II.G.4 Nuclear Reactor/Hydrogen Process Interface

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General Atomics, La Jolla, California
University of California Berkeley, Berkeley, California
Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts
Ceramatec, Inc., Salt Lake City, Utah

Start Date: January 2004
Projected End Date: Project continuation and direction determined annually by DOE

Objectives

- Assist DOE in the development of a high-temperature (800-950°C) heat transfer network to enable the linkage of a high-temperature nuclear reactor (high-temperature heat source) to a nuclear hydrogen production plant (high-temperature heat sink).
- Support development of thermochemical/electrochemical hydrogen plant ancillary systems at needed scales (laboratory, pilot, engineering-scale).

Technical Barriers

In general, this work addresses specific technical issues associated with the centralized large-scale production of hydrogen using a nuclear power source (alternative energy source). This work contributes to an effort to produce hydrogen by water splitting without producing greenhouse gas emissions at a lower cost than standard water electrolysis. The specific technical barriers that must be overcome are the following:

- High-temperature materials identification, selection and qualification
- High-temperature heat exchanger design
- Effective/efficient coupling method for linking a high-temperature heat source with a thermochemical hydrogen production process

Technical Targets

This work is part of the overall DOE Nuclear Hydrogen Initiative (NHI). While this work does not address specific technical targets listed in the HFCIT Multi-Year RD&D Plan, the overall goal of the DOE Nuclear Hydrogen Initiative is to develop and demonstrate the technologies to enable the nuclear powered production of hydrogen from water splitting. An engineering-scale plant (50 MW to 600 MW) is scheduled for start-up in 2019, which, if successful, may lead to the large-scale commercial production of hydrogen at a cost less than standard water electrolysis sometime in the 2020-2030 timeframe (less than $2.75/gge, the 2015 water electrolysis production target).

Accomplishments

- Mechanical properties of select high-temperature alloys (Hastelloy C-22, C-276, Inconel 617, Incolloy 800H, Waspalloy) were measured to fill in gaps in the literature. Alloys 617 and 800H were found to be most suitable above 800°C but should not be used above 900°C for pressure containment.
- Stress corrosion cracking behavior of high-temperature alloys was examined in the presence of H_2SO_4/NaI solutions. Hastelloy C-276 was determined to be the best choice for this application below 300°C.
- New alloy materials were developed (Inconel 617 + 1% Pt, Incolloy 800H + 1% Pt) in an attempt to combine heat exchanger and SO_3 decomposition functions for the sulfur-iodine (S-I) thermochemical process.
- Ceramic materials were selected for further heat exchanger development work (SiC, Si_3N_4, SiAlON, Al_2O_3, C/SiC composites). So far, testing of SiC has shown that it maintains high strength at required temperatures and is very corrosion-resistant to sulfuric acid attack at operational temperatures.
- Manufacturing techniques for compact C/SiC heat exchanger plates are being developed.
- Extensive corrosion testing of materials exposed to $HI\text{-}I_2\text{-}H_2O$ solutions at 300-400°C has been performed, and corrosion-resistant alloys have been identified (Ta-2.5W, Ta-10Nb, some Cu-Ni alloys). Ag has been shown to resist concentrated (95+%) phosphoric acid.
- Computational fluid dynamics modeling work is being performed on compact micro-channel heat exchangers.

- Laboratory testing of simulated micro-channel heat exchanger plates has begun in order to validate heat exchanger models and improve model accuracy.
- Integrated nuclear plant/hydrogen plant models are under development that will incorporate steady-state and transient system behaviors and responses.
- Risk-based and defense-in-depth safety analyses are being performed in order to optimize the trade-offs between system performance and system safety. Initial studies show that a minimum spacing of 60-110 meters must exist between the hydrogen plant and the nuclear plant.

Introduction

The nuclear reactor/hydrogen plant interface is the intermediate heat transport loop that will connect a very-high-temperature gas-cooled nuclear reactor (VHTR) to a thermochemical, high-temperature electrolysis, or hybrid hydrogen production plant. The combined nuclear/chemical plant concept is known as the Next Generation Nuclear Plant (NGNP). The nuclear reactor/hydrogen plant interface is responsible for transporting high-temperature thermal energy from the nuclear reactor to the hydrogen plant while protecting the nuclear plant from operational disturbances at the hydrogen plant. Development of the interface is occurring under the DOE Nuclear Hydrogen Initiative and involves the study and design of high-temperature heat exchangers, heat transport systems, materials, and safety and energy optimization studies. Research and development work on the system interface began in 2004 and is expected to continue at least until construction of an engineering-scale demonstration plant for the NGNP is begun. An engineering-scale demonstration of the NGNP is currently scheduled to begin operation in 2019.

Approach

Initially, parallel research paths are being pursued on materials, heat exchanger designs, system modeling, and safety. Information gathered along these parallel paths is being integrated to build more accurate system models, address immediate safety concerns, and design prototype equipment. Prototype equipment will be tested under simulated and representative chemical environments to assess functionality and durability and to improve system models still further. At the pilot scale, an operating system interface will be assembled and operated using an electrical or fossil fuel heat source in order to gather systematic operational data. Once pilot-scale testing is significantly accomplished, a full engineering-scale system interface will be constructed and operated as part of the NGNP.

Results

Materials are the first area of research. In the shorter term, metals will be used for system piping, seals, valves, and most heat exchanger components.
In the longer term, ceramic materials may be substituted in specific applications because of ceramics' greater strength and creep resistance at the temperatures of interest (800-950ºC). Immediate use of ceramic materials for some applications isn't yet possible due to the less developed state of ceramic component manufacturing techniques in comparison to metals. Refinement of ceramic-metal sealing technologies may be needed in some cases, and this will also increase the time it takes to incorporate ceramics into designs.

So far, the mechanical properties of select commercially available high-temperature metal alloys have been measured (Hastelloy C-22, C-276, Inconel 617, Incolloy 800H, and Waspalloy), and it has been determined that only Alloys 617 and 800H in the above list would be suitable for system interface applications above 800ºC (UNLV). (See Figure 1 for an example of the type of data collected.) Other alloys may offer superior creep resistance at this temperature range (e.g., oxide dispersion solution alloys), but these have not been emphasized in testing due to their relative newness on the market. Alternative versions of Alloys 617 and 800H containing 1% Pt have been developed that combine the superior structural strength of the base alloys with the ability to catalyze the sulfuric acid decomposition reaction needed by the S-I thermochemical method (MIT). Catalytic effectiveness and stability testing of the new alloy materials is ongoing.

Ceramic materials have been examined in the literature and in the laboratory (Ceramatec). Literature studies and a study of equipment requirements yield a short list of suitable ceramic materials for system

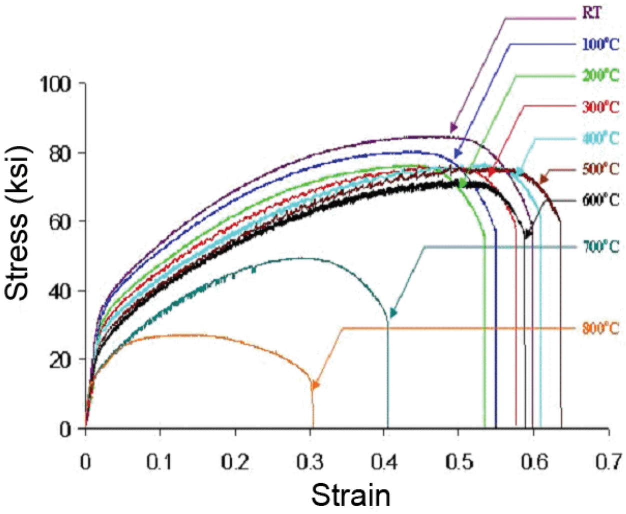

FIGURE 1. Stress-Strain Measurements of Alloy 800H up to 800ºC

interface applications: SiC, C/SiC composites, Si_3N_4, SiAlON, and Al_2O_3. Environmental testing of SiC exposed to sulfuric acid vapor at 800°C for extended time periods showed that the material increases in strength relative to the unexposed material due to the formation of a protective layer of SiO_2 on the surface of the SiC which acts to strengthen surface imperfections and cracks. Work is underway to develop cheaper methods for manufacturing C/SiC heat exchanger plates using Teflon molds University of California, Berkeley.

Corrosion testing of nickel alloys, refractory metals, and refractory alloys in H_2O-I_2-HI solutions at 300-350°C was performed (General Atomics). The H_2O-I_2-HI solutions, also known as “HIx”, are found in one of the sections of the S-I thermochemical process and are known to be more corrosive than sulfuric acid vapor at 800°C. Long-term testing has shown that Ta-2.5W, Ta-10Nb, and some Cu-Ni alloys are able to resist corrosion in this chemical environment for longer than 1500 hours with no measurable weight changes. In one part of the process, concentrated phosphoric acid (>95%) must be used, and silver metal has been determined to be appropriate for this application.

Heat exchanger design and modeling efforts are underway (UNLV, UC Berkeley, Ceramatec). Work is focused on the design of the two main heat exchangers – the input heat exchanger (intermediate heat exchanger) and the output heat exchanger (process heat exchanger). While there may be more than one heat exchanger involved in the interface, in its simplest form only two heat exchangers are needed. Finite element analysis and thermal-hydraulic calculations are being performed on compact heat exchanger designs offered by Heatric, Ceramatec, and the University of California, Berkeley to study thermal/mechanical stresses and material flows. Figure 2 shows an example of calculated temperature distributions in simulated heat exchanger channels. Experimental testing of compact heat exchanger plates is beginning at UNLV and Ceramatec. Air and water are being used under similar fluid flow conditions (similar Re, Pr, etc.) to measure location-specific pressures and overall pressure drop. Figure 3 shows a test in which local pressures are being measured as a function of fluid flow rate.

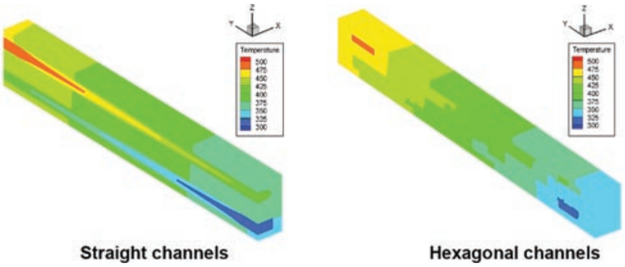

FIGURE 2. Calculated Temperature Distributions in Micro-Channel H_2SO_4 Decomposer

Global, steady-state system models are being developed under a DOE International Nuclear Energy Research Initiative (I-NERI) agreement among INL, Argonne National Laboratory and the Korea Atomic Energy Research Institute. The global models will use existing established codes (GAS-PASS/H, HYSYS flowsheets, others) to calculate the energy and mass balances in the nuclear and non-nuclear portions of the system, and integrate the results using a common framework. The framework software will be controlled through a graphical user interface. At present, the integrated model includes a detailed description of a high-temperature electrolysis plant. A simplified representation of the S-I plant is also available, and increasingly complex and accurate versions of the S-I flow sheet will be incorporated as more process data becomes available. An alpha version of the integrated code will be ready for testing by the end of this fiscal year. Transient behaviors will be identified and incorporated into the models in the coming year. The combined model will be used to study differing configurations of power plant conversion units; interface designs; and variations in hydrogen plant size, configuration, and operational set points.

Initial safety studies have been performed to determine the minimal plant spacing between the nuclear plant and the hydrogen production plant (INL). From an operational standpoint, distance needs to be minimized to reduce heat losses and capital costs of the system interface. Safety considerations provide an opposite motivation to extend the system interface to provide maximum protection for the nuclear plant. Based on statistical and risk-based approaches, the minimal distance has initially been identified to fall within 60-110 meters. The addition of defense-in-depth features such as an earthen mound (see Figure 4), placing the nuclear reactor below ground, and incorporating blast panels near the hydrogen plant may help reduce the minimum distance. Further analyses of the minimum distance and quantification of safety features will continue, and further changes to this minimum distance are expected to occur. Licensing requirements of the nuclear plant will have an influence on plant spacing, and it is possible that the actual

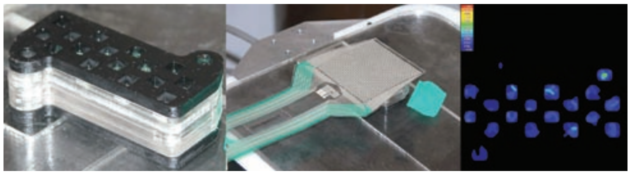

FIGURE 3. Pressure/Flow Measurement Experiment with Example Ceramic Heat Exchanger Plate

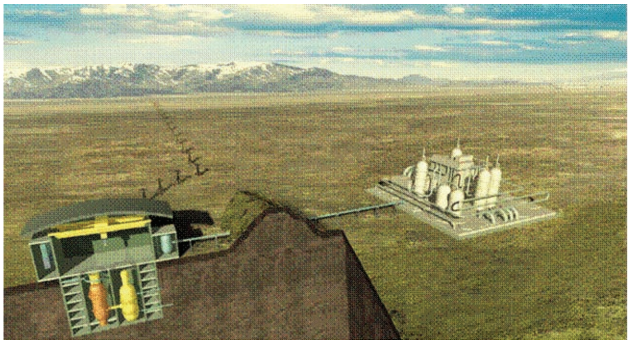

FIGURE 4. Placement of Earthen Mound between Plants Reduces Required Spacing Distance

plant spacing needed may be greater than the technical minimum.

An I-NERI agreement is in place between the INL and Commissariat à l'Energie Atomique (French Atomic Energy Agency) to allow for the exchange of technical information relating to nuclear reactor/hydrogen plant interface development.

Conclusions and Future Directions

In conclusion, some high-temperature alloys, ceramics, and refractory metal alloys have been identified as candidates for use in heat exchangers and hydrogen plant equipment as related to the nuclear plant/hydrogen plant interface. Heat exchanger design work is underway, and initial concepts are beginning to undergo testing in the laboratory. The scope of work for heat exchanger analyses will be expanded to look at packed-bed tubular reactors and other specific equipment configurations outside of the compact heat exchanger type. Global system models are being constructed, and overall safety assessments of the combined nuclear plant/hydrogen plant are being performed to understand the relationships between system safety and function, and the influence of these factors on the physical configuration of the nuclear reactor/hydrogen plant interface. International agreements are in place to take advantage of work being performed in other nations on this subject.

Though the work in this area is diverse, some high-level milestones have been established for future years. These milestones are as follows:

- Issue DOE NHI Materials and Components Test Plan, 2007.
- Initiate laboratory-scale testing of key interface components in representative chemical environments, 2008.
- Complete development of global system model that includes transient behaviors, 2008.
- Choose heat transfer fluid (either helium or liquid salt) for the pilot-scale testing of the interface, 2009.
- Provide all necessary documentation to support selection of pilot-scale demonstration processes, 2011.

FY 2006 Publications/Presentations

1. S.R. Sherman, "Technical Barriers and Opportunities in Nuclear Plant/Hydrogen Plant Connection Technologies", Presentation #182f, AIChE 2006 Spring National Meeting.

2. C. Oh, R. Barner, C. Davis, S. Sherman, "Thermal Hydraulic Analyses for Coupling High-temperature Gas-Cooled Reactor to Hydrogen Plant", Idaho National Laboratory, accepted for presentation at 13th International Heat Transfer Conference, Sydney, Australia, August 13-18, 2006.

3. A. Hechanova, "High-temperature Heat Exchanger Annual Report", University of Nevada Las Vegas, October 2005. Available at http://nstg.nevada.edu/heatexchangers.html. Contains complete references of for the UNLV-related work (UNLV, UC-Berkeley, General Atomics, Ceramatec). Quarterly reports are also available on the web site.