INL/CON-08-14016
PREPRINT

Hydrogen Production from the Next Generation Nuclear Plant

National Hydrogen Association 2008

M. Patterson
C. Park

March 2008

Idaho National Laboratory

Hydrogen Production from the Next Generation Nuclear Plant

M. Patterson and C. Park
Idaho National Laboratory

1. Next Generation Nuclear Plant

The Next Generation Nuclear Plant (NGNP) will demonstrate the technical, licensing, operational, and commercial viability of High-Temperature Gas-Cooled Reactor (HTGR) technology to provide high-temperature process heat for the production of electricity, hydrogen and other industrial applications. This nuclear based technology can provide high-temperature process heat (up to 950°C) that can be used as a substitute for the burning of fossil fuels for a wide range of commercial applications. The HTGR is a passively safe nuclear reactor concept with an easily understood safety basis that permits substantially reduced emergency planning requirements and improved siting flexibility compared to current and advanced light water reactors (LWRs).

The project will be accomplished though the collaborative efforts of the Department of Energy (DOE) and its national laboratories, commercial industry participants, and international government agencies. Project management and technology development leadership is being provided by the Idaho National Laboratory (INL) in Idaho Falls, Idaho acting as the agent for DOE.

High-level NGNP project objectives support both the NGNP mission and the DOE vision, as follow:

- Develop and implement the technologies important to achieving the functional performance and design requirements determined through close collaboration with commercial industry end-users.
- Demonstrate the basis for commercialization of the nuclear system, the heat transfer & transport system, the hydrogen production process, and the power conversion concept. An essential part of the prototype operations will be demonstrating that the requisite reliability and capacity factor can be achieved over an extended period of operation.
- Establish the basis for licensing the commercial version of NGNP by the Nuclear Regulatory Commission (NRC). This will be achieved in major part through licensing the prototype by NRC and initiating the process for certification of the nuclear system design.
- Foster rebuilding the U.S. nuclear industrial infrastructure and contributing to making the U.S. industry self-sufficient for nuclear energy production needs.

2. Organization

The NGNP Project will be structured as a Public-Private Partnership under a common NGNP management structure. The project is sponsored by the DOE Office of Nuclear Energy (NE) and is managed under the Office of Gas Reactor Deployment (NE-33). DOE has assigned overall responsibility for planning, Pre-Conceptual and Conceptual Design, Research and Development (R&D), execution, and testing and turnover of the NGNP Prototype Project to the management and operations (M&O) Contractor of INL. To accomplish this, an INL NGNP Project Office has been established. The INL NGNP Project Office is responsible for coordinating, directing, and managing subcontractors, DOE laboratories, and universities that support the NGNP project.

Industry partners may include power generation companies whose role would be to provide current and practical project input to assure that the prototype nuclear plant will be licensable and representative of future marketable reactor system designs. Partners will also include commercial entities representing the end-user of process heat for the production of hydrogen (H_2) and other commodities. The companies will also support design, permitting, licensing, construction, startup, and operational activities. Determination of specific partners and technologies will be made during the project initiation and Conceptual Design Phases. Specific vendors and technologies down-selections will be made at the end of Conceptual Design. The acquisition strategy will be updated and the overall approach for the design, construction, testing, and integration activities implemented as Preliminary Design is initiated.

3. Technologies Needs

Specific milestones in the project logic require appropriate progress in selected aspects of the technology development. For the NGNP Project nuclear system, critical technology development areas include: nuclear fuel development, evaluation of irradiated graphite properties and intermediate heat exchanger (IHX)/heat transport development.

3.1. Nuclear Fuel Development

Qualification of the HTGR nuclear fuel production process will establish that the number of manufacturing defects is negligible. Operational and accident performance of the fuel that precludes the need for a pressure containment surrounding the reactor systems must also be demonstrated. Qualification of the fuel will be achieved by optimizing fuel manufacturing processes, irradiating fuel particles from those processes in a test reactor, and performing post-irradiation examinations (PIE) of the fuel. Some of the fuel will be tested to failure. Burn-up values and source terms for the fission products during normal operations and postulated accident scenarios will be determined from the PIE. Data obtained during irradiation testing will be integrated into the licensing and design of the NGNP.

3.2. Irradiated Graphite Properties

The nuclear graphite previously used in the United States for HTGRs is no longer available. Graphite grades that are suitable for a pebble bed HTGR may not be ideal for a prismatic HTGR. Graphite properties vary widely based on the petroleum source and manufacturing processes used for graphite production. Hence, data are required for the physical, mechanical (including radiation-induced creep), and oxidation properties of potential new graphites and take account of in-billet, between billets, and lot-to-lot variations of properties. A radiation effects database must be developed for the currently available graphite materials, and this requires a substantial graphite irradiation program. Irradiation demonstrations for graphite will be integrated with the design and licensing processes.

3.3. Intermediate Heat Exchanger (IHX)/Heat Transport Development

The IHX(s) transfers energy from the nuclear system to both the power conversion and hydrogen production processes. Substantive development of the IHX is required from the standpoints of material application and engineering design. Focused development plans are necessary to support the schedule logic, including early operational demonstration of heat exchanger candidate concepts for scalable sizes at representative temperatures and pressure differentials. Closely linked to the IHX development is the choice of heat transport medium for the intermediate energy transport loop (e.g., helium, liquid salt, etc.). Other nuclear system development areas such as civil and structural engineering, power conversion technology development and balance of plant design are not currently anticipated to control the schedule logic.

For the NGNP Project, the development of the hydrogen production facility and its demonstration are comparable in complexity to that of the nuclear system. For the thermo-chemical process or high-temperature electrolysis, the controlling path is directly through development of the technology, including laboratory-scale, pilot-scale, and engineering-scale demonstrations. It is important to de-couple the success of hydrogen production facility development from that of the nuclear system. This will include testing at the engineering scale using an alternate source of high-temperature process heat before coupling the hydrogen facility to the nuclear heat source.

4. Hydrogen Technology Development

The Hydrogen Fuel Initiative (HFI), of which the DOE Nuclear Hydrogen Initiative (NHI) is a component, is a research and development (R&D) effort to reverse America's growing dependence on foreign oil and expand the availability of clean, abundant energy. Hydrogen is produced today on an industrial scale in the petrochemical industry by a process of steam reforming, using natural gas as both source material and heat source. A potentially better option is the use of advanced nuclear technology to produce hydrogen. High-temperature heat from an advanced nuclear system could be supplied to a hydrogen-producing thermochemical or high-temperature electrolysis (HTE) plant to support high efficiency hydrogen production and avoid the use of carbon fuels. The NGNP is expected to be this source of High-Temperature heat.

4.1. Current Status of NHI R&D

The U.S. Hydrogen Program is developing a broad range of technologies for a future hydrogen economy. DOE is investigating hydrogen production methods based on a range of feedstocks and power sources (e.g., fossil, renewables, nuclear), as well as storage, distribution, and end use technologies. The NHI is developing hydrogen production processes that use process heat available from a nuclear heat source. Its purpose is to provide a database on nuclear hydrogen production options and costs helping industry make informed decisions on private sector investments. The current NHI research program schedule, as shown in the NHI Ten-Year Plan, is generally consistent with the NGNP construction schedule. The major nuclear hydrogen production milestones identified in the NHI 10-Year Plan are:

- Selection of pilot-scale process(es) based on completion of successful laboratory-scale experiments (FY-09)
- Selection of nuclear heated engineering scale demonstration technologies based on successful pilot scale experiments (FY-12).

NHI milestones are intended to enable industry decisions to begin about 2015. The 2021 operation date for the NHI engineering-scale demonstration is consistent with the Hydrogen Program's needs and the proposed NGNP—with the potential to allow for an operational testing period using a non-nuclear source of process heat before connection to the NGNP. If the hydrogen production method selection for the engineering scale demonstration needs to be earlier than FY 2011 as planned by NHI, the method selected could be based on laboratory-scale data. Subsequent pilot-scale work would confirm the engineering approach, but not be used for the decision. This will involve higher technical risk, but could accelerate the hydrogen process demonstration.

The NHI is developing hydrogen production options for use with advanced high-temperature reactors to produce hydrogen from non-fossil resources (i.e., water). The major program elements in the NHI are investigating candidate hydrogen production processes and high-temperature interface technologies required to couple a high-temperature thermochemical or electrolysis process to the NGNP. These major NHI program priorities identified in the NHI 10-Year Program Plan are:

- *Hydrogen Production Process Development.* Develop thermochemical and high-temperature electrolytic hydrogen production processes and interfaces compatible with the thermal output characteristics of a Generation IV reactor to produce economically competitive hydrogen.
- *System Interface Technologies.* Develop advanced heat exchanger and materials to efficiently and safely couple the high-temperature hydrogen production process to advanced high-temperature reactors.
- *Alternative Nuclear Hydrogen Production Methods.* Investigate advanced or alternative production processes to the baseline cycles to assess the potential for higher efficiency or lower cost.

Process Development: Thermochemical Cycles

Thermochemical cycles produce hydrogen through a series of chemical reactions, resulting in the production of hydrogen and oxygen from water at much lower temperatures than direct thermal decomposition. Energy is supplied to drive the endothermic reactions, generally at 750 to 1000°C or higher. All process chemicals in the system are fully recycled. Hybrid thermochemical cycles include both chemical and electrolytic steps to produce hydrogen. In general, the electrical energy requirement for the hybrid electrolysis step in hybrid cycles is less than that for conventional electrolysis of water.

Process Development: High-Temperature Electrolysis

High-temperature electrolysis (HTE), or steam electrolysis, has the potential for higher efficiency than conventional electrolysis because thermal energy is used to provide part of the energy requirement for water splitting, reducing the electrical energy required for electrolysis. HTE requires low-cost electricity and energy to produce steam in the 750 to 950°C range. High-temperature electrolysis cells use similar electrodes and electrolyte materials as those used in solid-oxide fuel cells. Individual electrolyzer cells will be relatively small so that large-scale applications would be composed of many electrolyzer modules. Research on HTE for nuclear applications addresses both cell and stack engineering issues, and HTE systems design to determine viability and performance of this approach.

> <u>*Hydrogen Production Process Recommendation*</u>
> The goal of the NHI research is to provide the necessary information at each stage of process development to make an informed decision on the next stage of scaling and resource commitment, with the goal of demonstrating all key process technology steps before proceeding to the next step. The scaling of candidate production processes is performed in phases:
>
> <u>*Hydrogen Process Selection and NGNP Schedule*</u>
> Near-term NHI research focuses on laboratory-scale work on process development to support the pilot scaling decision in FY-09. Beyond FY-09, the major activities address construction and operation of pilot- and engineering-scale experiments. Although design and scaling issues are process-specific, the sequence of major milestones would be similar for any of the baseline or alternative processes selected.

The current S-I thermochemical research program involves significant international cooperation. This brings additional resources, but also the possibility of different priorities and schedules during the project. The intermediate heat transfer loop and the design of the process-side heat exchangers are coordinated by the Systems Interface and Support Systems area. NHI completed early scoping studies (with some help from Gen IV), performing scoping analysis of heat transfer losses, pressure drops, materials limitations, and corrosion for molten salt intermediate working fluids. The program includes work on heat exchanger designs, materials testing, and ceramic components.

4.2. Integration of NGNP Hydrogen Process and Heat Transport Systems

The Next Generation Nuclear Plant (NGNP) project was authorized in the *Energy Policy Act of 2005* (EPAct), in which the U.S. Department of Energy (DOE) was tasked with providing a demonstration of High-Temperature Gas-Cooled Reactor (HTGR) technology. The NGNP will demonstrate the technical, licensing, operational, and commercial viability of HTGR technology to provide high-temperature process heat for the production of electricity and hydrogen. It is the objective of the NGNP to complete the demonstration in a time frame that meets industry expectations as required by the EPAct (i.e., demonstration by 2021). The current target schedule for initial operation of the reactor is 2021 with a subsequent 3 year initial operating period.

Currently, the NGNP is in the conceptual design phase and development of the hydrogen production process (one of the project's largest technical risks), is included in that work. Hydrogen production research conducted by the National Hydrogen Initiative (NHI) under separate funding will be integrated into NGNP project plans during FY 2008. Incorporation of previous work regarding heat transport systems configurations, component designs and heat transport fluids will also be integrated with the project.

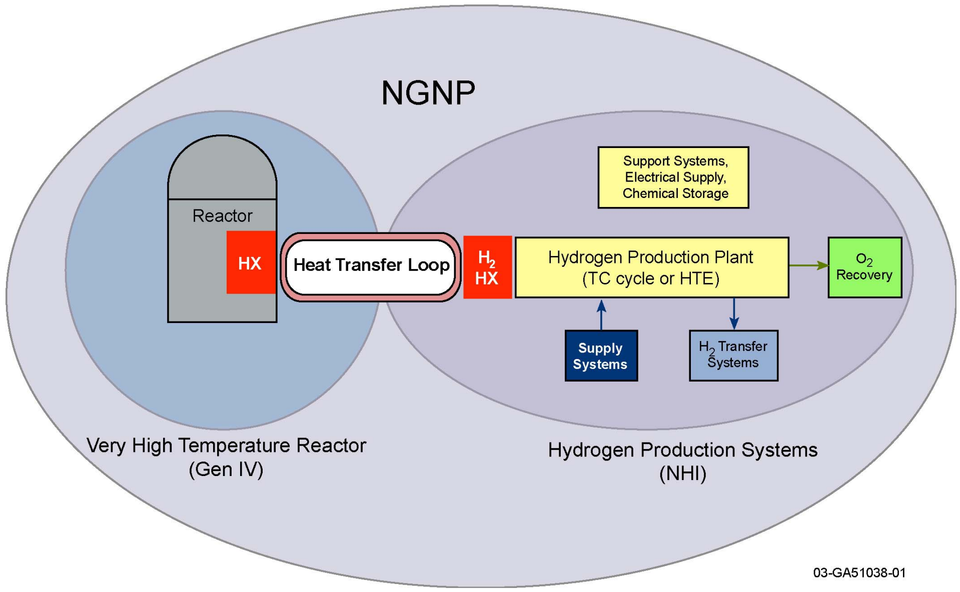

Figure 1: Major reactor-hydrogen interface and balance of plant systems

NHI will continue research of hydrogen production processes, but as the NGNP project matures, further development of the hydrogen production systems will transition to NGNP in support of design and licensing. The configuration in Figure 1 reflects a hydrogen production plant connected to an indirect heat transfer loop; however, multiple configurations with or without process heat or electrical applications are possible.

The NGNP Project will select a hydrogen process for demonstration based on systems engineering and comparisons of the leading hydrogen processes. The project schedule dictates when this decision will be made. After selecting the first technology for demonstration, further analysis and pilot plant and engineering scale demonstrations will increase the technology's maturity until it can be demonstrated during NGNP operation. Figure 2 is a high level decision tree that will be used in the systems engineering process.

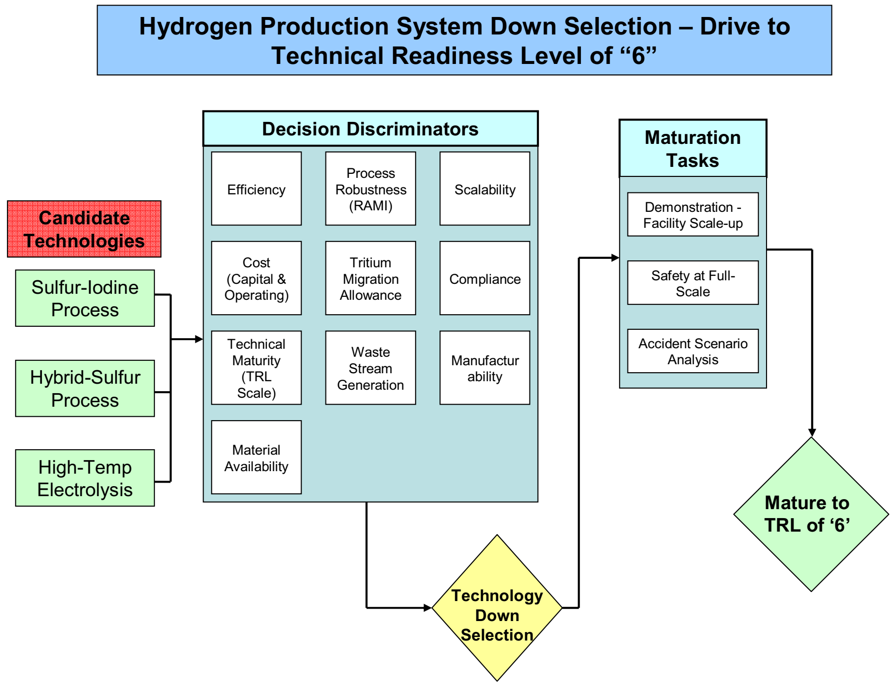

Figure 2: Decision Tree for Hydrogen Process Down-Selection

The lower-level activities needed to answer the questions illustrated in the decision tree will form the basis for the project plans, high level schedule and life cycle cost estimates that will be completed by NGNP in FY 2008. Included in the plans will be the outline of ongoing interface with the NHI.

5. Component Test Facility

Testing of a large high-temperature helium loop is crucial to the design effort for the heat transport loop that will connect the high-temperature nuclear reactor to the hydrogen production plant. Typically, increasing size from laboratory-scale through pilot plants, and engineering-scales reduce the technical and financial risk of any demonstration. The pressing need for large-scale demonstration of components and systems is common to NGNP and NHI. Design and construction of a facility for this purpose will be needed and is called the Component Test Facility (CTF).

The United States has some ability to test high-temperature (>700ºC) lab-scale heat exchangers. Current capability developed by NHI includes a bench-top helium closed-loop test apparatus at Ohio State University that will allow testing of small (~1 kW) heat exchangers. The University of Nevada Las Vegas has capabilities to test simple heat exchanger configurations under scaled fluid conditions. The scaled tests are not performed at high temperatures, but the data can be scaled to high-temperature high-pressure conditions for the purposes of constructing and testing better heat exchanger models and optimizing heat exchanger designs. Plans for a laboratory-scale single-effects heat exchanger testing laboratory at an Idaho State University facility adjacent to the INL was not funded in FY 2008. Other limited capacity for lab-scale testing exists at varied vendors and universities across the United States.

There is very limited capability to test high-temperature heat exchangers that are larger than laboratory-scale. A review of world-wide test capability revealed that the only test loops with close to full-scale test capacity include those in the Republic of South Africa and in Russia. The other large-scale loop, the German KVK loop, is no longer in operation. The remainder have much smaller capacities, (i.e., laboratory and pilot scale) designed for special purpose testing. Moreover, availability is problematic in light of growing competition for nuclear–related test capacity.

Preliminary scoping performed at the INL and two feasibility studies conducted by independent vendors identified high level requirements for the CTF. The facility must support testing at temperatures up to 950°C, pressures up to 9 MPa, and mass flow rates up to 160 kg/s. Generally, the facility can be defined as providing:

- Qualification and testing of large scale components in a high-temperature, high-pressure environment such as the:
  - Intermediate Heat Exchanger (IHX)
  - Ducting and insulation
  - Mixing chambers
  - Steam generator
  - High-temperature valves
  - Specific application high-temperature instrumentation
  - Industrial hydrogen components
  - Helium circulators
  - Scaled reactor pressure vessel integration and reactor internals testing
  - Chemistry control systems for helium coolant and associated contaminants and impurities
- Design code development verification and validation collaboration
- Materials development and qualification
- Manufacturer and supplier evaluation and development
- Steady-state and transient analysis of coupled systems and components

As stated, such information is also valued by the DOE NHI, and having this information prior to full-scale deployment would greatly enhance the reliability of the heat transport systems at the engineering-scale.

6. Summary

The NGNP Project will demonstrate the technical, licensing, operational, and commercial viability of HTGR technology to provide high-temperature process heat for the production of electricity, hydrogen and other industrial applications. The NHI performs the research and development of potential hydrogen processes and previously managed the integration of support systems such as heat transport loops and heat exchanger development. Because the NGNP has matured to the conceptual design phase, heat transport and integration functions were transferred to the NGNP. Hydrogen production process evaluations, component development and heat exchanger testing are being managed using systems engineering techniques that will eventually lead to full scale demonstration. While laboratory-scale and pilot plant testing will continue with existing (or potentially new) demonstrations, a large-scale facility is needed to progress to a commercial-scale demonstration. This facility is called the Component Test Facility and is crucial for both the NGNP Project and NHI. Continued close collaboration will be needed to ensure the success of both programs.

7. Acknowledgements

Work supported by the U.S. Department of Energy, Assistant Secretary for the Office Nuclear Energy (NE) under DOE-ID Operation Office contract DE-AC07-05ID14517.