Nuclear Reactor/Hydrogen Process Interface

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May 17, 2006

INL/CON-06-11126

Project ID #
PD 18

Overview

Timeline

- Start date: January 2004
- End date: 2016+
- On-going support of DOE Nuclear Hydrogen Initiative (NHI) and coordinated with DOE Generation IV Advanced Nuclear Reactor projects

Budget

- Total DOE share projected at $47M through 2016
  - Covers initial lab-scale development through engineering-scale execution
  - Cost share may be pursued after 2010
- FY05 funding, $2.79M
- FY06 funding, $2.90M

Barriers

- High temperature material identification, selection, and qualification
- High temperature heat exchanger designs
- Effective/efficient coupling method for linking high temperature heat source with thermochemical H_2 process

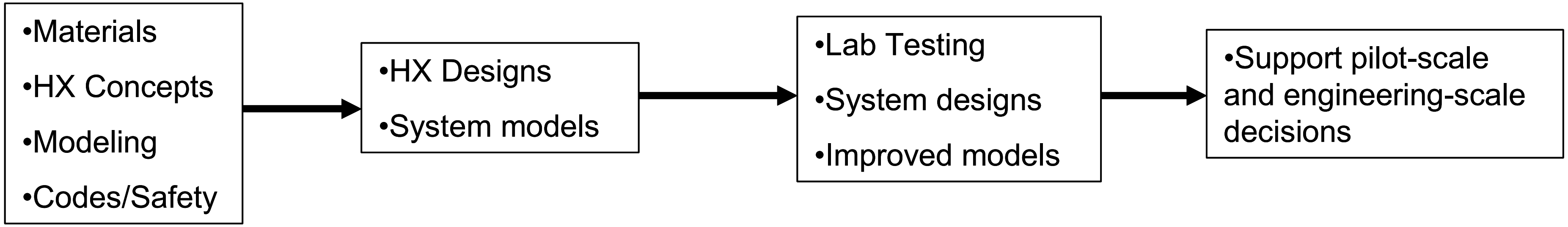
Partners

- National laboratories: ANL, INL, ORNL, Sandia
- Universities: UNLV, MIT, UCB, UWis, JH
- Companies: General Atomics, Ceramatec
- International: CEA, KAERI

Objectives

- Overall Project Objectives
  - To assist DOE in the development of a high-temperature 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 (lab, pilot, engineering-scale)
- FY06 Objectives
  - Characterize mechanical/thermal/corrosivity behavior of candidate structural materials
  - Explore heat exchanger/reactor design options through analysis and experimentation
  - Develop integrated system simulation tools
  - Improve understanding of safety-related issues
  - Develop deeper understanding of all technical issues and develop strategies for optimizing the research effort

Approach

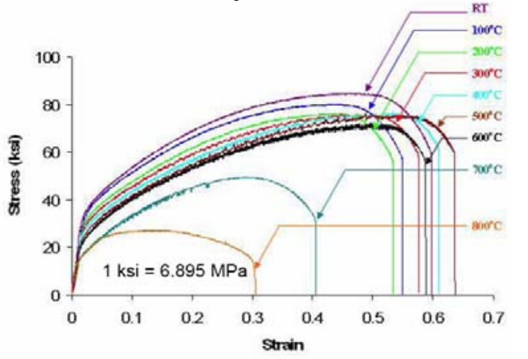


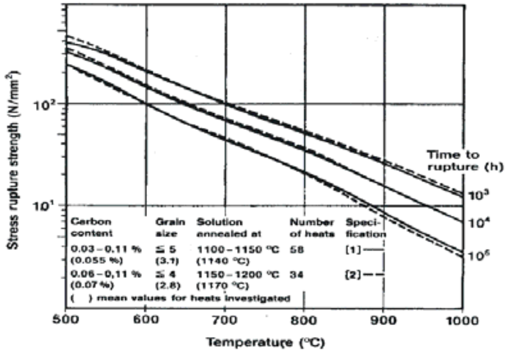
- Initially, pursuit of parallel research paths
- Periodic assessments are made in each area and lessons learned are integrated into other areas
  - Example: SiC has been found to be very corrosion resistant to hot H_2SO_4 vapor, so HX concepts for the sulfuric acid decomposer may be focused on using SiC in the designs
- Systematic approaches are being developed to perform down-selects on technology paths that will be generally applicable across the project
- Will eventually narrow focus on select technologies, and will demonstrate these technologies at the laboratory, pilot, and engineering-scale
- Leveraging of technical information from collaborators not directly funded by the DOE NHI
  - International partners: CEA, KAERI
  - Companies: Rocketdyne, Framatome, etc.

Technical Accomplishments (1)

- Mechanical properties of select high-temperature alloys measured to fill in holes in literature values (UNLV)
  - Hastelloy C-22, C-276; Inconel 617, Incoloy 800H, Waspalloy up to 1000 °C
  - 617 and 800H offer highest strength above 800 ºC
- Stress corrosion cracking behavior of select metals with pre-stressed samples also examined in presence of H_2SO_4/NaI solution up to 350 ºC (UNLV)
  - C-276 worked best
- New alloy materials -- 617 + 1% Pt and 800 + 1% Pt -- were developed and are being tested for SO_3 decomposition catalytic activity and corrosion resistance (MIT)
  - May be more corrosion resistant than standard 617/800
  - Has catalytic activity (extent still being determined)
- Related results
  - CEA (France) has done long-term testing on 617 and Haynes 230
  - The DOE NGNP project is favoring 617 for nuclear IHX

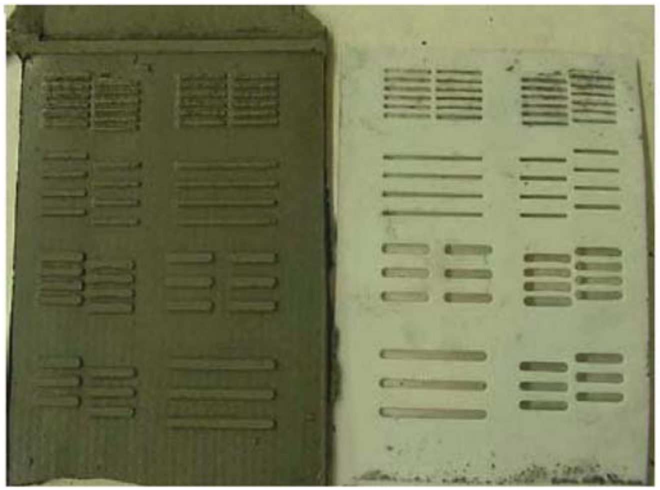
Alloy 800H





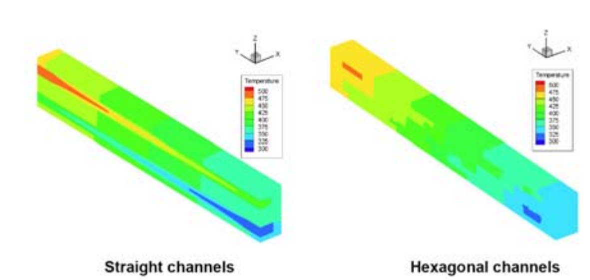
Technical Accomplishments (2)

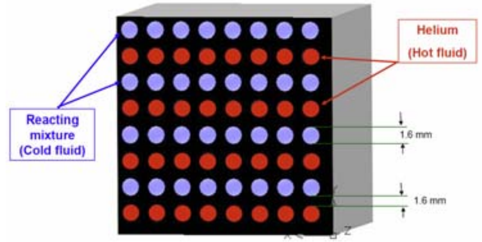
- Ceramic materials also studied (Ceramatec, UC-Berkeley)
  - Ceramics offer much higher strength and creep resistance than metals at high temperatures
  - Down-selects to SiC, C/SiC, Al_2O_3, Si_3N_4, SiAlON based on property and manufacturing screens
  - SiC, Si_3N_4 exposed to H_2SO4/O_2 vapor mixture at 850 C for up to 1000 h
    - No reduction in strength
    - Asymptotic build-up of SiO_2 on surface layer
- Advances made in manufacturing techniques for C/SiC compact HX plates (UC-Berkeley)
  - Flexible Teflon™ molds used to shape plates before pyrolizing
  - Can form features down to 1.5 mm in width or less
  - Carbon CVD coatings are needed to ensure hermeticity due to porosity of the C/SiC material

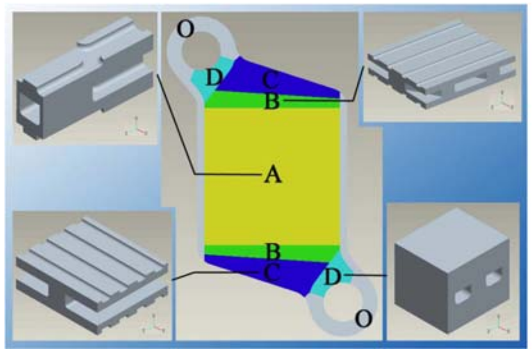


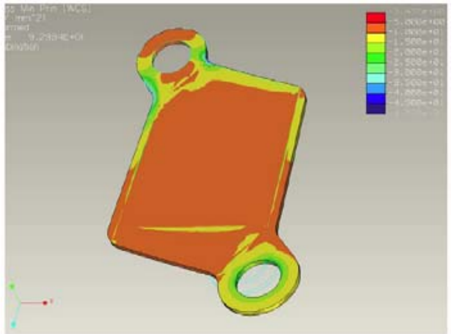
Technical Accomplishments (3)

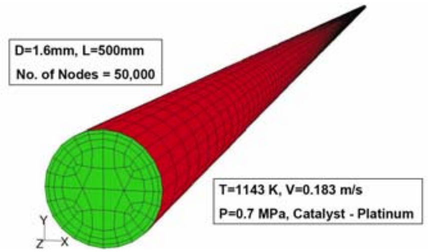
- Extensive corrosion testing of materials exposed to HI-I_2-H_2O solutions at 300-350 °C (GA, UNLV)
  - Ta-2.5W, Nb-10Hf, Ag show good corrosion resistance
  - May require development of cladding materials
- High temperature heat exchangers (UNLV, UCB, Ceramatec)
  - CFD, thermal/mechanical stress analyses being performed on compact heat exchanger concepts
    - Conventional finite-element analyses
    - “Zone” approach for larger plate sections
  - Full design for lab-scale Heatric compact HX completed (MIT)
    - N-stamped and certified up to 889 ºC for Alloy 617/800





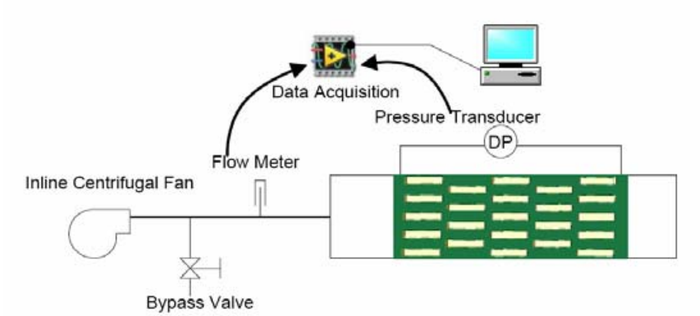


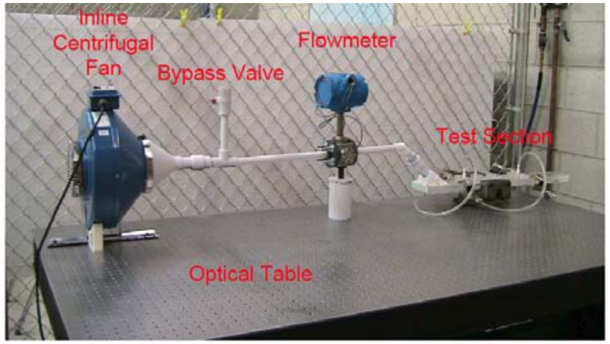


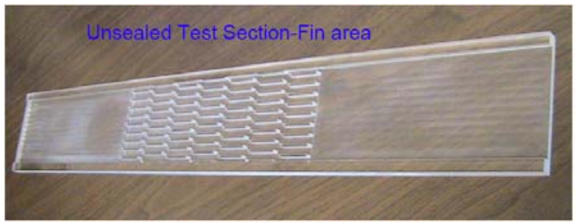


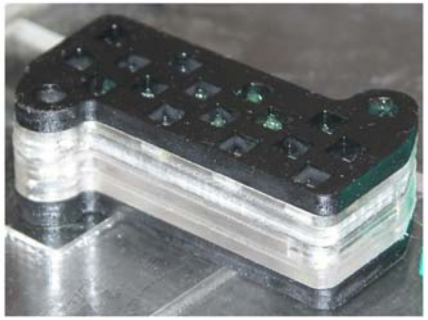
Technical Accomplishments (4)

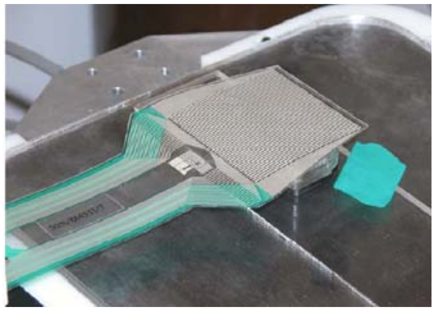
- Laboratory testing of heat exchanger flow channels is underway (UNLV, Ceramatec)
  - UNLV has constructed a Lexan/aluminum mock-up facility that will use water and air to simulate scaleable fluid flow conditions (Re, Pr, etc.)
    - Measure localized pressure flow, heat transfer
  - Ceramatec has constructed mock-ups of microchannel ceramic heat exchanger plates
    - Measure localized pressure and flow
- Testing results will be used to improve models

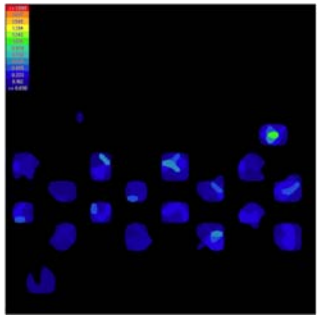






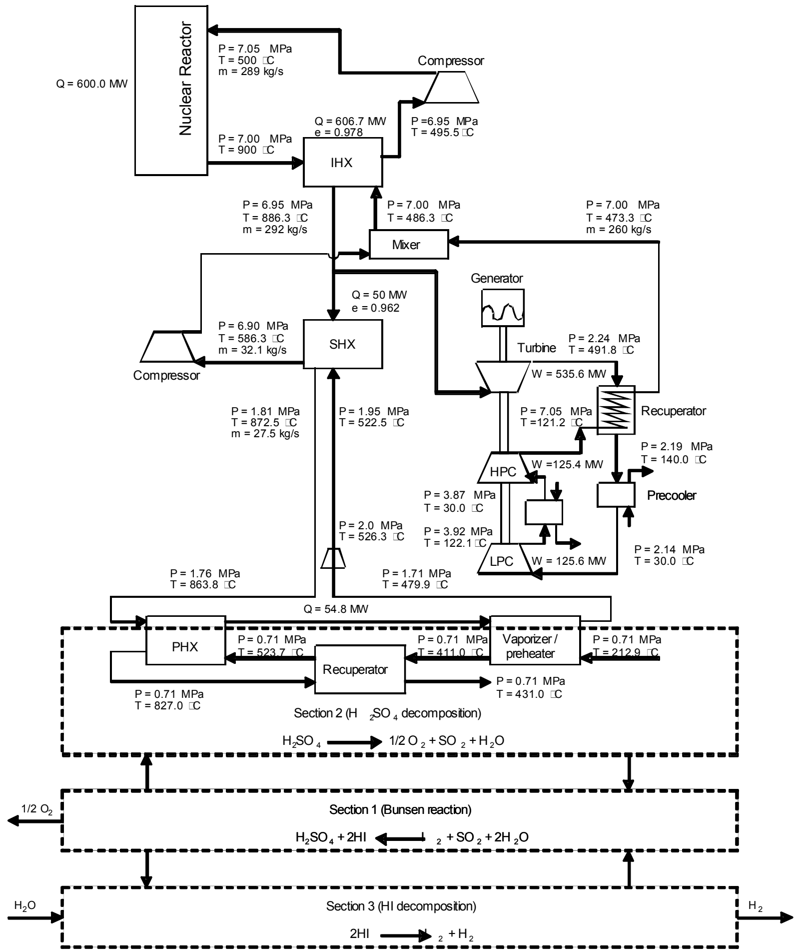






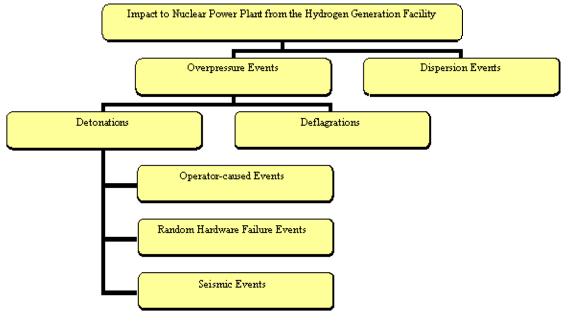
Technical Accomplishments (5)

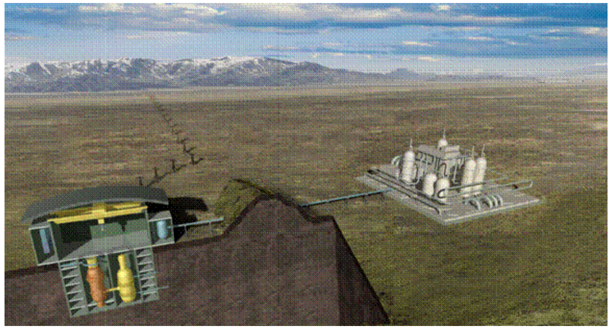
- Initiated a I-NERI project to develop modeling tools for the integrated nuclear reactor/hydrogen plant system
  - HyPEP, “Hydrogen Process Efficiency Program”
  - INL, ANL, and KAERI
  - Will link nuclear reactor codes (GAS-PASS/H, others) with chemical process codes (HYSYS) with a GUI-driven software superstructure
  - Will allow steady-state simulations and performance of energy efficiency calculations
  - May involve transient elements
  - Results will be benchmarked against established codes and CEA’s CYCLOP code
- Modeling assumptions are being coordinated with the DOE Generation IV Advanced Nuclear Reactor development program



Technical Accomplishments (6)

- Nuclear plant/hydrogen plant studies are being revised (INL)
  - Continuation of probabilistic risk assessment work to assess risk posed to nuclear plant by the hydrogen production plant
  - Last year study concluded minimum spacing was 60-120 m
  - Improvements this year
    - Inclusion of chemical plant accident data and operational information from sulfuric acid plants
    - Detailed assessment of specific equipment in S-I plant
    - Expansion of H_2 event scope from 100 kg to 1000 kg
    - More detailed examination of control room location issues
  - Results will be compared to empirically-based CEA safety studies of combined facility
- Involvement in ASME H_2 codes and standards committees (INL)
- Performing an assessment of relevant codes and standards to a combined nuclear/non-nuclear facility (INL)
- Mapping of technical issues to past and on-going work





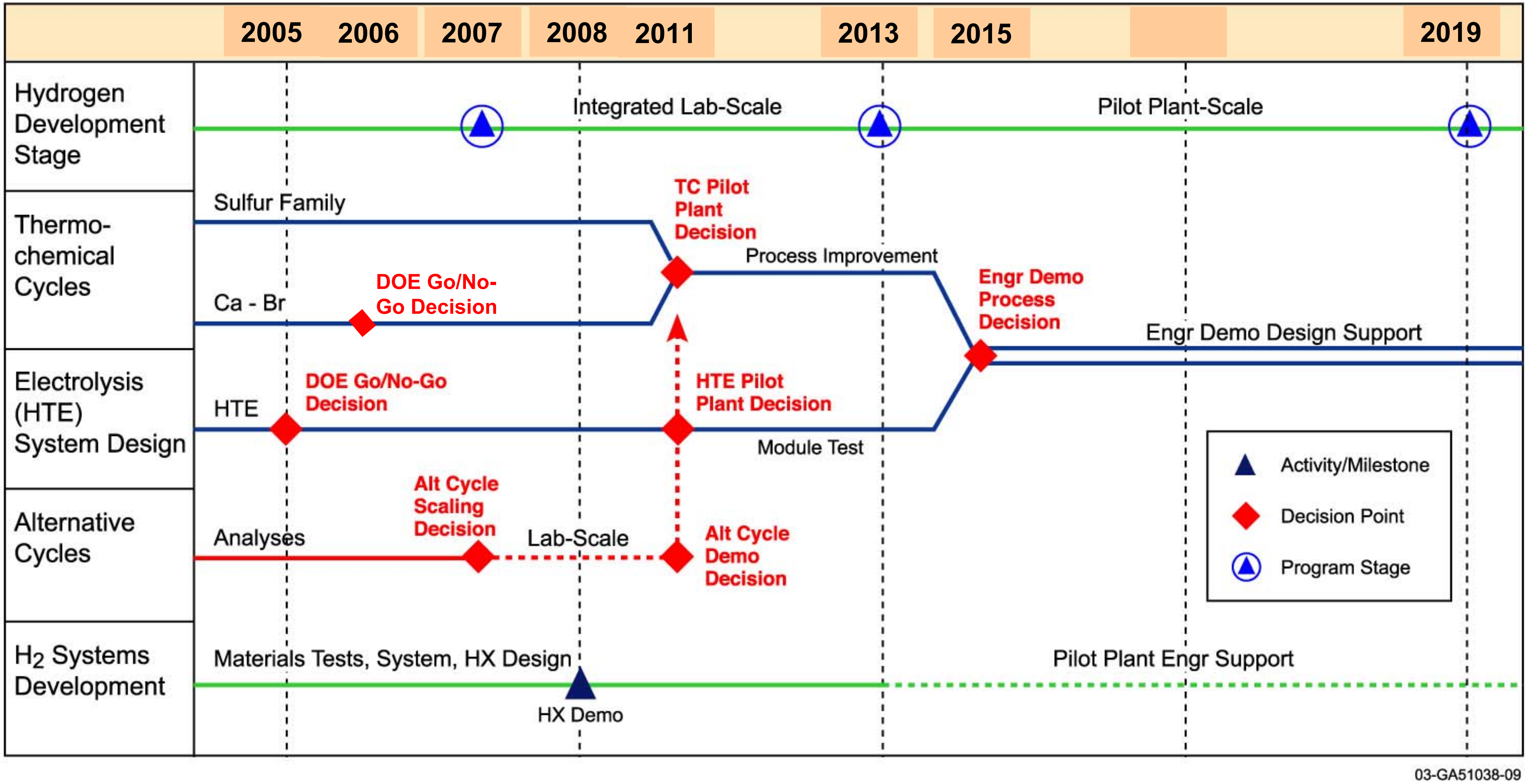
Future Work (1)

- Remainder of FY06
  - Development of NHI Materials and Components Test Plan (INL, ORNL, others as needed)
    - Plan will examine candidate materials and material/component combinations for the nuclear hydrogen production process currently under study (S-I, Hybrid S-I, high temperature electrolysis, Ca-Br(?))
    - More importantly, will provide decision criteria for selecting materials and components
      - Phased approach: initial concept, screening, lab-scale, pilot-scale, engineering-scale
      - Blend of deterministic and risk-based criteria
  - Examination of hazardous chemical material/component test loop requirements and related safety issues (INL)
    - Need for dedicated test flow loop(s) for high temp H_2SO_4, O_2, SO_2, H_2 and long exposure times (1000's hours)
  - Initiate project on study of high-temperature thermal barrier coatings for pipe/vessel interiors (INL)
    - Using internal insulation will lower temperature of pressure containment walls and reduce tendency to creep
  - Ongoing work in:
    - Materials
    - HX design

Future Work (2)

- FY07
  - Continue materials and component development work
    - Modeling, experimental mock-ups
  - Complete draft materials & components test plan
  - Develop detailed hazardous loop designs and perform match-up to a facility
  - Continue development of HyPEP
  - Continue on-going safety assessments
  - Examine environmental issues, as needed, for eventual permitting of pilot plant
  - Become more coordinated with VHTR development work
  - Continue to work closely with international partners (CEA, KAERI)

Future Work (3)



Summary

- Project is highly collaborative
  - National laboratories, universities, private entities, international partners
- Project is becoming highly coordinated
  - Cross-cutting work with thermochemical and high temperature electrolysis development efforts
  - Coordinated with VHTR development
- Research being performed is consistent with the strategic path forward
- Progress is on track to support pilot-scale decisions in 2011 and engineering-scale decisions in 2015
- Planning tools are being developed to reinforce forward momentum

END

SUPPLEMENTAL VIEWGRAPHS

Responses to Previous Year Reviewers' Comments

- "No industry involvement was indicated."
  - Collaborations now in place with CEA and KAERI
  - Working directly with industry through the UNLV RF: General Atomics and Ceramatec
  - Periodic feedback on work with Rocketdyne, Framatome at UNLV RF Project Quarterly Meetings
- "High project costs and long time frame make project management difficult."
  - Detailed project tracking performed monthly using PRC software
  - Research coordinated under a larger 10-year plan
  - Project-specific materials/components plan with decision criteria is under development
- "Milestones to complete design in the barriers area provide little insight/confidence they will be overcome."
  - Technical issues/project map has been constructed
  - Individual research work is assessed during planning exercises against issues and work is coordinated in response to the needs
  - Longer timelines for this project provide flexibility in directing resources to tackle key issues before project milestones are reached

Recent Publications and Presentations

1. C. Smith, S. Beck, B. Gaylean, INL/EXT-05-00137, "An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor", Revision 0, March 2005.
2. C. Davis, C. Oh, R. Barner, S. Sherman, and D. Wilson, INL/EXT-05-00453, "Thermal-Hydraulic Analyses of Heat Transfer Fluid Requirements and Characteristics for Coupling a Hydrogen Production Plant to a High-Temperature Nuclear Reactor", Revision 0, June 2005.
3. T. Lillo, R. Williamson, T. Reed, C. Davis, D. Ginosar, INL/EXT-05-00690, "Engineering Analysis of Intermediate Loop and Process Heat Exchanger Requirements to Include Configuration Analysis and Materials Needs", Revision 0, September 2005.
4. NERI 05-032, "Silicon Carbide Ceramics for Compact Heat Exchangers", Johns Hopkins University.
5. NERI 05-132, "Molten Salt Heat Transport Loop: Materials Corrosion and Heat Transfer Phenomena", University of Wisconsin.
6. NERI 06-024, "Ni-Si Alloys for the S-I Reactor-Hydrogen Process Interface", University of Missouri-Rolla.
7. NERI 06-041, "Dynamic Simulation and Optimization of Nuclear Hydrogen Production Systems", Massachusetts Institute of Technology.
8. NERI 06-060, "Development of Efficient Flowsheet and Transient Modeling for Nuclear Heat Coupled Sulfur Iodine Cycle for Hydrogen Production", Purdue University.
9. 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 list of references for UNLV related work. Quarterly reports and presentations are also provided.
10. S.R. Sherman, "Progress in High Temperature Materials and Systems in the U.S. DOE Nuclear Hydrogen Initiative", Presentation #405a, AIChE 2005 Annual Meeting
11. S.R. Sherman, "Technical Barriers and Opportunities in Nuclear Plant/Hydrogen Plant Connection Technologies", Presentation #182f, AIChE 2006 Spring National Meeting
12. 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.

Critical Assumptions and Issues (1)

- Critical Assumption #1: Funding and research on the Generation IV Very High Temperature Reactor (VHTR) will continue to be provided in the face of the new Global Nuclear Energy Program (GNEP)
  - A high temperature heat source (800 °C or greater) is needed to drive the leading thermochemical hydrogen production process under study, the Sulfur-Iodine process. The VHTR can provide the high-temperature thermal energy needed by the S-I process. GNEP has the potential for requiring huge financial resources, and funding for VHTR development may be negatively affected. If the VHTR is de-emphasized, project resources will need to be re-directed towards lower-temperature operation with different chemicals/methods for producing hydrogen.
- Critical Assumption #2: The high-temperature hydrogen production methods under study will ultimately reach the projected levels of energy efficiency -- greater than 35%.
  - Nuclear hydrogen production makes sense if the delivered price of hydrogen is less than can be delivered by liquid water electrolysis, and the market needs are such that hydrogen supplied from natural gas is not readily available or expensive for use near the nuclear reactor. If the target efficiency cannot be achieved, then the hydrogen production processes will not receive favorable market attention and the project will not be relevant to commercial hydrogen production. While questions related to natural gas supply are out of the project’s control, hydrogen process efficiency is an item that is under great scrutiny, and the project is striving for overall efficiencies greater than 40%. Global economic studies are periodically performed as new data develops in order to assess the potential price of hydrogen from a nuclear source.

Critical Assumptions and Issues (2)

- Critical Assumption #3: There are materials and/or engineering solutions to all of the the corrosion and high-temperature challenges posed by the nuclear/process interface that will not require significant changes in the nuclear reactor output temperature or hydrogen plant operating set points.
  - So far, the operating targets of the nuclear/process coupling system in terms of temperature, pressure, and material flows all appear feasible in light of available materials and postulated design concepts. Work will be concentrated on the equipment having the highest technical risk of success in order to continue to ensure system feasibility and operability.
- Critical Assumption #4: The cost of the nuclear/process coupling system will not be prohibitive.
  - Once the technical problems are assured of being solved, cost will become a focus. The capital and operating costs of system components will need to be balanced with demands for good performance, durability and safety. It is assumed that basic performance, durability and safety will be emphasized through the pilot-scale demonstration, while economics will begin to play an important role in decision-making once the engineering-scale demonstration is underway.