Method and System for the Production of Hydrogen at Reduced VHTR Outlet Temperatures

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Chang H. Oh
Eung S. Kim

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METHOD AND SYSTEM FOR THE PRODUCTION OF HYDROGEN AT REDUCED VHTR OUTLET TEMPERATURES

Chang H. Oh and Eung S. Kim
Idaho National Laboratory
Idaho Falls, Idaho 83415
Email: Chang.Oh@inl.gov, Eungsoo.Kim@inl.gov

ABSTRACT

The Department of Energy and the Idaho National Laboratory are developing a Next Generation Nuclear Plant (NGNP) to serve as a demonstration of state-of-the-art nuclear technology. The purpose of the demonstration is two fold 1) efficient low cost energy generation and 2) hydrogen production. Although a next generation plant could be developed as a single-purpose facility dedicated to hydrogen production, early designs are expected to be dual purpose. While hydrogen production and advanced energy cycles are still in its early stages of development, research towards coupling a high temperature reactor with electrical generation and hydrogen production is under way. Many aspects of the NGNP must be researched and developed in order to make recommendations on the final design of the plant. Parameters such as working conditions, cycle components, working fluids, and power conversion unit configurations must be understood.

The integrated system of a Very High Temperature Reactor (VHTR) and a High Temperature Steam Electrolysis (HTSE) hydrogen production plant is being investigated and this system, as it is currently envisioned, will produce hydrogen by utilizing a highly efficient VHTR with a VHTR outlet temperature of 900°C to supply the necessary energy and electricity to the HTSE unit.

Though the combined system may produce hydrogen and electricity with high efficiency, the choices of materials that are suitable for use at 900°C are limited due to high-temperature strength, corrosion, and durability (creep) considerations. The lack of materials that are ASME (American Society of Mechanical Engineers) code-certified at these temperatures is also a problem, and is a barrier to commercial deployment.

If the current system concept can be modified to produce hydrogen with comparable efficiency at lower temperatures, then the technical barriers related to materials selection and use might be eliminated, and the integrated system may have a much greater probability of succeeding at the commercial scale. This paper describes a means to reduce the outlet temperature of the VHTR to approximately 700°C while still maintaining plant high efficiency.
INTRODUCTION

Although a next generation plant could be developed as a single-purpose facility, early designs are expected to be dual-purpose. While hydrogen production and advanced energy cycles are still in its early stages of development, research towards coupling a high temperature reactor, electrical generation and hydrogen production is under way. Many aspects of the NGNP (MacDonald et al. (2003)) must be researched and developed in order to make recommendations on the final design of the plant. Parameters such as working conditions, materials, stresses, cycle components, working fluids, coupling of the hydrogen production plant and power conversion unit (PCU) configurations must be understood.

The VHTR (Next Generation Nuclear Plant (NGNP)) reference concept is helium-cooled, graphite-moderated, thermal neutron spectrum reactors with an outlet temperature of up to 1000 °C (MacDonald et al. 2003). As indicated in Figure 1, an outlet temperature near 900°C to 1000 °C will allow the reactor to be used for a large number of process heat applications, including hydrogen production.

The NGNP reactor core could be either a prismatic graphite block type core or a pebble bed core. Use of a liquid salt coolant is also being evaluated in the reactor primary loop. The NGNP will produce both electricity and hydrogen. The process heat for hydrogen production will be transferred to the hydrogen plant through an intermediate heat exchanger. The reactor will be designed to ensure passive decay heat removal without fuel damage during hypothetical accidents. The fuel cycle will be a once-through very high burnup low-enriched uranium fuel cycle.

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Figure 1. Temperature requirements for various process heat applications.

Figure 2 shows a schematic of 600MWt NGNP. The helium is proposed to be used in the primary and the secondary flow loop. The power conversion unit (PCU) consists of a high pressure turbine, two high pressure compressors, and intercoolers between the compressors. The helium exit flow enters the PCU and transfers heat to the intermediate heat exchanger. Then the heat is transferred to two hydrogen production plants, Sulfur-Iodine (S-I) thermochemical plant and a high temperature steam electrolysis (HTSE) plant. The independent technology review group (2004) recommended a maximum 900°C VHTR outlet temperature due to material problems.
The VHTR is expected to generate outlet temperatures in the range of 850-950°C at a pressure of up to 7 MPa. At this temperature and pressure, the choices of structural materials that can be used for reactor outlet piping and intermediate heat exchangers are limited to a small subset of materials that can retain their strength at temperature. In a heat exchanger application, the heat exchanger surfaces are subject to the highest-temperature conditions, and insulating materials cannot be used to facilitate the use of more common materials of construction (e.g., copper alloys, carbon steel, and 316 stainless steel). The high-strength materials under examination fall into two classes – metallic alloys, and ceramics.

The high-temperature metallic alloys most often identified for use in high-temperature heat exchangers for the VHTR are Inconel 617, Incoloy 800H, Haynes 230, and Hastelloy XR. These high-strength alloys have been made to retain their strength and maintain creep resistance to very high temperatures, but even these alloys have their physical limits. Figure 3 shows measurements of the tensile strength of Alloy 800H measured up to 1000 °C (Mukhopadhyay, 2006).

In Figure 3, Alloy 800H maintains much of its room-temperature strength up to about 600 °C, and then begins to drop. At 700 °C, the reduction in strength is noticeable, but drops precipitously above 800 °C. This behavior is typical of the class of high-temperature metallic alloys, and no commercially available alloy has yet been identified that can be used above 900 °C for heat exchanger applications involving anything but a negligible pressure drop across the heat exchanger surfaces.
The creep rupture strength of a material also depends on the operating time at a given temperature. Figure 4 shows that the rupture strength of Alloy 800 decreases sharply with temperature (Davis et al., 2005). At an operating time of 100,000 h (about 11 years), the rupture strength is 240 MPa at 500 °C, but decreases to 8 MPa at 900 °C. The rupture strength also depends on the time at temperature. At 900 °C, the rupture strength increases from 8 to 16 MPa when the operating time decreases from 100,000 h to 10,000 h. The data presented in Figure 8 suggest that the mechanical design of the heat transport loop will be a challenge because of the desired high temperature and the long lifetime, both of which act to reduce the rupture strength.

The creep rupture strengths of three candidate materials for the heat transport loop are shown in Figure 4 for a temperature of 900 °C. These three materials are Alloy 800HT, which is a high-temperature variation of Alloy 800 (Special Metals 2004a), Alloy 617 (Special Metals 2004b), and Hastelloy X (Haynes International 2005). Alloy 617 has the highest rupture strength of these three materials at 900 °C. The allowable stress will eventually be specified by an applicable code, but will be less than the strengths shown in Figure 5 to account for safety factors. For this analysis, the allowable stress was assumed to be half of the creep rupture strength.
ASME codification of metallic alloys for nuclear use at 900 °C is incomplete. Under current codes, Subsection NH of Section III provides design rules for Class 1 components at higher temperatures, but limits the maximum temperatures to 760 °C for high-nickel alloys (including Alloy 617 and 800H) and 816 °C for austenitic steels (Shah, et al.). A draft code case was prepared for Alloy 617 in 1989 that would allow for its use in Class 1 applications up to 982 °C, but this draft case was not pursued in later years. Operation at the high temperatures needed by the VHTR reference design would require that ASME codification work of high-temperature alloys at the conditions of interest be resumed.

Corrosion of high-temperature alloys is accelerated at higher temperatures. Corrosion can occur from impurities in the helium used to cool the VHTR core, and this corrosion is accelerated at temperatures in excess of 800° C (Quadakkers, 1985) unless the chemistry of the helium impurities is carefully controlled.

Ceramic materials such as SiC or Si₃N₄ might be substituted for metallic alloys in high temperature applications because their high-temperature strength is largely the same at 1000 °C as it is at room temperature and because of their superior corrosion resistance. Unfortunately, there are no ASME code certified ceramics for use in nuclear systems and a code case would have to be created from the start for the ceramics of interest. Also, the technologies related to the manufacturing of large ceramic components and in bonding ceramics to metals are still under development, and some components made from ceramic materials may require long lead times to produce.

**METHOD**

The cycles were modeled and optimized using HYSYS (Aspen Technology, 2005). The efficiency of the power conversion unit was calculated as follows

\[
\eta_{PCU} = \frac{\sum W_T - \sum W_C - \sum W_{CIR}}{Q_{th} - Q_{IHTL}},
\]

(1)

where \( W_T \) is the total turbine workload, \( W_C \) is the total compressor workload, \( W_{CIR} \) is the circulator workload in the primary and secondary side, \( Q_{th} \) is the reactor thermal power and \( Q_{IHTL} \) is the heat delivered to the intermediate heat transfer loop (IHTL) through the hydrogen plant. The efficiency of the overall cycle including the HTSE plant was calculated as follows

\[
\eta_{overall} = \frac{\sum W_T - \sum W_C - \sum W_{CIR} - \sum W_S - Q_{EL} + Q_{H_2}}{Q_{th}}
\]

(2)
where \( W_S \) is the plant stationary load, \( Q_{EL} \) is the power supplied to the electrolyzer, \( Q_{H2} \) is the lower heating value of the produced hydrogen and \( Q_{th} \) is the reactor thermal power.

Once the cycle efficiencies had been calculated the relative sizes of the turbomachinery and heat exchangers were estimated. The actual size of the turbomachinery was not calculated but rather parameters that gave some indication to their relative size. The volume of the heat exchangers was calculated.

To determine the relative sizes of the heat exchanger, the UA values (overall heat transfer coefficient times the heat transfer area) of the heat exchangers were calculated by HYSYS. The U values were calculated, the heat transfer areas were determined, and the heat exchanger volume was calculated. This gives a relative estimation of the heat exchanger sizes for the different configurations.

The IHX, and recuperator were assumed to be printed circuit heat exchangers (PCHE) as designed by Heatric (2005). PCHE are composed of channels chemically etched into plates. The plates are then stacked and diffusion bonded together and headers are attached to form the heat exchanger. For this study Alloy 617 was used as the construction material for the heat exchangers. The thermal conductivity was assumed to be constant over the length of the heat exchangers and was obtained from www.specialmetals.com.

The detail analysis methods are described by Oh et al. (2006) and Davis et al. (2005).

In the electrolyzer model (Oh et al. 2007), the oxygen stream produced at the anode is assumed to mix with a sweep gas stream that is introduced at the anode. The combined stream then exits the electrolyzer. The hydrogen stream produced at the cathode is assumed to mix with a feed stream that is introduced at the cathode. The feed stream is composed of water vapor to be electrolyzed, hydrogen gas for maintaining reducing environment, and possibly an inert gas, presently assumed to be nitrogen.

**ELECTROLYZER MODEL**

A. Energy Equation

An energy balance on the electrolyzer gives

\[
\sum_j \dot{n}_{p-j} H_{p-j} (T_p, P) = \sum_j \dot{n}_{R-j} H_{R-j} (T_R, P) + Q + W
\]

where

\[
\begin{align*}
\dot{n} & \quad \text{species mole flow rate,} \\
H & \quad \text{enthalpy per mole,} \\
Q & \quad \text{rate of heat transfer to the electrolyzer,} \\
W & \quad \text{rate of electrical work supplied to the electrolyzer,} \\
T & \quad \text{temperature,} \\
P & \quad \text{pressure,}
\end{align*}
\]

and where we have used subscripts \( R \) for reactants and \( P \) for products. Their mass flow rates are defined
\[ m_{H_2O-o-cath} h_{H_2O-o-cath} (T_o, P) + m_{H_2-o-cath} h_{H_2-o-cath} (T_o, P) + m_{N_2-o-cath} h_{N_2-o-cath} (T_o, P) \]
\[ m_{H_2-o-anode} h_{H_2-o-anode} (T_o, P) + m_{N_2-o-anode} h_{N_2-o-anode} (T_o, P) = \]
\[ m_{H_2O-i-cath} h_{H_2O-i-cath} (T_i, P) + m_{H_2-i-cath} h_{H_2-i-cath} (T_i, P) + m_{O_2-i-cath} h_{O_2-i-cath} (T_i, P) \]
\[ m_{N_2-i-cath} h_{N_2-i-cath} (T_i, P) + m_{N_2-o-anode} h_{N_2-o-anode} (T_i, P) + Q + W \]

where
\[ m = \text{species mass flow rate (kg/s)}, \]
\[ h = \text{specific enthalpy (Joules/kg)}, \]

and where subscripts \( i \) and \( o \) represent inlet and outlet, respectively.

B. Species Mole and Mass Flow rates

The species mole flow rates entering and leaving the electrolyzer are related to the current density through the relationships

\[ \dot{n}_{H_2O-o-cath} = \dot{n}_{H_2O-i-cath} - \frac{iA}{2F} \]
\[ \dot{n}_{H_2-o-cath} = \dot{n}_{H_2-i-cath} + \frac{iA}{2F} \]
\[ \dot{n}_{O_2-o-anode} = \dot{n}_{O_2-i-anode} + \frac{iA}{4F} \]
\[ \dot{n}_{\text{sweep-o-anode}} = \dot{n}_{\text{sweep-i-anode}} \]
\[ \dot{n}_{N_2-o-cath} = \dot{n}_{N_2-i-cath} \]

where
\[ i = \text{current density (amps/m}^2), \]
\[ A = \text{electrode surface area, (m}^2) \text{ and} \]
\[ F = \text{Faradays constant}. \]

The species mass flow rates and mole flow rates are related as follows: For an individual species

\[ \dot{m}_k = A_k \dot{n}_k \text{ and } \dot{m}_k = A_k \dot{n}_k, k = H_2O, H_2, O_2, \text{ and } N_2. \]

where \( A_k \) is the atomic weight of species \( k \) in kg per mole and subscript \( o \) is the outlet and \( i \) is the inlet.

C. Cell Voltage and Electrical Work

The voltage drop across the electrolyzer is the sum of the electrode Nernst potential and the resistance of the cell. In estimating the resistance, the activation and the concentration overpotentials are lumped in with the cell internal resistance. The cell voltage is then assumed given by

\[ V_{cell} = V_{Nernst} + i \cdot ASR \]

where
\[ V_{\text{Nernst}} = \]  
\[ \text{is the Nernst potential, and} \]

\[ \text{ASR} = \]  
\[ \text{is the area-specific cell resistance (ohms-m}^2). \]

The electrical work done in the cell is

\[ W = V_{\text{cell}} \cdot i \cdot A . \]  \hfill (8)

The active species giving rise to the Nernst potential satisfy the chemical balance equation

\[ H_2O (g) \rightarrow H_2 (g) + \frac{1}{2} O_2 (g) . \]  \hfill (9)

The change in Gibbs free energy for this reaction carried out at temperature \( T \) and pressure \( P \) is

\[ \Delta G(T,P) = \Delta G_f(T,P) + RT \ln \left( \frac{f_{\text{H}_2} f_{\text{O}_2}^{\frac{1}{2}}}{f_{\text{H}_2O}} \right) \]  \hfill (10)

where \( f \) is the molar fraction of a species and \( \Delta G_f(T,P) \) is the Gibbs free energy in forming the products at temperature \( T \) and pressure \( P \) minus the same for the reactants, that is,

\[ \Delta G_f(T,P) = G_{f-\text{H}_2}(T,P) + 1/2 G_{f-\text{O}_2}(T,P) - G_{f-\text{H}_2O}(T,P). \]  \hfill (11)

where \( G_{f-}(T,P) \) is the Gibbs free energy on a per mole basis of forming species \( i \) at conditions \( T \) and \( P \). In turn \( \Delta G_f(T,P) \) is written in terms of \( \Delta G_{f-}^0(T) = \Delta G_f(T, P_{\text{STD}}) \) where \( P_{\text{STD}} = 0.101 \text{ MPa} \). Then setting the change in Gibbs free energy equal to the electrical work done the voltage developed by the cell is

\[ V_{\text{Nernst}} = \frac{-1}{2F} \left[ \Delta G_f^0(T) + RT \ln \left( \frac{f_{\text{H}_2} f_{\text{O}_2}^{\frac{1}{2}}}{f_{\text{H}_2O}} \left( \frac{P}{P_{\text{STD}}} \right)^{\frac{1}{2}} \right) \right] \]  \hfill (12)

where \( P_{\text{STD}} = 0.101 \text{ MPa} \) and \( P \) is the cell pressure. Then the average value of \( V_{\text{Nernst}} \) was calculated suing the following equation.

\[ \overline{V}_{\text{Nernst}} = \frac{1}{2F(T_p - T_R)}(y_{\text{O}_2,\text{A}} - y_{\text{O}_2,\text{A}})(y_{\text{H}_2,\text{C}} - y_{\text{H}_2,\text{C}}) \times \]

\[ \frac{y_{\text{H}_2,\text{C}}}{y_{\text{O}_2,\text{C}}} \int_{T_R}^{T_p} \int_{y_{\text{O}_2,\text{A}}}^{y_{\text{O}_2,\text{A}}} \int_{y_{\text{H}_2,\text{C}}}^{y_{\text{H}_2,\text{C}}} \Delta G(T) - RT \ln \left( \frac{1 - y_{\text{H}_2} - y_{\text{N}_2}}{y_{\text{H}_2} y_{\text{O}_2}} \right) dy_{\text{H}_2} dy_{\text{O}_2} dT \]  \hfill (13)

The mole fractions at any point in the electrolyzer are related to the molar mass flow rates at that point through
The current density and active cell area are then specified, yielding the total operating current. Care must be taken to insure that the specified inlet gas flow rates and total cell current are compatible. The minimum required inlet steam molar flow rate is the same as the steam consumption rate, given by:

\[
\dot{N}_{i, H_2O, min} = \Delta \dot{N}_{H_2O} = \frac{I}{2F} N_{cells} = \frac{i A_{cell}}{2F} N_{cells} = \Delta \dot{N}_{H_2}
\]  

which is of course also equal to the hydrogen production rate.

**REFERENCE DESIGN**

Figure 6 illustrates one of the INL NGNP Reference designs, indirect serial configuration. This reference design was used as a baseline case to compare the efficiency with this paper. In this configuration, the secondary heat exchanger (SHX) is located upstream of the IHX that is linked to the PCU. Therefore, the heat from the VHTR is firstly transferred to the HTSE system, and then the rest of heat is transferred to the PCU. Basically the process heat from VHTR via SHX preheats the streams (stream 1 to 6) in the high temperature steam electrolysis shown in Figure 7.
PARAMETRIC STUDY

In this section, the effects on the plant efficiency were estimated for various operating parameters. These parameters included reactor inlet temperature and turbine and compressor efficiencies. Note that the parametric studies on reactor inlet temperature were performed with the reactor outlet temperature fixed at 900 °C, which is assumed dictated by HTSE system requirements. The Configuration 1 system with He-He-He working fluids combination was selected as the reference case for analysis.

Figure 8 shows the effect of compressor efficiency and core inlet temperature on the overall system efficiency. As shown in this figure, the system efficiency increases with the compressor efficiency. The maximum efficiency ranges around the core inlet temperature of 600~700 °C. The reason for the efficiency increase with compressor efficiency is obvious because high compressor efficiency reduces irreversibility of the system. In our calculation, one percent increase of compressor efficiency results in about 0.3 ~ 0.6 percent increase of overall efficiency. Thus, improving the compressor efficiency is a very useful way to get a more efficient system. Of course, this also means that a decrease of the compressor efficiency during operation can cause the overall efficiency to decrease.

The effect of core inlet temperature is quite complicated. Core inlet temperature is closely related to PCU flow rate, and also directly to the flow rate in the primary side. As the core inlet temperature is raised, the PCU flow rate can also be increased, resulting in PCU efficiency increase. However, the increase of core inlet temperature requires higher flow rate in the primary side (since reactor power and outlet temperature are maintained constant), requiring higher circulation power. As shown in Figure 8, the overall efficiency increases with core inlet temperature below 500 °C from the increase of PCU flow rate, but above 600°C, the efficiency is reduced due to the increase of circulation power. Essentially, there is a break point where the decrease in efficiency from increased compressor losses is opposite and equal to the efficiency gain resulting from a higher average core temperature.
Figure 8. Effect of core inlet temperature and compressor efficiency on overall plant efficiency (He-He-He).

Figure 9 shows the effects of turbine efficiency and core inlet temperature on overall efficiency. The optimal temperature occurred around 650 °C. As expected, the overall efficiency was increased with turbine efficiency. One percent increase of turbine efficiency caused 0.5~0.9% increase of overall efficiency. However, the rate of increase decreased as the operating temperature approached the optimal temperature. In this study, the efficiency of turbine seems to affect the overall efficiency a little more than the efficiency of one compressor.

Figure 9. Effect of core inlet temperature and turbine efficiency on overall plant efficiency (He-He-He).

Figure 10 shows the effect of ternary loop (intermediate heat transport loop) flow rate on the overall efficiency. In this calculation, the overall efficiency is decreased as the flow rate is increased. It is because the lower flow rate requires less circulation power. However, the effect of ternary loop flow rate was nearly negligible around the optimal temperature, because the portion of ternary loop circulation power was too small compared with the other part. In this calculation, the effect of ternary loop flow rate seems very effective especially at a core inlet temperature below 500°C, since the low core inlet temperature results in low PCU flow rate, and the flow rate in turbine cycle is relatively decreased with the ternary flow rate. Therefore, it leads to the overall efficiency drop.

Figure 10. Effect of ternary loop flow rate on overall efficiency.
Figure 10. Effect of core inlet temperature and ternary flow rate on overall plant efficiency (He-He-He).

Figure 11 shows the effect of the medium pressure compressor (MPC) outlet pressure on the overall efficiency. The MPC outlet is the position where the highest system pressure is located. According to the figure, at low temperature, the efficiency is highly affected by the increase of the MPC outlet pressure, while it is only slightly affected around the optimal core inlet temperature. Figure 12 illustrates the variation of optimal pressure ratio along the MPC outlet pressure and the core inlet temperature. It shows the optimal pressure ratio increases significantly as the core inlet temperature decreases, while the variation by the MPC outlet pressure is very slight. It means the optimal pressure ratio is a sensitive factor to the PCU flow rate. Generally, PCU flow rate determines the PCU operating temperature range and it also determines the optimal operating pressure range.

Figure 11. Effect of core inlet temperature and MPC outlet pressure on overall plant efficiency (He-He-He).
Finally, the effect of heat exchanger effectiveness on the overall efficiency was estimated. As shown in Figure 13, the efficiency increases with the heat exchanger effectiveness. These trends are similar at both low and high core inlet temperatures. As a result, one percent increase of heat exchanger effectiveness increases the overall efficiency by around 0.5~0.8%. It means effective heat exchanger performance is a very important factor for achieving more effective system performance. Since the increase of the effectiveness usually requires larger effective surface area, which increases the heat exchanger size and the capital cost, an optimal VHTR system requires a heat exchanger with a very high effectiveness. In this study, the printed circuit heat exchanger (PCHE) is considered as the main heat exchanger in the VHTR, with a commonly accepted effectiveness of around 95%.

Figure 13. Effect of core inlet temperature and SHX effectiveness on overall plant efficiency (He-He-He).

**METHOD AND SYSTEM TO REDUCE NGNP OUTLET TEMPERATURE TO ACHIEVE COMPARABLE EFFICIENCIES**

The goal of this study is to achieve 45% efficiency at a 700°C VHTR outlet temperature by using, in combination, 1) a hydrogen recycle to pre-heat the feed to the HTSE unit, 2) a molten salt in the thermal transmission piping to reduce pumping power, and 3) a supercritical CO₂ cycle in the power conversion unit to achieve high electrical conversion efficiency.

Figures 14 and 15 show the schematic of the coupled plant and the schematic of detailed HTSE coupled to VHTR, respectively.

A. Three components
i. Hydrogen combustion pre-heat
In order to maintain solid oxide fuel cell (SOFC) characteristics, it is important to maintain higher SOFC operating temperature. In order to achieve the increase of the SOFC temperature, a small fraction (0.014 mole fraction) of hydrogen produced in the electrolyzer is proposed to be used in reaction with oxygen or air to preheat the water inlet to the electrolyzer. The reaction of H$_2$ and O$_2$ is highly exothermic reaction and thus it can be utilized for the preheating purpose. The product of this reaction is water that can be recycled to the system without a heat exchanger.

The power requirement for the HTSE was calculated based on the energy balance and electrolyzer model. The details of the calculation are shown in the reference of Oh et al. (2007).

![Figure 14. Schematic of the coupled plant.](image)

Figure 14. Schematic of the coupled plant.

![Figure 15. Schematic of detailed HTSE coupled to VHTR.](image)

Figure 15. Schematic of detailed HTSE coupled to VHTR.

ii. Molten salt
The advantage of molten salt is to reduce the pumping power in the primary flow loop as compared to high pressure helium. In addition, the diameter of thermal transmission piping can be reduced. Using the molten salt, the overall efficiency can be enhanced by 3 to 4% compared with helium. Figure 16 shows the relative advantage of using a molten salt versus high-pressure helium for a hypothetical 90 m long pipe designed to transmit 50 MW in thermal energy. A comparison was made between helium at 2 MPa and 7 MPa to the molten salts FLiNaK and NaBF4-NaF.
Molten salts have been used in a molten salt reactor located at Oak Ridge National Laboratory for more than 10 years (Forsberg 2006, and Peterson, and Zhao, 2006)).

This paper brings an efficiency of 45% with molten salts with the VHTR outlet temperature of 700 C. However, with helium in the primary loop instead of molten salts, the efficiency is only 4 % lower than the molten salt in the primary.  The final comparisons are shown in the conclusion of this report.

iii. S-CO$_2$ cycle

The advantage of S-CO$_2$ cycle is to reduce the compression work due to high density of S-CO$_2$ (Oh et al, 2006)(Angelino, 1969).  The indirect CO$_2$ cycle shown in Figure 14 was simulated assuming a high compressor outlet pressure.  The higher compressor outlet pressure was used to take advantage of compression around the critical point and decrease compressor work.

In this scheme, a higher pressure is proposed to achieve the higher polytropic expansion temperature out of the high pressure turbine that can be used to heat the outlet temperature from SHX (Figure 14).

B. Effects of combined use

i. Lower temperature with comparable energy efficiency

HYSYS was used to calculate the overall thermodynamic plant efficiency of the proposed coupling plant shown in Figures 6 and 8.  The base case was a system with helium and an indirect serial cycle. This base case utilizes helium in the primary, the secondary, and the ternary flow loop.  Figure 17 shows a snapshot of HYSYS model that is based on coupling VHTR and HTSE. The reactor outlet temperature was 900C and the steam inlet temperature to the electrolysis is 826C. We used this configuration as a baseline case and compare results from the proposed concepts. Results of the baseline case are based on the process optimization described in the preceding section. The overall thermodynamic efficiency is 46.2% with the same coupling configuration as the proposed concept except the helium recuperated power conversion unit for the baseline case (helium in all flow loops) vs. S-CO$_2$ high compression PCU for the proposed concept (molten salt in the primary and S-CO$_2$ in the secondary and ternary flow loop).

Figure 17 shows a snapshot of the HYSYS model for the reference NGNP case. The baseline case that operates with a nuclear reactor output temperature of 900°C and helium coolant for the reactor, power conversion unit, and thermal transmission piping. The fluid for the primary, the secondary, and the tertiary is all helium gas.
Figure 18 shows a snapshot of HYSYS model that consists of an indirect serial S-CO\(_2\) recompression cycle in PCU that is also shown in Figure 14.

Figure 19 depicts HYSYS model of the electrolyzer. Only a small fraction (0.014 mole fraction) of hydrogen produced from the electrolyzer is recycled to CRV-101 where an oxidation reaction releases exothermic heat to preheat the electrolyzer inlet stream from 670°C to 827°C.

![Figure 17. Snapshot of HYSYS model for the baseline case.](image)
Figure 18. Snapshot of HYSYS of the proposed coupling concept.
ii. Side effects

A higher system pressure of 19 MPa in PCU used in this paper gives a large pressure drop between the primary (7 MPa) and the secondary (19 MPa) resulting in thicker heat exchanger wall requirement. However, pressure drop is less of an issue at 700°C than at 900°C because of the higher creep rupture strength of the materials. S-CO₂ equipment may still need to be perfected.

CONCLUSIONS

This paper presents an improved NGNP system that can be operated at the reduced VHTR outlet temperature of 700°C to achieve an overall plant efficiency of 45%, which is only 2 to 3% lower than 47% efficiency with a reference design based on 900°C VHTR outlet temperature. This improved configuration consists of a combined innovation of (a) molten salt for reducing the pump power in the primary loop (b) improved Brayton cycle with CO₂, and (c) preheat of the HTSE inlet stream by exothermic energy produced from a small fraction hydrogen-oxygen combustion. The use of molten salt or liquid fluoride salt is not a new idea and it has been studied extensively at ORNL and UC Berkeley.

The final concept of the NGNP has not been made yet and this study can provide some inputs to the NGNP decision making process. Again at this time, the NGNP configuration including the design type and the VHTR outlet temperature have not been determined yet. The DOE states that the possible reduction of the VHTR outlet temperature is being considered to 800°C.

Table 1 summarizes overall cycle comparisons.
Table 1. Summary of overall plant efficiency

<table>
<thead>
<tr>
<th>PCU Type</th>
<th>Primary Coolant</th>
<th>Secondary Coolant</th>
<th>Tertiary Coolant</th>
<th>Tmax [°C]</th>
<th>Efficiency [%]</th>
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<tr>
<td>Base</td>
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<td></td>
<td>He</td>
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<td>Precompression</td>
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<td>S-CO2</td>
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ACKNOWLEDGEMENTS

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REFERENCES


Peterson, P. and H. Zhao, A Flexible Baseline Design for the Advanced High Temperature Reactor Using Metallic Internals (AHTR-MI), Proceedings of ICAPP ’06, Reno, NV USA, June 4-8, 2006”

