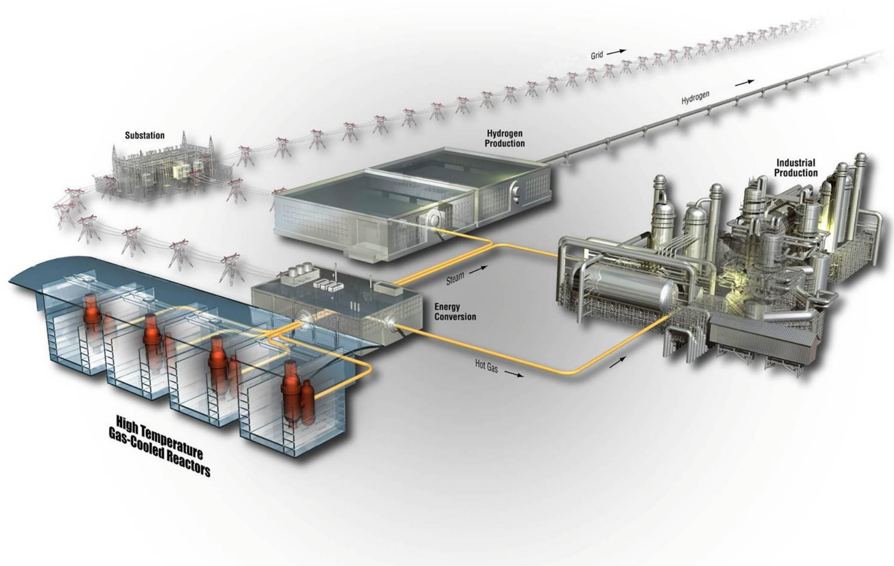
INL/EXT-11-21537

Optimum Reactor Outlet Temperatures for High Temperature Gas-Cooled Reactors Integrated with Industrial Processes

April 2011



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Approved by:

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ABSTRACT

This report summarizes the results of a temperature sensitivity study conducted to identify the optimum reactor outlet temperature for generating the primary and secondary outputs from a high temperature gas-cooled reactor. This study assumed that the primary output of the reactor was steam delivered at 17 MPa and 540°C or helium delivered at 7 MPa and 625–925°C. The secondary output was electricity or hydrogen. For the power generation analysis, it was assumed that the power cycle efficiency was 66% of the maximum theoretical efficiency of the Carnot thermodynamic cycle. Hydrogen was generated via the high-temperature steam electrolysis or the steam methane reforming process. The study indicates that the optimum reactor outlet temperatures for the primary and secondary outputs vary from 750 to 950°C depending on which process is coupled to the reactor and depending on specific end user needs. Additional study is recommended to identify the optimum reactor outlet temperatures for the process evaluations that were developed for high temperature gas-cooled reactor-integrated production of synthetic transportation fuels, ammonia, and ammonia derivatives, oil from unconventional sources, and substitute natural gas from coal.

SUMMARY

Under direction from the Department of Energy (DOE), the Next Generation Nuclear Plant (NGNP) Project has evaluated the integration of high temperature gas-cooled reactor (HTGR) technology with industrial processes. The evaluations showed that HTGR-integrated processes will reduce the carbon dioxide and other greenhouse gas emissions that are generated by conventional processes, primarily by replacing the heat derived from natural gas and coal combustion with high-temperature process heat from the HTGR.

The detailed process models developed for HTGR-integrated production of synthetic transportation fuels and ammonia and the recovery of unconventional oils were based on a reactor outlet temperature (ROT) of 750°C, the temperature at which the NGNP is expected to operate. This report summarizes the results of the temperature sensitivity study conducted to identify the optimum ROTs for producing the heat and hydrogen required by these industrial processes.

The study assumed that the outputs of an HTGR were steam delivered at 17 MPa and 540°C and helium delivered at 7 MPa and 625–925°C. The secondary outputs of the HTGR were electricity and hydrogen. For the power generation analysis, it was assumed that the power cycle efficiency was 66% of the maximum theoretical efficiency of the Carnot thermodynamic cycle. Hydrogen was generated via the high-temperature steam electrolysis or the steam methane reforming process.

The analysis for process heat showed that the helium or steam returning from the industrial process must be within a specific temperature range to maintain the correct reactor inlet temperature and to best utilize the heat generated by the HTGR. For example, the temperature of steam returning from an industrial process cannot exceed the temperature of saturated liquid water because it needs to be pumped back to the steam generator. Because of this constraint, the optimum HTGR ROT for generating steam at 540°C and 17 MPa is 770°C. The optimum HTGR ROT for high-temperature helium depends on the needs of the industrial process being supplied by the high-temperature helium.

The evaluation shows that the optimum HTGR ROT for electricity production is 950°C, for hydrogen production via HTSE is 850°C, and for hydrogen production via steam methane reforming is 875°C.

The results of the temperature sensitivity study indicate that optimum ROTs or a range of ROTs could be identified to further refine the process evaluations developed for HTGR-integrated production of synthetic transportation fuels, ammonia and ammonia derivatives, oil from unconventional sources, and substitute natural gas from coal. These evaluations were initially based on an HTGR ROT of 750°C. The results of the preliminary temperature sensitivity analysis for processes that utilize the primary and secondary HTGR outputs are shown in Figure ES-1.

Additional modeling is required to provide a more precise estimate of the optimum ROTs, but the exact optimum for each process is expected to be bound by the ranges shown in the figure. The optimum HTGR ROT for processes that use high-temperature helium is approximately 35°C higher than the maximum process temperature range to account for the two heat exchangers located between the HTGR and the process. The optimum HTGR ROT for processes that utilize steam is 770°C.

The study reached the following conclusions:

- The optimum HTGR ROTs for steam generation (delivered at 540°C and 17 MPa), electricity generation, hydrogen production via high temperature steam electrolysis, and hydrogen production via steam methane reforming are 770, 950, 850, and 875°C respectively.
- The optimum HTGR ROT for steam production varies depending on the temperature and pressure of the steam produced.

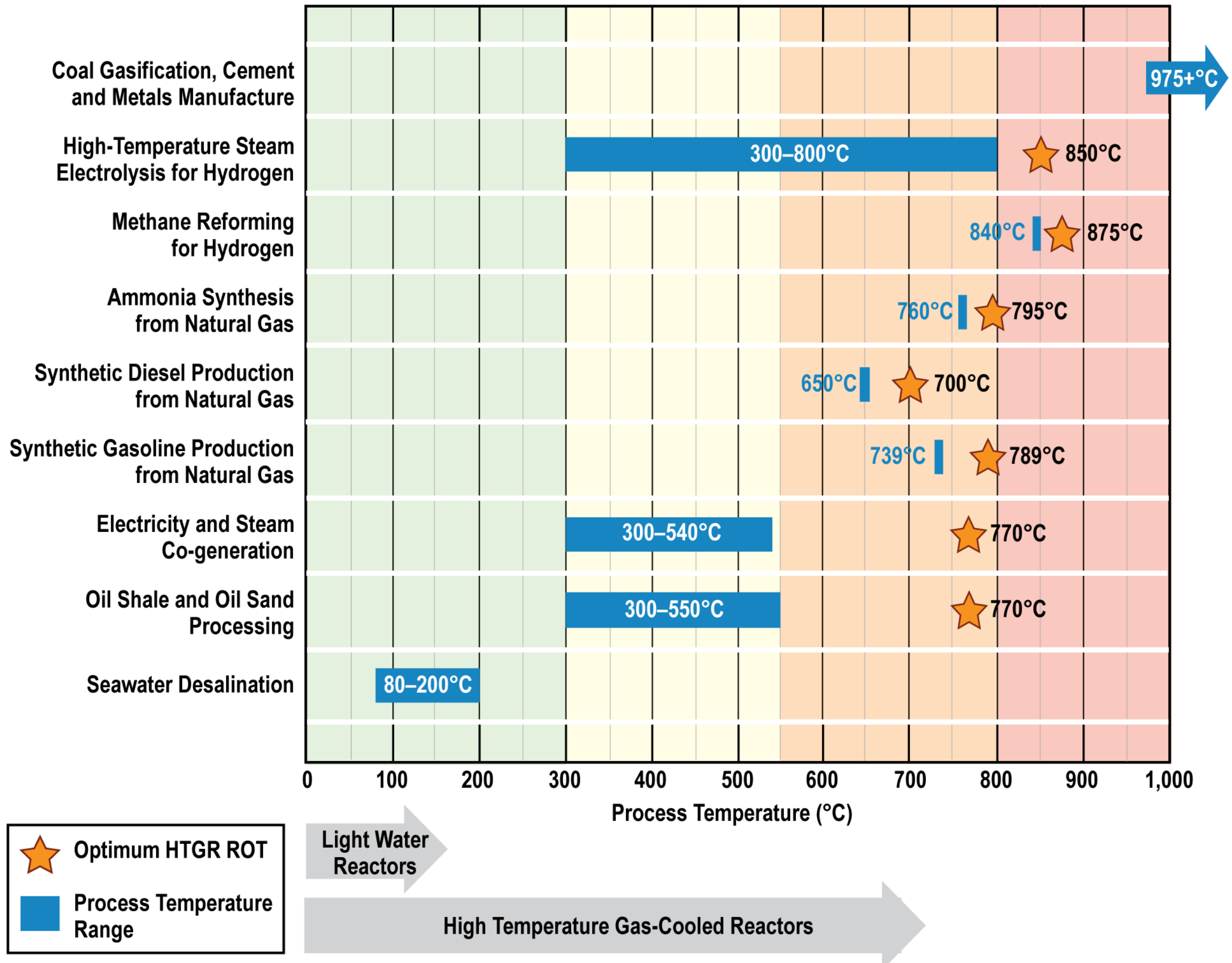

Figure ES-1. Optimum HTGR ROTs and the process temperature range associated with HTGR-integrated industrial processes.

- The optimum HTGR ROT for process heat delivered as helium (or other hot gas) does not exist, because the optimum is process dependent.
- Because this study was based solely on mass and energy balance information, economic analyses are required to identify more realistic optimum HTGR ROTs.
- In order to perform an economic analysis, the HTGR cost as a function of configuration, size, and temperature is required.
- Based on a preliminary high-level analysis, the optimum HTGR ROT for hydrogen production, ammonia synthesis from natural gas, production of synthetic fuels from natural gas, cogeneration of electricity and steam, and oil shale and oil sand processing varies from 750 to 950°C. Additional study is required to identify a more precise optimum HTGR ROT for these processes.

Based on the results of this study it is recommended that a temperature sensitivity study be conducted for the processes shown in Figure ES-1 that includes the impact of economic considerations. To adequately address economic considerations, it is recommended that a cost model be developed for the HTGR to include the impact of HTGR configuration, size, and 750–950°C HTGR ROT on the HTGR capital and operations and maintenance cost.

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Optimum Reactor Outlet Temperatures for High Temperature Gas-Cooled Reactors Integrated with Industrial Processes

1. INTRODUCTION

Under Department of Energy (DOE) direction, the Next Generation Nuclear Plant (NGNP) Project has evaluated the integration of high temperature gas-cooled reactor (HTGR) technology with industrial processes. After potential applications were identified in an initial survey,[1] detailed models based on typical plant production capacities were developed and comprehensive evaluations were conducted for the following processes[2,3,4,5,6,7,8]:

- Synthetic gasoline production from coal and natural gas
- Synthetic diesel production from coal and natural gas
- Ammonia derivatives production from natural gas
- Steam-assisted gravity drainage (SAGD) for bitumen recovery from oil sands
- Oil production from oil shale
- Substitute natural gas production from coal.

The evaluations showed that HTGR-integrated processes will reduce carbon dioxide and other greenhouse gas emissions generated by conventional processes, primarily by replacing the heat derived from natural gas and coal combustion with high-temperature process heat from the HTGR. HTGR-integrated processes will also prolong the availability of limited natural resources so they can be directed toward more valuable uses, such as using natural gas as a petrochemical feedstock.

The detailed models developed for these HTGR-integrated industrial processes (see References 2–8) were based on an ROT of 750°C, the temperature at which the NGNP is expected to operate.

Temperature sensitivity studies were conducted[9,10,11,12,13,14,15,16,17] to identify the optimum reactor outlet temperatures (ROTs) for producing the heat, electricity, and hydrogen. This report summarizes the modeling assumptions used in these studies (Section 2), approach (Section 3), affects of varying the ROT from 650–950°C on the primary and secondary outputs (Section 4), implications for HTGR-integrated industrial processes (Section 5), and overall conclusions and recommendations for future work (Section 6).

2. MODELING ASSUMPTIONS

The primary output of an HTGR is heat, which requires a steam generator or intermediate heat exchanger downstream of the HTGR to supply the heat as high-temperature steam, helium, or other fluid. Secondary outputs—electricity, hydrogen, and oxygen—can be provided when additional equipment is added downstream. The potential outputs from a 600-MW(t) HTGR are described in Table 1. A schematic diagram of an HTGR reactor and accompanying steam generator and intermediate heat exchanger pressure vessel is shown in Figure 1.

Table 1. Primary and secondary outputs from a 600-MW(t) HTGR.

Primary Outputs	Description
High-temperature process heat	
• Helium	• 625–900°C (7–9.1 MPa)
• Steam	• 540°C (17 MPa)
Secondary Outputs	**Description**
Electricity	Generated by a Rankine, Brayton, or combined Brayton/Rankine power cycle
Hydrogen (H_2) and oxygen (O_2)	Produced by high-temperature steam electrolysis (HTSE)
Hydrogen (H_2)	Produced by steam methane reforming

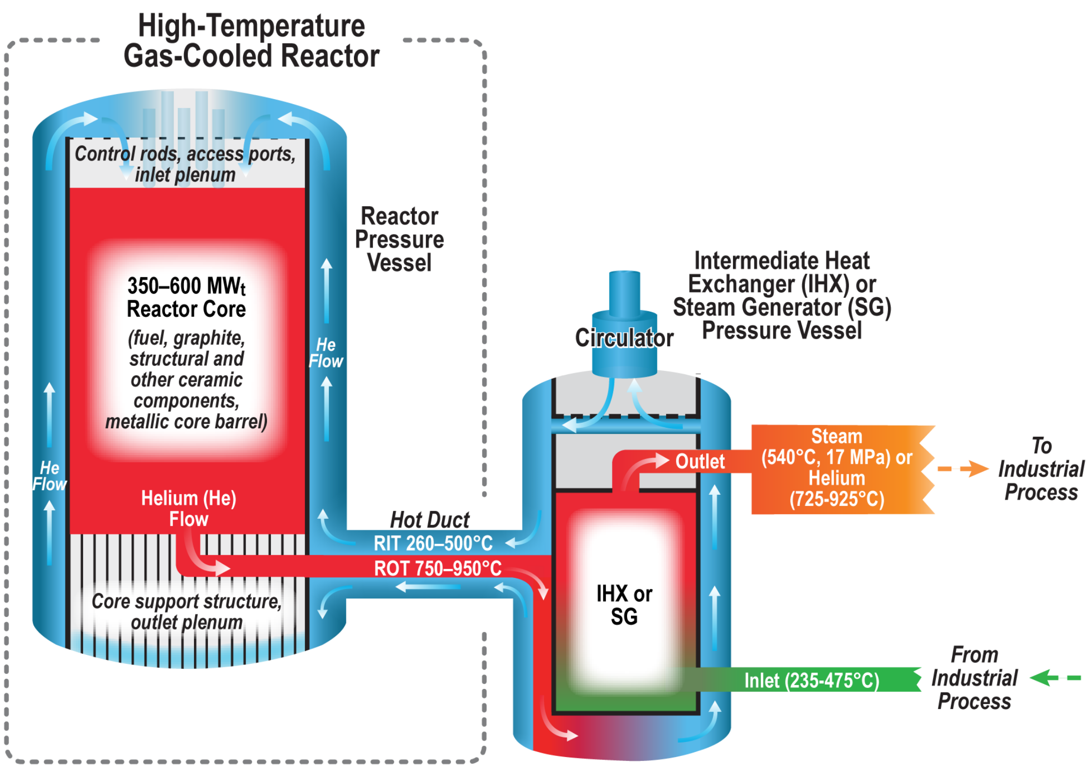

Figure 2. Schematic diagram illustrating an HTGR reactor pressure vessel and accompanying intermediate heat exchanger or steam generator.

As shown in Figure 1, heat (350–600 MW(t)) is generated by nuclear fission in the reactor core. Helium coolant travels back and forth from the core to the intermediate heat exchanger or steam generator in a closed loop. When the helium leaves the core, it is carried in the hot duct to the intermediate heat exchanger or steam generator at an ROT range of 750–950°C. There, the heat is transferred to either helium in the intermediate heat exchanger or water in the steam generator so these high-temperature fluids can be carried by piping to the industrial process. The cooled helium returns to the core at a reactor inlet temperature (RIT) range of 260–500°C where it can again be heated.

The study assumed steam would be delivered at 17 MPa and 540°C and helium would be delivered at 7 MPa and 625–925°C. For the power generation analysis it was assumed that the power cycle efficiency was 66% of the maximum theoretical efficiency of the Carnot thermodynamic cycle. This assumption was verified based on a comparison with power cycle efficiencies as reported in scientific literature.[9]

Detailed Aspen Plus models were developed, based on the assumptions and calculations summarized in Table 2, to determine how varying the ROT impacts the quantity of primary and secondary HTGR outputs. Optimum ROTs—the temperatures at which the maximum output of a desired product is produced from a given amount of heat and material—were determined by varying the ROT from 650–950°C in increments of 50°C. The relationship between the RIT and ROT was based on an analysis of currently or previously operating HTGRs.[15] The correlation developed for the HTGR RIT is for the purposes of this report only. The actual relationship between the HTGR RIT and ROT would be developed during future design activities and is used in this report to provide a preliminary estimate of how the RIT changes relative to the ROT. In practice, the RIT is a function of several factors, not just the ROT. If a particular application appears promising, additional study will be required to select and optimize both the RIT and the ROT as part of reactor design activities.

Table 2. Assumptions used to calculate the primary and secondary outputs of an HTGR as the ROT varies from 650–950°C.

Assumption	Value
HTGR ROT	650–950°C in 50°C increments
Intermediate heat exchanger approach temperature	25°C
HTGR RIT[a]	RIT(°C) = 0.82050 * ROT(°C) – 242.68°C[a]
Primary circulator efficiency	75%
Heat loss in piping between HTGR and process application[b]	0°C
Efficiency of compressors and turbines	90%
Process heat exchanger minimum approach temperature	10°C minimum (except when demonstrated industrial experience indicates differently)
Phase of water returning to steam generator	Liquid water (allows pumping)

a. See TEV-981, “An Analysis of the Effect of Reactor Outlet Temperature of a High Temperature Reactor on Electric Power Generation, Hydrogen Production, and Process Heat,” M. McKellar, September 14, 2010.

b. This assumption was verified with heat transfer calculations and applies to distances less than 0.5 km. The heat loss in piping is approximately 1% per kilometer, due mainly to the energy required to pump the fluid.

3. APPROACH

The INL has performed a significant amount of analysis for a variety of customers over the past several years. These efforts required the development of an extensive library of conventional process models of petrochemical plants, which are kept up to date to accurately reflect current industrial processes. The work described in this section was developed from the existing library of process models.

3.1 Primary Output—Process Heat

Process heat for petrochemical and other processes can be generated by an HTGR without carbon dioxide emissions, as shown in Figure 1. Heat is provided as high-temperature helium or steam. For this analysis, the steam temperature and pressure were assumed to be 540°C and 17 MPa, respectively. Helium was supplied at a temperature and pressure of 725-925°C and 7 MPa, respectively.

3.2 Secondary Output—Electricity

High-temperature helium or steam from an HTGR can be used by a power cycle to generate electricity, as shown in Figure 2. HTGR-generated electricity will not produce carbon dioxide emissions.

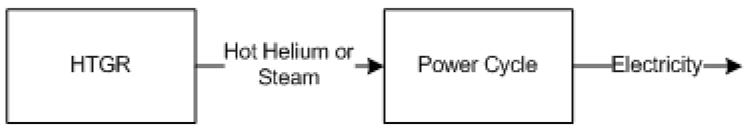

Figure 3. Electricity generation from heat produced in an HTGR.

3.3 Secondary Output—Hydrogen

Two methods of hydrogen production were considered: high-temperature steam electrolysis (HTSE), which uses water, heat, and electricity to generate relatively pure hydrogen and oxygen; and steam methane reforming, which uses water, heat, and methane to generate hydrogen and carbon dioxide. These processes produce some carbon dioxide emissions.

3.3.1 Hydrogen from HTSE

A simplified block flow diagram of the HTSE process is shown in Figure 3. The HTGR supplies high-temperature helium to both the power cycle to generate electricity for the HTSE unit and to the HTSE unit itself. If the HTGR ROT is less than 850°C, topping heat is supplied by natural gas combustion to bring the helium to a temperature of 850°C, the temperature needed to bring the HTSE process to the required operating temperature of 800°C.

3.3.2 Hydrogen from Steam Methane Reforming

A simplified block-flow diagram of a steam methane reforming process for an HTGR-integrated plant is shown in Figure 4. The HTGR-integrated process uses high-temperature helium to provide heat for the process. However, if the HTGR ROT is less than the 850°C required for the process, topping heat is supplied by natural gas combustion to bring the helium to a temperature of 850°C.

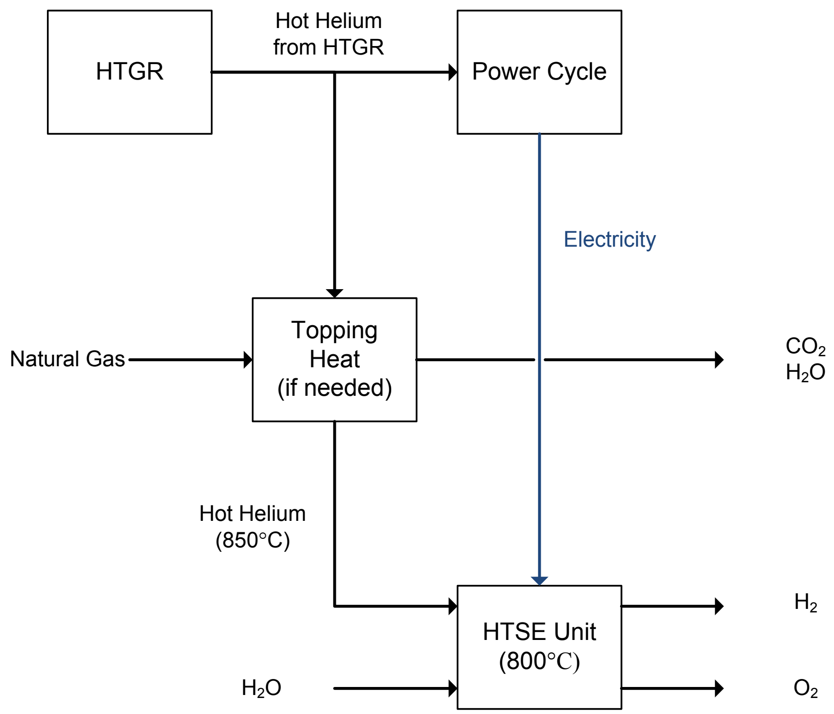

Figure 3. HTGR-integrated hydrogen production via HTSE.

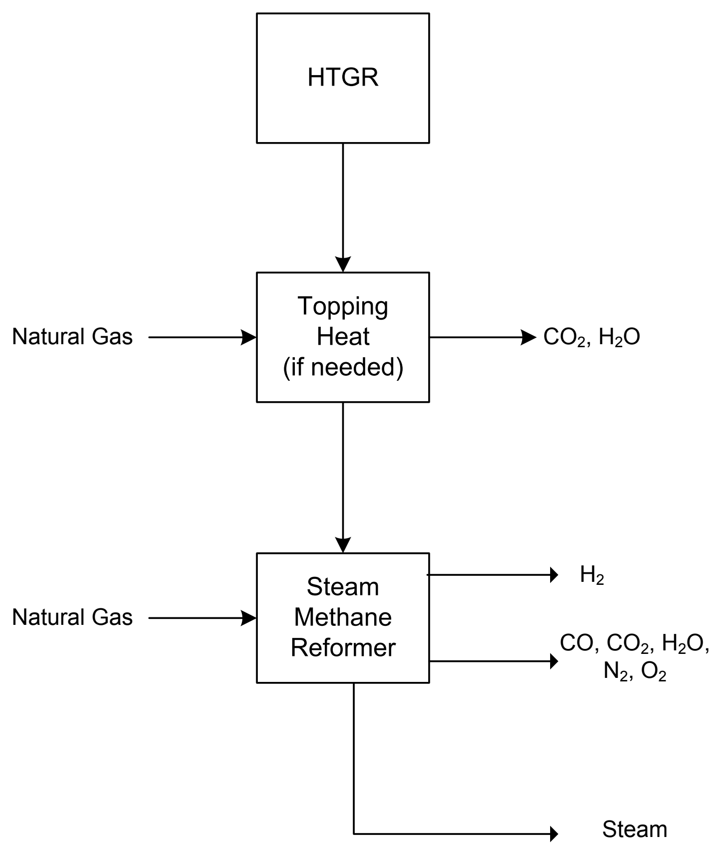

Figure 4. HTGR-integrated hydrogen production via steam methane reforming.

4. RESULTS

A summary of the analyses of the various HTGR outputs—process heat, electricity, and hydrogen—shows that as the HTGR ROT is increased from 650–950°C, the quantities of the primary and secondary outputs vary. An optimum HTGR ROT was identified for each of these outputs.

4.1 Process Heat Generation

The analysis showed that the maximum flow rate of steam and helium varied as the HTGR ROT varied from 650–950°C as shown in Table 3. This study assumed that steam is provided at a temperature of 540°C and 17 MPa and helium is supplied at a pressure of 7 MPa as follows:

- The optimum HTGR ROT for steam production was determined to be 770°C, which is the temperature at which the steam flow rate of 402.6 kg/s is achieved. Above 770°C, the increase in maximum flow rate of steam is negligible because the returning liquid water temperature remains at 349.8°C, the maximum temperature of liquid water at a pressure of 17 MPa. The optimum HGR ROT would change if a different pressure was assumed for steam delivery.
- For delivery of high-temperature helium, the optimum HTGR ROT is dependent upon the downstream process.

Table 3. Process heat (steam at 540°C and 17 MPa; helium at 7 MPa) delivered as a function of HTGR ROT.

	Steam			Helium		
HTGR ROT (°C)	**Supply Temperature (°C)**	**Optimum RIT (°C)**	**Maximum Flow Rate (kg/s)**	**Supply Temperature (°C)**	**Optimum RIT (°C)**	**Maximum Flow Rate (kg/s)**
650	540	246.6	272.4	625	244.1	321.8
700	540	294.4	306.1	675	283.5	313.9
750	540	334.3	360.8	725	322.9	306.4
770[1]	**540**	**349.8**	**402.6**	—[2]	—[2]	—[2]
800	540	349.8	402.9	775	362.3	299.3
850	540	349.8	403.4	825	401.7	292.5
900	540	349.8	403.9	875	441.2	286.0
950	540	349.8	404.3	925	480.6	279.7

1. The optimum HTGR ROT for steam production is 770°C. Above this temperature, steam production does not increase significantly.
2. Calculations for helium production were not completed at this ROT.

4.2 Electricity Generation

The analysis showed that electricity generation efficiency improves as the HTGR ROT increases from 650–950°C as shown in Table 4. The optimum HTGR ROT is 950°C since electricity output is highest at this temperature. This study was based on incorporating a generic power cycle that generates electricity with an efficiency of 66% of the ideal Carnot cycle.[15] The net electricity generation efficiency, which includes the impact from the electrical power needs of the HTGR, is the actual efficiency obtainable.

Table 4. HTGR electricity generation efficiency as a function of HTGR ROT.

HTGR ROT (°C)	Net Electricity Generation Efficiency
650	**43.2%**
700	44.3%
750	**45.2%**
800	46.1%
850	46.8%
900	47.5%
950*	48.2%

* The optimum HTGR ROT for electricity production is 950°C, below which, the net electricity generation efficiency diminishes as the ROT decreases from 950–650°C.

4.3 Hydrogen Production

The analysis considered HTGR-integrated hydrogen production via HTSE and steam methane reforming.

4.3.1 Hydrogen Production from HTSE

The analysis showed that hydrogen production from HTGR-integrated HTSE increases as the HTGR ROT increases from 650–950°C, as shown in Table 5. The optimum ROT for delivered process heat is 850°C because it is the lowest temperature at which topping heat is not required. As the ROT falls below 850°C, increasing amounts of topping heat are required to achieve the desired 800°C operating temperature. Because approximately 90% of the energy required to produce hydrogen is electricity, the HTSE process performs even more efficiently at 950°C because of the improved efficiency of generating electricity.

Table 5. Calculated hydrogen production from HTGR-integrated HTSE as a function of ROT.

	Steam Sweep HTSE			Air Sweep HTSE		
HTGR ROT (°C)	Process Heat for HTSE (MW(t))	Hydrogen Flow (kg/s)	CO_2 Emissions (tons/day)[a]	Process Heat for HTSE (MW(t))	Hydrogen Flow (kg/s)	CO_2 Emissions (tons/day)[1]
650	607.3	1.90	35	607.7	1.94	36
700	606.6	1.94	31	607.0	1.98	33
750	605.8	1.97	27	606.2	2.02	29
800	605.0	2.00	23	605.3	2.05	25
850[b]	**600.0**	**2.04**	**none**	**600.0**	**2.07**	**none**
900	600.0	2.07	none	600.0	2.10	none
950[c]	**600.0**	**2.10**	**none**	**600.0**	**2.12**	**None**

a. CO_2 emissions are produced when topping heat is required to bring the HTGR ROT up to 850°C.
b. Optimum HTGR ROT for delivered process heat.
c. Optimum HTGR ROT for electricity generation.

4.3.2 Hydrogen Production via Steam Methane Reforming

The analysis showed that when the natural gas flow rate is 49.2 MM scfd, more hydrogen is produced from an HTGR-integrated steam methane reforming process with an HTGR ROT of 725°C than from a conventional process. Furthermore, hydrogen production increases as the ROT increases to 925°C, as shown in Table 6. Both conventional and HTGR-integrated cases emitted 3,000 tons/day of CO_2.

The optimum HTGR ROT for hydrogen production is 875°C, the temperature at which heat is best utilized for hydrogen generation rather than steam production. At higher and lower HTGR ROTs, more of the heat is used to produce steam that does not directly supply the steam methane reformer. Also, at 925°C compared to 875°C, the hydrogen flow rate increases by approximately 1.5%. This relatively small increase in hydrogen production does not warrant the higher ROT.

Table 6. Hydrogen production rate from HTGR-integrated steam methane reforming over a range of ROTs. Outputs from a conventional steam methane reforming process are shown as a basis for comparison.

	HTGR ROT (°C)	HTGR Process Heat In (MW(t))	Hydrogen Flow (kg/s)	Steam Production (MM Btu/hr)
Conventional steam methane reforming	NA	NA	3.63	23.6
HTGR-integrated steam methane reforming	725	132	4.10	199
	775	159	4.37	167
	825	195	4.73	127
	875[a]	**238**	**5.17**	**77**
	925	256	5.25	121

a. Optimum HTGR ROT for steam methane reforming; nearly all the HTGR heat is used to generate hydrogen.

5. DISCUSSION

The NGNP project evaluated the impact that increasing the HTGR ROT from 650–950°C would have on the primary output of an HTGR (process heat) and secondary outputs (electricity and hydrogen from either HTSE or steam methane reforming). The results were used to determine the optimum HTGR ROTs for each of these outputs as described in Table 7 and summarized as follows:

- The optimum ROT for process heat delivered as steam was 770°C, but this temperature for hot helium was dependent on the temperature requirements of the process
- The optimum ROT for electricity generation was 950°C, the maximum temperature assessed in this study
- The optimum ROT for hydrogen production via HTSE were 950°C for electricity generation and 850°C for process heat; both HTGR outputs are required for HTSE
- The optimum ROT for hydrogen production via steam methane reforming was 875°C.

Table 7. Optimum ROTs for primary and secondary outputs from an HTGR.

Primary HTGR Outputs (Process Heat)	Optimum HTGR ROT (°C)	Comments
High-Temperature Steam delivered at 540°C and 17 MPa	770°C	A higher ROT will not increase the maximum flow rate of steam delivered at 540°C and 17 MPa. The optimum ROT will vary depending on the supplied steam temperature and pressure.
High-Temperature Helium delivered at 625–925°C and 7–9 MPa	varies	The optimum ROT depends on the temperature requirements of the process that utilizes the heat.
Secondary HTGR Outputs		
Electricity generated by a generic power cycle	950°C	The electricity production efficiency of a generic power cycle increases from 43.2–48.2% as the ROT varies from 650–950°C.
Hydrogen via HTSE	850°C for process heat, 950°C for electricity	The ROT for generating process heat depends on the operating temperature of the HTSE process, which is 800°C. Electricity generation efficiency is greatest at 950°C, the maximum temperature considered in this study.
Hydrogen via Steam Methane Reforming	875°C	The optimum ROT varies from 790–880°C depending on the desired composition of the product off-gas.

5.1 Implications of Optimum ROTs on HTGR-Integrated Industrial Processes

The results of the temperature sensitivity study indicate that optimum ROTs or a range of ROTs could be identified to further refine the process evaluations that were developed for HTGR-integrated production of synthetic transportation fuels, ammonia and ammonia derivatives, oil from unconventional sources, and substitute natural gas from coal. The evaluations were based on using an HTGR ROT of 750°C for the primary and secondary outputs (see References 2–8).

The preliminary estimates of the optimum ROTs for these industrial processes are summarized in this section. In all cases, additional work is needed to identify the optimum HTGR ROT or range of optimum ROTs and to evaluate their preliminary economics.

5.1.1 Processes that Use Steam

Detailed evaluations of HTGR-integrated production processes for recovering bitumen from oil sands and oil from oil shale were developed for processes that use natural gas based on an HTGR ROT of 750°C. Based on the results of the temperature-sensitivity analysis, 770°C is the optimum HTGR ROT for generating superheated steam at 17 MPa, if supplied at 540°C as shown in Table 8.

However, local site conditions and needs will determine the desirable steam conditions for bitumen and oil recovery operations, such as when HTGR-generated steam needs to be transported over significant distances before it is used. As a result, it would be beneficial to discuss specific site requirements with potential end users to determine whether steam delivery at 540°C and 17 MPa meets their needs.

Table 8. Preliminary implications of the optimum HTGR ROTs required to produce steam and generate electricity for oil and bitumen recovery.

HTGR-Integrated Processes	Primary and Secondary HTGR Outputs Required	Optimum HTGR ROT (°C)	Comments
Oil recovery from oil shale Bitumen recovery from oil sands	Process heat supplied as steam Electricity	770°C (if steam is supplied at 540°C and 17 MPa) 950°C for electricity	If the process requires steam delivered at a different temperature and pressure, the optimum HTGR ROT will change.

5.1.2 Processes that Use Methane Reforming

Detailed evaluations of HTGR-integrated production processes for synthetic diesel, synthetic gasoline, and ammonia derivatives were developed for processes that use natural gas and require hydrogen from methane reforming based on an HTGR ROT of 750°C. Synthetic gasoline and ammonia derivative processes use a two-step reformer—steam methane reforming and autothermal reforming—to produce hydrogen. Synthetic diesel production only uses autothermal reforming.

The optimum HTGR ROTs for the production of synthetic diesel, synthetic gasoline, and ammonia derivatives should be the minimum temperatures needed to support methane reforming for the particular plant configuration, as shown in Table 9. However, the actual HTGR ROT and heat requirements for the process will depend on a determination of the optimal heat recovery from methane reforming and other processes, which can supply the heat and power needs in other portions of the plant. After the energy crisis of the early 1970s, industrial process plants were pressured to maintain their profitability while facing rising energy costs. Some companies were unsuccessful and went out of business, but others increased their profitability by improving their overall energy efficiency. In 1970, for example, the synthesis of ammonia required 40 GJ/MT (gigajoules per metric ton), but by 1999, improved heat integration and more efficient pumps and compressors had decreased the energy requirement for synthesis to 28 GJ/MT.[18,19]

Table 9. Highest assumed temperature provided with a maximum HTGR ROT of 750°C for processes that use methane reforming to produce synthetic diesel, synthetic gasoline, and ammonia derivatives.

HTGR-Integrated Processes using Natural Gas for Methane Reforming	Highest Assumed Temperature of HTGR-Provided Heat (°C)	Required HTGR ROT (°C)	Comments
Synthetic Diesel Production	650	700	Heat supplied by the HTGR is used to preheat the natural gas feed to 650°C. Oxygen is added to combust the methane and raise the auto-thermal reforming temperature to 1021°C.
Synthetic Gasoline Production	739	789	Heat supplied by the HTGR is used primarily to preheat the natural gas feed.
Ammonia Derivatives Production	760	795	The initial detailed analysis utilized an HTGR ROT of 750°C. If 795°C heat could be supplied by the HTGR, that would be a better operating temperature.

In a modern conventional natural gas-to-synthetic diesel plant, shown as a simplified block flow diagram in Figure 5, the heat recovered from the autothermal reformer and Fischer-Tropsch synthesis units is enough to generate more than enough electricity to meet all plant electrical power needs. The excess electrical power is sold to the grid and represents a significant revenue stream (see Reference 2). Energy efficiency is also achieved by burning some of the light gas product to generate the heat required for separating the crude products into diesel, naphtha, and light gases.

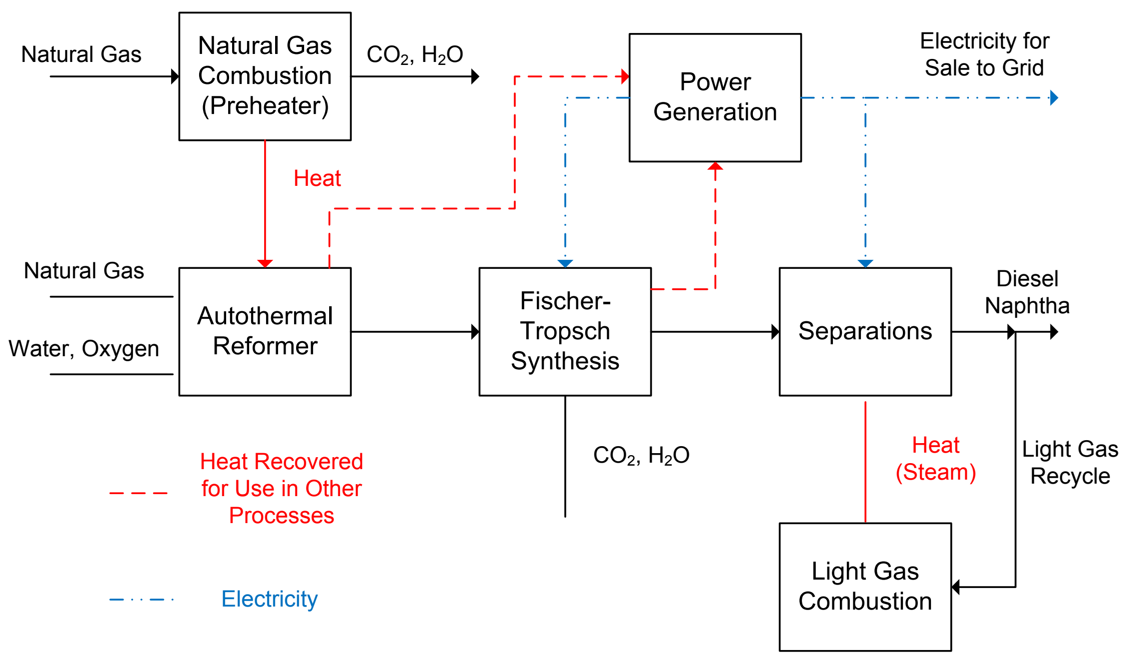

Figure 5. Simplified block flow diagram for a conventional natural gas-to-diesel process plant.

Based on the results of the temperature-sensitivity analysis, the optimum HTGR ROT for the production of synthetic diesel, synthetic gasoline, and ammonia derivatives would be the minimum temperature needed to support methane reforming for the particular plant configuration as shown in

Table 9. For example, an HTGR-integrated synthetic diesel plant that incorporates significant heat integration, as shown in the block flow diagram in Figure 6, is estimated to require a maximum HTGR ROT of 750°C. The HTGR is used to preheat natural gas and water to 650°C. Oxygen is added to combust some of the methane in the natural gas so the autothermal reforming process reaches a suitable operating temperature. Energy efficiency is achieved by using heat left over from the autothermal reformer and the Fischer-Tropsch synthesis units to generate electricity.

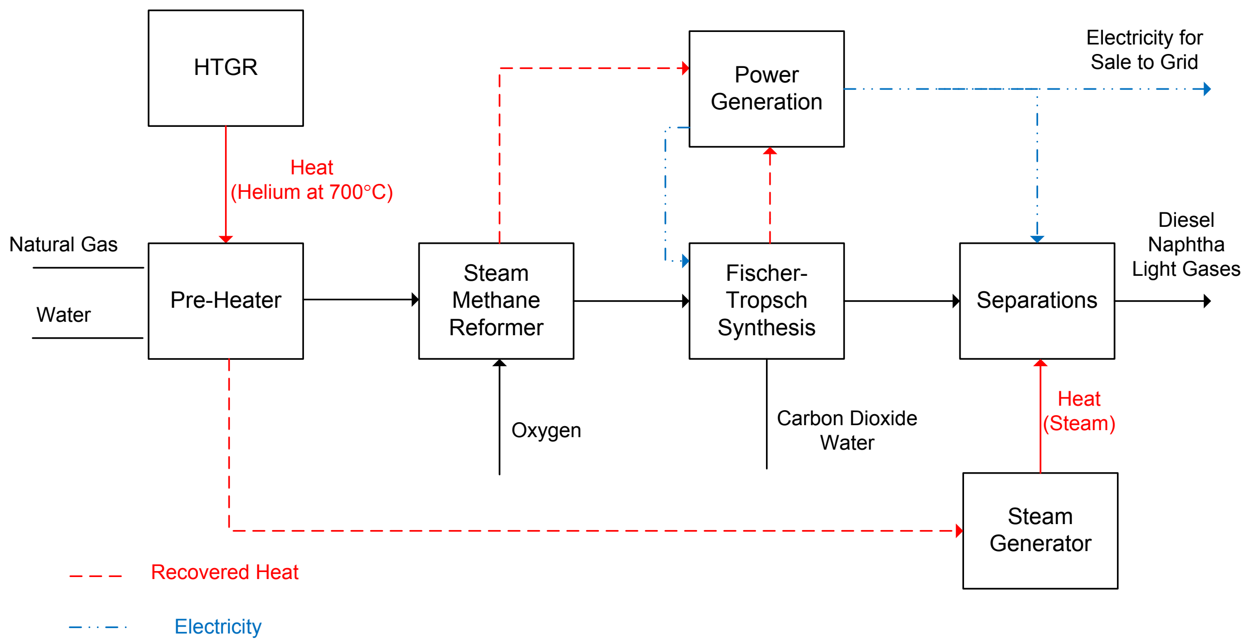

Figure 6. Simplified block flow diagram for an HTGR-integrated natural gas-to-synthetic diesel industrial process plant.

It would be beneficial to discuss specific plant configurations with potential end users to determine the most desirable HTGR ROTs for their heat delivery needs.

5.1.3 Processes that Utilize HTSE

Detailed evaluations of HTGR-integrated production processes for synthetic diesel, synthetic gasoline, and substitute natural gas were developed for processes that use coal and require hydrogen from HTSE based on an HTGR ROT of 750°C.

The optimum HTGR ROT for these processes is estimated to be 850°C for process heat and 950°C for electricity generation, as shown in Table 10, which corresponds precisely with the optimum ROT determined in the temperature-sensitivity analysis for hydrogen production via HTSE. Since HTSE requires an operating temperature of 800°C, higher than the 750°C ROT assumed in the detailed process evaluations, natural gas combustion is required to provide topping heat.

The detailed evaluations did not consider hydrogen production via methane reforming, however the economic analyses may indicate that steam methane reforming is an economically viable alternative to HTSE. If so, optimum HTGR ROTs would also need to be determined for these processes.

Heat integration opportunities should also be considered. If these processes used reactive coal, additional heat integration opportunities could be achieved by gasifying the coal in a Lurgi or fixed bed coal gasifier at approximately 950°C, which would correspond to an HTGR ROT of 975°C.

Table 10. The optimum HTGR ROTs for processes that use coal and use heat and hydrogen from HTSE for synthetic diesel, synthetic gasoline, and substitute natural gas production.

HTGR-Integrated Processes utilizing Coal	Optimum HTGR ROT(°C)	Comments
Synthetic diesel production Synthetic gasoline production Substitute natural gas production	850°C for process heat supplied as steam to the HTSE process 950°C for electricity generation)	If reactive coal is used, gasification could be done at 950°C in a Lurgi or fixed-bed gasifier, which would correspond to an HTGR ROT of 975°C.

5.1.4 Summary—Optimum HTGR ROT for Industrial Processes

The preceding section summarizes the estimated optimum ROTs or range of ROTs for industrial processes that utilize heat, electricity, or hydrogen generated by an HTGR. As illustrated in Figure 7, the optimum ROTs further refine the estimated process temperature ranges that were determined in the detailed HTGR-integrated industrial process evaluations.[20] The optimum HTGR ROT for processes that utilize high-temperature helium is 35–50°C higher than the maximum process temperature range to account for the two heat exchangers located between the HTGR and the process. The optimum HTGR ROT for processes that utilize steam is 770°C. Additional modeling is required to provide a more precise estimate of the optimum ROTs; however, the exact optimum for each process is expected to be bound by the ranges that have already been determined.

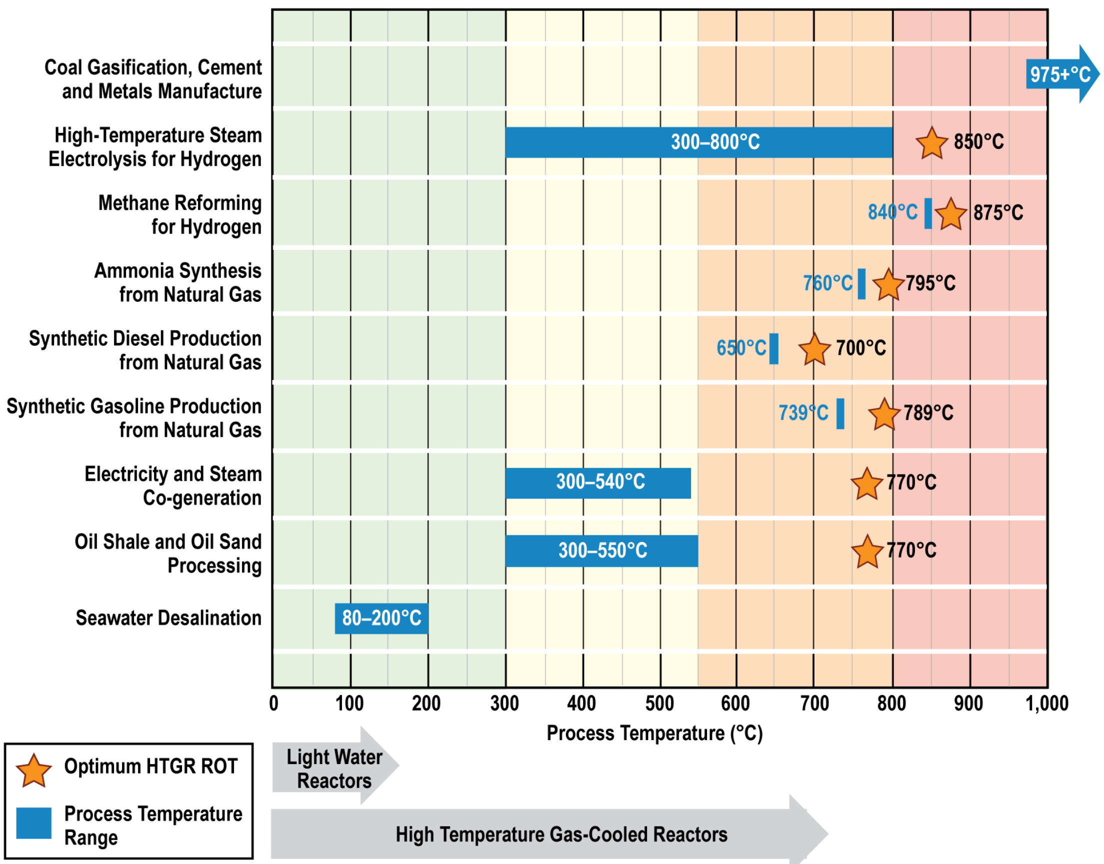

Figure 7. Optimum HTGR ROTs and the process temperature range associated with HTGR-integrated industrial processes.

6. CONCLUSIONS

Based on the results of this study, it can be concluded that:

- The optimum HTGR ROTs for steam generation (delivered at 540°C and 17 MPa), electricity generation, hydrogen production via HTSE, and hydrogen production via steam methane reforming are 770°C, 950°C, 850°C, and 875°C, respectively.
- The optimum HTGR ROT for steam production varies depending on the temperature and pressure of the steam produced.
- The optimum HTGR ROT for process heat delivered as helium (or other hot gas) does not exist, because the optimum is process dependent.
- The results of the temperature-sensitivity analyses have implications for the detailed HTGR-integrated industrial process evaluations that use the primary and secondary outputs studied in this report and suggest that there is an optimum HTGR ROT for these industrial processes.
- Because this study was based solely on mass and energy balance information from the industrial processes, economic analyses are required to identify more realistic optimum HTGR ROTs.
- In the future, a more detailed study regarding the optimum HTGR ROT should include impacts of reactor operation, core physics, and mechanistic source term considerations, as well as the industrial process applications. It is likely that a coupled analysis would serve to further optimize both the RIT and the ROT for industrial applications of interest.
- In order to perform an economic analysis, the HTGR cost as a function of configuration, size, and temperature is required.
- Reactor suppliers should consider increasing the RIT relative to the ROT to better suit process heat applications.

7. RECOMMENDATIONS FOR FUTURE WORK

The following recommendations for future work are based on the results of this study:

- There are obvious technical advantages to increasing the HTGR ROT up to 950°C. Similar work has been completed to evaluate the economics of the increasing HTGR ROT, however the results are based on a constant HTGR cost estimate. To improve the accuracy of the economic evaluation, it is recommended that a cost estimate for the HTGR be evaluated as a function of configuration, size, and HTGR ROT of 750–950°C.
- There are obvious advantages of increasing the HTGR ROT for generating primary and secondary outputs, but for the past 2 years, the NGNP Project has been performing evaluations assuming an HTGR ROT of 750°C. It is recommended that the previous detailed analyses for production of synthetic transportation fuels, co-generation of steam and electricity, and ammonia synthesis be reevaluated at higher HTGR ROTs to determine if improved process efficiency and economics would result. It is also recommended that higher HTGR ROTs be considered as future evaluations are conducted.

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