IV.G.5 Nuclear Hydrogen Initiative System Interface and Support Systems

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End Date: Project continuation and direction determined annually by DOE

Objectives

- Assist DOE in the development of a high-temperature heat transfer network to enable linkage of a high-temperature nuclear reactor to a nuclear hydrogen production plant.
- Support development of hydrogen plant ancillary systems and infrastructure for pilot-scale and engineering-scale nuclear hydrogen production plants.

Technical Barriers

This project addresses the following technical barriers of the Nuclear Hydrogen Initiative:

- Long-term
  - Cost of combined nuclear reactor/hydrogen production facility.
- Shorter term
  - High-temperature materials that are corrosion resistant and durable for application to heat exchangers, valves, and other components.
  - Process realization – achieving reasonable performance in prototype equipment during small-scale experiments.

Approach

- Initially, research and develop along parallel paths
  - Materials and heat transfer fluid analyses and characterization
  - Heat exchanger concept development
  - System modeling and simulation
  - Cataloging of applicable codes and standards
- Focus on more detailed designs and concepts
  - Detailed heat exchanger concepts and designs
  - Static and dynamic system models
- Test at laboratory-scale
  - Prototype heat exchanger and component testing
  - Integration of laboratory data into system models
- Test at larger scale (pilot-scale and engineering scale)

Accomplishments

- Defined infrastructure requirements for pilot-scale hydrogen production plants.
- Defined initial balance-of-plant requirements for hydrogen production plants.
- Identified system interface requirements and technical issues.
- Performed initial study of plant spacing requirements between the nuclear plant and the hydrogen plant in a co-generation facility.
- At first analysis, minimum plant spacing may be 60-120 m.
- Performed stress-strain measurements and stress corrosion cracking studies of Waspaloy, Incoloy 800H, Zr-705, Nb-12Zr, Nb-7.5Ta.
- Developed computational fluid dynamics models of ceramic compact heat exchanger concepts for application to system interface heat exchangers.
- Performed corrosion screening of materials for application to sulfuric acid decomposition and in the presence of hydrogen iodide, iodine, and water (HIx) solutions for application to components in the sulfur-iodine hydrogen production process.
- Identified non-metallic material candidates and manufacturing techniques for ceramic heat exchangers.
- Developed alloys 800+Pt and 617+Pt for possible application to a catalyzed high temperature metallic heat exchanger for sulfuric acid decomposition.
- Completed thermal-hydraulic analyses of heat transfer fluid requirements and characteristics for coupling a hydrogen production plant to a nuclear plant.

Future Directions

- Remainder of FY 2005
  - Analyze heat exchanger requirements and material needs for individual system interface heat exchangers.
  - Complete initially planned experiments in the areas of corrosion and mechanical properties measurements of metallic and non-metallic materials for application to heat exchanger construction.
  - Continue computational modeling of compact heat exchanger designs.
- FY 2006
  - Complete assessment of applicable codes and standards.
  - Design laboratory test loops for materials and heat exchanger testing.
  - Revise balance-of-plant and plant spacing documents.
  - Continued studies of structural and fluid materials for application to high-temperature heat transfer network.
- FY 2007
  - Perform laboratory testing of prototype heat exchangers.
  - Confirm longevity of materials for sulfur-based thermochemical process equipment.
  - Complete pilot-scale balance-of-plant designs for baseline processes.
  - Initiate permitting activities for pilot-scale hydrogen plant experiments.
- FY 2008
  - Complete design and testing activities to support pilot-scale decisions.
  - Complete documentation of work to support pilot-scale decisions.

- FY 2009 and beyond
  - Support design and construction of pilot-scale and engineering-scale hydrogen production plant.
  - Support design and construction of system interface loop for pilot-scale and engineering-scale hydrogen production plant.

Introduction

The System Interface and Support Systems activity under the Nuclear Hydrogen Initiative consists of three areas of responsibility. These areas and their associated boundary assumptions are:

- *Reactor/Process Interface*: This task area concerns the development of all connections and interfaces that must be made to connect a high-temperature nuclear reactor to a hydrogen production plant. It is an area of critical importance to the development of nuclear hydrogen capabilities and is the primary focus of the System Interface and Support Systems research in the near term. It also addresses the operational behavior of such a system, and includes efforts to understand and model potential negative impacts from system or component failures, control functions, or process feedback from one side of the interface to the other, and all work to control or eliminate those negative impacts.
- *Balance of Plant (BOP)*: Balance of plant encompasses all components and systems of the hydrogen production plant that do not directly perform or support the chemical or electrolysis processes involved in generating hydrogen. Examples are heat exchangers that do not provide direct reaction heat, product and byproduct handling systems, waste handling systems, off-gas treatment, water treatment systems, and sampling systems. This task area concerns the definition, design, and implementation of all balance-of-plant operations at the pilot and engineering scale.
- *Process Infrastructure and Support Facilities*: Process infrastructure includes everything outside the plant that is required to keep the plant operating. Infrastructure includes physical space requirements, electrical, non-electrical energy sources, support laboratories, physical space requirements, permitting, and other such infrastructure and support requirements. This task area concerns the definition and implementation of all needed infrastructure in support of the pilot and engineering scale hydrogen production plants.

The scope of the System Interface and Support System function is to ensure that all supporting systems and reactor interface issues and requirements are met and are ready to support the decision process as the different hydrogen generation processes mature towards the pilot and engineering scale decision points.

Approach

Figure 1 shows the approach in developing a working system interface and to support balance-of-plant and infrastructure decisions for a hydrogen production plant. In the early stages, parallel research pathways in materials, heat exchanger design, modeling, and in the codes/safety area will be pursued. As the pathways become more mature, the focus will be narrowed to developing concrete heat exchanger concepts and flexible static and dynamic system models. This information will be used to build heat exchanger prototypes for testing in the laboratory and to refine the materials testing work, so that this information can be used to increase the accuracy of the models. Once adequate laboratory-scale tests have been performed, the detailed system models and successfully tested laboratory-scale heat exchanger designs will be applied to the definition and design of the pilot-scale and engineering-scale system interface and hydrogen plant systems. It is recognized that the process is iterative, and that many

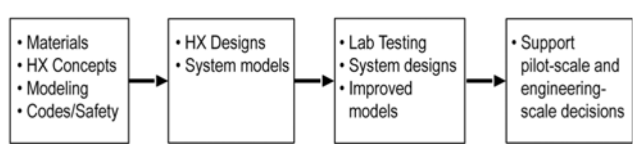

Figure 1. Approach to System Interface Research and Development

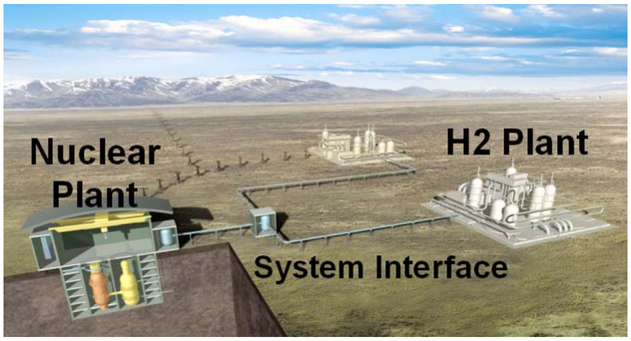

Figure 2. Schematic of Combined Nuclear Plant/ Hydrogen Plant Facility

repeated passes through the sequence may be needed to achieve success.

Results

A risk-based analysis was performed to examine how close a hydrogen plant can be located to a high-temperature nuclear reactor (Figure 2) without causing the probability of reactor core damage due to an accident at the hydrogen plant to exceed $1E^{-6}$/year. In this analysis, various accident scenarios were characterized (e.g., seismic events, blast analyses, chemical dispersion, etc.) and system fault trees were developed. Probabilities were assigned to the fault trees, and various configurations of the nuclear plant/hydrogen plant complex were analyzed using the SAPHIRE risk analysis model. According to this work, a minimum distance of 100 m is needed between the nuclear plant and the hydrogen plant to maintain the risk of nuclear reactor core damage to less than $1E^{-6}$/year. The distance may be minimized by employing a blast barrier between the plants, burying the nuclear plant or the hydrogen plant, or by locating the control room greater than 500 m away from the combined plant complex. The plant spacing report will be revised as needed when new data become available and plant designs become more certain in the future.

Thermal-hydraulic analyses were performed of seven possible configurations of the nuclear reactor energy conversion cycle/system interface in order to determine relative energy efficiencies, pressure and temperature constraints, and practicality. Two types of heat transfer fluids were assumed for the system interface – gases, as represented by pure helium, and molten salts, as represented by FLiNaK and $NaBF_4$-NaF. Material limitations were also taken into account by examining metallic creep rupture strength of several high-temperature alloys (i.e., Alloy 617, 800HT, Hastelloy X). Figures 3 and 4 show two examples of configurations that were analyzed. Some conclusions from this study are:

- Creep rupture strength will limit the pressure of the system interface boundaries to less than 2 MPa for simple shell-and-tube heat exchanger configurations.
- Molten salt is a more efficient heat transfer fluid to use than helium.
- Three of the seven configurations studied were eliminated from further consideration due to projected high capital costs.
- Use of lower pressure helium (<2MPa) for the planned engineering-scale demonstration plant (600 MWth VHTR, 50 MWth hydrogen production plant) may be useful for lowering capital costs and reducing the mechanical complexity of the system interface components but higher pressure helium or molten salt will need to be used for larger plants in order to decrease power transmission losses.

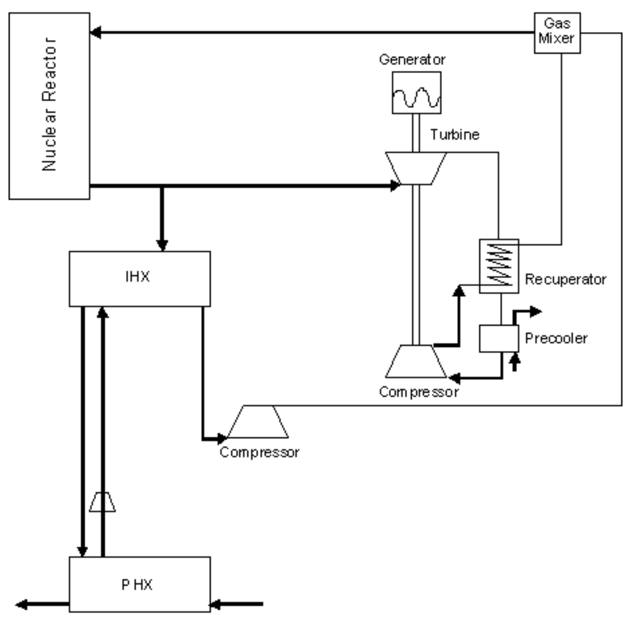

Figure 3. Direct Electrical Cycle and Parallel Intermediate Heat Exchanger

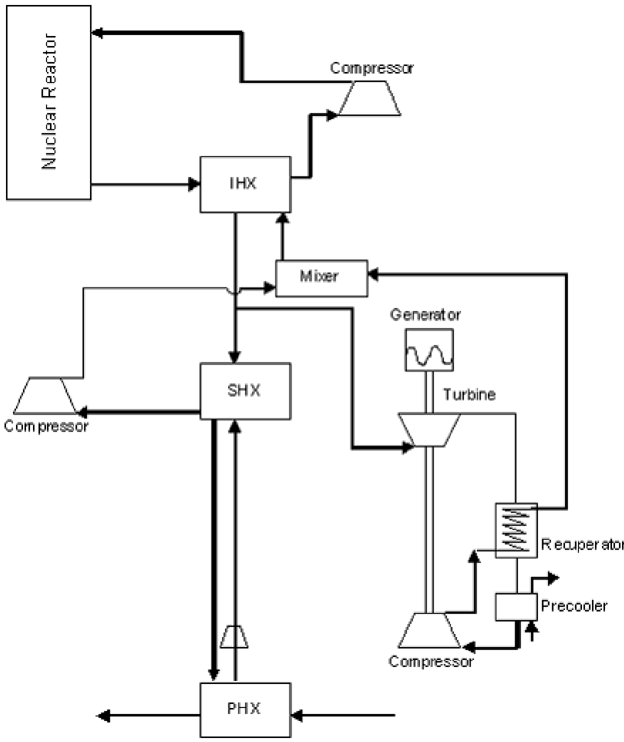

Figure 4. Indirect Electrical Cycle and a Parallel Secondary Heat Exchanger

Materials corrosion tests are still underway for materials exposed to high-temperature sulfuric acid and HIx, but some preliminary results have been obtained:

- Of the metals, only the refractory metals and alloys have shown good corrosion resistance, specifically Ta, Ta-7.5Nb, and Ta-40Nb.
- Ceramics such as SiC, mullite, and others have also shown very good corrosion resistance.
- These results may indicate that heat exchangers designed for such environments may require refractory-clad parts, or combined ceramic-metallic construction.

The Alloy 800 + 1-5%Pt and Alloy 617 + 1-5% Pt have shown very good corrosion resistance properties for application to sulfuric acid decomposition vessels. Catalytic testing of the alloys is planned for later in the fiscal year. If the alloys show catalytic activity and continued corrosion resistance, the next step will be to design and test a prototype heat exchanger that would be able to decompose sulfuric acid directly into SO_2, H_2O and O_2 without having to add pelletized platinum catalyst.

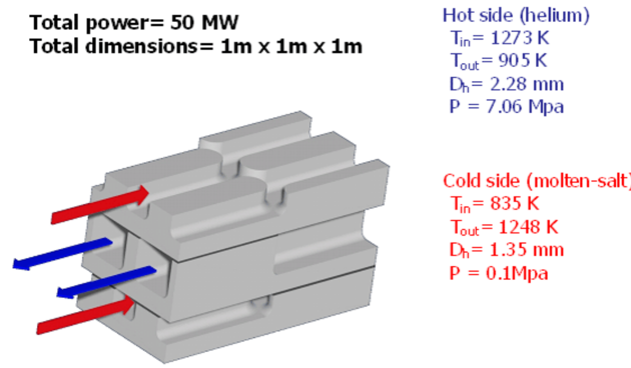

Figure 5. Compact Off-Set Heat Exchanger Unit Cell for Helium/Molten Salt Fluids

Design and optimization modeling of compact heat exchanger concepts is continuing for both metallic and ceramic heat exchanger options. Examinations have been made on the 2-D and 3-D channel configurations, model grid spacing, temperature and mechanical stress distributions. An example of compact heat exchanger flow channels is shown in Figure 5. Also, materials properties are being incorporated into the models as new materials are adopted or new information becomes available on existing materials or material composites.

These results support the approach of pursuing parallel research paths in the beginning, and then narrowing the focus of the research to generate specific heat exchanger concepts and complete system models. These results will be used to focus research in FY 2006 on identifying materials candidates for heat transfer fluids and heat exchangers, developing prototype heat exchanger concepts for eventual laboratory testing, and in building steady-state overall system models that include the nuclear plant, the system interface, and the hydrogen production plants.

FY 2005 Publications/Presentations

1. C. Smith, B. Gaylean, "Analysis Methods and Objectives for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor," January 2005.
2. C. Smith, S. Beck, B. Gaylean, "An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor", INL/EXT-05-00137 Rev. 0, March 2005.

3. S.R. Sherman, "2005 DOE Hydrogen Program: NHI System Interface and Support Systems", 2005 DOE H_2 Annual Review, Project ID #PD31.
4. C.B. Davis, C.H. Oh, R.B. Barner, S.R. Sherman, D.F. Wilson, "Thermal-Hydraulic Analyses of Heat Transfer Fluid Requirements and Characteristics for Coupling a Hydrogen Production Plant to a High-Temperature Nuclear Reactor", INL/EXT-05-00453, June 2005.
5. T. Lillo, "Analysis Methods and Desired Outcomes of the Analysis of Intermediate and Process Heat Exchanger Loop Requirements", INL/EXT-05-00478, June 2005.
6. S.R. Sherman, "Reactor-Hydrogen Production Process Interface", Advanced Reactor, Fuel Cycle, and Energy Products for Universities, June 16-17, 2005, Doubletree Hotel, Rockville, MD (NERI Workshop).