STATUS OF ONGOING RESEARCH AND RESULTS: HYDROGEN PRODUCTION PROJECT FOR THE VERY HIGH TEMPERATURE REACTOR SYSTEM

C. Sink(1), N. Sakaba(2), P. Yvon(3), Y.J. Shin(4), M.T. Dominguez(5) and S. Suppiah(6)

(1) Carl Sink– U.S. Department of Energy (*carl.sink@nuclear.energy.gov*)
(2) Nariaki Sakaba – Japan Atomic Energy Agency (*sakaba.nariaki@jaea.go.jp*)
(3) Pascal Yvon – Commissariat à l'énergie atomique (*pascal.yvon@cea.fr*)
(4) Young-Joon Shin – Korea Atomic Energy Research Institute (*nyjshin@kaeri.re.kr*)
(5) Maria Teresa Dominguez – Empresarios Agrupados (*mdb@empre.es*)
(6) Sam Suppiah – Atomic Energy of Canada Limited (*suppiahs@aecl.ca*)

I. INTRODUCTION

High temperature processes for large-scale production of hydrogen are being investigated as potential uses of process heat from the Very High-Temperature Reactor (VHTR) system. Hydrogen currently has a large market worldwide for fertilizer production and in crude oil refining. Future applications for hydrogen are seen in increasing use of fuel cells, in production of alternative liquid fuels, and in production of chemicals. Additional benefits of hydrogen production from nuclear energy include higher efficiency and reduced green-house gas emissions than the currently predominant production methods.

The VHTR Hydrogen Production Project is beginning to compile the results obtained to date and provided to the project by the member countries. Working groups of technical experts are being organized to focus cooperative efforts on specific topics. Areas of cooperation include: developing and optimizing the thermo-chemical water splitting processes of the sulphur family, giving priority to the sulphur-iodine (S-I) cycle; advancing the high-temperature electrolysis process; evaluating alternative thermo-chemical hydrogen-generation processes (including processes amenable to operation with other Generation IV reactor systems); and defining and validating technologies for coupling reactors to process plants. Progress in these areas will be described in this paper.

II. DEVELOPMENT OF THE SULPHUR-IODINE (S-I) CYCLE

This portion of the project focuses on the evaluation of the Sulphur-Iodine (S-I) thermo-chemical cycle for H_2 production, which is one of the potential processes for large-scale deployment and coupling with the nuclear VHTR. The S-I process has been chosen as a reference amongst the multiplicity of alternate thermo-chemical cycles because it exhibits the best prospect regarding efficiency. The S-I process is illustrated in Figure 1. Acquisition of reliable thermodynamic data for the three basic reactions of the S-I thermo-chemical process is essential to assessing its potential for hydrogen production, as well as to determining operating parameters and estimating the cost of hydrogen production. In the S-I cycle, iodine and sulphur dioxide are added to water in an exothermic reaction that creates sulphuric acid and hydrogen iodide. The sulphuric acid can be decomposed at about 850°C, releasing oxygen and recycling sulphur dioxide. The hydrogen iodide (HI) can be decomposed at about 450°C, releasing hydrogen and recycling iodine.

(1)	$2H_2O + SO_2 + I_2 \rightarrow 2HI + H_2SO_4$	100°C	(exothermic)
(2)	$H2SO4 \rightarrow SO2 + H2O + ½O2$	850–900°C	(endothermic)
(3)	$2HI \rightarrow I2 + H2$	400–500°C	(endothermic)

$H_2O \rightarrow H_2 + ½O_2$

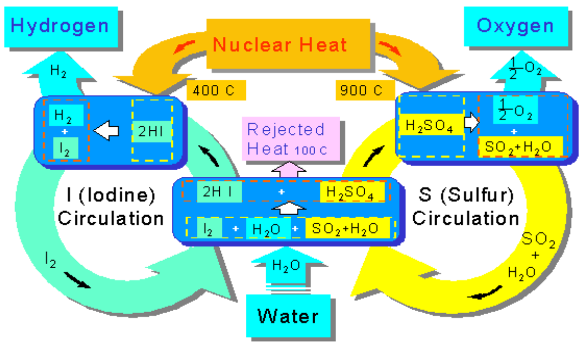

Figure 1: Sulphur-Iodine process

Several members are providing flow sheet analyses of the S-I cycle. These analyses are planned to be synthesized into a combined overview of the state of the art by the end of 2010. Benchmark exercises on a reference flow sheet are also planned to be performed. Several members are providing results of materials screening which has been performed via coupon tests and autoclave tests in environments simulating the different sections of the S-I process. Other materials screening and development activities involve membranes and adsorbents for separations, and catalysts for SO_3 and HI decomposition.

Interested members have progressed to performance of component and closed-circuit bench-scale experiments at full temperature, pressure, and flux rates to define and evaluate key parameters such as thermodynamic properties, rate constants. These activities are expected to be conducted over the next couple of years by various members to obtain additional experience with scaling up the process and constructing components with engineering materials. For future planning, interest has been expressed in international collaboration on pilot-scale plant construction and performance tests to confirm scaling parameters and materials performance.

III. DEVELOPMENT OF HIGH-TEMPERATURE ELECTROLYSIS (HTE) PROCESS

High temperature electrolysis (HTE) is one of the promising methods of producing hydrogen from nuclear energy. The technology and materials for a high temperature electrolytic cell is similar to that being developed for the solid oxide fuel cell program. The solid oxide electrolytic cell (SOEC) as being developed in current programs requires temperature in the range of 750 to 900°C for optimum efficiency. The energy content in the high temperature steam reduces the electrical energy requirement for the electrolysis, resulting in an overall efficiency improvement over conventional electrolysis. The HTE R&D program will focus on the production of hydrogen from the VHTR, with a core outlet temperature in the range of 900 to 950°C. It is anticipated that future work will also include examination of techniques for extending the temperature range of the HTE hydrogen production methods to other Generation IV reactor systems. Since HTE splits water in a device very similar to a solid oxide fuel cell (SOFC), the results of several national programs for electricity production from fuel cells will be monitored to assure the progress in SOFC technology provides key developmental data for the HTE program.

The electrochemical reactions taking place in the solid oxide cell are shown in Figure 2. An inlet stream containing steam at 800-830°C, plus about 10% hydrogen to maintain reducing conditions, is introduced to one edge of the cell. The water molecules are dissociated at the electrode-electrolyte interface and the oxygen is transported as $O^=$ ions through the electrolyte. A mixture containing about 90% hydrogen and the residual steam exits from the opposite edge of the cell. Oxygen molecules are formed at the electrolyte-anode interface and exits from the cell through flow fields adjacent to the anode. In reality, the oxygen flow fields are perpendicular to the place of the diagram, such that the oxygen and hydrogen are flowing are right angles to one another.

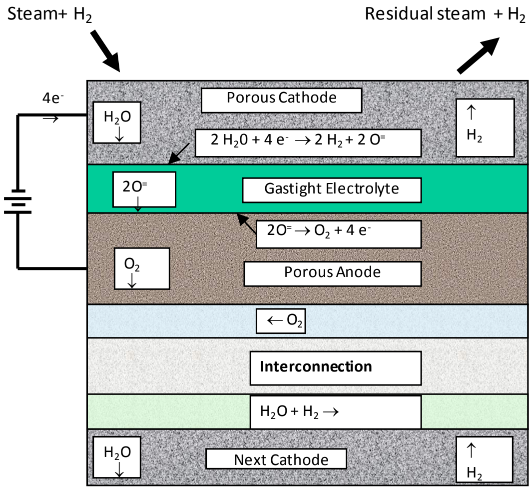

Figure 2: HTE processes in a High Temperature Solid Oxide Electroysis Cell.

Modeling activities for the HTE process have included optimizing system design for various plant configurations, examination of cogeneration options, and analyses of performance of cell configurations. Tests of button cells and small stacks of "standard" cells were conducted to investigate performance and longevity issues. In 2008 a HTE integrated laboratory-scale experiment was operated at 15 kWe with an initial hydrogen production rate of over 5000 liters per hour. However, over a two month period of operation the electrolyzer performance degraded significantly. Current efforts are focused on identifying the causes of cell degradation and performing tests of small stacks of cells. Three members are actively pursuing advancements in electrode materials, cell interconnect technologies, leak management solutions, and optimized operating conditions.

IV. ASSESSMENT OF ALTERNATIVE CYCLES AND ECONOMIC EVALUATION

Of the hundreds of methods for producing hydrogen that are available, only the S-I thermo-chemical cycle and high temperature electrolysis were agreed upon for initial collaborations under this project. Knowing that there was interest in various countries in other cycles, a work package was established to encompass technical evaluation of potential alternative cycles. Many cycles have been evaluated by several member countries with reference to S–I and HTE regarding methodology, feasibility and process efficiency and economics. Two of the cycles which have generated a great deal of international interest have been the Hybrid Copper-Chloride (Cu-Cl) cycle and the Hybrid Sulphur (HyS) cycle. Other cycles are being pursued as well to a lesser degree. Additionally, tasks involving economic evaluation of the various hydrogen production processes coupled to nuclear reactors are being performed.

Preliminary process development is proceeding for cycles of interest. In the case of HyS, there is a proposal to create a separate work package to focus additional R&D on that cycle.

V. COUPLING OF REACTORS AND ANY HYDROGEN PRODUCTION PROCESS

The final area of collaboration being pursued under this project regards analysis of the issues encountered when coupling hydrogen production processes to a nuclear reactor. Factors being considered are design-associated risk analysis, safety (including tritium abatement), and system integration. Performance calculations for interactions between the reactor and hydrogen plants are being evaluated in steady state to be followed by dynamic simulations. Work is beginning on coupling component technologies, such as process heat exchangers, high-temperature isolation valves, hot fluid ducting, and a thermal load absorber.

Figure 3 depicts a notional schematic of a VHTR, heat transfer loops, and coupling to the thermo-chemical and/or high-temperature electro-lysis plants.

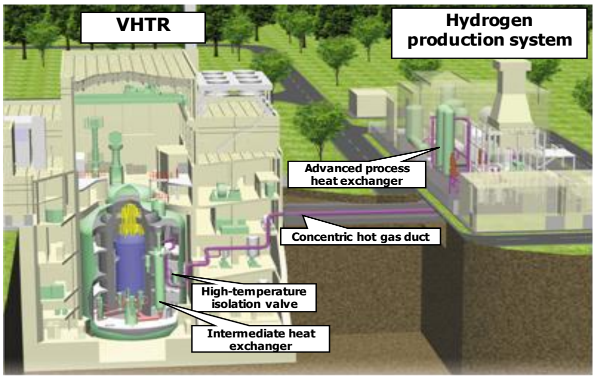

Figure 3: Artist's description of a hydrogen-production unit coupled to a very high-temperature reactor.

IV. CONCLUSION

Since the signing of the project plan in mid-2007, the VHTR Hydrogen Production Project members have been working to assemble and catalog their contributions of data which was generated prior to the formalization of the multilateral agreement. This process is anticipated to be complete in the spring of 2009. At the same time, the formal process for contributing deliverable reports for work completed within the scope of the project during 2008 and 2009 is being exercised in accordance with the GIF guidelines. Once these technical reports have been made available to the entire project members, plans call for workshops to draw summary conclusions and plan additional tasks to move the research forward or fill in gaps in the data as needed.

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