. The copper-chlorine cycle development, as I mentioned before, is approaching lab-scale demonstration, operation of the integrated system. So, the current sum of the effort is in the solid transfer and also energy optimization.

All the above hydrogen production process still require a demonstration of economical production capabilities. Technically they've all been demonstrated reasonably well. But what I feel is that with advances through planned developments that are currently going on, there is very strong investments in these technologies. I believe, it is believed that economical hydrogen production can be achieved with these processes. With that I end my presentation and thank you for listening to people all over the world and I can take some questions I think.

Berta Oates
Thank you, Sam, very much for sharing your expertise with us. As questions are being typed in the question pane, we'll just take a quick look at the upcoming webinars. In May, Performance Assessment for Fuels and Materials for Advance Nuclear Reactors. A presentation in June on Comparison of 16 Reactors, Neutronic Performance in Closed Thorium-Uranium and Uranium-Plutonium cycles. And in July a presentation on the Overview of Small Modular Reactor Technology Development.

I am getting a little bit of a feedback from some of the participants that not all of the browser updates include the ability to see the questions pane but I believe there is a chat pane that should be available. So, if you don't see a question pane in your display when you open up the control panel with the orange rectangle and the white arrow, the best strategy for getting your questions answered I believe will be sending an email, and we will have to just follow up in that regard. We do have several questions that have been typed in.

Sam, if you could see the questions pane, the first one deals with GEN IV has 6 reactor concepts, where does the SMR fit in? With SMR, what is the hydrogen production strategy?

Sam Suppiah
SMR sort of basically uses some of these technologies covered in the GEN IV program. For example, Canada is looking at SMR technologies for demonstration at Chalk River in Canada. And some of these technologies that we are looking at are really a part of the GEN IV systems. So, as far as the hydrogen production is concerned, we would cover any work that's done with SMR that sort of uses some of these technologies, either the gas-cooled reactor technology, high temperature reactor technologies or even the low temperature, moderate temperature reactors like molten salt reactor systems. So, these will be covered as far as I am concerned on the hydrogen side on the Hydrogen PMB.

Berta Oates
Thank you. The next question reads, if money was unlimited, how fast could we switch to a synthetic liquid fuel economy for transportation? At

the current rate research funding and development, how long will it take to attain such a goal?

Sam Suppiah
Actually the synthetic fuel, in fact 38-39 years ago I was at British Gas Corporation, UK, and we were working on syngas production. So, the technology is there. I think it is the willingness to make it happen is the issue here. So I think if there is a lot of money and there is the will to do it, I think it can be done now. I don't see it as a major problem. But you have to remember that the synthetic fuel processes also produce to some extent greenhouse gases, and that you need to look after how to get rid of the greenhouse gas or to minimize greenhouse gas emissions. So, I think the technologies are there but it's just a matter of wanting to do it.

Berta Oates
Thank you. What is the expected lifetime cycle of SCOC [ph] cells or stack in a medium term?

Sam Suppiah
In the medium term, I think 5 to 10 years is what I have seen. Some of them are 3 years but I think 5 to 10 years is reasonable.

Berta Oates
Thank you. Ignoring hydrogen generation technical challenges, which reactor type is best suited to deliver the highest efficiency, HTGR?

Sam Suppiah
Yes, because the high temperature gas-cooled reactors can be integrated with the sulfur-iodine process or the high temperature steam electrolysis without any loss of efficiency due to sort of lower temperature operations. So, if you can operate, if your reactor can provide heat at a high temperature, at 800-900 degrees Celsius, then the hydrogen processes will produce hydrogen very efficiently. So I would say yes, high temperature gas-cooled reactors.

Berta Oates
Thank you. Two questions, does it exist a special work package for safety within the current project? And the other one is pure water is a scarce resource, what is the price order of magnitude for the desalination and purification of sea water for compliance with HTSE requirements.

Sam Suppiah
The safety, yes, actually our work package IV covers, I only said coupling, but I ignored. Unfortunately, there are a lot of safety aspects that are covered in the work package IV. So, various safety aspects related to coupling the hydrogen production to the nuclear reactor as well as

individual actually the hydrogen production safety issues themselves looked at.

Another item that is looked at is at very high temperature reactors you do have tritium related issues. Tritium is generated in the core of the reactor and aspects related to tritium, removal of it or basically sort of containing it within whatever the heat exchanger or within the core of the reactor etcetera, those aspects are also part of the work package IV. So yes, safety is considered as part of the work package IV. What was the second part of the question?

Berta Oates
It talks about pure water being a scarce resource. What is the price and the order of magnitude for desalinization and purification of sea water for compliance with the HTSE requirements?

Sam Suppiah
It's a good question, I'm not sure whether I have a good answer for that. Yes, water is important because you are splitting water to produce hydrogen and oxygen. So, in places where you don't have clean water, desalination is a process. Desalination itself is not cheap. It's expensive, and so that cost I don't think anybody has, at least we haven't in Canada, but I don't think others have looked at this in detail to see how the impact of that on the cost of hydrogen produced by high temperature steam electrolysis or any other process.

Berta Oates
Thank you. What would be the challenges on licensing the coupling NTT and hydrogen production?

Sam Suppiah
There will be challenges but I don't think they are insurmountable challenges. It is a chemical plant, so they are producing hydrogen and there are again as part of the Hydrogen PMB and also the various groups that are looking at hydrogen production are sort of looking at the coupling aspects, the challenges, the licensing aspects of it. Personally, I don't think it will be – I mean when it comes to nuclear reactors and doing anything to do with nuclear reactors, yes, there will be licensing challenges. But I think the problems are that great. It's just basically a matter of going through that process and how you place the hydrogen production process in relation to the nuclear reactor system. Those all will be part of licensing discussions going forward.

So personally I don't think it will be a major issue. And also, all countries and all nuclear reactor system people have come to the realization or appreciation that hydrogen production using nuclear is an incredibly clever idea and people will find ways of doing it, licensing such hydrogen production using nuclear reactors.

Berta Oates
Thank you. It seems that PMB now is looking at several different hydrogen production technologies. Do you think at some point the PMB would recommend to focus on just one very promising technology?

Sam Suppiah
Actually, this was discussed 10-15 years ago. Personally, I think all these different processes have merits under different reactor conditions, under countries that have various interests and things like that. So I would think that Hydrogen PMB, there is no real issue in focusing on any particular project. In fact there was a lot of focus on the sulfur-iodine process as part of the Hydrogen PMB. So there isn't really an issue with having these four different processes as part of the hydrogen PMB because there are different countries involved. In the past there was South Africa involved and now England is interested in joining, so these countries will have different interests, so I would think that we will continue. If anything, it might be a good idea to expand the hydrogen production process considerations as part of the Hydrogen PMB. The idea is that when you bring different processes, different groups, different countries to look at these things, there can be some synergistic activities. And that can really lead to advancements in these processes. So personally I think the plan is really not to focus on one process because we don't know which process at the end or how many processes in the end will be successful for industrial implementation.

Berta Oates
The next question reads, for example, Japan seems to be readying to transition to hydrogen-based vehicles. If, for example, 10 million vehicles for hydrogen power with an average of 15,000 kilometers per year, how much hydrogen would be needed? There might be more math than we can do verbally.

Sam Suppiah
I am reasonably good at math, but I am not that good.

Berta Oates
There's another question similar that compares the price of gasoline to the cost of hydrogen equivalent.

Sam Suppiah
Actually right now the cost of hydrogen is not that cheap. So I think it's something like $13-$14 per kilogram for hydrogen, if you want gas to fill hydrogen vehicle in places like California and all. But I think the issue here is that the cost of hydrogen is high right now, because it's not

produced in a large scale, and large scale does bring the cost down quite a bit. And as I pointed out, as the French analysis shows that you need to have large scale production of both the materials, components, and things to bring the cost of the hydrogen down. And I think it's happening quite fast. The cost will come down. And when that comes down, then it will be hydrogen cars, Japan can grow to a hydrogen economy basically for their transportation side. I don't know whether that answered the question.

Berta Oates
Thank you. What is the peak hydrogen production rate for the outline technologies in mass per unit time rather than volume per unit time?

Sam Suppiah
The plan, the thinking is that you want to be able to produce, mass production at the rate that the SMRs, Steam Methane Reformers produce hydrogen at. So, 100 tons per day is not out of the realm to produce hydrogen in large scale. So 100 tons per day. I think the hydrogen plant that is being built in the US right now, I've just forgotten the name of the company that's building. And they are talking about 400 tons per day hydrogen. And these large-scale processes, like the copper-chlorine cycle or the sulfur-iodine process or even the high-temperature steam electrolysis, you have to look at that kind of 100 tons per day kind of range.

Berta Oates
Are there any ISO TC dedicated to topics discussed today or is it purely an R&D maturity level?

Sam Suppiah
No, there are ISO technical committees involved in the hydrogen production area in Canada, and also in the US I am sure. There are a lots of things going on right now. Safety aspects, some of my colleagues are involved with the safety aspects of hydrogen applications and also on the production side.

Berta Oates
You've kind of touched on this before but there's a little bit of a follow-up. Early on with the VHTR and the hydrogen production plant collocating, proximity locating in terms of safety was a concern. Has any progress been made on this from a regulatory perspective? Is collocating still the current thinking?

Sam Suppiah
I think collocating is still the thinking. I should say that we haven't really done a whole lot of – I mean, a lot of discussions as part of the PMB or in general has been collocating these hydrogen production processes.

Locating at a faraway location, the hydrogen plant, has its advantages as well as disadvantages. You have the transportation, the piping of hydrogen to the site, and things like that, the heat to the hydrogen production process. There's lot of losses and things involved. Right now the thinking is sort of collocating it, and I don't think I've been involved with that much discussion on sort of separating it completely away or putting the hydrogen plant completely away from the nuclear plant.

Berta Oates
Thank you. What is your best estimate of deployment date for commercial based…

Sam Suppiah
I am partial here, but when we demonstrate the copper-chlorine cycle, next year…

Berta Oates
I'm sorry, for commercial nuclear based production.

Sam Suppiah
Oh, commercial nuclear based, so that I think is at least 10 years down the road.

Berta Oates
Will nuclear-based hydrogen production be able to compete with REN coupled to low temperature electrolysis?

Sam Suppiah
Like what I said, and if I understand the question right, the high temperature electrolysis has a distinct advantage in terms of efficiency. Because it is operated at high temperature, there are very major efficiency improvements can be achieved. So, it definitely can compete. It will be a better process. It will produce hydrogen. If the capital cost aspects are all sorted out, it will produce hydrogen at lower cost.

Berta Oates
Thank you. What do you expect in the future regarding the cost of hydrogen when comparing electrochemical, and thermochemical water splitting? That might be something you've touched a little bit on before too.

Sam Suppiah
So it's electro-chemical and thermochemical. Actually, some of the cost estimates for the thermochemical processes, including the Canadian copper-chlorine cycle, they are all in the same ballpark. They are high temperature steam electrolysis as well as the thermochemcial processes, hybrid in our case. In Canada's case it's hybrid thermochemical

processes. I think they are in the same ballpark. And one good thing about these thermochemical processes is that the scale can have a significant merit, advantage for the cost of the hydrogen produced. So, you can really produce very large-scale hydrogen using the thermochemcial processes.

Berta Oates
What are the limitations and drawbacks of methane-based technologies? I think it's steam methane reforming partial oxidation etcetera versus the copper-chlorine cycle technology.

Sam Suppiah
The main disadvantage of the steam methane reforming is that the amount of CO2 that it would send – I mean the whole idea right now is that we want to develop a process that is more environmentally friendly. The steam methane reforming process, as I had mentioned in my presentation, so every ton of hydrogen produced puts something like 10 tons of CO2 into the atmosphere. So basically it comes down to the environmental issues really.

Berta Oates
Can you share your opinion maybe about which country maybe taking the lead in hydrogen production with VHTR?

Sam Suppiah
With VHTR, I would say China is very active in hydrogen production using one of the processes that I have discussed. They are quite aggressive in their development. They already have the HTR10 process, the HTR10 nuclear system. It's a small system, but they've got the larger one, the HTR DM or something. Anyway, so they have the largest system under construction, and China has their plan to couple the HTR10 to hydrogen production process. I think probably China will be the first one to do this I would think.

Berta Oates
Alright thanks. Just a follow up on one of the questions that you'd answered a couple of questions ago, a simple statement of REN as renewable energy. For industrial or even the JAEA demonstration, many sensors and a good INC [ph] process control system is needed. What work has been done in intelligent control systems?

Sam Suppiah
It's again, another good question. From the involvement in the Hydrogen PMB, we haven't really focused a lot on this aspect. I think it is needed because if you take the processes, they are complex processes. Perhaps the high temperature steam electrolysis is less complex but the other processes are complex, so you would need to consider this. So far we

haven't really spent a lot of effort on this. It's been mainly the process development and getting the process to work, to look at the materials related issues and things like that. It is something to look at as part of the future program.

Berta Oates
Someone has pointed out that the handouts didn't download or open for them. So if you click on them they should download and open, and if they don't, I apologize. I'm not sure why that is. But I have posted a link that the PDF version of today's slide deck is posted and available at that link right now, so you can go there to get the slide deck. And then again, today's presentation is being recorded and we will upload the audio video portion as soon as it's done rendering, if you just give us a little bit of time to do that. Thank you for pointing that out.

Light-water reactor technology is mature, commercial technology. Would coupling LTE production plant to an LWR provide for a useful demonstration for a nuclear hydrogen production concept?

Sam Suppiah
Definitely, yes, in fact any of the reactor systems right now available can be integrated with some of these technologies, the hydrogen production technologies. And so again, it's really the will to do this and it will demonstrate the integration of the nuclear system to hydrogen production process. So current reactor systems can be integrated with these processes. Of course, there will be a little bit of a loss in the overall efficiency of the production of hydrogen, but it can be done now.

Berta Oates
What about environmental friendliness of coupling steam methane reforming in HTGR as in energy source?

Sam Suppiah
I think I did point out. There is clear assessment of this coupling steam methane reforming to high temperature reactor. Korea has done quite a bit of work, and in fact some of the other countries have also done this work. And we also, in Canada we have interest in doing it and we have touched on it. So, when you use the high temperature reactor, all what you are doing is replacing some of the methane used to produce the heat in the steam methane reformer with nuclear heat. So, it definitely reduces the CO2 emissions, quite significantly. And there are numbers, unfortunately, I can't remember the numbers right now but there are clear numbers calculated, evaluated for this coupling.

Berta Oates
Great thank you. Thank you so much again Sam for sharing your expertise and taking the time to put your presentation together. Thanks

everyone else for attending. We had a great attendance today. Those are the list of questions that have been submitted. We've gone about 90 minutes. So if there are no further questions, I will bid everyone safe and farewell.

Sam Suppiah
Thank you Berta for your help and thanks to everybody who was listening and I hope there's some extra support for hydrogen production using nuclear power.

Patricia Paviet
Thank you again Sam that was a great, great presentation.

Sam Suppiah
Patricia thank you.

Patricia Paviet
Okay goodbye everybody.

Sam Suppiah
Bye-bye.

END