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Capabilities to Support Thermochemical Hydrogen Production Technology Development

Daniel Ginosar

May 2009

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Idaho National Laboratory
Science and Engineering
Idaho Falls, Idaho 83415

http://www.inl.gov

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Approved by:

Daniel Ginosar Principal Investigator and Author	5/28/2009 Date
Richard Garrett NGNP Engineering Director	5/28/09 Date
Greg Gibbs NGNP Project Director	5/28/09 Date

ABSTRACT

This report presents the results of a study to determine if Idaho National Laboratory (INL) has the skilled staff, instrumentation, specialized equipment, and facilities required to take on work in thermochemical research, development, and demonstration currently being performed by the Nuclear Hydrogen Initiative (NHI). This study outlines the beneficial collaborations between INL and other national laboratories, universities, and industries to strengthen INL's thermochemical efforts, which should be developed to achieve the goals of the NHI in the most expeditious, cost effective manner. Taking on this work supports INL's long-term strategy to maintain leadership in thermochemical cycle development. This report suggests a logical path forward to accomplish this transition.

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ACRONYMS

CFA	Central Facilities Area
CTC	component test capability
DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
HyS	hybrid sulfur
HYTEST	hybrid energy system test
IEDF	INL Engineering Design Facility
ILS	integrated laboratory scale
INL	Idaho National Laboratory
IRC	INL Research Center
MECS	Monsanto Enviro-Chem Systems, Inc.
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
ORNL	Oak Ridge National Laboratory
PDU	Process Demonstration Unit
PEM	proton exchange membrane
R&D	research and development
S-I	sulfur-iodine
SNL	Sandia National Laboratory

Capabilities to Support Thermochemical Hydrogen Production Technology Development

1. SUMMARY

This report presents the results of a study conducted to determine if Idaho National Laboratory (INL) has the skilled staff, instrumentation, specialized equipment, and facilities required to perform the work of thermochemical hydrogen production process research, development, and demonstration planned or anticipated by the Nuclear Hydrogen Initiative (NHI). If successfully developed and demonstrated at small and intermediate scales, the thermochemical process will be demonstrated at an engineering scale by the Next Generation Nuclear Plant (NGNP) Project. The study shows that INL has the beneficial collaborations with other national laboratories, universities, and industries to strengthen its thermochemical process development efforts that should be performed to achieve the goals of the NHI in the most expeditious, cost effective manner. Transition of this work to INL supports INL's long-term strategy to maintain leadership in thermochemical cycle development and integrates it more closely with the NGNP Project and the industrial processes that will use the hydrogen. This report suggests a logical path forward to accomplish this transition.

Over the past 6 years, INL has been significantly involved in developing technologies for producing hydrogen from water-splitting processes driven by nuclear energy, including both high temperature electrolysis and thermochemical cycles. Because of these and other related efforts, the laboratory has a trained staff with the specific skills needed to successfully develop thermochemical hydrogen production technology, thereby achieving NHI mission success. One of the key features of being a multiprogram laboratory is being able to retain key skills during periods of uncertain funding.

The study also shows that INL has the specific instrumentation, specialized equipment, and facilities needed to conduct all aspects of NHI's mission. Multiple facilities exist at INL that can support hydrogen research and development (R&D), pilot plant, engineering scale, and demonstration scale operations. Test capabilities planned by the NGNP project will be tailored to the hydrogen process or processes chosen for demonstration with the project. Scale-up of the hydrogen process will be integrated with the NGNP project schedule for timely demonstration of commercial hydrogen production capability.

The study shows that INL has experience in teaming with other national laboratories, universities, and industry and can therefore draw on these relationships to transition thermochemical activities to its facilities in a timely and efficient manner. This transition supports the primary objectives of the laboratory and is synergistic with its other laboratory programs, including the hybrid energy test bed (or HYTEST), component test capability (CTC) and the NGNP project as a whole.

2. OBJECTIVE

The study was conducted to determine if INL has the skilled staff, instrumentation, specialized equipment and facilities required to transition the Department of Energy (DOE) Office of Nuclear Energy's (NE) NHI thermochemical hydrogen process research, development, and demonstration work to INL. The study outlines the beneficial collaborations with other national laboratories, universities and industry to strengthen the INL's thermochemical efforts that should be developed to achieve the goals of the NHI in the most expeditious, cost effective manner. This transition supports the INL's long term strategy to maintain leadership in thermochemical cycle development and integrates the work with other programs such as HYTEST, CTC and the NGNP project. The final objective of the study was to suggest a logical path forward to accomplish the transition.

3. BACKGROUND

INL has taken an active role in developing thermochemical water-splitting cycles, which began with a large multiyear investment of internal funds in FY 2003. Through this initial work, INL made advances applicable to the sulfur-iodine (S-I) and hybrid sulfur (HyS) cycles in the areas of catalysts, energy efficient membrane separations, materials of construction for harsh acidic environments, and electrodes for SO_2 electrolysis. In FY 2004, INL defined requirements and capabilities to conduct development activities relative to integrated laboratory scale (ILS), pilot plant scale, and engineering development scale systems at the Idaho site. Recently, thermochemical activities were directed by two sequential National Technical Directors at INL.

The laboratory's role in thermochemical efforts has continued to expand, primarily through direct funding from the DOE-NE NHI, but also through continued internal investment in critical areas. The Laboratories continued internal investments from 2003 through the current year have been used to support strategic hires, develop staff skill sets, and increase hydrogen related equipment and instrumentation capabilities at INL.

In FY 2008, the NGNP project developed a technology development roadmap (TDRM) that included the thermochemical hydrogen production processes. With collaborative input from NHI, INL, and industry using a methodology developed by the National Aeronautics and Space Administration and Department of Defense, the technology readiness levels (scale of 1 to 10) were quantified. The activities needed to develop thermochemical processes from their current readiness level to commercial scale were identified, as well as activity sequences and performance criteria for progression through each readiness level. The report was published in FY 2009 and updated to reflect the changes to the TDRM introduced by reducing the reactor outlet temperature to 750°C.

Through these efforts, the laboratory now has a significant pool of personnel with experience and expertise in thermochemical water-splitting technologies. In parallel, the laboratory has expanded the equipment and facilities needed to perform this R&D and to demonstrate these technologies on both a pilot scale and engineering scale.

3.1 Thermochemical Cycles

The NHI has been investigating several options for producing hydrogen from water using nuclear energy. These options fall into three categories; high-temperature steam electrolysis, pure thermochemical cycles that use only thermal energy, and hybrid thermochemical cycles that use a combination of electrical and thermal energy. DOE-NE is funding three thermochemical technologies in FY 2009: the S-I cycle, HyS cycle, and copper chlorine cycle. However, only the S-I and HyS thermochemical cycles are sufficiently advanced to merit testing at scales larger than laboratory scale.

The S-I cycle, depicted in Figure 1, is a pure thermochemical cycle. It employs three coupled chemical reactions: two are endothermic and the other is exothermic. The HyS cycle, shown in Figure 2, includes one endothermic chemical reaction and one electrolysis reaction (the electrolytic coupling of SO_2 and water to form sulfuric acid and produce hydrogen). These cycles are being developed internationally and are of great interest to the United States, Japan, South Korea, Italy, France, Canada, and South Africa.

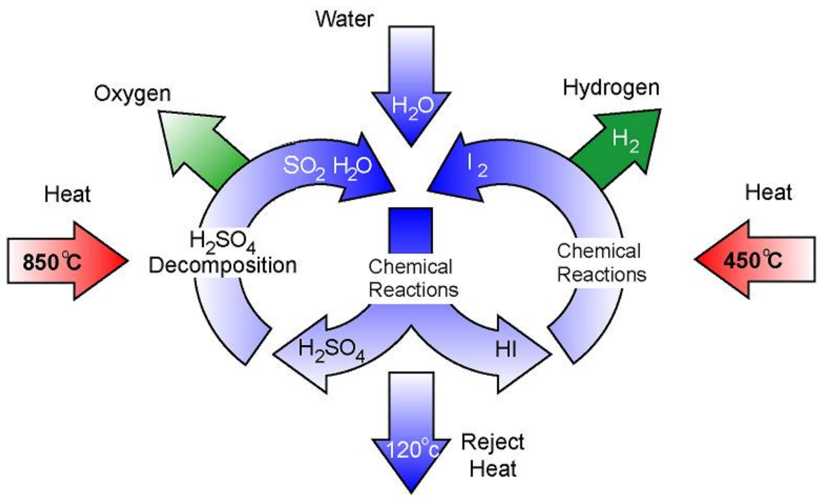

Figure 1. S-I thermochemical cycle.

One of the significant shortcomings of the S-I process is the requirement to recycle large quantities of liquid iodine to drive the separation of iodine compounds from sulfuric acid in the main, or Bunsen, reaction. INL is aware of work at the ENEA Casaccia Research Center in Italy to develop a polymeric adsorption based separation technology that eliminates the need for excess iodine in the Bunsen reaction.[1,2] This advance is extremely significant since it eliminates the need for large inventories of iodine and for extractive distillation or reactive distillation of the $HI/I_2/H_2O$ stream entering the iodine decomposition section. Demonstration of reactive distillation has been identified as a requirement for achieving a technology readiness level that allows prediction of successful scale-up to commercial operations.[3] INL has shown that efficient dewatering of HI, beyond azeotrope levels, can be accomplished using pervaporation[4,5,6,7] and that equilibrium levels of HI decomposition can be accomplished catalytically even in the presence of water.[8] The efficiency of the cycle can be further improved by increasing the temperature of the exothermic Bunsen reaction to 120°C and using that heat to dewater both sulfuric acid and HI streams [Refs. 6 and 7], an advance that not only adds appreciably to the cycle's efficiency, but also has a considerable impact on reducing corrosion rates that would otherwise take place at boiling and condensing acid/metal interfaces.

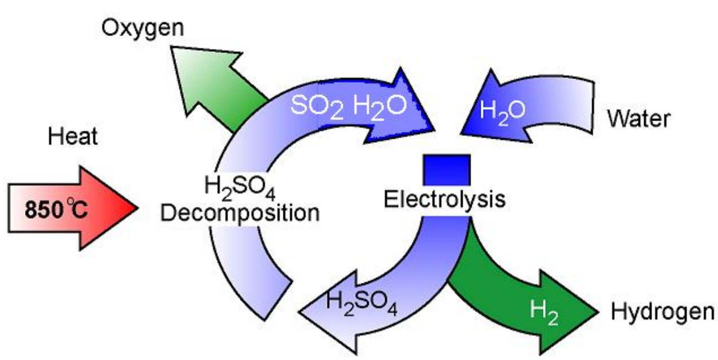

Figure 2. Hybrid sulfur-electrolysis cycle.

South Korean efforts to develop the HyS cycle found that ionic liquids can be used to efficiently remove the trace quantities of SO_2 that could potentially cross over the sulfuric acid electrolyzer membrane.[9] Alternatively, energy efficient, solid-phase adsorbents could be employed to provide a contaminate free hydrogen product. INL has determined that by increasing the electrolyzer temperature to 120°C, the energy from the over potential used to drive the electrochemical reaction can be captured and used within the cycle to drive water removal processes. Likewise, any shunt currents that develop in the electrolyzer can be recovered as heat to drive separation processes. As with the S-I cycle, the use of low temperature heat in conjunction with pervaporation could significantly add to the cycle's process efficiency and reduce corrosion problems.

3.2 Requirements to Advance Thermochemical Cycles

The institution selected to lead and conduct thermochemical research, development, and demonstration must have the required staff skill sets, equipment, facilities, and infrastructure to advance thermochemical cycles.

In general, the staff skill set to advance either the S-I or HyS cycles must include chemists, material scientists, chemical engineers, mechanical engineers, nuclear engineers, program managers, technicians, and craftsmen who can solve the challenging issues relative to the harsh environment associated with thermochemical water-splitting cycles.

The specific skills require (1) material scientists and engineers with the ability to develop and evaluate material compatibility and stability at high temperatures in corrosive environments under oxidizing and reducing (hydrogen) conditions and who can develop and design high-temperature heat transfer equipment; (2) catalyst scientists and chemical reactor design engineers with expertise in SO_2/O_2, H_2SO_4/H_2O, H_2SO_4/HI, $I_2/HI/H_2O$ separations, including scale-up of equipment to carry out those separations; and, if the HyS cycle is selected, (3) scientists and engineers with skills related to electrochemistry and proton exchange membrane (PEM)-based electrolysis.

Skilled engineering personnel are required to design and construct systems and facilities ranging from ILS to the engineering scale. These personnel include: chemical engineers with process simulation strengths; mechanical engineers with process equipment design skills and heat transfer design experience (nuclear and/or chemical engineers may also fill this need, depending on individual skills), applied material scientists who can recommend designs for process materials, civil engineers and power-based electrical engineers who can design the infrastructure for the facilities required to support the requisite levels of testing, and especially, persons with process control skills to enable the integration of the cycles. Further, systems engineering skills will be needed to enable facilities to be designed that use resources most efficiently. Other project personnel needed include those with successful project management experience, site permitting specialists, and Environmental, Health and Safety specialists.

The facilities required to advance S-I and HyS cycles differ slightly. In both cases, typical laboratory facilities will be needed to conduct research in areas such as catalysis, materials, and separation that still need development and/or improvement. Larger facilities and infrastructure are required to conduct the development and demonstration efforts that include an ILS unit, a pilot plant unit, and engineering scale demonstration such as those currently under consideration for the HYTEST program and component test capability (CTC).[10]

The S-I cycle has been partially demonstrated at the ILS level; however, the HyS cycle has not. Pilot scales are typically the scale at which integral demonstrations begin and the results inform the design for subsequently larger demonstrations. The thermochemical cycles will be sized to utilize 70 to 300 kW of primary heat to drive the cycle(s), which could produce up to 20,000 NL/hr of hydrogen [Ref 3]. The design basis for the engineering scale plant will be to utilize up to 6 MW of thermal and electrical energy (conservatively bounded) and produce hydrogen at approximately 425,000 NL/hr. Both the pilot plant and the engineering scale development systems should be heated from a high temperature (750–900°C) high-pressure (70–90 bar) circulating fluid system, employing a heat transfer fluid such as helium. Since the

S-I system has been mostly demonstrated at the ILS scale, work for that cycle might advance directly to the pilot plant scale. However, demonstration of reactive distillation or an equivalently efficient HI decomposition method should be demonstrated at the laboratory scale prior to integral pilot scale demonstration [Ref 3]. Facility requirements described in Section 4.6 conservatively bound both thermochemical cycles, changes in scale from discovery, auxiliary equipment needs, and conversion losses from converting electrical power to heat. Ultimately, the end state for this development would be use of up to 50 MW of primary heat to power a prototypic commercial scale facility.

Estimated infrastructure requirements for the S-I and HyS cycles were performed in 2004[11] and are summarized in Table 1. Briefly, facilities required to support an ILS project will need to provide 1,000 ft^2 of floor space and accommodate equipment up to 8 ft tall. Power requirements would be on the order of 500 kW. Deionized water will need to be provided at a rate up to 1 gpm, fresh water to 20 gpm, and waste water to the drain system could be up to 20 gpm. The facility must have a capability to vent up to 200 NL/hr of hydrogen and up to 100 NL/hr of potentially pure oxygen. Typically the ILS units are organized in a set of skids that are enclosed in Plexiglas. Each skid would need to be properly vented to remove any fugitive emissions or catastrophic release of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors.

The pilot scale projects should be housed in a facility that can provide approximately 5,000 ft^2 of floor space and accommodate a 20 ft tall vessel. Power requirements (thermal and electrical combined) would be on the order of 500 kW. Deionized water will need to be provided at a rate up to 1 gallon per minute (gpm), fresh water to 40 gpm, and waste water to the drain system could be up to 40 gpm. The facility must have a capability to vent or flare 20,000 NL/hr of hydrogen and 10,000 NL/hr of potentially pure oxygen. The pilot plant would not be enclosed, but would open within the facility. The facility would need to be properly vented to remove any fugitive emissions and catastrophic releases of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors.

Table 1. Approximate facility and utility requirements for thermochemical processes.

	S-I Cycle			HyS Cycle		
	ILS	**500 kW**	**5 MW**	**ILS**	**500 kW**	**5 MW**
Heating Load (electrical or fossil)	200 kW	500 kW	5 MW	156 kW	390 kW	3.9 MW
Electrochemical Load	0	0	0	44 kW	110 kW	1.1 MW
Power for Prime Movers	10 kW	20 kW	200 kW		60 kW	600 kW
Fresh water	1 gpm	1 gpm	10 gpm		1 gpm	10 gpm
Cooling	100 kW (20 gpm)	200 kW (40 gpm)	2 MW (400 gpm)		200 kW (40 gpm)	2 MW (400 gpm)
Waste Water System	1 gpm	1 gpm	8 gpm		1 gpm	8 gpm
Process Space Requirement						
No. of Vessels	—	23	23		22	22
No. of Processing Sections	4	3	3	3	3	3
Vessel Footprint		100 ft^2	400 ft^2		70 ft^2	310 ft^2
Plant Footprint (based on 10:1 ratio)	500 ft^2	1,000 ft^2	4,000 ft^2	500 ft^2	700 ft^2	3,100 ft^2
Access Area	400 ft^2	1,400 ft^2	3,000 ft^2	400 ft^2	1,000 ft^2	2,400 ft^2
Control System	100 ft^2	100 ft^2	500 ft^2	100 ft^2	100 ft^2	500 ft^2
Total Process Space Requirements	1,000 ft^2	2,500 ft^2	7,500 ft^2	1,000 ft^2	1,800 ft^2	6,000 ft^2
Tallest process vessel	8 ft	20 ft	40 ft	8 ft	12 ft	25 ft
Support Systems						
Feed Tanks		600 ft^2	3,000 ft^2		250 ft^2	1,000 ft^2
Waste Tanks		600 ft^2	3,000 ft^2		250 ft^2	1,000 ft^2
Water Purification and Storage		100 ft^2	500 ft^2		100 ft^2	500 ft^2
Cooling Tower		100 ft^2	500 ft^2		100 ft^2	500 ft^2
Off-Gas Scrubbers		100 ft^2	500 ft^2		100 ft^2	500 ft^2
Flare		100 ft^2	500 ft^2		100 ft^2	500 ft^2
Heat Source and Transfer Systems		100 ft^2	500 ft^2		100 ft^2	500 ft^2
Total Support Systems Space		1,700 ft^2	8,500 ft^2		1,000 ft^2	4,500 ft^2
Total Space Requirements	1,000 ft^2	4,200 ft^2	16,000 ft^2	1,000 ft^2	2,800 ft^2	10,500 ft^2

The engineering scale system would most likely be located outdoors, built on a concrete pad with a building that would house control systems, laboratory space and a dedicated maintenance shop. The requirements for the engineering scale demonstration were used as input to the requirement set for the CTC. Some variation is expected as the processes mature, and the requirements listed here were conservatively bounded. These requirements will be met by the CTC, either at dedicated INL facilities or locations evaluated as part of a CTC alternatives evaluation [Ref 10]. The overall facility footprint would cover approximately 16,000 ft^2 and accommodate a 40 ft tall vessel. A building with 1,500 ft^2 should be adequate to house control systems, laboratory space and a small maintenance shop. Power requirements would be on the order of 6.0 MW. Deionized water will need to be provided at a rate up to 10 gpm. The site should include a 400 gpm cooling tower with an anticipated waste water drain capacity of up to 100 gpm. The facility must have a capability to flare 6,000 NL/hr of hydrogen and safely vent 3,000 NL/hr of potentially pure oxygen. The pilot plant would not be enclosed but would require gas and liquid systems to safely collect and/or scrub any releases from the facility. The facility should also to be located in an area that could safely deal with fugitive emissions or catastrophic releases of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors.

4. INL CAPABILITIES

INL is a multiprogram national laboratory and only one of two engineering test- and evaluation-focused laboratories in the DOE complex. Over its 60 years of operations, the laboratory has had lead responsibility for development of codes and engineering responses to nuclear reactor failures, advanced processes for spent nuclear fuel reprocessing, low head hydropower production, geothermal power generation, advanced electric vehicle battery testing and evaluation, and nuclear waste treatment and processing. The laboratory has conducted a large number of complex engineering experiments including engineering materials irradiation and testing, large scale water infiltration subsurface injections, airport explosives detection, remote assay of large cargo containers, and simulation of nuclear reactor loss of coolant failures.

One of the primary attributes of the INL Site is its location in an unpopulated area in southeastern Idaho. With a land area of more than 890 square miles, it is ideally suited for hazardous concept testing and evaluation. The INL Site is situated on the Snake River Plain which has experienced extensive volcanic activity. This volcanic activity has created an extremely stable and almost vibration free environment. The INL Site is serviced by three major utilities and has access to ample amounts of electrical power, natural gas, and water. It has an extensive infrastructure of facilities, utilities, emergency services, fabrication equipment, transportation equipment and roads, and construction equipment, which is needed to support its diverse missions.

Two new test beds are planned at the laboratory. The hybrid energy test bed (or HYTEST, to be discussed later) program is designed to evaluate process operation and control issues associated with combinations of nuclear, renewable and or fossil energy systems. The CTC is intended to test large-scale heat transport components and systems for the NGNP and support testing needs of other programs requiring high temperature process heat. Development of the HYTEST program and the CTC are closely coordinated at the INL Site.

In addition to its test and evaluation facilities, INL has more than 200,000 ft^2 of laboratory research facilities where a wide range of applied research is performed in support of laboratory and national missions. As a consequence of this support, a wide range of technical disciplines are maintained, including biology, materials science, and physics. These laboratories house a wealth of equipment such as electron microscopes, advanced material test equipment, lasers, chemical reactors, and analytical instrumentation.

4.1 Thermochemical Development Compliments INL Programmatic Mission

INL's mission is to ensure the nation's energy security with safe, competitive, and sustainable energy systems and unique national and homeland security capabilities. To accomplish this, INL will be the preeminent nuclear energy laboratory with synergistic world-class, multiprogram capabilities and partnerships.

A key program at INL is the NGNP, wherein INL develops and implements technologies to commercialize a new generation of advanced nuclear plants, particularly high temperature gas-cooled reactor (HTGR) technology. This NGNP will supply clean, economical heat to generate electricity and clean burning hydrogen. NGNP will also supply source heat to domestically produce clean burning hydrogen and improve technologies for application to petrochemical and other industries.

INL has the best set of capabilities to demonstrate hydrogen production using nuclear heat. Its reputation for successfully leading collaborative efforts among industry, academia, and other laboratories gives INL the advantage for directing thermochemical hydrogen production R&D. INL has a reputation for directing work to institutions that can best accomplish the work regardless of location. In this way a variety of university, industry, and other laboratory capabilities combine to accomplish program objectives. Because thermochemical R&D compliments INL's overall mission, there are a number of complimentary programs that yield significant synergies. The following describes specific INL capabilities to support the development of thermochemical nuclear hydrogen production.

4.2 Laboratory Staff

The INL's staff is heavily oriented toward engineering; 18% of its approximately 4,000 personnel have engineering degrees and backgrounds. In addition to engineering capabilities, the laboratory has scientist, project managers, technicians, and skilled workers, such as machinists, that are available to support the NHI. Within the engineering staff, NHI applicable skills include chemical, materials, mechanical, construction, operation, and systems abilities. These backgrounds make up approximately 35% of the total engineering staff. INL also houses a scientific and research staff that performs applied research activities. Approximately 64 of these employees have scientific skills that apply directly to NHI development activities. INL has supported the NHI since 2003 in various programmatic and research efforts. In addition to the professional staff, INL has several hundred technical and skilled workers who have skills relevant to the NHI program and can be employed as needed.

As detailed above, INL has significant expertise in the areas needed to progress thermochemical processes from a laboratory concept to an operational prototype. It has more than 30 chemists with backgrounds aligned with technical needs associated with both thermochemical cycles and has related expertise associated with high temperature processing, steel and aluminum manufacturing, glass production, coal combustion, and high temperature fuel cell operation. INL has staff whom are specifically knowledgeable in the challenges associated with thermochemical hydrogen production, have existing capability in catalyst testing and development, and have a history of catalysts research for the NHI program. INL is working to develop durable catalysts for the sulfur-based cycles and has made extended duration evaluations of catalysts for the sulfuric acid decomposition reaction and the hydroiodic decomposition reaction.

INL uses its extensive materials engineering and science capabilities to develop and test new materials. Its scientist and engineers have been involved in developing corrosion resistant materials—primarily engineering alloys—for long-term storage of nuclear fuel, high temperature coal combustion boilers, and advanced high temperature fuel cells, making them uniquely suited to develop corrosion-resistant materials.

INL staff has thermohydraulic and two-phase heat transfer capabilities (advanced nuclear reactor technology) that include designing advanced heat exchangers and steam generators. This experience and capability is directly transferable to the NHI program.

INL staff has performed extensive catalysts research for the NHI program. It has tested and evaluated a number of catalyst formulations for long-term durability and sustained catalytic activity. INL has also performed extensive separations research for the NHI program and has extensive capabilities in the area of low temperature membrane separations, and the development of advanced membrane materials.

INL has been actively involved in a range of fuel cell development activities related to TC processes. These activities include the development of advanced materials for PEM and the design and operation of solid oxide fuel cells. In addition, INL is the lead laboratory for the electric vehicle battery evaluation program, which has supporting electrochemists and battery engineers who can technically assist with NHI activities.

INL has extensive experience related to development of experimental prototypes. The chemical engineers associated with the process technology organization have extensive experience in process simulation using computational models such as ASPEN II. A group of mechanical engineers associated with the Center for Modeling and Simulation and the NGNP program have extensive experience in modeling heat transfer and thermohydraulics. INL personnel also have extensive capabilities in systems engineering, human factors, process control, and man-machine interface design. Specially trained staff test and evaluate material properties and performance. This testing is achieved through advanced computational modeling and static and dynamic material tests.

INL has an extensive construction engineering and construction project management organization with skills that are routinely employed to complete facility construction and development of new and novel test fixtures, test beds, and laboratories. As an integral component of these construction capabilities, INL maintains experienced staff to evaluate environmental consequences. It has Safety and Health professionals who work with the programs to find ways of safely performing program activities. INL also maintains a team of environmental scientists who support development of all types of environmental impact documents and permit applications for both for INL Site and town activities.

One of the important features of being a multiprogram national laboratory is the ability to retain key skills during periods of uncertain funding. Historically, INL personnel have been deployed on a range of programs or projects. The staff is very aware of changes in funding for programs and has the ability to prepare proposals for projects that employ their unique skills. Further, INL has developed a range of federal and private customers who provide the laboratory with a diverse business mix that can employ a wide range of technical skills and expertise.

INL has access to a range of sources for hiring new or strategic staff. Battelle Energy Alliance (the INL manager) includes five national universities: North Carolina State, Massachusetts Institute of Technology (MIT), University of New Mexico, University of Wisconsin, and University of Idaho that have outstanding engineering schools and graduate programs. In addition to the contracted universities, INL is surrounded by universities that have good to outstanding engineering schools including Montana State University, Washington State University, Colorado School of Mines, Brigham Young University, and Utah State University. INL maintains a national and international staff recruiting organization that actively searches for top talent, key technical skills and early career scientists for filling key technical needs at the laboratory.

Finally, development and demonstration of the nuclear heat source driving the hydrogen process is being developed and demonstrated at INL. Process applications, typically integrating hydrogen production with the specific application, are being modeled and optimized by a team of INL mechanical, nuclear, and chemical engineers. Access to industrial partners who may require hydrogen production as part of their business model, as well as interface with NRC regulators dedicated to licensing of HTGRs, is unique to INL.

4.2.1 Staff with Direct Experience Relevant to NHI

The laboratory has hired and trained a staff with the specific skills required to carry out the NHI's mission. These persons include material scientists and engineers who can develop and evaluate material compatibility and stability at high temperatures in corrosive environments, under oxidizing and reducing conditions. The laboratory employs engineers and material scientists who can develop and design high-temperature heat transfer equipment. A group of catalyst scientists and chemical reactor design engineers reside at the laboratory. The laboratory employs scientists and engineers who specialize in separations and have skills for scale-up of equipment to carry out those separations. It also has scientists and engineers with skills related to electrochemistry, and PEM-based electrolysis.

The laboratory has a large body of staff with the required engineering skills to design and construct systems that range in scale from ILS to engineering scale facilities. This includes chemical engineers with process simulation strengths; mechanical engineers with process equipment design skills and engineers (multiple disciplines) with heat transfer design experience. INL supports applied material scientists and engineers who can provide design recommendations for process materials and the civil and power-based electrical engineers needed to complete the facilities for the plants. An especially important skill set at the laboratory includes process control engineers who can integrate the cycles. Further, the laboratory has systems engineers with the necessary skills to design plants that use resources most efficiently. The laboratory also has staff personnel with the necessary project skills, including successful project management experience, site permitting specialists, and Environmental, Health and Safety specialists.

INL's chemical engineering staff has modeled many chemical processes over the years, developing extensive capability in this area. Aspen Plus, a state-of-the-art chemical process simulator, is used for most modeling projects requiring rigorous heat and material balances. However, other process simulators are available and used frequently at INL. Honeywell's UniSim software, routinely used to model petrochemical processes, includes dynamic simulation capabilities. Bryan Research & Engineering's ProMax software is also used because of its unsurpassed ability to accurately model sulfur processes. For modeling fossil power plant cycles, Thermoflow's GTPro software is available and used routinely at INL.

In the first half of 2005, an effort was undertaken at INL to model the S-I thermochemical cycle for production of hydrogen. A steady-state model of the process was developed using Aspen Plus. In some ways, development of this model duplicated work previously performed by General Atomics, but at that time, General Atomics had developed separate Aspen Plus models for the individual process sections: recycle and acid generation, sulfuric acid concentration and decomposition, and hydrogen iodide concentration and decomposition. In contrast, a goal in developing the INL model was to couple all three process sections into a single process model. Building a model of the entire process made it possible to investigate how changes in one part of the process would impact performance in the other two process areas. Thermodynamic properties and equations of state for the model used only built-in Aspen Plus databanks and methods. This approach identified and confirmed the need for improved modeling methods previously identified by General Atomics—specifically for accurately modeling hydrogen iodide chemistry and sulfuric acid behavior under extreme conditions. Shortly after completion of the initial model, decisions were made to shift work on the S-I cycle away from INL to other sites; hence, planned improvements to the model were never pursued. However, INL is currently developing integrated process models for coupling hydrogen processes to the HTGR in multiple configurations and optimization of integrated models is planned into FY 2010.

In addition to process modeling expertise, INL excels at chemical reactor modeling and design. Outotec's HSC Chemistry is routinely used to investigate equilibrium constraints for a given chemical system. When kinetic constraints must be considered for a reacting system, INL has experience using Reaction Design's Chemkin software. For modeling of reaction kinetics, INL also has expertise using the open-source code Cantera. Fluid dynamics are also an important consideration in chemical reactor design. INL has extensive experience with the major commercial computational fluid dynamics (CFD) packages including FLUENT and STAR-CD. INL also has expertise using specialized CFD codes such as NPHASE, which is currently in use at INL to simulate Fischer Tropsch synthetic fuel production using a slurry bubble column reactor.

4.3 INL Materials Characterization Capabilities

INL has been active in R&D on high temperature materials for nuclear generation of hydrogen for a number of years. An internally funded project characterized interactions between high temperature materials and environments representative of high temperature decomposition of sulfuric acid. Experiments were carried out at high temperature and pressure to examine the advantages of silica forming materials compared to more typical chromia forming high temperature alloys.

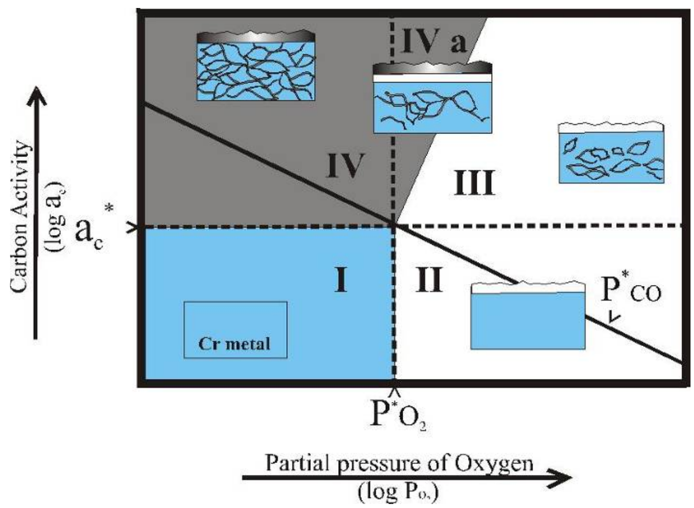

Figure 4. NGNP Materials interaction.

As a result of work on the NGNP project, INL developed considerable testing capabilities for the high temperature materials that will be used for the heat transfer loop between the primary reactor circuit and the hydrogen generation plant. The mechanical properties and environmental resistance of Inconel 617, Haynes 230, and Incoloy 800H are being characterized in laboratory air and under prototypical NGNP helium chemistries. Six servo-hydraulic test frames are being used for creep-fatigue testing; including one with the capability of testing under controlled chemistry. Detailed experimental studies of microstructure development under creep conditions are being carried out in collaboration with Boise State University. Experimental studies are also being done in collaboration with Argonne National Laboratory to develop a well characterized compilation of creep data that is used to develop constitutive models in collaboration with Oak Ridge National Laboratory (ORNL).

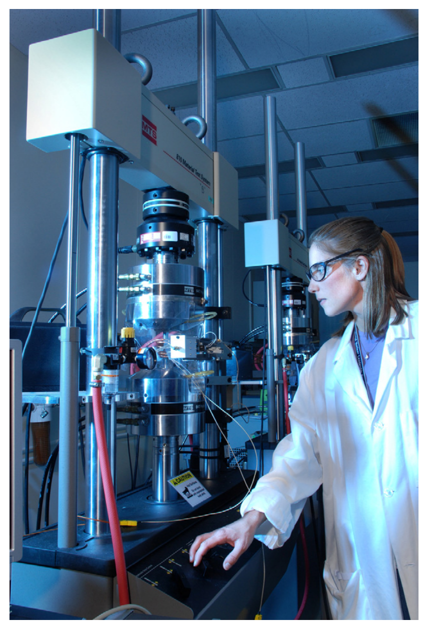

Figure 3. Creep-fatigue testing of high temperature Ni based alloys for NGNP heat transfer loop.

The NGNP work at INL is complemented by ongoing collaboration with an Electric Power Research Institute working group on creep fatigue and an ASTM Standards round-robin test activity to validate a new creep-fatigue standard for which INL has provided input in the draft stage. Creep-fatigue testing is also being conducted at INL (see Figure 3) in collaboration with ORNL on advanced austenitic alloys for fast spectrum reactors through the Advanced Fuel Cycle Initiative program.

Fundamental studies of environmental interaction are being carried out at INL in collaboration with University of Michigan, MIT, and the CEA Laboratory for Non-Aqueous Corrosion at Saclay, France. These studies include microstructural evaluation after exposure to prototypical NGNP chemistries as well as studies of the impact of environmental interaction and aging on mechanical properties. Phenomenological models to predict the nature of interaction between chromia formers and NGNP helium chemistries as a function of oxygen partial pressure and carbon activity of the gas have been developed as a result of this work. Fundamental studies of the potential for brittle failure as a result of stress assisted grain boundary oxidation in the heat exchanger alloys are being carried out in collaboration with MIT. The potential for brittle failure in steam generators that might be incorporated into the heat transfer loop are being examined in collaboration with Argonne National Laboratory.

Schematic representation of the interaction of prototypical NGNP primary coolant chemistries with nickel based Cr_2O_3 forming alloys is shown in Figure 4. Region I represents reduction of the chromia scale to Cr metal and decarburization; regions II and III represent the most stable condition—formation of a protective chromia scale; region IV represents bulk carburization due to loss of the protective scale and consequent brittle behavior.

INL's involvement with materials research for thermochemical hydrogen cycles began in FY 2003 through internal laboratory funding. The focus of that work was to evaluate the corrosion resistance of materials to environments expected in the S-I thermochemical hydrogen cycle. A testing program was devised that consisted of a screening –type evaluation using boiling sulfuric acid (~250°C) at atmospheric pressure. Commercial alloys exhibiting corrosion resistance to this environment were then tested under conditions closer to those expected in the S-I cycle, namely liquid, concentrated sulfuric acid at temperatures up to 411°C and 500 psig. A static corrosion system was developed to safely perform tests for extended periods of time (>300 hours) as shown in Figure 5. INL is also a collaborator with researchers at the Missouri University of Science and Technology under a National Energy Research Institute program to develop advanced Ni-Si alloys for use in the S-I cycle. The goal of the project is to develop a high silicon alloy that will develop a silicon dioxide protective surface layer during operation and be suitable for virtually all components in the sulfuric acid decomposition section of the S-I cycle. The alloy will also have adequate ductility for forming piping and other components.

A closed loop, dynamic materials test system for HTGR materials has also been developed to evaluate the high temperature corrosion behavior of materials in tightly controlled environments—feedback control of impurity levels down to the ppm level—at temperatures up to 1,000°C and exposure times exceeding 500 hours. These systems demonstrate that INL is capable of developing complex testing systems to evaluate materials degradation resistance to various aggressive environments.

INL also has expertise in thermal spray coatings for corrosion protection as well as joining expertise (fusion welding as well as friction stir welding). INL's materials characterization capabilities include optical metallography, scanning electron microscopy, transmission electron microscopy, x-ray diffraction, and various surface analysis techniques for identifying corrosion products.

4.4 INL Capabilities for Integrated Laboratory Testing

Through the high-temperature steam electrolysis effort, the laboratory has developed a group of technologists with expertise relevant to high-temperature hydrogen production cycles as well as skills and instrumentation specifically relevant to electrochemistry.

INL's staff built an experimental stand that is capable of performing a variety of experiments on the production of hydrogen. The ILS facility, which is located in Bay 9 of the Bonneville County Technology Center (BCTC) and shown in Figure 6, was initially used for testing high temperature electrolysis modules in 2007 and 2008. The components numbered in Figure 6 are defined in Table 2.

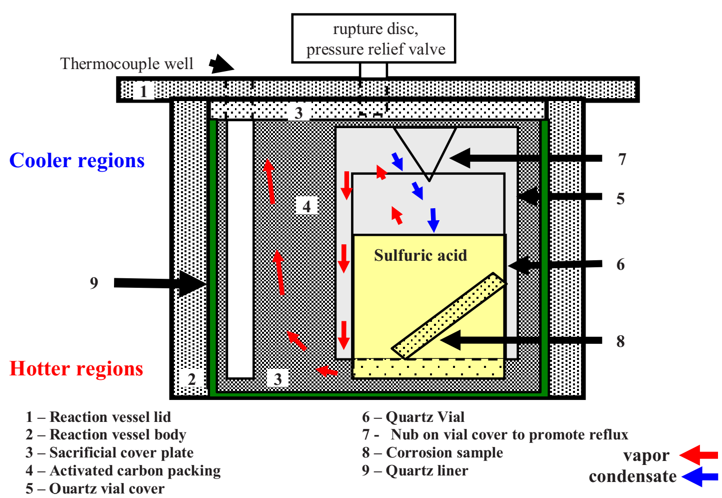

Figure 5. Elevated temperature, pressurized sulfuric acid testing apparatus.

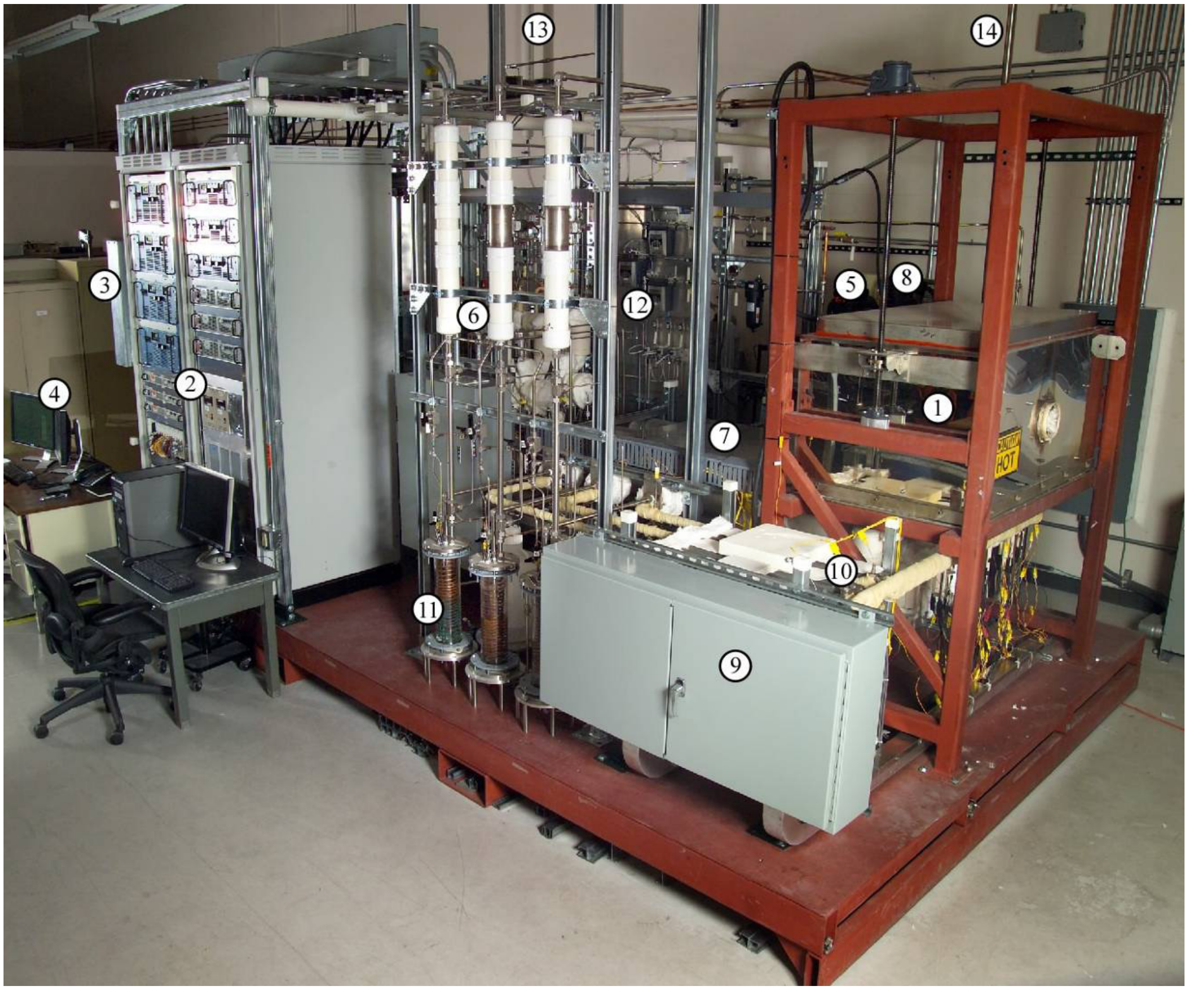

Figure 6. Right side view of the INL ILS facility, with major components labeled.

Table 2. Identifiers for Figure 4.

1	Hot zone enclosure lid	8	Air compressor
2	Power supply and instrument racks	9	Patch panel
3	Electrical distribution cabinet	10	Product finned cooler
4	Data acquisition and control monitors	11	Steam condenser
5	Deionized water system	12	Mass flow controllers
6	Steam generator	13	H_2 vent
7	Steam and H_2 superheaters	14	Air and O_2 vent

The ILS consists of a skid, 10 × 16 ft, to which all of the components have been bolted. The skid was designed so that, should it be necessary to move the experiment, the skid could be lifted by a heavy-duty fork lift using the rectangular channels visible below the steam condensers (#11). Inputs to the ILS include 3-phase 480 VAC, city water, and compressed air. Outputs are hydrogen (#13), air/oxygen (#14), and cooling water to a floor drain. The skid contains a 480/208, 120, 75 kVA transformer, a reagent water deionization system and an auxiliary air compressor. The racks (#2) contain 13 power supplies for a variety of ranges (0–100 V and 0–100 A). All of the power supplies are computer controlled.

The hot zone (#1) is ~0.5 m x 0.5 m x 1.0 m (internal) and is capable of attaining 900° C through the use of its internal heaters in the lid. The lid can be raised by a motorized screw drive for access to the hot components of the experiment. Gas, power and instrument connections are made through the baseplate, which can be changed, depending on the experiment. The steam generators/superheaters are capable of heating water/steam or air to 850° C.

During the HTE ILS experiment, hydrogen was produced in three independent trains, each consisting of mass flow controllers, water metering equipment, steam generator/superheaters, air heaters, heat recuperators, electrolytic cells, coolers, condensers and dew point meters. The experiment operated 24/7 for 45 days under Labview software for both control and data logging. The experiment required 20 feedback loops.

The 6 years of experiments on the use of solid oxide cells for electrolysis have produced an inventory of skills and equipment for the operation of high temperature experiments and the instrumentation of electrolytic processes that may be needed in the development of other thermochemical processes.

Bay 9 is equipped with a system to monitor concentration of hydrogen, CO, CO_2, and oxygen above the normal atmospheric concentration of 21%. The monitoring system setpoints are shown in Table 3.

Table 3. Alarm set points for industrial gases in the INL NHI Laboratory.

Gas of Interest	Basis for Set Point Values[a]	Initial Warning Alarm Set Point (ppm)	Evacuation Alarm Set Point (ppm)
Hydrogen	Flammability (10% and 25% of LFL)	4,000	10,000
Carbon dioxide	Toxicity (50% and 100% of TLV)	2,500	5,000
Carbon monoxide	Toxicity (50% and 100% of TLV)	13	25
Oxygen	Flammability (OSHA enriched O_2 value of 23.5%)	225,000	235,000

a. LFL = lower flammable limit
TLV = threshold limit value
OSHA = Occupational Safety and Health Administration

4.5 Hybrid Energy Systems (HYTEST) Capability

INL is planning to build a complex of integrated energy research, development, testing, and demonstration resources to support hybrid energy systems development and testing ranging from laboratory scale to commercialization. Referred to as HYTEST, these facilities and resources will provide multiscale research, testing, and demonstration operations to develop and demonstrate expanded uses of nuclear energy and hydrogen generation and integration with renewable and fossil energy. The complex of facilities will include the ILS, bench scale, pilot scale, and engineering scale activities. The progressively larger reconfigurable and flexible testing scales will each contain the necessary utilities, instruments, monitors, controls, safety protection, and waste management services to support rapid setup and testing of components operating in an interconnected system. Thus, HYTEST will expedite the process of transforming energy technologies from breakthrough concept through development and deployment to the marketplace, thereby reducing investment costs and programmatic risk.

INL HYTEST facilities will be established around five platforms that group technologies for systems integration: Feedstock Processing, Energy Integration, Energy Storage and Product Synthesis, By-Product Management, and Systems Integration, Monitoring, and Control. Hydrogen production and use is a crucial element in each of these platforms. For example feedstock processing includes demonstration of hydrotreatment and hydrocracking of biomass or fossil fuels pyrolysis oils. Energy storage includes processes that generate and store or use hydrogen to produce higher value chemicals. In addition, by-product management concepts are keying on the use of hydrogen to recycle carbon dioxide (CO_2) back to fuel. Consequently, HYTEST facilities are being designed to expressly include hydrogen generation, which includes the integration of heat cycles that will serve as surrogates and represent the heat produced from an HTGR. Table 4 illustrates the correlation between desired hydrogen production rates, and integrated gasification and product synthesis for INL HYTEST operations.

The proposed HYTEST scales align with the National Hydrogen Initiative Roadmap for testing and demonstrating high temperature steam electrolysis and high temperature thermochemical production cycles. For example, lab-scale testing will be located in the same test bay as the high temperature steam electrolysis ILS. HYTEST can also receive and compress the hydrogen provided by the ILS thermochemical test setup (*ca.* 100 NL/hr) to the feed conditions necessary for production of synthetic fuels. Product generation can be reduced to match this flow while performing an integrated hydrogen-synthetic fuels generation demonstration. Similarly, the pilot scale thermochemical pilot plant test skid (*ca.* 600 NL/hr) matches the requirement for the 1 gal/day bench-scale HYTEST operations.

Table 4. Correlation between desired hydrogen production rates and integrated gasification and product synthesis for INL HYTEST operations.

HYTEST Scale	Liquid Fuels Production Rate		Total Hydrogen Feed Rate		HYTEST Facility
Lab	1 L/day	~1 quart/day	140 NL/hr	0.27 kg/day	BCTC
Bench	4 L/day	~1 gal/day	560 NL/hr	1.1 kg/day	IEDF
Small Pilot	156 L/day	1.0 bbl/day	22 Nm^3/hr	43 kg/day	IEDF or PDU
Large Pilot	~31 m^3/day	200 bbl/day	4,400 Nm^3/hr	8,500 kg/day	PDU or CTC
Engineering	~310 m^3/day	2,000 bbl/day	44,000 Nm^3/hr	85,000 kg/day	Commercial demonstration

The pilot scale thermochemical unit (*ca.* 6,000 NL/hr) will “ideally” support the operation of a 1 bbl/day synthetic fuels column planned for installation in the INL Engineering Design Facility (IEDF) or in small pilot scale HYTEST facility that is currently being planned. IEDF HYTEST operations will likely be supported by a biomass gasifier, a tailgas reformer, gas separations, and synthetic fuels production integrated test. Hence, the hydrogen produced by the thermochemical skid could provide the hydrogen addition needed to avoid CO shift. The integrated components will demonstrate the lowest achievable carbon fuel standards for transportation fuels. Similarly, the demonstration-scale thermochemical hydrogen mock-up “ideally” matches the make-up hydrogen needed to operate a 200 bbl/per day synthetic fuels reactor in HYTEST.

INL has already committed funding to build-up the indicated HYTEST facilities. Approximately $300,000 of program development is being spent in FY 2009 to support HYTEST planning and preparation. Technical leads for the five platforms have worked with management and a technical steering council in planning and preparing for INL HYTEST activities. Three laboratory research projects totaling

$400,000 were awarded in FY 2009 to establish and commence laboratory scale HYTEST studies at the BCTC in proximity of the high temperature steam electrolysis ILS hydrogen skid. Commencing in FY 2010 over $2,000,000 per year of laboratory-directed research funding will be directed to the design, setup, and execution of HYTEST lab-scale and bench-scale experiments. All of these studies may interface with and use the hydrogen produced by thermochemical test skids.

INL further committed $1,250,000 to the design and establishment of a HYTEST project at the IEDF. This project will set up over 5,000 ft^2 of high-bay space with an operator control room, structured-steel supports, flammable gas compressors, heating and ventilation, emissions control, natural gas, and utilities necessary to support HYTEST activities. An additional $1,200,000 project request is being advanced to support the setup of an expandable high-temperature gas circulation loop and biomass hydrothermal gasification loop. The procurement of a 1 bbl/ day slurry bubble column for fuel synthesis is also being considered for FY 2009. All of these activities will require a source of hydrogen that could be supplied by concurrent setup and operation of a hydrogen generation test loop. A high temperature helium heat source that could be used for the hydrogen generation test unit is included in the facility operations basis. The hydrogen generation skid would benefit from the established utilities and monitoring and controls station that will be equipped to support multiple independent or coupled test operations. In lieu of such a capability, the program will be relegated to supply hydrogen from a standard low-temperature water electrolysis skid, or from high-pressure merchant hydrogen tube trailers.

Finally, conceptual plans are underway for the HYTEST pilot plant. INL is seeking to construct a small pilot scale facility that can support larger scale hybrid energy system integration testing. A request for Expressions of Interest has been issued to potential facility providers. Technical and functional requirements are being developed for this facility. The planning basis includes the setup and concurrent testing of a thermochemical hydrogen generation loop.

4.6 Physical Facilities

Successful demonstration of thermochemical hydrogen production technologies requires adequate facilities at various scales and with varied capabilities. Three levels of integrated cycle demonstration are needed including ILS project(s), a pilot scale project, and an engineering scale demonstration. Because each thermochemical process has different requirements to pass from one scale to the next, and because each successful demonstration will inform the design for the next scale, sizes for the physical facilities in this section are intended to conservatively bound the facility needs as they are understood now. This provides adequate assurance that discovery as the technologies mature will not result in an undersized capability that will hinder further development.

The NGNP Project plans to demonstrate components, systems and subsystems as outlined in the TDRMs. The TDRMs include demonstration plans for the thermochemical hydrogen production processes and outline an integrated approach to fabricating progressively larger demonstrations. The following specific demonstrations are planned:

1. Static tests of heat transport components (small scale demonstration #1 [SSDT-1]). Testing of NGNP components will include component and material testing specific to the thermochemical cycles.
2. Once-through dynamic tests of heat transport components (small scale demonstration #2 [SSDT-2]). Testing of NGNP components will include component testing specific to the thermochemical cycles.
3. Pilot scale environmental loop for long-term testing of small heat exchanger and steam generator sections and testing of coupled process applications such as hydrogen production processes (small scale demonstration #3 [SSDT-3]). The statement of work for design of an environmentally controlled loop is currently being finalized with the intent of completing fabrication in late FY 2010

as part of NGNP. The loop will be capable of supplying process heat to the leading hydrogen production processes, including thermochemical cycles.

4. Engineering scale testing of heat exchanger and steam generator sections and engineering scale testing of coupled process applications such as hydrogen production processes. Pending the outcome of an alternatives evaluation for the CTC, this testing is anticipated to occur in a component test facility constructed initially for the NGNP and subsequently serving development of hybrid energy systems as part of the HYTEST program.

As the systems and technologies mature, modification of scaling and subsequent sizing may be altered. Still, it is anticipated that NGNP and thermochemical cycle development can be closely integrated to manage the informed changes in test plans resulting from testing. Design and fabrication of these test capabilities is being closely integrated with the HYTEST program.

4.6.1 Integrated Laboratory Scale Facilities

Facilities required to support an ILS project will need to provide 1,000 ft^2 of floor space and accommodate equipment up to 8 ft tall. Power requirements would be on the order of 500 kW. Deionized water will need to be provided at a rate up to 1 gpm, fresh water to 20 gpm, and waste water to the drain system could be up to 20 gpm. The facility must have a capability to vent 200 NL/hr of hydrogen and 100 NL/hr of potentially pure oxygen. Typically the ILS units are organized in a set of skids that are enclosed in Plexiglas. Each skid would need to be properly vented to remove any fugitive emissions or hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors. Facilities that can support ILS projects are shown in Table 5. Although individual laboratories are shown many of them can be combined to support a single project.

Table 5. Potential ILS Facilities

Building	Building Name	Room	Square Ft.	Ceiling Height
New	Research and Education Lab	various	13,400	12 to 14
New	Process Demonstration Unit	multiple	Up to 60,000	Up to 40
New	Component Test Capability	multiple	TBD	TBD
IF-603	IRC Laboratory Building	B104	1,690	32
IF-603	IRC Laboratory Building	B103	1,303	≥ 8
IF-605	Energy Storage Technology Lab	101	1,308	≥ 8
IF-605	Energy Storage Technology Lab	102	2,740	≥ 8
IF-613	North Boulevard Annex	32	1,299	16
IF-613	North Boulevard Annex	13	2,702	16
IF-613	North Boulevard Annex	40	2,192	16
IF-615	May Street South	104	1,427	≥ 8
IF-615	May Street South	105	2,455	≥ 8
IF-627	System Analysis Facility	117	1,362	≥ 8
IF-638	IRC Physics Laboratory	115	3,004	≥ 8
IF-639	North Holmes Laboratory	LAB J-1	3,176	≥ 8
IF-651	North Yellowstone Laboratory	114-1	1,469	12
IF-657	INL Engr Demonstration Facility	E1,E2	1,311	30
IF-657	INL Engr Demonstration Facility	E3, E4	1,296	30
IF-657	INL Engr. Demonstration Facility	W2 & 3	1,598	41
IF-665	Center for Advanced Energy Studies	116	2,359	≥ 8
IF-665	Center for Advanced Energy Studies	212	1,272	≥ 8
IF-670	Bonneville County Technology Center	9	1,847	21
IF-670	Bonneville County Technology Center	5	2,179	21
IF-670	Bonneville County Technology Center	2	2,126	21
IF-670	Bonneville County Technology Center	1	2,144	21
IF-670	Bonneville County Technology Center	3	2,097	21
IF-670	Bonneville County Technology Center	8	2,114	21
IF-670	Bonneville County Technology Center	7	2,112	21
IF-670	Bonneville County Technology Center	6	2,835	21
IF-675	PINS Laboratory	100, A-C	3,806	≥ 8
CF-622	Multicraft Shop #2 and High Temp Lab	100	5,331	≥ 8

The most likely facilities to support ILS testing are shown below.

IF-New
Research and Education Laboratory

Capabilities

- 40,000 ft2 of Multipurpose Labs

Activation Year

Begin Construction 2009

Complete Construction 2011

IF-605
Energy Storage Technology Laboratory

Capabilities

- Offices
- Battery Laboratory

Programs

- Energy Storage & Transportation Systems

Bldg Gross
5,160 ft^2

Annual Lease
INL Owned

Activation Year
1984

IF-603
IRC Laboratory Building

Capabilities

- Electronic Laboratories
- Wet Laboratories
- Bio-Wing

Programs

- Biological Systems
- Energy Resource Recovery
- Energy Efficiency

Bldg Gross 112,380 ft2

Activation Year 1984

IF-613
North Boulevard Annex

Capabilities

- Robotics Laboratories

Programs

- Robotics & Intelligent Systems

Bldg Gross 14,201 ft2

Activation Year 1963

IF-615
May Street South

Capabilities
- Industrial Technology Laboratory
- Spray Forming

Programs
- Energy Efficiency & Industrial Technology

Bldg Gross 6,161 ft2

Activation Year 1960

IF-638
IRC Physics Laboratory

Capabilities
- Offices
- Applied Physics Laboratory

Programs
- Nuclear Science & Engineering

Bldg Gross
7,767 ft^2

Annual Lease
INL Owned

Activation Year
1991

IF-627 (SAF)
System Analysis Facility

Capabilities
- Secure Offices
- Electronics Laboratory

Programs
- Special Programs

Bldg Gross
11,525 ft^2

Annual Lease
INL Owned

Activation Year
1988

IF-651
North Yellowstone Laboratory

Capabilities
- Electronic Laboratories Glass Shop
- Storage

Programs
- Material Science & Engineering

Bldg Gross
8,000 ft^2

Activation Year
1984

IF-639
North Holmes Laboratory

Capabilities
- Machine Shop
- High Bay

Programs
- Nuclear Nonproliferation

Bldg Gross
22,030 ft^2

Activation Year
1960

IF-657
INL Engineering Demonstration Facility

Capabilities
- High Bay Laboratories

Programs
- Energy Systems & Technologies
- Nuclear Science & Engineering
- Special Programs

Bldg Gross
8200 ft^2

Annual Lease
INL Owned

Activation Year
1995

IF-665 (CAES)
Center for Advanced Energy Studies

Capabilities
- Offices
- Visualization Laboratories
- Radiological Laboratories

Programs
- University Collaboration
- Fundamental & Applied Energy Research

Bldg Gross 38,500 ft2

Activation Year 2008

IF-675
PINS Laboratory

Capabilities
- Training Laboratory

Programs
- Nuclear Nonproliferation Army Funded

Bldg Gross
6,500 ft^2

Activation Year 2007

IF-670 (BCTC)
Bonneville County Technology Center

Capabilities

- Centrifuge Laboratory
- High Temperature Laboratory
- Electronics Laboratories

Programs

- Energy & Natural Resource Mgmt
- Nuclear Science & Engineering
- Special Programs

Bldg Gross 19,504 ft2

Activation Year 2000

4.6.2 Pilot Plant Scale Facilities

Pilot scale projects will require approximately 5,000 ft^2 of floor space and accommodate up to a 20 ft tall vessel. Power requirements would be on the order of 600 kW. Deionized water will be provided at a rate up to 1 gpm, fresh water to 40 gpm, and waste water to the drain system could be up to 40 gpm. The facility must have a capability to vent or flare 20,000 NL/hr of hydrogen and 10,000 NL/hr of potentially pure oxygen. The pilot plant would not be enclosed but open within the facility. The facility would need to be properly vented to remove any fugitive emissions or hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors.

Potential sites for the pilot plant would include the combined space listed for the ILS above and would also include the facilities listed in Table 6. Process heat from SSDT #3 would be used to provide thermal input to the process. A conceptual floor plan for the process demonstration unit (PDU) proposed as part of the HYTEST program is shown in Figure 7.

Table 6. Potential Pilot Plant Facilities

Building No.	Name	Room	Square Ft.	Ceiling Height
IF-670	Bonneville County Technology Center	BAY 6,7,8	7,061	21
New	Research and Education Lab	various	13,400	12 to 14
CF-622	Multicraft Shop #2 & High Temp Lab	100	5,331	20
New	Process Demonstration Unit	various	Up to ~ 60,000*	Up to 40

* Up to 13,000 ft^2 dedicated to thermochemical hydrogen process demonstration

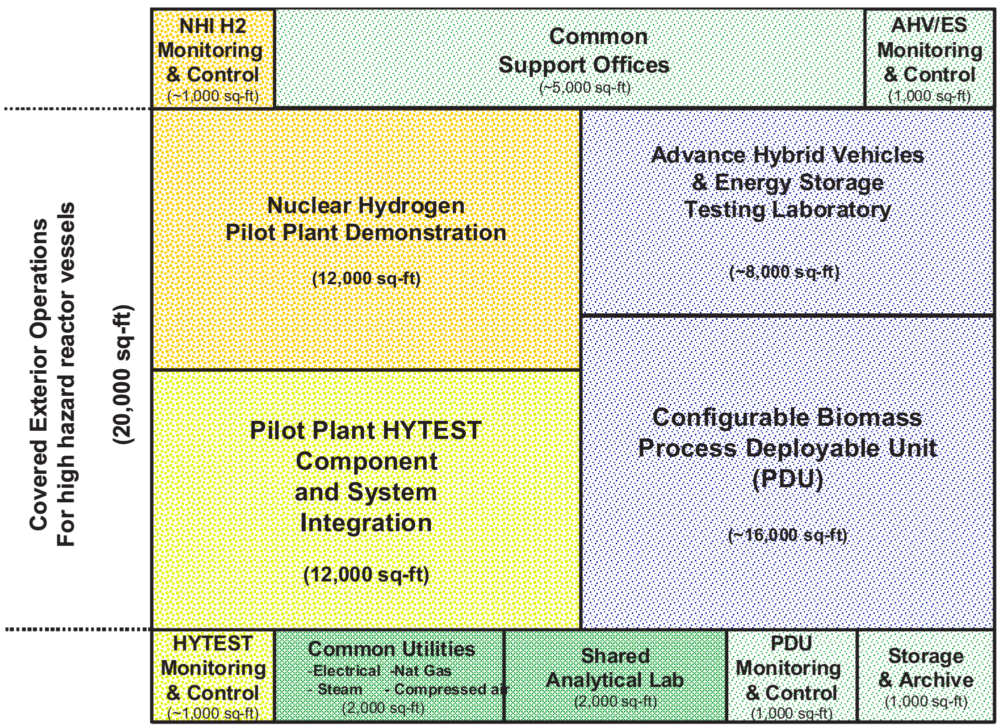

Figure 7. Conceptual floor plan for proposed PDU facility.

4.6.3 Engineering Scale Demonstrations Projects

Engineering scale demonstrations will likely be located outdoors and built on a concrete pad, with a building that would house control systems, laboratory space and a dedicated maintenance shop. The overall facility footprint would cover approximately 16,000 ft^2 and accommodate a 40 ft tall vessel. A building with 1,500 ft^2 should be adequate to house control systems, laboratory space and a small maintenance shop. Power requirements would be on the order of 6 MW. Deionized water will need to be provided at a rate up to 10 gpm. The site should include a 400 gpm cooling tower with an anticipated waste water drain capacity of up to 100 gpm. The facility must have a capability to flare 425,000 NL/hr of hydrogen and safely vent 210,000 NL/hr of potentially pure oxygen. The engineering scale demonstration would not be enclosed but would require gas and liquid systems to safely collect and/or scrub any releases from the facility. The facility should also to be located in an area that could safely deal with fugitive emissions or hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor for either cycle. The S-I cycle would also need venting to control emissions of HI and I_2 gases and vapors.

Candidate locations are based on the potential to locate one or more of the engineering-scale demonstration processes at a single site and be able to accommodate scale-up of a given hydrogen technology to a maximum of 50 MW demonstration plant. These requirements have been incorporated in evaluations and planning for the NGNP CTC. A conceptual lay-out of the CTC (the SI process demonstration is identified, but HyS process demonstration could be substituted in the same location) and aerial photographs of the proposed locations are shown in the Figures 8–10 below.

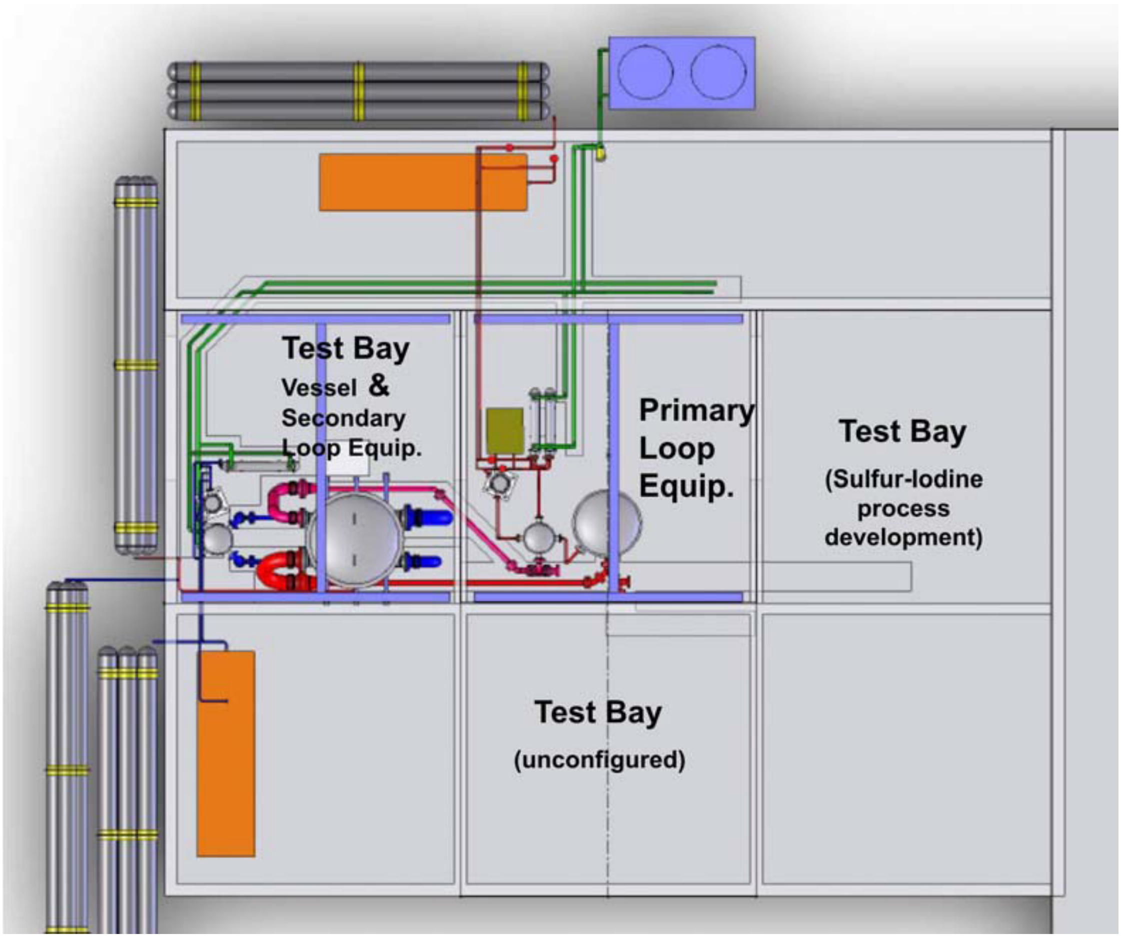

Figure 8. Conceptual floor plan for the proposed CTC.

Central Facilities Area (CFA) on INL Site is 45 miles west of Idaho Falls

The CFA-1 location shown in Figure 9 was the previously used site of the old transportation complex, which was demolished and removed. CFA-2 is the location of the old Health Physics Instrumentation Laboratory, scheduled for demolition. Both areas have utilities in the area and are supported by other existing support facilities and the CFA power substation. Craft and machine shops, analytical chemistry laboratories, and office areas are also nearby.

Figure 9. Central Facilities Area.

Research and Education Campus— INL Research Center (IRC) in Idaho Falls

The IRC shown in Figure 10 has space near the IEDF, with craft shops nearby. Utilities would be connected to the City of Idaho Falls. Analytical chemistry laboratories and office areas are located at IRC. However, a residential area and an elementary school are located less than half a mile from this site and may not be well suited to the engineering scale or demonstration scale projects due to perceived or actual public safety concerns.

Table 7 summarizes the infrastructure and utilities capabilities that are associated with each of these candidate engineering scale demonstration sites.

Siting in Idaho Falls will also vary depending on the availability of private property available for purchase and the contracting mechanism by which an Architectural-Engineering firm and construction company is chosen.

Figure 10. INL Research Center.

Table 7. Summary of attributes of the facilities of interest.

Location/Space	Electrical Power	Water & Sewer	Support Facilities	Permitting and Safety Concerns
CFA-1 270,000 ft^2	CFA power loop is nearby with reasonable power, additional power available at CFA Substation	Previous transportation complex installation has abandoned connections	Available in adjacent buildings nearby	Isolated from public and within a security area
CFA-2 200,000 ft^2	Adjacent CFA substation can easily provide power needs	Previous HPIL installation with abandoned connections	Available but farther away than CFA-1	Isolated from the public and within a security area
Idaho Falls-IRC 360,000 ft^2	Will require some upgrades to city power	Available nearby at the IRC	Available nearby at the IRC complex	Minimal isolation from the public: businesses, residential, and school within 0.5 mile

5. GENERAL TRANSITION STRATEGY

Transition of thermochemical work to INL will depend heavily on the cycle or cycles chosen to be advanced by the program. Until the down selection process is complete, only a preliminary strategy can be suggested.

Since both the S-I and HyS cycles employ the sulfuric acid decomposition reaction, INL will need to work closely with Sandia National Laboratory (SNL). If the S-I cycle will advance within the NHI, the next logical step will be to address significant limitations through R&D efforts and design, and to build and test a pilot plant. The laboratory will need to work with General Atomics, SNL, and CEA to understand the equipment and operational issues and limitations identified during the ILS work in San Diego. The INL technical group will assess advances made internationally (see for example references 1 and 2), and define any research that needs to be performed for the cycle to be viable. Industrial partners will also need to be brought on board. The sulfuric acid industry and the iodine industry have been operating on an industrial scale in the United States for nearly a century. Expertise and experience in those industries related to materials of construction or engineering solutions should advance cycle development. MECS, formally known as Monsanto Enviro-Chem Systems, Inc, is the lead producer of sulfuric acid in the United States. INL has interacted with MECS on catalyst development and they have expressed strong interest in expanding the working relationship. Westinghouse, who has developed a sulfuric acid reactor design, should be engaged in the program.

The HyS still needs to be demonstrated in an integrated system. As discussed above regarding the S-I cycle, the laboratory should work with skilled partners to expedite the development of this cycle. The most logical path forward is to leave the SO_2 skid at Savannah River National Laboratory where they can focus on the development of the membrane electrolysis assembly. The HyS cycle ILS should be build on previous SNL SO_2 decomposer design and integrate the decomposer with the SO_2 electrolyzer. The SNL skid used Teflon fittings and tubing where possible and has a pressure rating of 10 bars. By building a new skid with anticipated materials of construction, and rated to anticipated operating pressures, the new ILS will provide more valuable engineering data. Significant technology limitations will be identified and very focused R&D activities will be directed to advance those issues. Through partnerships with industry, academia and the national laboratories the cycle, if still considered viable, will be advanced through pilot and engineering scales.

Following the down selection process, a detailed transition plan will be developed that will include costs and schedules.

6. CONCLUSIONS

Over the past 6 years, INL has had significant involvement in developing technologies for producing hydrogen from water-splitting processes driven by nuclear energy. The laboratory's involvement has been in both high temperature electrolysis and thermochemical cycles. Through these and related efforts, the laboratory has hired and trained staff with specific skills who are required to carry out the mission of the NHI. As a multiprogram, engineering test- and evaluation- focused laboratory, INL has the staff skill mix to successfully carry out research, development and demonstrations activities necessary to achieve mission success for NHI. One of the key features of being a multiprogram laboratory is the ability to retain key skills during periods of uncertain funding.

An evaluation of INL's set of specific instrumentation, specialized equipment and facilities revealed that all aspects of the NHI can be conducted at the INL Site. Multiple facilities exist at INL that can support hydrogen R&D, pilot plant, engineering scale, and demonstration scale operations.

Through a strong history of teaming with other national laboratories, universities and industry, INL can transition thermochemical activities to the laboratory in a timely and efficient manner. This transition supports the primary objectives of the laboratory and is synergistic with other laboratory programs.

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