II.J.10 Nuclear Reactor/Hydrogen Process Interface Including the HyPEP Model

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Subcontractors:

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- General Atomics, La Jolla, CA
- University of California – Berkeley, Berkeley, CA
- Massachusetts Institute of Technology, Cambridge, MA
- Ceramatec, Inc., Salt Lake City, UT

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

Objectives

- Guide the development of technologies to enable the connection of a Very High Temperature Gas-Cooled [nuclear] Reactor (VHTR) to a high-temperature hydrogen production plant.
- Resolve technical issues and challenges offered by the DOE Nuclear Hydrogen Initiative (NHI) and Next Generation Nuclear Plant (NGNP) Project in regard to nuclear connection design, construction, operation, safety, economics, and nuclear plant licensing.
- Work closely with the NHI Thermochemical and High-Temperature Electrolysis areas to define and test components and systems.

Technical Barriers

In general, this work addresses specific issues associated with the centralized large-scale production of hydrogen using a nuclear power source (alternative energy source). This work contributes to the 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 resolved 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 or high-temperature electrochemical hydrogen production process.

Technical Targets

This work is part of the overall DOE Nuclear Hydrogen Initiative. 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 hydrogen production plant (50-65 MW) is scheduled for initial operations by the 2018-2021 time frame, which, if successful, may lead to large-scale commercial production of hydrogen at a cost less than standard water electrolysis. The targeted cost of hydrogen to be produced using nuclear energy is less than $2.75/gge in 2005 dollars, the 2015 water electrolysis production target.

Accomplishments

- Mechanical properties of select high-temperature alloys up to 1,000ºC were measured (Hastelloy C-22, C-276, Inconel 617, Incolloy 800H, Waspaloy) to fill in gaps in the literature data. A down-select to study further the mechanical properties and creep-fatigue behaviors of Inconel 617 and Haynes 230, an alloy with very similar mechanical properties to Inconel 617, is forthcoming.
- Corrosion testing of metals exposed to hydrogen iodide (HI), I_2, and water was continued from the previous year, and some conclusions were drawn from the testing. Hastelloys B and C are suitable for vapor phase exposure to HI and steam, while Ta, Ta-2.5W, and Ta-10W must be used for liquid solutions of $HI/I_2/H_2O$, the so-called “HIx” solution formed in the General Atomics Sulfur-Iodine process.
- Corrosion testing of ceramic materials exposed to H_2SO_4, SO_2, and water vapor at 800ºC showed that SiC, Si_3N_4, and Al_2O_3 all have excellent corrosion resistance to these chemicals.

- Exposure of metallic samples to FLiNaK molten salt at 800°C showed that nickel-coated Incoloy 800H and pure nickel resisted corrosion.
- Multiple heat exchanger designs for a high-temperature sulfuric acid decomposer were analyzed using thermal-hydraulics codes and finite element analysis including the Sandia Bayonet design, the Ceramatec ceramic compact decomposer design, and a traditional tubular reactor design. The calculations did not uncover any obvious problems with these designs and point to the need for better catalyst and chemical kinetics data.
- Integrated nuclear plant/hydrogen plant models were developed using HYSYS, GAS-PAS/H, and new model called HyPEP (Hydrogen Process Efficiency calculation Program). HyPEP is being developed as a joint project between the Idaho National Laboratory (INL) and the Korea Atomic Energy Research Institute (KAERI) and will allow for rapid comparison of differing configurations of nuclear/hydrogen plants.
- A technical readiness evaluation system was developed to evaluate the technical maturity of components and systems being developed or tested for use in nuclear hydrogen production.
- The nuclear connection research area has been re-organized to better coordinate the work that is occurring at the University of Nevada, Las Vegas and with the DOE companion program, the Next Generation Nuclear Plant Project.

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Introduction

The Nuclear Reactor/Hydrogen Plant interface is the intermediate heat transport loop that will connect a VHTR to a thermochemical, high-temperature electrolysis, or hybrid hydrogen production plant. A prototype plant called the NGNP is planned for construction and operation at the Idaho National Laboratory in the 2018-2021 timeframe, and will involve a VHTR, a high-temperature interface, and a hydrogen production plant. The interface is responsible for transporting high-temperature thermal energy from the nuclear reactor to the hydrogen production plant while protecting the nuclear plant from operational disturbances at the hydrogen plant. Development of the interface is occurring under the DOE NHI and involves the study, design, and development of high-temperature heat exchangers, heat transport systems, materials, safety, and integrated system models. Research and development work on the system interface began in 2004 and is expected to continue at least until the start of construction of an engineering-scale demonstration plant.

Approach

Initially, parallel research paths are being pursued on materials, heat exchanger designs, system modeling, safety, and codes and standards. 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 and stress environments to assess functionality, durability, and to adjust and validate system models. At the pilot-scale (1-5 MW), an operating system interface will be assembled and operated at actual system pressures using an electrical or fossil fuel heat source. After pilot-scale testing is accomplished, a full engineering-scale system interface loop (50-60 MW) will be constructed and integrated into the nuclear and hydrogen facilities. Research and development work will be monitored and controlled through the use of a new technical readiness evaluation system and a supporting NHI Components Database.

Results

Within the last year, continuing studies of the mechanical and creep properties of high-temperature metallic alloys were measured. The metals examined included C-22, C-276, Waspaloy, 800H, Inconel 718, and Inconel 617. These measurements showed that the measured yield strength, ultimate tensile strength, and failure stresses for C-22, C-276, 800H, and Waspaloy all fell precipitously above 600°C, and that the curves for these metals were indistinguishable above 800°C. Alloys 617 and 718 showed higher strength than the metals previously mentioned, but also became exceedingly weak above 900°C, such that the yield strengths were less than 25 MPa.

Continued corrosion studies of materials exposed to chemical mixtures found in the HI decomposition section of the Sulfur-Iodine thermochemical hydrogen production method helped define which materials would be suitable for this section of the process. For sections containing liquid $HI/I_2/H_2O$ solutions (HIx), Ta, Ta-2.5W, and Ta-10W were identified as being the most suitable with a corrosion rate of less than 1 mil per year in the range of 350-450°C (see Figure 1). In the dry vapor phase, Hastelloy B and C were found to work well in resisting corrosive attack.

Exposure of ceramic samples to sulfuric acid vapor mixtures at 800-900°C showed that SiC, Si_3N_4, and Al_2O_3 were best for this application. In fact, the mechanical properties of SiC improved slightly after exposure due to the formation of a thin surface layer of SiO_2, which helped fill in small surface defects. These

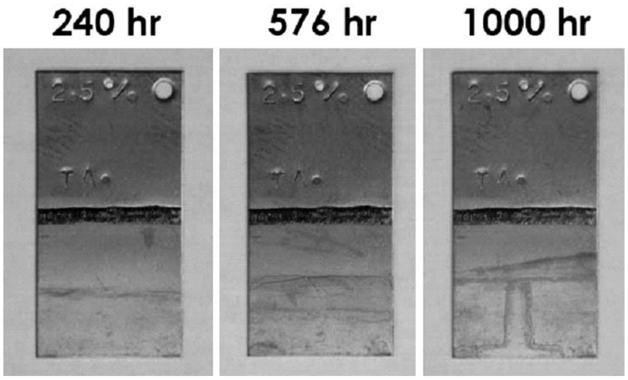

FIGURE 1. Ta-2.5W after Exposure to HIx Solutions at 400°C

materials will be examined further in the future for use in high-temperature heat exchangers.

Corrosion testing of metallic samples exposed to the molten salt FLiNaK showed that nickel-plated Alloy 800H and pure nickel worked best to resist attack by the salt over 500 hours. The principle method of corrosive attack was dissolution of the base material at the grain boundaries in most samples. Future studies will concentrate on the use of nickel coatings on high temperature alloys to combine corrosion resistance with high-temperature strength and creep resistance.

Sulfuric acid heat exchanger/decomposer designs were examined using finite element analysis techniques. Concepts of interest included the Sandia Bayonet sulfuric acid decomposer (see Figure 2), a more standard shell-and-tube catalyzed sulfuric acid decomposer, and the Ceramatec compact plate catalytic decomposer design. The studies indicate that all of the designs, at least in a model, can perform the sulfuric acid decomposition function, and that the differentiating factors will be found in the manufacturing processes and costs, and in the ability to maintain a functioning sulfuric acid decomposer in the laboratory.

Integrated models have been constructed of the combined nuclear plant/hydrogen plant. Two approaches have been used – steady-state simulations using HYSYS, a commercial chemical plant simulation package, and pseudo-steady-state modeling with a dynamic nuclear-based modeling package called GAS-PASS/H. The results of these models are then used to verify and validate the on-going work on HyPEP. HyPEP is a steady-state modeling package that is being developed under a joint project between Argonne National Laboratory, Idaho National Laboratory, and the Korea Atomic Energy Research Institute. The models have been used to study the differences in the nuclear connection configurations and to understand how changes in the nuclear connection conditions (e.g., direct versus indirect power conversion cycle, heat transfer fluid selection, etc.) affect the functionality and projected energy efficiencies of the overall plant configuration. Results indicate that overall energy efficiencies in the range of 41-47% are achievable in a number of ways, with the best results obtained by using a supercritical CO_2 power conversion cycle and the use of a molten salt for the long-distance heat transfer loop to the hydrogen plant as opposed to using high-pressure helium as the heat transfer fluid.

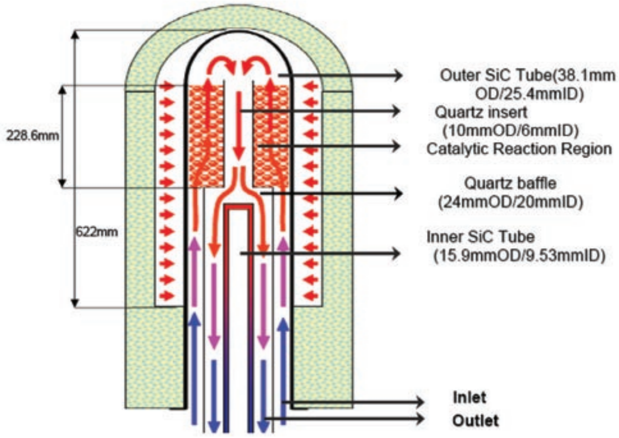

FIGURE 2. Schematic of Sandia Bayonet H_2SO_4 Decomposer

A component technical readiness level evaluation system was developed to characterize the relative technical maturity of the components that are being developed for nuclear hydrogen production plants (see Figure 3). The technical readiness evaluation system will be implemented in FY 2008 and will be supported by a Component Case File database. The Component Case File database will be used to store the supporting documentation for the development of the component and the evaluation documents, and may be used to support future intellectual property applications.

The Nuclear Connection area under the DOE Nuclear Hydrogen Initiative is becoming more coordinated with its university partners and a closely related nuclear project, the Next Generation Nuclear Plant Project. Associate technical directors were named at the University of Nevada, Las Vegas to help coordinate the high-temperature heat exchanger research and to provide additional technical expertise in the field. The NGNP Project is responsible for the design and construction of the high-temperature nuclear reactor and related systems that would supply the high-temperature heat to the nuclear hydrogen production processes. The NGNP Project and the DOE Nuclear Hydrogen Initiative are physically joined at the nuclear connection, and so research in the area of high-temperature heat exchangers and related technologies has significant impact on both programs. Research tasks in the coming year will be shared with the Next Generation Nuclear Plant Project.

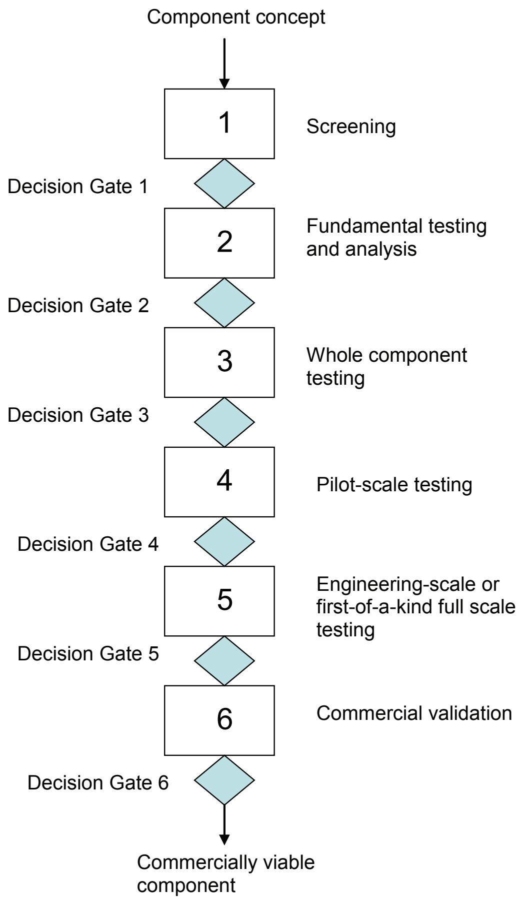

FIGURE 3. DOE NHI Component Technical Readiness Levels

Conclusions and Future Directions

Some high temperature alloys, ceramics, and refractory metal alloys have been identified as candidates for use in heat exchangers and other components that may be used in the nuclear plant/hydrogen plant interface. Heat exchanger and component design work is underway and will be monitored and controlled by applying a new technical readiness evaluation system. Integrated system models are under development that can be used to analyze the steady-state and transient behaviors of the interface. The research teams have been reorganized to better coordinate the research activities between the national laboratories, universities, and private companies.

In the near term (FY 2008), several significant projects will be pursued.

- Establishment of a high-temperature heat exchanger and component testing laboratory.
- Further examination of the creep-fatigue properties of Inconel 617 and a related metal, Haynes 230, in order to begin to fill in the gaps for an ASME code case for these metals for nuclear applications.
- Construction of one or more heat exchanger prototypes suitable for laboratory testing and model validation.
- Continued detailed modeling of high-temperature heat exchanger designs.
- Dynamic system modeling including energy and mass distributions.
- Implementation of the NHI Components Database and the component technical readiness evaluation system.
- Continued research into materials corrosion caused by exposure to Sulfur-Iodine process solutions and molten salts.

Publications/Presentations Since Last DOE H_2 Merit Review

1. Hechanova, A.E., “High Temperature Heat Exchanger Project: Quarterly Progress Report, April 1, 2006 through July 31, 2006”, UNLV Research Foundation, August 2006.

2. Hechanova, A.E., “High Temperature Heat Exchanger Project: Quarterly Progress Report, August 1, 2006 through September 30, 2006”, UNLV Research Foundation, October 2006.

3. Hechanova, A.E., “High Temperature Heat Exchanger Project, Quarterly Progress Report, October 1, 2006 through December 31, 2006”, UNLV Research Foundation, January 2007.

4. Hechanova, A., Chen, Y., Ponyavin, V., “NHI Report: Hydrodynamic, Thermal and Decomposition Performance for Ceramic Sulfuric Acid Decomposer”, UNLV HTHX Project, May 31, 2006.

5. Chen, Y., Trabia, M., Hechanova, A., Ponyavin, V., Mohamed, T., “Mechanical and Thermal Stress Analysis of Ceramic HTHX”, University of Nevada Las Vegas, September 15, 2006.

6. Hechanova, A., Chen, Y., Ponyavin, V., De Losier, C., “NHI Report: Optimization Studies and Manifold Design of Compact Off-set Strip Fin HTHX”, UNLV HTHX Project, May 31, 2006.

7. Wilson, M., Lewinsohn, C., “FY2006 Materials Characterization and Heat Exchanger Design Development for NHI Applications”, Ceramatec Report to UNLV HTHX Project, October 23, 2006.

8. Wong, B., Brown, L., Besenbruch, G., “Corrosion Studies of Construction Materials in HI Decomposition Environments”, General Atomics Report to UNLV HTHX Project, July 15, 2006.

9. Ward, B., “Balance of Plant Requirements for a Nuclear Hydrogen Plant”, INL/EXT-06-11232, April 2006.

10. Russel, M.J., “Assessment of Codes and Standards Applicable to a Hydrogen Production Plant Coupled to a Nuclear Reactor”, INL/EXT-06-11482, Idaho National Laboratory, June 2006.

11. Smith, C., Beck, S., Galyean, B., "An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor", INL/EXT-05-00137 Rev. 1, Idaho National Laboratory, July 2006.

12. Sherman, S.R., Pawel, S.J., Wilson, D.F., "NHI Materials and Components Development Plant (Draft)", ORNL/TM-2006/563, Oak Ridge National Laboratory, September 2006.

13. Oh, C.H., Davis, C.B., Han, J., Barner, R., Sherman, S.R., Vilim, R., Lee, Y.J., Lee, W.J., "HyPEP FY06 Report: Models and Methods", INL/EXT-06-11725, Idaho National Laboratory, September 2006.

14. Sridharan, K., Anderson, M., Corradini, M., "Molten Salt Heat Transport Loop: Materials Corrosion and Heat Transfer Phenomena Quarterly Progress Report", April 2006 to June 2006, NERI Project 05-154, University of Wisconsin, DOE Nuclear Hydrogen Initiative.

15. Sridharan, K., Anderson, M., Corradini, M., Allen, T., Olsen, L., Ambrosek, J., "Molten Salt Heat Transport Loop: Materials Corrosion and Heat Transfer Phenomena Quarterly Progress Report", July 2006 through September 2006, NERI Project 05-154, University of Wisconsin, DOE Nuclear Hydrogen Initiative.

16. Roy, A., Pal, J., Koripelli, R., Venkatesh, A., Mukhopadhyay, C., Ghosh, A., "Tensile Property Measurements of Structural Materials for High-Temperature Heat Exchanger Applications", UNLV HTHX Project, November 2006.

17. Wong, B., Brown, G., Besenbruch, G., "FY2006 Year End Report: Corrosion Studies of Construction Materials for HI Decomposition Environment", General Atomics Report to UNLV HTHX Project, December 2006.

18. Vilim, R., "Dynamic Modeling Efforts for System Interface Studies for Nuclear Hydrogen Production", ANL-07/16, DOE NHI Report, Argonne National Laboratory, March 2007.

19. Oh, C.H., Barner, R., Davis, C., Sherman, S., "Evaluation of Working Fluids in an Indirect Combined Cycle in a Very High Temperature Gas-Cooled Reactor", Nuclear Technology, Vol. 156, October 2006, p. 1-10.

20. Oh, C.H., Davis, C., Barner, R., Sherman, S., "High-Temperature Gas-Cooled Reactor Coupled with High Temperature Steam Electrolysis", Paper14001-33C, presented at AIChE 2007 Spring National Meeting, Houston, TX, April 2007.

21. Sherman, S.R., "Nuclear Plant/Hydrogen Plant Safety: Issues and Approaches", accepted for presentation at the ANS Embedded Topical: Safety and Technology of Nuclear Hydrogen Production, Control and Management (ST-NH2), American Nuclear Society, Boston, MA, June 24-28, 2007.

22. Sherman, S.R., "DOE NHI: Progress in Nuclear Connection Technologies", accepted for presentation at the ANS Embedded Topical: Safety and Technology of Nuclear Hydrogen Production, Control and Management (ST-NH2), American Nuclear Society, Boston, MA, June 24-28, 2007.

23. Oh, C., Han, J., Barner, R., Kim, E., Sherman, S., "Steam Generator Component Model in a Combined Cycle of Power Conversion Unit for Very High Temperature Gas-Cooled Reactor", accepted for presentation at the ANS Embedded Topical: Safety and Technology of Nuclear Hydrogen Production, Control and Management (ST-NH2), American Nuclear Society, Boston, MA, June 24-28, 2007.

24. Oh, C., Barner, R., Davis, C., Hawkes, B., Morton, J., Sherman, S., "Power Cycle and Stress Analyses for High Temperature Gas-Cooled Reactor", ICAPP'07, Nice, France, May 13-18, 2007.

25. Oh, C.H., Davis, C., Barner, R., Sherman, S., "Design Configurations for Very High Temperature Gas-Cooled Reactor Designed to Generate Electricity and Hydrogen", ICONE14-89868, the 14th International Conference on Nuclear Engineering, Miami, FL, July 17-22, 2006.

26. Oh, C.H., Barner, R., Davis, C., Sherman, S., "Thermal Hydraulic Analyses for Coupling High Temperature Gas-Cooled Reactor to Hydrogen Plant", the 13th International Heat Transfer Conference, Sydney, Australia, August 13-18, 2006.

27. Oh, C.H., Davis, C., Sherman, S., Barner, R., "Thermal Hydraulic Analysis of HTGR Coupled with Hydrogen Plant", ANS Annual Meeting, Reno, NV, June 2-8, 2006, pp. 621-622.

28. Oh, C.H., Barner, R., "Effects of Interstage Cooling on Brayton Cycle Efficiency", ANS Annual Meeting, Reno, NV, June 2-8, 2006, pp. 619-620.

29. Vilim, R.B., "Power Requirements at the VHTR/HTE Interface for Hydrogen Production", Proceedings of ICAPP Nice, France, May 13-18, 2007.

30. Vilim, R.B., "Dynamic Behavior of the VHTR/HTE Plant from Time Constants and Energy Capacitances", accepted for presentation at the ANS Embedded Topical: Safety and Technology of Nuclear Hydrogen Production, Control and Management (ST-NH2), American Nuclear Society, Boston, MA, June 24-28, 2007.

31. Vilim, R.B., "GAS-NET: A Two-Dimensional Network Code for Prediction of Core Flow and Temperature Distribution in the Prismatic Gas Reactor", Proceedings of ICAPP 2007 Nice, France, May 13-18, 2007.

32. Vilim, R.B., "Nuclear Hydrogen at ANL: A Progression Through Temperature", Argonne National Laboratory presentation at MIT, January 31, 2007.