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Dependable Hydrogen and Industrial Heat Generation from the Next Generation Nuclear Plant

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Abstract

The Department of Energy is working with industry to develop a next generation, high-temperature gas-cooled nuclear reactor (HTGR) as a part of the effort to supply the US with abundant, clean and secure energy. The Next Generation Nuclear Plant (NGNP) project, led by the Idaho National Laboratory, will demonstrate the ability of the HTGR to generate hydrogen, electricity, and high-quality process heat for a wide range of industrial applications. Substituting HTGR power for traditional fossil fuel resources reduces the cost and supply vulnerability of natural gas and oil, and reduces or eliminates greenhouse gas emissions. As authorized by the Energy Policy Act of 2005, industry leaders are developing designs for the construction of a commercial prototype producing up to 600 MWt of power by 2021. This paper describes a variety of critical applications that are appropriate for the HTGR with an emphasis placed on applications requiring a clean and reliable source of hydrogen. An overview of the NGNP project status and its significant technology development efforts are also presented.

1. Introduction

U.S. industries face four energy challenges to compete in a global economy: (1) the rising costs for premium fuels, such as light crude oil and natural gas, (2) dependence on unstable foreign sources for these premium fuels, (3) concerns about carbon dioxide and other greenhouse gas (GHG) emissions, and (4) the use of fossil fuels for hydrogen production. A high-temperature gas-cooled reactor (HTGR) can meet these challenges by providing process heat and/or power for efficient hydrogen production and other industrial applications.

The demand for nuclear power will increase to support industrial applications involving electricity, high-temperature heat, steam, hydrogen, and oxygen. This increase will accelerate as the real cost of carbon emitting technologies is accounted for. To achieve energy security and stability, the U.S. Energy Policy Act of 2005 (EPAct) defined a strategy to demonstrate an HTGR, including the cogeneration of electricity and hydrogen. Since then, the U.S. Department of

Energy (DOE) has led a sustained effort to develop this next generation of clean, safe, proliferation-resistant nuclear power - designated as Generation IV.

Recent technological developments in next generation nuclear reactors have sparked renewed interest in nuclear process heat for industrial applications. This paper describes some of the most promising applications, with an emphasis on those applications requiring hydrogen. A brief description of the Next Generation Nuclear Plant (NGNP) project is presented below.

To implement EPAct, the NGNP project is expected to become a public/private partnership to advance the initial HTGR. The project is currently in the conceptual design stage, while the NGNP is planned to be operational in 2021 with a 60-year design life. NGNP will be licensed by the U.S. Nuclear Regulatory Commission and will meet or exceed current nuclear standards in reliability, nonproliferation, waste management, and security. The helium-cooled reactor outlet temperature is planned to be between 750 and 800°C, and the most promising reactor core options being evaluated include a prismatic block or a modular pebble bed design. Figure 1 presents a schematic of the NGNP.

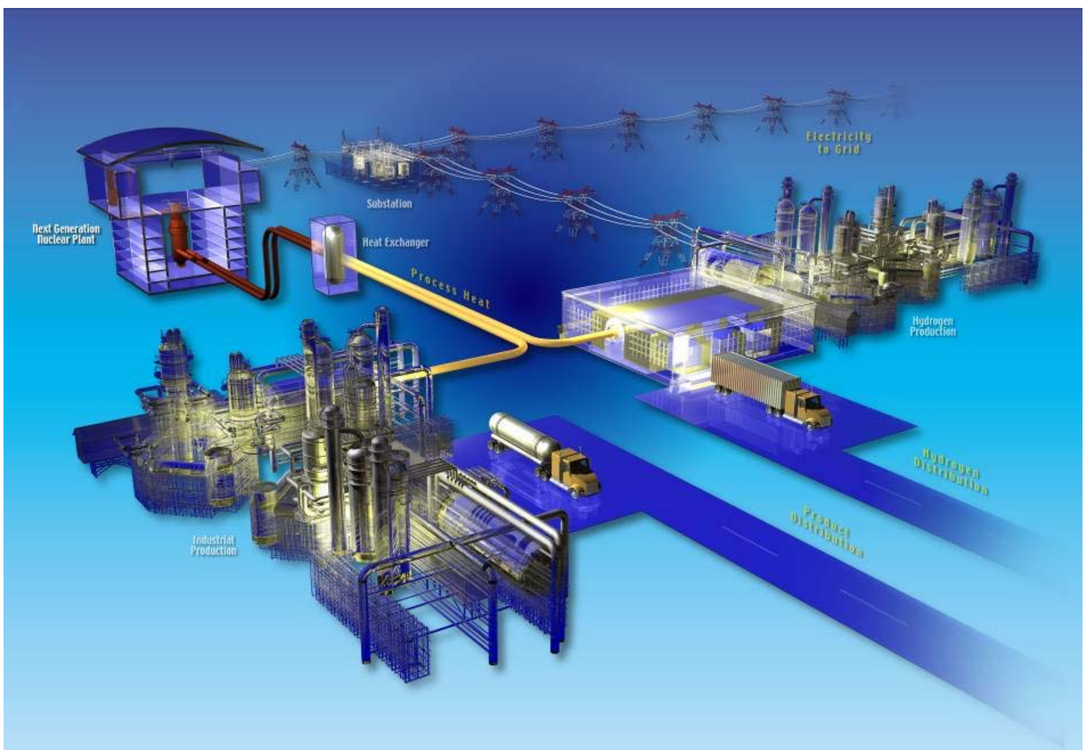

Figure 1. Schematic of the Next Generation Nuclear Plant.

Today, industry burns fossil fuels to provide the majority of its power and processing heat, and current generation nuclear power plants primarily produce steam to generate electricity. About 450 power reactors operate worldwide, of which about 100 are in the U.S. The maximum reactor outlet temperature for these plants is around 300°C. As energy needs increase, this current generation technology will be increasingly used for industrial applications. As shown in

Figure 2, light water reactors (LWRs) can support applications such as desalination, district heating, ethanol concentration, and some petroleum refining. However, an HTGR with temperatures up to 800°C can support a variety of industrial applications requiring both clean and reliable hydrogen and/or high-temperature heat. Extending the outlet temperature to 950°C could include coal gasification as a process application. Some of the most beneficial applications are discussed below.

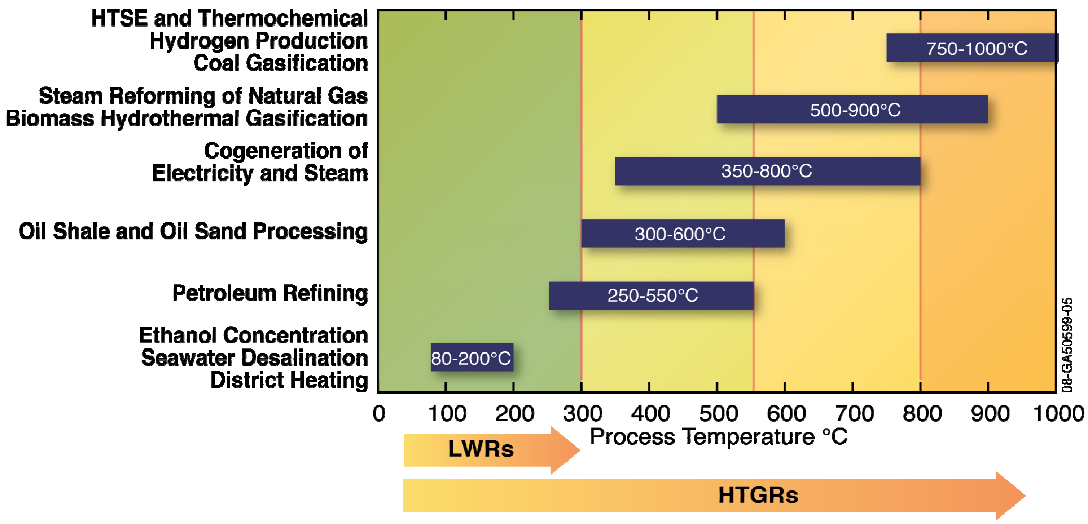

Figure 2. Required temperatures for process heat applications.

2. Nuclear Hydrogen Generation

The annual U.S. demand for hydrogen is over 12 million tons and is expected to grow to over 30 million tons by 2030 [EIA/DOE, 2008]. Hydrogen is currently produced primarily from steam methane reforming (SMR) using natural gas as both the source of the hydrogen and as the heat source. Current and future hydrogen production and storage favor large facilities that compliment the characteristics of nuclear power plants. Assuming that economically competitive nuclear hydrogen can be produced, this production may become a primary use of nuclear energy and the basis of a hydrogen economy. Three major potential hydrogen markets are transportation, electric power, and production industries. Presently, hydrogen is mainly used to produce ammonia for fertilizer (~45%), to sweeten heavy crude oil (~45%), and to produce methanol (~5%). Nuclear hydrogen may be the enabling technology for an effective renewable energy future because it can allow energy storage to help balance variable energy production with variable energy demand. As detailed below, hydrogen can be produced by various processes, all of which may benefit from using an HTGR as the primary energy source:

- Conventional water electrolysis—*using nuclear-generated electricity*:

  Conventional water electrolysis is a well-commercialized technology. Carbon emission from this form of hydrogen generation depends on the source of the electricity. When nuclear energy is used, those emissions are completely eliminated.

- High-temperature electrolysis—*using HTGR-generated electricity and steam:*

  High-temperature steam electrolysis is an advanced technology currently under development. This technology reverses the process of solid oxide fuel cells to produce hydrogen from steam. When coupled to an HTGR, this process can potentially double efficiencies (to 50% lower heating value) compared to conventional electrolysis.

- Thermochemical water splitting cycles—*using high-temperature HTGR heat*:

  A number of thermochemical water splitting cycles have been identified in recent years. These cycles essentially split water into hydrogen and oxygen through a series of heat-driven chemical reactions. Laboratory testing of the leading cycles is under development in the U.S., Japan, France, and other countries. In these thermochemical processes, only water, heat, and electricity are needed to produce hydrogen and oxygen. Most of the current U.S. development work has focused on the sulfur-iodine (SI) process.

- Hybrid Sulfur (HyS) cycle—*combining thermochemical and electrolytic steps:*

  Hybrid cycles combine the benefits of thermochemical and electrolytic reactions for water splitting. This technology offers the possibility of lower reaction temperatures by using electrolysis as a substitute for one of the chemical reactions.

- Steam methane reforming (SMR)—*using HTGR energy for the reaction heat and steam:*

  In the U.S. SMR is widely deployed to produce over 3 billion standard cubic feet (scf) of hydrogen per year, while consuming over 1.2 billion scf of natural gas [EIA/DOE, 2008]. The SMR reaction (Eq. 1) is endothermic and, therefore, does not generate CO_2. The reforming heat, however, is supplied through combustion of approximately 20-30% of the methane, which does generate CO_2. Furthermore, to increase the hydrogen yield, the syngas generated during reforming is shifted with water (Eq. 2) to produce 33% more hydrogen by converting all the original methane carbon to CO_2.

$$CH_4 + H_2O \rightarrow CO + 3H_2 + \text{combustion products including } CO_2 \qquad \text{(Eq. 1)}$$

$$CO + 3H_2 + H_2O \rightarrow CO_2 + 4H_2 \qquad \text{(Eq. 2)}$$

The overall result is that the mass of CO_2 produced is 10.6 times the mass of hydrogen produced [Koroneos et al. 2004]. However, an HTGR can provide the heat energy for the SMR process eliminating nearly 30% of the natural gas used, reducing carbon dioxide emissions, and increasing methane to hydrogen conversion efficiencies to 80%.

3. Applications Involving Hydrogenation of Fossil Fuels

The hydrogen produced from emission-free HTGRs will provide a significant economic and environmental benefit for current applications associated with the hydrogenation of both conventional and unconventional fossil fuel resources. Methods for generating cleaner hydrocarbon fuels (e.g., synthetic crude oil, substitute natural gas) from both secure conventional (e.g., coal and crude oil) and unconventional (e.g., oil sands, heavy oil and oil shale) fossil sources include:

1. The conversion of coal to substitute natural gas (SNG) and syngas through gasification;

2. The post recovery upgrading and refining of heavy oils, oil shale, and tar sands.

The above applications require sources of hydrogen to increase the hydrogen to carbon (H/C) ratio of the final hydrocarbon product to levels that ensure less GHG emissions upon their deployment (i.e., oxidation and combustion).

3.1 Coal Gasification and Liquefaction

Processes to convert large coal reserves to cleaner gas-based synthetic fuels are under consideration and evaluation. Unfortunately, these synthetic fuel processes generate GHGs, in addition to consuming large amounts of electricity directly (through coal hydrogenation) and indirectly (through the use of coal power plants for electricity).

However, by coupling a clean hydrogen producing HTGR to specific coal-to-gas (CTG) processes, GHGs are eliminated and high efficiencies are achieved. Specifically, the HTGR provides:

- Direct heat for some coal gasification reactions

- Better coal utilization

- Reactant hydrogen

The known CTG processes produce substitute natural gas/SNG (pipeline quality methane) and/or synthesis gas (i.e., mostly hydrogen and carbon monoxide) utilizing four different methods (steam /air, steam/oxygen, hydro, and catalytic gasification) of various scales. Regardless of which processes are used, the ability of an HTGR to produce clean, economical, and efficient quantities of hydrogen at the coal gasification site results in:

- Reliable control of the coal gasification process in a manner to eliminate or reduce the generation of CO_2.
- Elimination of cryogenic air separation units (ASU) since oxygen is also produced through efficient water splitting techniques.

3.2 Conventional and Unconventional Fossil Fuel Upgrading and Refining

The two processes for converting both unconventional and conventional liquid fossil fuel resources into useful transportation and petrochemical products are upgrading and refining. They both consist of a variety of unit processes involving the addition of hydrogen (hydrogenation) to increase the usefulness, marketability and profitability of the end products (gasoline, diesel, aviation fuel, kerosene, and various petro chemical feed stocks). As mentioned, increasing the H/C ratio through hydrogenation is environmentally beneficial because it provides for a cleaner burning fuel. The H/C ratio also can be increased by decreasing the carbon in the fuel via coking, but this reduces the final amounts of cleaner burning fuels that can be delivered to market.

Refineries indirectly produce nearly half of their necessary hydrogen as a by-product of catalytic reforming. The other half is provided by SMR at the refinery site or supplied by a nearby hydrogen vendor. In the past, refineries did not produce or purchase additional hydrogen since most crude was lighter (sweeter). Because high quality crude is no longer in abundant supply, refineries are required to process heavier and heavier crudes requiring ever greater quantities of hydrogen. This trend will increase as the remaining sources of high quality crude are depleted.

Although refineries contain upgrading operations, stand-alone upgrading facilities without refining processes also exist. The conventional (or sweet) crudes and some heavy oils are light enough and of low enough viscosity to be piped directly to a refinery for all necessary hydrogen-based upgrading and refining steps. In contrast, the stand-alone upgrading facilities are always located near unconventional fossil fuel recovery sites and consist of enough hydrogen production to ensure that the heavy unconventional fossil resource can be made of low enough viscosity to be piped to conventional refineries as synthetic crude. These unconventional fossil fuels include high density heavy oils, in situ extracted oil shale (a kerogen), liquefied coal product, and in situ extracted oil sands (bitumen).The upgrading facilities, in contrast to the complete upgrading/refining facilities, do not produce hydrogen as a by-product, requiring all their hydrogen to be produced onsite. This is demonstrated by the large number of SMR units at the oil sands upgrading facilities in Alberta, Canada.

The specific hydrogen-based unit processes go by a variety of names, including but not limited to, hydrogenation, hydrocracking, hydrotreatment, hydrogenolysis, hydrodenitration, hydroretorting, and hydrodesulphurization. Full discussion of these different hydrogen addition methods for various fossil fuels is not presented here, but they involve cracking, catalysts, and/or impurity removal. More important is that they all require varying amounts of hydrogen depending on the quality of the incoming raw fuel as well as on the desired characteristics of the refined product (e.g., gasoline, diesel, petrochemical feed stock). As such, nuclear hydrogen via an efficient HTGR is uniquely capable of meeting this robust and changing hydrogen demand as well as conserving methane and eliminating the GHGs of SMR.

3.3 HTGR Long Distance Heat Transfer for In-situ Oil Shale and Oil Sand Recovery

In addition to the hydrogenation applications for both oil shale upgrading and refining, an additional benefit of the HTGR is direct application of its high temperature heat for the future in situ recovery of oil shale.

Geologically, oil shale is conventional crude that has been incompletely 'pressure cooked'. It lacks the substance of conventional crude oil and is embedded as kerogen in low porosity sedimentary rock. As a result, oil shale produces both gaseous and liquid hydrocarbons that can be recovered with established drilling methods when slowly heated in situ to 400°C. The in situ process has the potential to eventually recover the full extent of the shale reserve because compared to mining, it is not only environmentally friendlier, but can access both shallow and deep seams. Some recent testing involving the in situ slow heating method used grid electricity to supply the large underground heat source: and even though coal power plants could provide this electricity, the use of coal is unattractive for the following reasons:

- The exothermic complete combustion of coal releases CO_2 – a major GHG.
- Coal is considered a viable commodity as a feed stock for other uses, such as clean synthetic fuel and even cleaner substitute natural gas via liquefaction and gasification technologies.
- Electricity as a heat source is only 40% efficient at best. That is, over 60% of the energy input of the coal is lost in the steam-to-turbine-to-generator conversion of the power plant.

For these reasons, the HTGR is a viable alternative for supplying the in situ heat over relatively long distances. Early qualitative and semi-quantitative analysis reveals that the advantages of an HTGR more than balance the HTGR capital cost and the cost of the relatively long distance piping infrastructure needed to transport its heat. This is true even over a relatively long radius for subsequent heat exchange to the recirculating in situ heat pipes at the oil shale parcels.

Unlike oil shale, the recovery of oil sands in Alberta, Canada is well established. These large deposits of bitumen hold the equivalent of 900 billion barrels of proven reserves over 140,000 sq km. Already, over 1.2 million barrels per day (BPD) are produced via both mining and in situ technologies; with over a dozen companies involved in either mining, in situ removal (mostly by steam assisted gravity draining [SAGD]), and/or oil sands upgrading.

Given the economic success of oil sands production, expansion was estimated to exceed 3.8 million BPD by 2020 [Lee et al. 2007] prior to the recent recession and the previous drop in crude prices. Still, based on moderate growth rates, natural gas use for SAGD in situ recovery is expected to rise from 180 billion scf/yr to an environmentally unsustainable level of over 700 billion scf/yr by 2020. Consequently, it is understandable that the companies involved in oil sands operation are investigating alternative energy sources, including HTGRs. An HTGR will avoid both the volatility of methane price and the large quantities of GHGs. As a cleaner alternative, HTGR heat could be transferred relatively long distances and exchanged with steam at the SAGD wells.

4. Industrial Applications

4.1 Ammonia

More than 9 million metric tons of ammonia are domestically produced per year. Although a significant portion of this ammonia is for the manufacture of fertilizer, it is also used in the production of plastics, fibers, explosives, dyes, and pharmaceuticals. Current industry practice for ammonia production involves the high pressure Haber-Bosch reaction, whereas generation of reactant hydrogen is via traditional SMR. The escalating price of natural gas, growing concerns about carbon emissions, and the high energy cost associated with gas compressors all contribute to the ammonia industry searching for more cost efficient and cleaner production methods.

An HTGR provides an economical substitution involving the Haber-Bosch reaction by eliminating SMR. When used with the traditional ammonia production process, an HTGR eliminates the natural gas purification step, the carbon monoxide conversion stages, and waste condensates.

Furthermore, an HTGR can provide dedicated local power to the gas compressors and air separation units.

4.2 Methanol

Methanol (CH_3OH) is one of the most important feed stocks for the chemical industry and the conventional method for its production is by passing methane through syngas ($CO + H_2$). However, methanol is also produced from CO_2 by catalytic hydrogenation with the H_2 potentially provided by an emission free HTGR. As such, the later process is both cleaner and conserves methane in contrast with the conventional method. As a potential alternative to hydrogen as a future clean transportation fuel, methanol could replace gasoline. It contains half the energy density of gasoline but with a higher octane rating, meaning that the air-fuel mixture can be compressed to smaller volumes before being ignited. In addition, vehicles fueled by methanol will have lower overall emissions of air pollutants such as SO_2 and NO_x [Olah et al, 2006].

4.3 Industrial Gases (Oxygen/Hydrogen/Nitrogen)

A significant synergy of using water splitting for hydrogen production is to use the oxygen by-product in coal gasification operations. This avoids the use of air separation units and the removal of nitrogen in coal-produced syngas and SNG. To remove nitrogen via air separation units or downstream of the gasifier is expensive both in capital and energy operating costs. The downstream cleanup steps account for over 40% of the total energy demand of the CTG process, and the cleanup and recovery of a number of expensive solvents deployed in these off-gas stages account for a large fraction of this power expenditure. The air separation unit alone can use up to 14 MJ of energy for every kg of oxygen produced [Probstein et al. 2006].

Even though an HTGR does not produce nitrogen directly, using an efficient HTGR to power cryogenic air separation units indirectly reduces coal power plant GHGs and generates cost savings during production of nitrogen in ammonia manufacturing.

5. Conclusions

Nuclear energy can play a significant role in providing heat, electricity, steam, hydrogen, and oxygen to future industrial applications. In many cases, this will require high-temperature heat provided by an HTGR. The NGNP project is overcoming technological challenges to enable this deployment. The most significant current technology challenges are to qualify the next generation of nuclear fuel, to develop high-temperature materials, and to develop a method for commercial-scale hydrogen production.

Nuclear energy from an HTGR can produce hydrogen and also provide process heat to a variety of industrial processes. Use of the HTGR can improve efficiency and significantly reduce GHG emissions. Expanding the use of nuclear energy provides a realistic solution to economic stability, environmental sustainability, and resource security. The NGNP project is the flagship for developing and implementing this next generation of nuclear energy systems based on HTGR technology, with minimal CO_2 emissions and increased energy security.

6. Acknowledgments

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7. U.S. Department of Energy Disclaimer

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