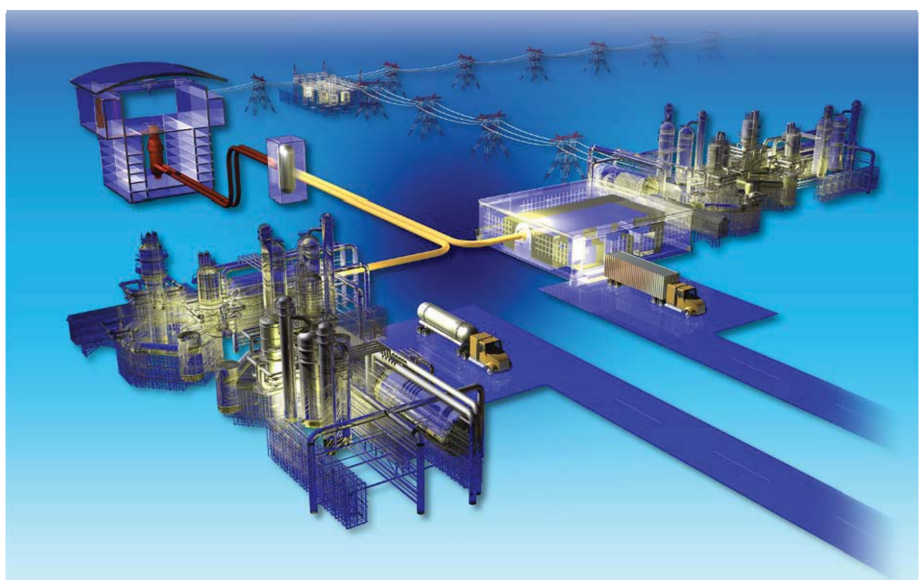
INL/EXT-09-16597

Evaluation of Transitioning Management of the Nuclear Hydrogen Initiative to Idaho National Laboratory

Charles Park
Mike Patterson

August 2009



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Idaho National Laboratory

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Science and Engineering

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Approved by:

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EXECUTIVE SUMMARY

The objective of this evaluation is to articulate the available and planned capabilities of Idaho National Laboratory (INL) to manage the development of nuclear-coupled hydrogen production technologies previously managed by the Nuclear Hydrogen Initiative (NHI). The Next Generation Nuclear Plant (NGNP) Project, managed by INL for the Department of Energy (DOE), will demonstrate high temperature gas-cooled reactor (HTGR) technologies that also generate electricity and/or produce hydrogen. Recent NGNP developments indicate that the most immediate need for HTGRs may be as a source of process heat for industrial applications, including hydrogen production integrated into one of several possible chemical processes. This evaluation therefore addresses integrating hydrogen development into the NGNP Project and leveraging other work at INL to develop pilot-scale helium test loops, Hybrid Energy Systems Testing and Demonstration (HYTEST) programs, and a large-scale component test capability. As such, this evaluation is responsive to *NHI FY 2009 Program Guidance*, dated December 18, 2008, which states:

> INL will assist the NHI Program Manager in conducting the process to select a single hydrogen technology in FY 2009 to carry forward for further development and demonstration in a pilot scale experiment. INL will assist in… development and implementation of a path forward as part of the formulation of the FY 2010 work plan for INL.

Specifically, this evaluation fulfills milestone DEGIN09NG070105, "Report on NHI Transition to INL," due to DOE-NE by August 31, 2009.

INL has been significantly involved in developing technologies for the leading hydrogen production technology candidates—high temperature steam electrolysis (HTSE), sulfur-iodine, and hybrid-sulfur processes—that produce hydrogen from water-splitting reactions driven by nuclear energy. Through these and related efforts, INL acquired and trained staff with specific skills well-suited to developing and demonstrating these technologies. A down-selection of these technologies conducted by an independent review team selected HTSE as the leading candidate for continued development and demonstration by the NGNP Project. The independent review team also recommended continued, slower development of back-up technologies to mitigate technical risk. Leveraging its strong history of teaming with other national laboratories, universities, and industry, INL can transition hydrogen production activities to the laboratory in a timely and efficient manner to reduce technical risk and continue its development of the HTSE process for primary demonstration.

Existing and planned INL facilities can or will accommodate progressively larger pilot-scale and engineering-scale demonstrations. Activities to expand facilities and capabilities are integrated with NGNP design, licensing, and construction activities, which is a logical progression from laboratory-scale investigations performed under the NHI to a more focused and integrated large-scale demonstration.

Figure E-1 illustrates existing and planned facilities needed to advance hydrogen production technologies to commercial scale. The Bonneville County Technology Center currently houses the HTSE integrated laboratory-scale experiment, and the INL Engineering Development Facility has been modified to accommodate further testing of hydrogen components. INL is currently reviewing expressions of interest to construct and lease-back an INL HYTEST Technology Demonstration Center (HTDC). This facility may be large enough to house integrated pilot-scale demonstrations. In addition, the NGNP Project will soon develop a process for comparing existing foreign and domestic capabilities to the option of building a component test capability at INL that could provide a platform for integrated testing of large- and full-scale technologies. A description of this capability is found in INL/EXT-09-15620, *Evaluation of Integrated High Temperature Component Testing Needs*, May 2009. This effort by the NGNP Project is seen as a potentially separate project under DOE Order 413.3, and would be sized to demonstrate an engineering-scale hydrogen process prior to final demonstration coupled to the NGNP.

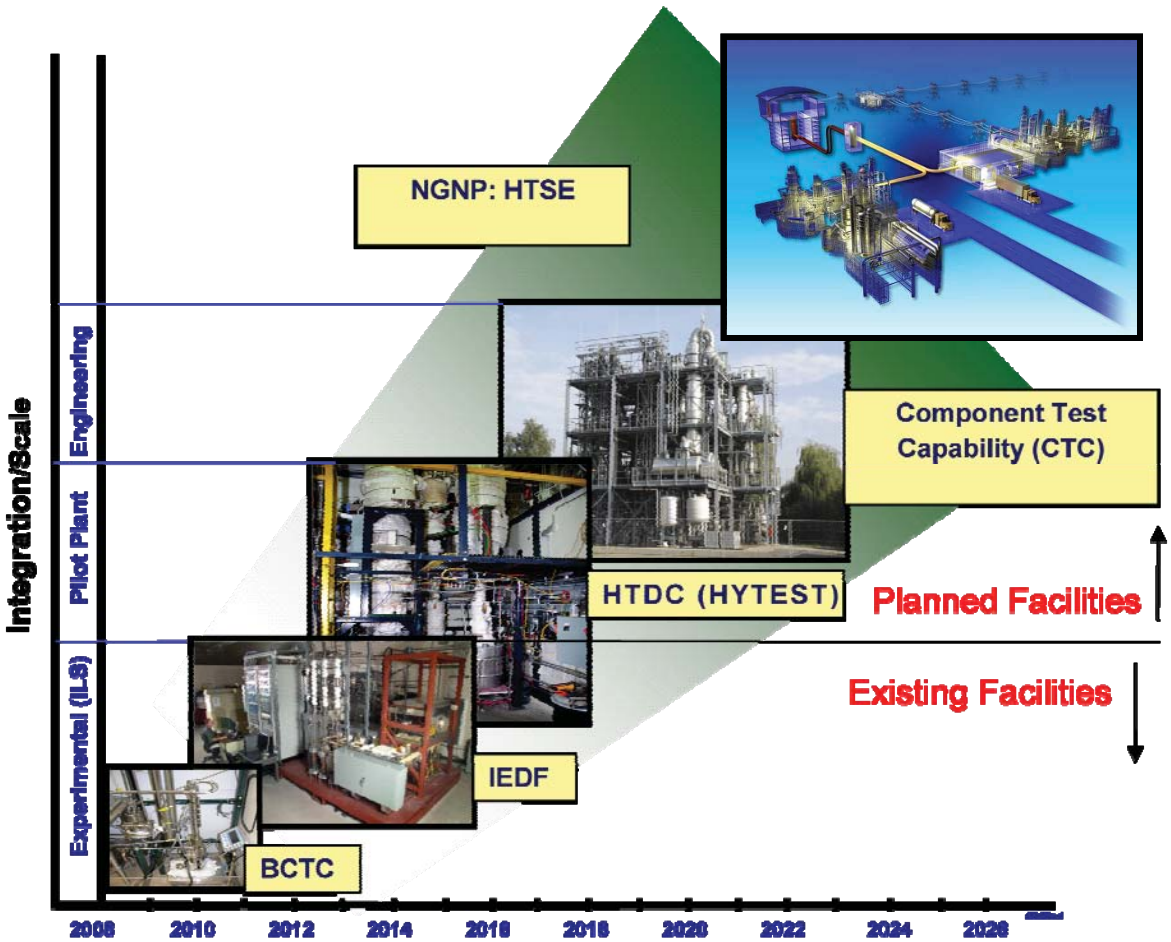

Figure E-1. Existing and planned INL facilities needed to advance the hydrogen production process to commercial scale.

Nuclear-coupled hydrogen production was originally envisioned as part of a hydrogen economy in which hydrogen was used as the main energy source for transportation vehicles. Even though it may be a while before the transportation sector is dominated by hydrogen-powered, electric-hybrid, or all electric vehicles, there exists an immediate need for secure transportation fuels that will continue into the foreseeable future. Renewable biomass and unconventional fossil fuels could play a major role in achieving energy security, but the process for its efficient development will require the integration of nuclear heat and hydrogen, which will also help minimize carbon dioxide emissions.

Integrated flow sheets for the coal-to-liquids (CTL) process using an HTGR as a heat and electrical source are a good example of hybrid energy systems that improve energy security and reduce the carbon footprint. The diagram in Figure E-2 illustrates that by using an HTGR to provide heat, electricity, and hydrogen for the CTL process, coal usage can be reduced by about 66% and carbon dioxide emissions can be reduced by over 96%. Assuming a carbon tax of $30 per ton of CO_2 (or cap and trade equivalent), that represents a cost avoidance of $1.18 million per day. Even if carbon capture technologies were applied to the traditional CTL flow sheet, CO_2 emissions are reduced by almost 84% and savings of $240K per day would be realized. A rigorous cost analysis has not yet been performed, but the opportunity to use domestic energy sources to improve energy security with little impact on greenhouse gas emissions should be investigated. The Department of Defense is investigating similar hybrid processes to improve the security of domestic and off-shore bases.

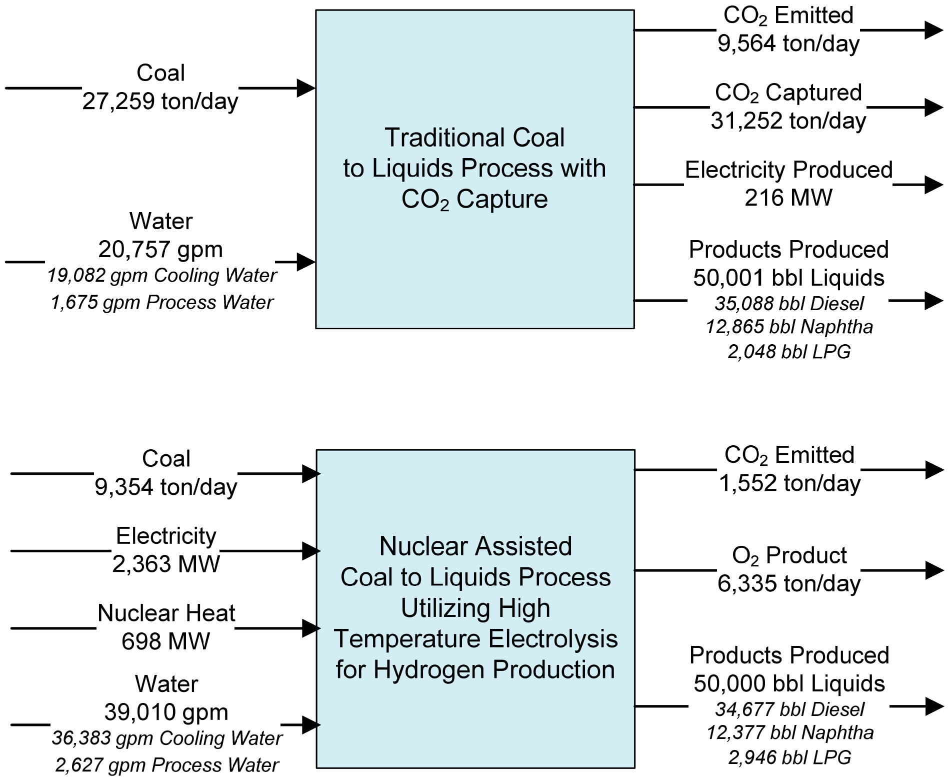

Figure E-2. Comparison of a traditional CTL plant to a nuclear coupled CTL plant with integrated hydrogen production.

Integrating hydrogen development into the NGNP Project now, as it progresses into conceptual design, is correct timing to integrate the hydrogen process with process applications that will use a combination of heat, electricity, and/or hydrogen from an HTGR. This timing and scope is also consistent with the Energy Policy Act of 2005 and several of the potential identified process applications for an HTGR. By including the hydrogen process as a critical system, structure, or component for the NGNP during preconceptual design activities and including it in the development of systems engineering technology development roadmaps, risk management, infrastructure planning, and evaluations of process applications, the groundwork has been laid to transfer the management of nuclear hydrogen development to the NGNP Project and successfully demonstrate that technology.

Meeting the following objectives is considered key to a seamless transition from management of hydrogen development under the NHI to management of hydrogen development under the NGNP Project.

- Maintain critical capabilities
- Leverage progressively larger demonstration capabilities
- Increase R&D focus
- Provide rigorous program controls
- Provide for meaningful collaboration.

All of these objectives are included in the NGNP Project's FY 2010 work plan. Incorporation of hydrogen production development as a focused, integrated subset of NGNP design and construction will improve the likelihood of success.

This evaluation determined that INL is fully capable of managing the development and deployment of nuclear-coupled hydrogen production technologies.

CONTENTS

FIGURES

TABLES

ACRONYMS

BCTC	Bonneville County Technology Center
CTC	Component Test Capability
CTL	coal-to-liquid
DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
GIF	Gen IV International Forum
HTDC	HYTEST Technology Demonstration Center
HTGR	high temperature gas-cooled reactor
HTSE	high temperature steam electrolysis
HyS	hybrid sulfur
HYTEST	hybrid energy system testing and demonstration
IEDF	INL Engineering Design Facility
ILS	integrated laboratory scale
INERI	International Nuclear Energy Initiative
INL	Idaho National Laboratory
IRC	INL Research Center
IRT	independent review team
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
R&D	research and development
ROT	reactor outlet temperature
SI	sulfur-iodine
SNL	Sandia National Laboratory
SOEC	solid oxide electrolysis cell
SRNL	Savannah River National Laboratory
TDRMs	Technology development roadmaps

Evaluation of Transitioning Management of the Nuclear Hydrogen Initiative to Idaho National Laboratory

1. OBJECTIVES

The objective of this evaluation is to articulate the available and planned capabilities of Idaho National Laboratory (INL) to manage the development and deployment of nuclear-coupled hydrogen production technologies. The Next Generation Nuclear Plant (NGNP) Project will demonstrate high temperature gas-cooled reactor (HTGR) technologies, which include generating electricity and/or producing hydrogen. Recent NGNP developments indicate that the most immediate need for HTGRs may be as a source of process heat for industrial applications, which may include hydrogen production integrated into one of several possible chemical processes. This evaluation therefore addresses integrating hydrogen development into the NGNP Project and leveraging other work at INL, and also in developing pilot-scale helium test loops, hybrid energy systems testing and demonstration (HYTEST) programs, and a large-scale component test capability (CTC). As such, this evaluation is responsive to the Nuclear Hydrogen Initiative (NHI) FY 2009 Program Guidance, dated December 18, 2008, which states:

> INL will assist the NHI Program Manager in conducting the process to select a single hydrogen technology in FY 2009 to carry forward for further development and demonstration in a pilot scale experiment. INL will assist in…development and implementation of a path forward as part of the formulation of the FY 2010 work plan for INL.

Specifically, it fulfills milestone DEGIN09NG070105, "Report on NHI Transition to INL," due to the Department of Energy (DOE) Office of Nuclear Energy (NE) by August 31, 2009.

The following evaluation objectives and recommendations are included:

- Provide a seamless transition such that research and development (R&D) momentum is maintained for critical capabilities
- Leverage progressively larger scales of demonstration and testing to enable technical advances
- Increase the focus of R&D to solve engineering barriers for successful deployment of hydrogen production technologies
- Provide rigorous and compliant program controls for cost, schedule, and risk
- Provide for meaningful collaboration with international partners, industry, academia, and other national laboratories to the extent determined by DOE.

This evaluation determined that INL is fully capable of managing the development and deployment of nuclear-coupled hydrogen production technologies. Transition of this function to INL leverages significant new capability for pilot-scale and large-scale testing, and integrates nuclear hydrogen production with the development of those hybrid energy systems that will use the HTGR as a source of process heat. The balance of this report presents the basis for this conclusion.

2. BACKGROUND

In 2003 the DOE-NE began the NHI as a part of the Advanced Fuel Cycle Initiative. The *Energy Policy Act of 2005* established the NGNP Project to be built as a demonstration plant that generates electricity and/or hydrogen. The shared objective of the NGNP Project and NHI Program has been to develop a hydrogen production technology that is commercially viable. Since their inception, both programs have consistently and effectively coordinated their R&D efforts. However, no funding is currently planned for the NHI Program in 2010, so the NGNP Project will assume responsibility at that time for nuclear-coupled hydrogen development and demonstration as part of its R&D, engineering, and coordination with HYTEST programs.

Nuclear-coupled hydrogen production was originally envisioned as part of a hydrogen economy in which hydrogen was used as the main energy source for transportation vehicles. Even though it may be a while before the transportation sector is dominated by hydrogen-powered, electric-hybrid, or all electric vehicles, there exists an immediate need for secure transportation fuels that will continue into the foreseeable future. Renewable biomass and unconventional fossil fuels could play a major role in achieving energy security, but the process for their efficient development will require the integration of nuclear heat and hydrogen, which will also help to minimize carbon dioxide emissions.

Integrated flow sheets for the coal-to-liquids (CTL) process using an HTGR as a heat and electrical source are a good example of hybrid energy systems that improve energy security and reduce the carbon footprint. The diagram in Figure E-2 illustrates that by using an HTGR to provide heat, electricity, and hydrogen for the CTL process, coal usage can be reduced by about 66% and carbon dioxide emissions can be reduced by over 96%. Assuming a carbon tax of $30 per ton of CO_2 (or cap and trade equivalent), that represents a cost avoidance of $1.18 million per day. Even if carbon capture technologies were applied to the traditional CTL flow sheet, CO_2 emissions are reduced by almost 84% and savings of $240K per day would be realized. A rigorous cost analysis has not yet been performed, but the opportunity to use domestic energy sources to improve energy security with little impact on greenhouse gas emissions should be investigated. The Department of Defense is investigating similar hybrid processes to improve the security of domestic and off-shore bases.

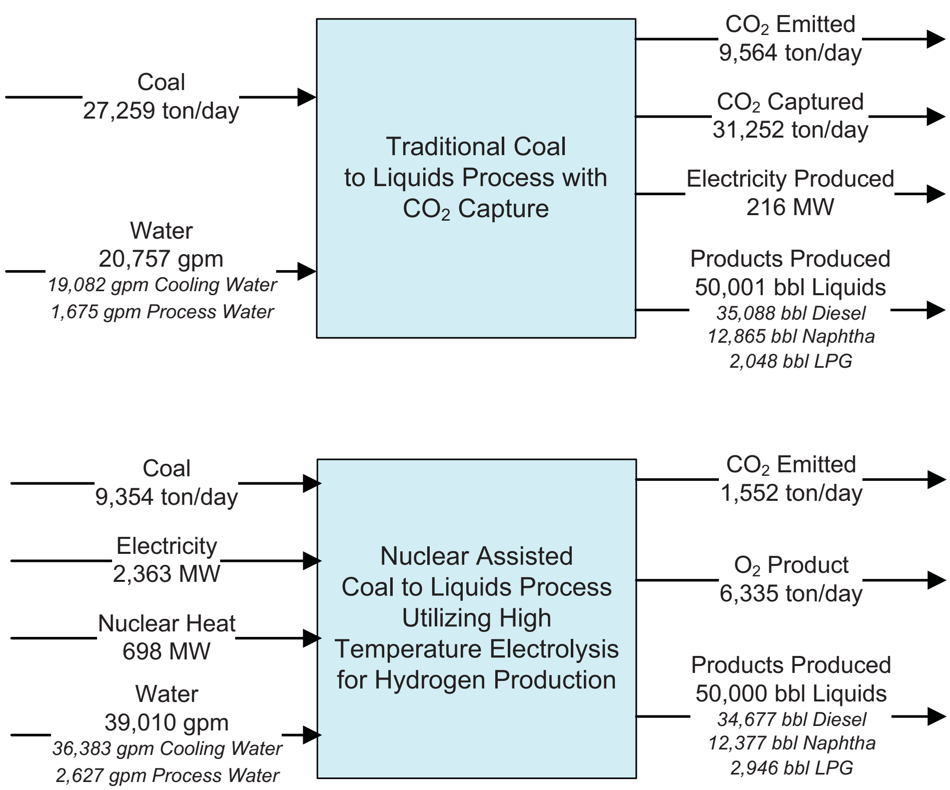

Figure 1. Comparison of traditional CTL plant to a nuclear coupled CTL plant with integrated hydrogen production.

3. HYDROGEN TECHNOLOGY DOWN-SELECTION

In May 2008, the NGNP Project issued a report indicating that up to $140 million could be saved by focusing R&D on the most viable hydrogen production technology in addition to funding a backup technology for the near-term. In January 2009, DOE-NE directed INL to evaluate and recommend a nuclear hydrogen production technology for deployment with NGNP. In February, INL issued a plan outlining the evaluation methodology. In March and April an independent review team (IRT) was selected, and in June DOE-NE approved the proposed down-selection criteria and weighting. Also in June, a week-long workshop was held in Denver where the technology leads presented information to the IRT and the technologies were scored.

The evaluation was based on the current NGNP project baseline which includes:

- Up to 600 MWth per reactor unit
- 750 to 800°C initial reactor outlet temperature (ROT)
- 7 MPa reactor outlet pressure
- Helium primary coolant
- Graphite moderated
- Pebble-bed or prismatic reactor core
- 60-year design life
- Scheduled startup in 2021.

Although future reactor outlet temperatures could be as high as 950°C, this evaluation was based on an initial ROT in the range of 750 to 800°C, which served as the primary evaluation criteria for near-term deployment of a hydrogen production process with the NGNP.

The hydrogen production process will interface with the NGNP via a process heat exchanger or steam generator. The interface parameters are as follows:

- Utilize up to 50 MWth total reactor power with any electric conversion at 40%
- Helium process heat exchanger outlet to the hydrogen process at 700°C and 7 MPa pressure
- Outlet temperature from steam generator up to 550°C at 15 MPa pressure
- Assume no contaminants that would affect the safety or operations of the hydrogen process are introduced at or upstream of this interface.

Three technologies were the focus of this down-select evaluation. The first was the hybrid sulfur (HyS) process being developed jointly by Savannah River National Laboratory (SRNL) and Sandia National Laboratory (SNL). The second is the sulfur-iodine (SI) process being developed jointly by General Atomics, SNL, and the Commissariat à l'Énergie Atomique (France). The third is high temperature steam electrolysis (HTSE) being developed by INL. DOE has funded research in nuclear hydrogen production since 2003, resulting in the current maturity of these three technologies, currently at or near integrated laboratory scale (ILS). Other technologies such as copper-chloride and calcium-bromine cycles have been evaluated, but these have not advanced as far as the three technologies considered.

The five member IRT was selected from a group of internationally recognized experts. Table 1 summarizes their scoring of the three technologies based on the approved DOE-NE criteria and weighting.

Table 1. Comparison of hydrogen production technology down-selection scores.

Goals	Criteria	Wt%	Worse <------ Scoring --------> Better					Comment	Ratings			Score		
			1	2	3	4	5		HTSE	HyS	SI	HTSE	HyS	SI
Performance (35%)	Quantity of H_2 Produced	10%	<10	10–12	12–15	15–20	>20	1,000's kg/day	3	2	2	0.3	0.2	0.2
	Purity of Hydrogen	5%	None	Almost none	Some	Most	All	Independent of Need	5	3	4	0.25	0.15	0.2
	Serve Various Applications	15%	Useless	Almost none	Some	Most	All	Demand circa 2009	4	4	3	0.6	0.6	0.45
	Waste Management	5%	Extreme	Significant	Typical	Modest	None	Industrial & Hazardous	4	3	2	0.2	0.15	0.1
Cost (30%)	Cost of Production	10%	>9	7–9	5–7	3–5	<3	$/kg	3	3	2	0.3	0.3	0.2
	Cost Uncertainty	10%	Unrealistic	Optimistic	Consistent	Conservative	Very Conservative	Confidence in scoring	3	3	2	0.3	0.3	0.2
	Development Cost (Relative)	10%	>1,200 (very high)	1,000-1,200 (high)	800-1,000 (medium)	600-800 (med-low)	<600 (low)	$M	4	3	2	0.4	0.3	0.2
Risk (35%)	Technical Maturity	15%	<2.5	2.5–3.4	3.5–4	4.1–4.5	>4.5	Composite	3	2	1	0.45	0.3	0.15
	Development Risk	20%	Insur-mountable	High	Medium to High	Low to Medium	Low	Composite	3.5	3	2	0.7	0.6	0.4
								Total	32.5	26	20	3.5	2.9	2.1
												Out of 5		

Following the evaluation, the IRT made the following recommendations:

1. DOE-NE should focus on the continued development of HTSE as the leading candidate for integration with NGNP in 2021. This conclusion is based on IRT's judgment that HTSE has the highest probability of meeting the down-selection criteria described in the report, including efficient production of hydrogen at NGNP conditions.
2. Both HyS and SI processes exhibit attractive attributes for hydrogen production that supports not abandoning either technology for future consideration. In fact, the IRT concluded it to be prudent to continue their development through the funding of well defined R&D projects of lesser scope than those dedicated to HTSE. The IRT identified between 10 to 15 short term R&D needs for each technology.
3. If faced with a choice between funding short term R&D for either HyS or SI, but not both, DOE should consider, as a minimum, giving higher priority in any R&D to topics that benefit both of these technologies, such as continued development and modeling of the sulfuric-acid decomposer. DOE-NE should prioritize the short term R&D activities identified by the IRT through coordination with private corporations or international organizations.

Technology development roadmaps (TDRMs) were developed by the NGNP industrial partners and the NHI technical directors in FY 2008 and FY 2009 for ROT of 950°C. Based on IRT's recommendations, the TDRMs will be revised and reflect the lower ROT of 750°C. Implementing activities will then be incorporated into the NGNP Project risk management plan and integrated priority list.

4. INL CAPABILITIES

The development of hydrogen production technology will require sufficient staff with education and expertise, equipment, facilities, and infrastructure. Staff capability must include chemists, material scientists, chemical engineers, mechanical engineers, nuclear engineers, program managers, systems engineers, technicians, and craftsmen who can solve the challenging issues relative to aggressive environments of high temperature and pressure. A compliant and effective environmental, safety, health, and quality organization is also required for success.

Adequate facilities required to advance hydrogen production processes are essential. Laboratory facilities will be needed to conduct research in areas such as membranes, catalysis, materials, corrosion, and chemical separations to advance the technology. Larger facilities and infrastructure are also required to develop ILS, pilot-plant, and engineering-scale demonstrations.

Figure 2 illustrates existing and planned facilities needed at INL to advance hydrogen production technologies to commercial scale. The Bonneville County Technology Center (BCTC) currently houses the HTSE ILS experiment and the INL Engineering Development Facility (IEDF), which has been modified to accommodate the next stage of hydrogen component testing. Larger scale facilities are planned. INL is currently reviewing expression of interest to construct and leaseback an INL HYTEST Technology Demonstration Center (HTDC). This facility will be large enough to house integrated pilot-scale demonstrations that would be followed by an engineering-scale demonstration. The NGNP Project is currently comparing existing foreign and domestic capabilities to the option of building a large component test capability at INL. A description of this capability is found in INL/EXT-09-15620, *Evaluation of Integrated High Temperature Component Testing Needs*, May 2009. This effort is envisioned as a DOE Order 413.3 subproject under NGNP that would be sized to accommodate an engineering-scale demonstration for the hydrogen production process prior to final demonstration coupled to the NGNP.

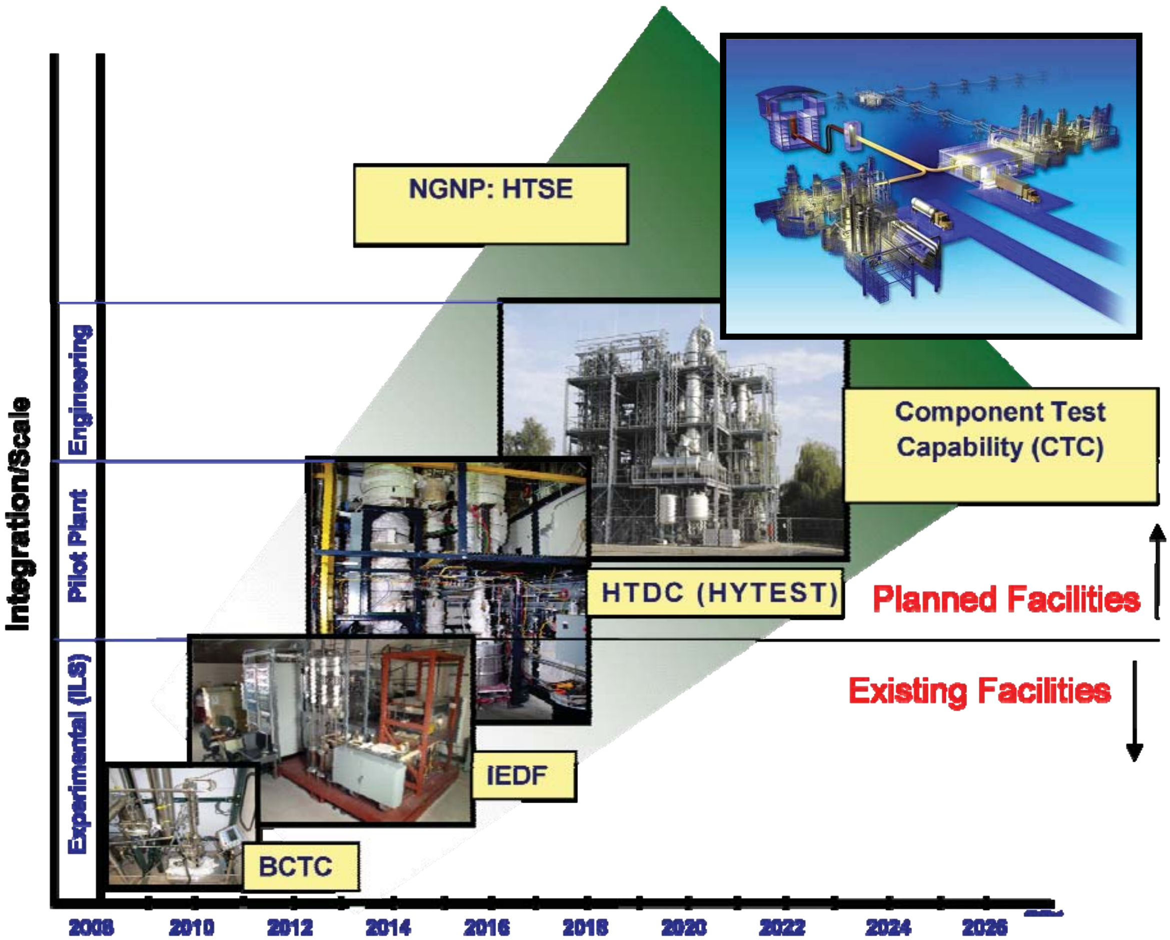

Figure 2. Existing and planned INL facilities needed to advance the hydrogen production process to commercial scale.

Section 4.1 describes existing INL facilities that are immediately available to support hydrogen development. Section 4.2 describes planned INL facilities and capabilities that will be available to continue hydrogen development at larger scales and integrate the hydrogen production process with other technologies in hybrid energy systems.

4.1 Existing INL Facilities supporting Hydrogen Development

In May 2009, INL issued the *Capabilities to Support Thermochemical Hydrogen Production Technology Development* report (INL/EXT-09-16040), which identified specific infrastructure needs for thermochemical processes, including footprint areas, clear height, and utility needs for technology development and demonstration. The HTSE technology consists of one main process, the HyS involves two, and SI involves three. Since HTSE will be demonstrated and deployed in a modular design, the area and room height requirements are less and therefore enveloped by thermochemical development needs.

Briefly, facilities required to support an ILS project for thermochemical processes will need 1,000 ft^2 of floor space and be able to 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 (gallon per minute), fresh water to 20 gpm, and waste water to the drain system could be up to 21 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 release of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor.

The pilot-scale projects require approximately 5,000 ft^2 of floor space and are able to 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 gpm, fresh water to 40 gpm, and waste water to the drain system could be up to 41 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 be open within the facility. The facility would be properly vented to remove any fugitive emissions or releases of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor.

The *Capabilities to Support Thermochemical Hydrogen Production Technology Development* report includes a comprehensive list of existing facilities that can support both thermochemical and electrolytic hydrogen production technologies. That facility listing is not be repeated here, but the conclusions of that report are as follows:

- INL has the beneficial collaborations with other national laboratories, universities, and industries to strengthen its thermochemical process development efforts
- INL has a trained staff with the specific skills needed to successfully develop thermochemical hydrogen production technology
- INL has the specific instrumentation, specialized equipment, and facilities needed to conduct all aspects of nuclear hydrogen development
- Multiple facilities exist at INL that can support hydrogen R&D and 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
- INL has experience in teaming with other national laboratories, universities, international partners, and industry to transition thermochemical activities to appropriate organizations and facilities in a timely and efficient manner.

No barriers were found to hinder the transition of the program direction for hydrogen production R&D and demonstration from NHI to INL.

4.2 Planned INL Facilities Supporting Hydrogen Development

INL plans to build HYTEST facilities to advance technology development and energy systems integration. HYTEST will help transform the current energy infrastructure to an era of clean, smart energy. A full description is found in the *INL Hybrid Energy Systems Development and Testing – HYTEST Facilities Plan*, to be issued in FY 2009.

An assessment of the R&D needs and challenges identified five key hybrid energy systems areas for INL to investigate, develop, and advance to commercialization:

1. Feedstock Processing and Energy Integration
2. Energy Storage
3. Byproduct Management
4. System Integration
5. Monitoring and Control.

INL HYTEST facilities will provide the physical space and essential utilities, safety systems, process monitoring and controls, emissions control, waste management, feedstock handling, product storage, and analytical services to support the building of hybrid energy systems, technology testing, and the integration of flexible/reconfigurable components under each platform.

BEA has initiated the immediate lease of a new, approximately 56,000 ft^2 facility to conduct research in the areas of bioenergy and biofuels, batteries and hybrid electric vehicles, and advanced build-hybrid-energy systems in support of HYTEST. A preliminary lease acquisition schedule has been identified. An Expression of Interest was published in March 2009, with multiple responses received. Initial lease agreement Statement of Work requirements have been developed and are being finalized. The final Statement of Work and Solicitation for Offer are planned for distribution to prospective Lessors in August 2009, with subsequent proposals requested in early November 2009. Lease submittal and DOE approval is anticipated from November 2009 through January 2010, allowing for a planned occupancy of the new leased facility in June 2011. The requirements for this acquisition strategy include conservatively bounding footprint and utilities requirements for hydrogen process demonstrations.

Engineering-scale hydrogen demonstrations are expected to be located outdoors and be built on a concrete pad with a building to house control systems, require analytical laboratory space, and have a dedicated maintenance shop. The requirements for the engineering-scale demonstration were used as input for the CTC. Some variation is expected as processes mature and as the requirements listed here are conservatively bounded. These requirements will be met by the CTC, either at dedicated INL facilities or locations identified as part of a CTC alternatives evaluation. 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 will be adequate to house control systems, laboratory space, and the small maintenance shop. Power requirements would be on the order of 5.0 MWe. 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 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 releases of hazardous gasses, including hydrogen, SO_3, SO_2, and hot sulfuric acid vapor.

Table 2 lists the progressively larger demonstrations needed to develop HTSE and the existing and proposed facilities to house them. Some variation to integrate the hydrogen demonstration with planned hybrid energy system testing can be accommodated by fabricating intermediate scale demonstrations on a skid so they could fit more than one facility or be moved after NGNP-related testing was completed.

Table 2. HTSE demonstration scale-up and related hybrid energy system testing.

	High Temperature Steam Electrolysis Testing Scale				Co-Located HYTEST Labs Component Testing Scales		
HYTEST Lab Location	(HTSE) Number of Electrolysis Modules	Electrolysis Power Rating	H_2 Production Rate		Fischer-Tropsch Liquid Prod. Rate	Coal/ Biomass Gasifier Feed Rate	Steam Methane Reformer Feed Rate
BCTC (Existing ILS)	3	15 kWe	5 (m^3/hr)	0.45 (kg/hr)	1 to 24 gpd	—	5,000 scfd
IEDF or HTDC	40	200 kWe	67 (m^3/hr)	6 (kg/hr)	24 gpd to 7.5 bbl/d	2.5 tpd	40,000 scfd
CTC (Small Loop)	1,000	2 MWe	1,667 (m^3/hr)	150 (kg/hr)	200 bpd	70 tpd	1.0 Mscf/d
CTC (Engineering-Scale)	10,000	5 MWe	16,667 (m^3/hr)	1,500 (kg/hr)	2,000 bpd	700 tpd	10 Mscf/d

4.3 Laboratory Staff

4.3.1 Specialized Staff

INL's staff is heavily oriented toward engineering; 18% of its approximately 4,000 personnel have engineering degrees and backgrounds. Within the engineering staff, 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 routinely performs applied research activities. Approximately 64 of these employees have scientific skills that apply directly to nuclear hydrogen production development activities. In addition to the professional staff, INL has several hundred technical and skilled workers with relevant skills that can be deployed as needed. Two past technical directors of NHI continue to work at INL and are available.

4.3.2 Hydrogen Production

As a result of its NHI support, a group of INL technologists have developed expertise and skills relevant to high-temperature hydrogen production cycles and instrumentation skills relevant to electrochemistry. INL staff built an ILS facility that is able to perform a variety of experiments on the production of hydrogen. This facility, located in Bay 9 of the BCTC, was initially used in 2007 and 2008 to test high temperature electrolysis modules. During HTSE ILS operations, INL personnel increased their expertise in mass flow controllers, water metering equipment, steam generator, superheaters, air heaters, heat recuperators, electrolytic cells, coolers, condensers, dew point meters, and the Labview software that will form the basis for scale-up of HTSE technology selected by the IRT. Six years of experiments at INL on the use of solid oxide cells for electrolysis have developed an inventory of skills and equipment for operating high temperature experiments and instrumentation of electrolytic processes that would require significant effort to duplicate or replace.

INL staff have significant expertise in the areas needed to progress hydrogen production processes from a laboratory concept to an operational prototype. More than 30 chemists have backgrounds aligned with technical needs associated with thermochemical cycles, and have related expertise associated with high temperature processing, steel and aluminum manufacturing, glass production, coal combustion, and high temperature fuel-cell operation. INL staff have a history of catalysts research for the NHI Program that gives them significant experience and capability in testing and developing catalysts. They are working to develop durable catalysts for the sulfur-based cycles and have made extended duration evaluations of catalysts for the sulfuric acid decomposition reaction and the hydroiodic decomposition reaction.

Finally, INL engineers are working to develop and demonstrate the nuclear heat source driving the hydrogen process. 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.

4.3.3 Materials Engineering and Science

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 hydrogen production.

INL personnel have been actively involved in a range of fuel cell development activities related to thermochemical processes. These activities include the development of advanced materials for proton exchange membrane 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.

4.3.4 Simulation Modeling

INL has extensive experience related to development of experimental prototypes. 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 Project 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. Trained staff test and evaluate material properties and performance. This testing is achieved through advanced computational modeling and static and dynamic material tests.

4.3.5 Construction Engineering and Project Management

INL has an extensive construction engineering and construction project management organization with skills that are routinely employed to complete facility construction and develop 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. Its Safety and Health professionals 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.

4.3.6 Staffing for Multiprograms

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, 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.

5. PROGRAM MANAGEMENT

With the termination of the NHI Program, future hydrogen production technology will be funded as a part of the NGNP Project. Within the NGNP Project, the R&D organization focuses on advancing the technology and the Engineering organization focuses on deploying the technology. In general, understanding the science behind the technology and resolving technical risks are part of R&D, and providing facilities, infrastructure, engineering evaluations, design and fabrication are a part of Engineering.

NGNP Project plans for FY 2010 require a total of $9 million. Specifically, $7 million is required to support R&D, which includes primary and back-up technology development. Consistent with the down-select evaluation and recommendations, the HyS process will be advanced as the alternative technology. Funding an alternative technology provides a contingency for the project if the HTSE technology cannot be demonstrated and also maintains an opportunity for deployment at higher ROTs or in specific process applications. NGNP Engineering funding in FY 2010 is planned at approximately $2 million.

HTSE technology development will continue at INL during FY 2010 and be performed in accordance with the TDRMs developed by NGNP during FY 2008 and FY 2009. Activities identified in the TDRMs will be modified or augmented by the recommendations of the down-selection IRT. Planned work will require approximately $5.1 million for HTSE, which includes:

- Degradation studies of solid oxide electrolysis cells (SOECs)
- Advanced design small scale tests of SOECs
- Pressurized testing small SOEC stacks
- Degradation modeling (atomistic scale)
- CFD support of advanced cell/stack designs
- Materials testing (SOECs and critical components)
- Project management
- Technical support and engineering
- Professional development activities (Gen IV International Forum [GIF] and technical conference support).

The remainder of the $7 million should be applied to limited HyS technology development. Activities such as electrolyzer development will continue at SRNL (electrolyzer) with support from SNL specific to the acid decomposer and support from INL specific to acid decomposer catalysts. Pilot-scale testing is expected to be eventually performed (if necessary) at INL with SRNL technical support. Planned work in FY 2010 for HyS technologies will be consistent with the activities outlined in the TDRMs, as modified by the recommendation of the down-selection IRT, and require approximately $2.0 million.

It is expected that significant industry involvement may be incorporated in FY 2010 as a part of the NGNP Project. The plans presented here may be revised to incorporate industry preferences and goals. Industry involvement greatly enhances the probability that NGNP deployment will meet commercial needs.

DOE-NE continues to fund academic R&D through its University Programs. The NGNP Project will monitor the progress of relevant university R&D to leverage new science and technology advances. INL coordinates this university effort by awarding grants as a part of DOE-NE's Center for Advanced Engineering Studies.

A number of international organizations are also pursuing nuclear hydrogen production. In the past, these countries coordinated their efforts through GIF. The NGNP Project intends to coordinate its efforts through GIF and the Gen IV Program as needed. No International Nuclear Energy Initiative commitments are planned after 2009.

The NGNP Project will continue to receive primary direction from the DOE-NE Federal Project Director. DOE-ID staff will continue to support and monitor the work and evaluate annual performance.

6. STRATEGY TO MEET TRANSITION OBJECTIVES

The groundwork for a transition was laid in FY 2008 and FY 2009. A financial structure was created in the NGNP project for continuing hydrogen R&D and engineering evaluations. TDRMs for each of the leading hydrogen production processes were completed with extensive input form the technical experts in each area. A down-selection was completed with recommendations to supplement the work identified in the TDRMs. Finally, a work plan for FY 2010 has been developed to continue hydrogen process development that maintains a primary and a back-up technology for approximately 2 years that can support deployment of the hydrogen process with the NGNP. Meeting the following objectives is considered key to having a seamless transition from management of hydrogen development under the NHI Program to management of hydrogen development under the NGNP Project:

- Maintain critical capabilities
- Leverage progressively larger demonstration capabilities
- Increase R&D focus
- Provide rigorous program controls
- Provide for meaningful collaboration.

6.1 Maintain Critical Capabilities

Personnel and equipment are considered critical capabilities. The allocation of resources outlined in Section 5 provides for continued maintenance of HTSE and HyS expertise. The BCTC laboratories and equipment are considered vital and would continue operation to address solid oxide electrolysis cell degradation and longevity. Engineering work in FY 2010 will be front loaded, updating TDRMs for a reactor outlet temperature of 750–800°C and the IRT recommendations. The cost estimates and schedules would be updated under NGNP Engineering to refine previous estimates to complete HTSE technology development. This work is of high priority and hence, would be performed in the first part of FY 2010 using many of the same personnel currently working on NHI R&D. This frontloading in the fiscal year provides a means of bridging a continuing resolution and maintaining critical personnel. Once the engineering work is completed, the personnel would be available to resume work in the R&D area.

Limited work on HyS processes would continue as a back-up to HTSE and also to maintain an opportunity. Ongoing evaluation of process applications under NGNP indicate that there will be multiple applications requiring hydrogen integration at higher outlet temperatures, which significantly improve the efficiency of the HyS process. Although these applications may not be the first demonstration of HTGR technologies, they appear to be very promising applications in terms of energy security and reduction of carbon emissions. Hence, limited funding for HyS is an opportunity to maintain key personnel and equipment and to reduce risk. Some funding for this process is recommended until at least 2011, at which time the commercialization of HTSE can be predicted with more certainty and further evaluations of HyS opportunities can be completed. It is anticipated that in evaluating HyS opportunities, NGNP engineering will develop process flows sheets and cost models. Continued limited R&D would be performed under a Memorandum Purchase Order (MPO) to SRNL and SNL.

6.2 Leveraging Increased Demonstration Capabilities

Continued technical development will require progressively larger facilities to reach commercial demonstration. Section 4.1 describes existing facilities that house current HTSE experiments and demonstrations. Section 4.2 describes planned facilities and their functional requirements, which are based (in part) on the utilities, power requirements, space requirements, and the hazardous chemical inventories of hydrogen production processes. The scale-up is tied to the TDRMs for each process and the performance criteria specified to advance from one technology readiness level to the next. In many cases, demonstrations of the process heat applications being considered for coupling to the NGNP will be housed in the same or adjacent facilities.

6.3 Increased R&D Focus

Evaluating development of technology neutral hydrogen processes in FY 2008 and developing a TDRM and performing a down selection in FY 2009 were early steps to focus R&D. Sequenced activities tied to the stages of design were identified, as well as a risk mitigation strategy that maintains a primary and back-up technology until the project can confidently predict scale-up to commercialization for the primary technology. These engineering planning activities will continue as the NGNP Project integrates hydrogen development into the project plan.

The proposed budget for FY 2010, which is approximately 22% engineering, will refine cost estimates and schedules for the deployment of hydrogen technology. A study of reliability, availability, maintainability, inspectability and other attributes will be performed for the HTSE to identify those areas that need focused R&D for successful scale-up. In some cases, the areas of development will be in the balance of plant, whereas previous work has focused almost entirely on the basic hydrogen production technology. The approach is to shift from R&D informing design to design-informed R&D. As the design progresses from conceptual through preliminary and on to final design, R&D demonstrations will become less broad as they focusing on the remaining items needed to complete a design that can be constructed.

R&D work will focus only on those activities identified in the TDRMs (as modified for IRT recommendations) and that R&D identified in the design data needs (DDNs) of the hydrogen process design. Assuming the HTSE process advanced successfully, the limited work for the HyS process would be discontinued at the end of conceptual design—the project stage where design decisions are typically made. While it is recognized that a great deal of valuable work remains in many areas of hydrogen production and use, that work would be funded under Gen IV or other programs external to the NGNP Project.

6.4 Providing Rigorous Program Controls

Section 5 describes the program controls for FY 2010, including a high-level discussion of scope. Generally, work under NGNP would be divided into two control accounts, one for R&D and one under Engineering. Both would include resource-loaded schedules and milestones. More detailed development of schedules and cost estimates are planned in the Engineering control account for early FY 2010, and that work would be incorporated in the NGNP baseline. Project controls ranging from trending, risk management, quality control, etc., are established at the appropriate level of maturity for the NGNP Project and the hydrogen process would be incorporated into this system of program controls.

6.5 Provide for Meaningful Collaboration

Collaboration under the NHI has included industrial partners, government agencies, and other governments under programs such as the GIF. As hydrogen production is assimilated by the NGNP Project, the focus of collaborations will shift to industrial partners, focusing eventually on a single technology. Collaborations with other government agencies or foreign governments may continue under the GIF, but it is expected that these collaborations will be maintained as part of the Gen IV Program consistent with the rationale provided in Section 6.3. Collaboration with the remaining industrial partners may become more involved and could require additional protection of intellectual property, supporting the rational that other collaborations be maintained outside the project.

All of the objectives outlined herein have been addressed in the NGNP Project's FY 2010 work plan. The further incorporation of hydrogen production development as a focused, integrated subset of NGNP design and construction will improve the likelihood of successful deployment. This evaluation determined that INL is fully capable of managing the development and deployment of nuclear-coupled hydrogen production technologies.

7. CONCLUSIONS

INL staff have had significant involvement in developing technologies for the leading technology candidates (HTSE, SI, and HyS processes) that produce hydrogen from water-splitting reactions driven by nuclear energy. Through these and related efforts, INL has acquired and trained staff with the specific skills needed to develop and demonstrate these technologies. A down-selection of these technologies, conducted by an IRT, selected HTSE as the leading candidate for continued development and demonstration with the NGNP. The IRT also recommended continued, slower development of back-up technologies to mitigate technical risk. 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 to reduce technical risk and continue development of the HTSE process for the primary demonstration.

Existing and planned INL facilities can or will accommodate progressively larger pilot-scale and engineering-scale demonstrations. Immediate development needs can be accomplished in existing facilities. Early contracting activities for the next scale demonstrations have been initiated under related INL programs, and engineering scale demonstrations will be timed to coincide with the NGNP CTC subproject. Expanding facility and capability activities are integrated with design, licensing, and construction activities for the NGNP. This is a logical progression from laboratory-scale investigations performed under the NHI to a more focused and integrated large-scale demonstration.

Integration of hydrogen development into the NGNP Project as it progresses into conceptual design is the correct timing to integrate the hydrogen process with process applications that will use a combination of heat, electricity, and/or hydrogen from an HTGR process heat. This timing and scope is also consistent with the *Energy Policy Act of 2005* and several of the potential identified process applications for an HTGR. By including the hydrogen process during NGNP preconceptual design activities and including it in development of system engineering TDRMs, risk management, infrastructure planning, and evaluations of process applications, the groundwork has been laid to transfer the management of nuclear hydrogen development to the NGNP Project and successfully demonstrate that technology.

Meeting the objectives of this report is considered key to a seamless transition from managing hydrogen development under the NHI Program to managing hydrogen development under the NGNP Project. The groundwork for a transition was laid in FY 2008 and FY 2009 and a financial structure was created in the NGNP project for continuing hydrogen R&D and engineering evaluations. This groundwork provides a bridge to complete the following objectives:

- Maintain critical capabilities
- Leverage progressively larger demonstration capabilities
- Increase R&D focus
- Provide rigorous program controls
- Provide for meaningful collaboration.

All of these objectives are addressed in the NGNP Project's FY 2010 work plan, and the incorporation of hydrogen production development as a focused, integrated subset of NGNP design and construction will improve the likelihood of their successful deployment.

This evaluation determined that INL is fully capable of managing the development and deployment of nuclear-coupled hydrogen production technologies.