

Sensitivity Studies of Advanced Reactors Coupled to High Temperature Electrolysis (HTE) Hydrogen Production Processes

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ABSTRACT

High Temperature Electrolysis (HTE), when coupled to an advanced nuclear reactor capable of operating at reactor outlet temperatures of 800 °C to 950 °C, has the potential to efficiently produce the large quantities of hydrogen needed to meet future energy and transportation needs. To evaluate the potential benefits of nuclear-driven hydrogen production, the UniSim process analysis software was used to evaluate different reactor concepts coupled to a reference HTE process design concept. The reference HTE concept included an Intermediate Heat Exchanger and intermediate helium loop to separate the reactor primary system from the HTE process loops and additional heat exchangers to transfer reactor heat from the intermediate loop to the HTE process loops. The two process loops consisted of the water/steam loop feeding the cathode side of a HTE electrolysis stack, and the sweep gas loop used to remove oxygen from the anode side. The UniSim model of the process loops included pumps to circulate the working fluids and heat exchangers to recover heat from the oxygen and hydrogen product streams to improve the overall hydrogen production efficiencies.

The reference HTE process loop model was coupled to separate UniSim models developed for three different advanced reactor concepts (a high-temperature helium cooled reactor concept and two different supercritical CO₂ reactor concepts). Sensitivity studies were then performed to evaluate the affect of reactor outlet temperature on the power cycle efficiency and overall hydrogen production efficiency for each of the reactor power cycles. The results of these sensitivity studies showed that overall power cycle

and hydrogen production efficiencies increased with reactor outlet temperature, but the power cycles producing the highest efficiencies varied depending on the temperature range considered.

1. INTRODUCTION

This paper describes analytical studies performed to evaluate the efficiency of large-scale nuclear hydrogen production processes using high temperature electrolysis. High temperature electrolysis involves the splitting of water into hydrogen and oxygen at high temperatures. The primary advantage of high temperature electrolysis over conventional electrolysis, which is a well established technology, is that considerably higher hydrogen conversion efficiencies can be achieved at the higher temperatures. This improvement occurs because heat can be directly added to the hydrogen production process without the losses associated with the conversion to electricity. Therefore, in high temperature electrolysis some of the energy needed to split the water is added as heat instead of electricity, thereby reducing the total energy required, and improving the overall process efficiency. An additional advantage of the use of nuclear energy for large-scale hydrogen production is that no greenhouse gases are produced. Current hydrogen production is based on steam reforming of methane which consumes fossil fuel and results in the release of significant quantities of carbon dioxide to the atmosphere.

To evaluate the potential benefits of nuclear-driven hydrogen production, the UniSim process analysis software was used to evaluate different reactor concepts coupled to a reference HTE process design concept. The reference HTE

concept included an Intermediate Heat Exchanger and intermediate helium loop to separate the reactor primary system from the HTE process loop and additional heat exchangers to transfer reactor heat from the intermediate loop to the HTE process loops. The two process loops consisted of the water/steam loop feeding the cathode side of the HTE electrolysis stack, and a sweep gas loop used to remove oxygen from the anode side. The UniSim model of the process loops included pumps to circulate the working fluids and heat exchangers to recover heat from the oxygen and hydrogen product streams to improve the overall hydrogen production efficiencies.

The UniSim model for the hydrogen production process was coupled to separate UniSim models for a high-temperature helium cooled reactor power cycle and two different supercritical CO₂ reactor power cycles so that the relative merits of the different reactor power cycles for the production of hydrogen could be evaluated. The primary focus was on the affect of reactor outlet temperature on power cycle and hydrogen production efficiencies. Therefore, sensitivity studies were performed by varying the reactor outlet temperatures over a range between 500° C and 950° C, so that the calculated power conversion and hydrogen production efficiencies for the three different reactor heat sources could be compared. The results of these sensitivity studies are discussed in the following sections. The next section briefly describes the overall electrolysis process including its interface with the reactor systems. This is followed by sections describing the three advanced reactor power cycles that are used to drive the electrolysis process, and the coupling of the reactor concepts with the electrolysis process. The final sections discuss results of the sensitivity studies performed and present the study conclusions.

2. ELECTROLYSIS PROCESS

Figure 1 shows the reference HTE design used in this study to evaluate the potential for large-scale hydrogen production using electrical and thermal power from an advanced high-temperature reactor to drive the process. This HTE plant design is derived from the 500 kW Pilot-Scale High Temperature Electrolysis Plant planned for development at the INL [1]. The UniSim model used in these analyses assumed a 600 MWt reactor operating with reactor outlet temperatures in the range of 500 °C – 950 °C driving the electrolysis process. Therefore, the process described in this report basically involves the scaling up of the pilot-scale plant to a size consistent with the 600 MWt nuclear plants currently being proposed as the next generation of advanced reactors.

The electrolysis flow sheet shown in Figure 1 receives heat and electricity from an advanced reactor indicated at the bottom left of the figure. Process heat is transferred to the hydrogen production plant through a secondary helium loop that isolates the reactor system from the hydrogen plant. The reactor also provides the electrical power for the electrolysis process that is shown on the right side of the figure. The hydrogen plant itself consists of two loops. The first loop at the top of the flow sheet provides the

water/steam that feeds the cathode side of the electrolysis process. The second loop is the sweep gas loop at the bottom right of the flow sheet that removes the oxygen product gas from the anode side of the electrolyzer. The hydrogen and oxygen product streams exit to the right of the electrolyzer. These product gas streams are then routed through recuperative heat exchangers to reduce their temperatures and recover heat to improve the overall efficiency of the HTE process.

This basic process was evaluated using three different advanced reactor cycles to drive the hydrogen production plant. The following section describes the reactor power cycles evaluated, and the next section provides a more detailed discussion of the HTE flow sheet and how the HTE plant model is coupled to the advanced reactor plant models.

3. REACTOR POWER CYCLES

UniSim models for three reactor power cycles were developed to evaluate their potential performance when coupled to a HTE hydrogen production plant. The three reactor power cycles selected were based on advanced reactor concepts capable of operating at reactor outlet temperatures up to 950°C. These high temperatures result in higher power cycle thermal efficiencies (45 to 55%) for these advanced reactor concepts than can be achieved with current generation reactors (30 to 35%). In addition, the high-temperature process heat available from these advanced high-temperature reactors can further enhance hydrogen production efficiencies when the reactor is coupled to a HTE hydrogen production plant. The three reactor power cycles investigated in this study were (1) a direct helium recuperated Brayton cycle, (2) a supercritical CO₂ recuperated Brayton cycle, and (3) a supercritical CO₂ recompression cycle. These power cycles and the UniSim models developed for this study are described in the following sections.

3.1 Direct Helium Recuperated Brayton Cycle

The UniSim model for the direct helium recuperated Brayton cycle is shown in Figure 2. For this particular cycle, the helium coolant is at a pressure of 7.0 MPa inside the reactor vessel. The helium coolant enters the reactor inlet (top left) at a temperature of about 540 °C, where the thermal energy from the reactor increases the coolant temperature to 900 °C. The majority of the coolant leaving the reactor enters the power conversion portion of the cycle where the coolant is expanded through a gas turbine to produce electric power. The helium, at a lower pressure and temperature, then passes through a recuperator and pre-cooler where it is further cooled before entering the low-pressure compressor. To improve compression efficiencies, the helium is again cooled in an inter-cooler heat exchanger before entering the high-pressure compressor. The two compressors provide the driving force to circulate the coolant back through the recuperator where the recovered heat raises the coolant to the reactor inlet temperature to complete the cycle.

Process heat for the HTE hydrogen production plant is provided by splitting the reactor coolant outlet flow into two streams, and allowing about 13% of the flow (stream 7 on the left side of Figure 2) to be bypassed through an intermediate

heat exchanger (IHX) (not shown) where heat is extracted for use in the hydrogen production process. The cooler helium leaving the intermediate heat exchanger (stream 13 on the right side of Figure 2) is then returned through a circulator, where the helium is compressed to the reactor inlet pressure and mixed with the primary coolant returning to the reactor.

The reactor power used in the UniSim calculation shown in Figure 2 was 600 MWt. The calculated stream conditions (flow rates, temperatures and pressures) at different points in the system for this particular analysis are shown in the figure. The calculated power conversion system efficiency (η_{pcs}) for the conditions shown in

Figure 2, defined as:

$$\eta_{pcs} = \frac{P_{turbine} - P_{compressors}}{P_{reactor} - P_{IHx}} \quad (1)$$

where

$P_{turbine}$ = Power of the primary side turbine

$P_{compressors}$ = Power of high and low pressure compressors

$P_{reactor}$ = Reactor Power

P_{IHx} = Intermediate Heat Exchanger duty,

is approximately 54 %. In this calculation, the intermediate heat exchanger duty is associated with the hydrogen production process, and therefore, is subtracted from the total reactor power (denominator of Equation 1) when calculating the power conversion system efficiency.

3.2 Supercritical CO₂ Recuperated Brayton Cycle

The supercritical CO₂ recuperated Brayton cycle shown in Figure 3 closely resembles that of the helium cycle above, but uses supercritical CO₂ at a pressure of 20 MPa as the working fluid. In this case, the supercritical coolant enters the reactor at approximately 755°C and exits the reactor at 900 °C. As in the previous cycle, the reactor outlet coolant flow is split, with the majority of the flow passing through the power conversion portion of the system, and approximately 13 % of the flow bypassed to the intermediate heat exchanger to provide process heat for the hydrogen production process.

The reactor power in this case was again set at 600 MWt, and the UniSim calculated stream conditions (flow rates, temperatures, and pressures) are shown at various points around the system in Figure 3. The calculated power cycle efficiency for the supercritical CO₂ recuperated Brayton cycle for these operating conditions is approximately 38 %.

3.3 Supercritical CO₂ Recompression Cycle

The supercritical CO₂ recompression cycle was developed as a means to improve the efficiency of previously investigated supercritical CO₂ cycles by overcoming the pinch point problem caused by the large irreversibility of the recuperator. This cycle, shown in Figure 4, also operates at a reactor coolant inlet pressure of

approximately 20 MPa. For this particular case, the coolant enters the reactor at a temperature of approximately 690 °C and leaves the reactor at 900 °C. The majority of the primary coolant flow enters the power conversion portion of the cycle where it is expanded through a turbine to produce electric power. The coolant, at a lower temperature and pressure then passes through high-temperature and low-temperature regenerators, where it is further cooled. The coolant flow is then split into two streams (bottom of Figure 4). One stream passes through a precooler that provides additional cooling to the working fluid before it enters Compressor 1. Compressor 1 provides the driving force to circulate the fluid back through the two regenerators where heat is recovered before the working fluid is returned to the reactor inlet to complete the cycle. The second split stream at the bottom of Figure 4 passes directly to Compressor 2 without any additional cooling, where it is compressed and joined with the first split stream before passing through the high temperature recuperator and returning to the reactor inlet to complete the cycle.

To provide process heat for the hydrogen production process, a portion of the reactor coolant outlet flow (13 %) is again split from the main coolant flow (stream 7) and routed through the intermediate heat exchanger (not shown). After the process heat is rejected through the intermediate heat exchanger, the return bypass flow (stream 13) is compressed and mixed with the primary coolant flow at the reactor inlet.

The reactor power in this case was again 600 MWt. The UniSim-calculated stream conditions (flow rates, temperatures and pressures) for the supercritical CO₂ recompression cycle at various points around the system are indicated in Figure 4. For this particular set of conditions, the calculated power conversion system efficiency is about 50 %.

4. COUPLED REACTOR-HTE PROCESS MODELS

Each of the reactor power cycles described in the previous section were coupled to two different HTE process models developed using the UniSim process analysis software. The first model (referred to as the reference case) included a steam sweep system to remove the oxygen product gas from the anode side of the electrolysis stack. This process model is shown in Figure 5.

The electrolysis model was developed using the first law of thermodynamics and the Nernst equation. Details of the model can be found in publications by O'Brien, et. al. [2, 3, 4] For this simulation it was assumed that the electrolyzer cells have cell cross sectional areas of 225 cm² and a current density of 0.25 amperes per cm² resulting in an electrical current of 56.25 amperes. Four millions cells were used, which required 292 MW of electrolysis power to produce 2345 g/s of hydrogen. The operating voltage was 1.3 volts per cell. The electrolysis process was operated above the thermal neutral voltage which resulted in an electrolysis outlet temperature that was above the inlet temperature. At the thermal neutral voltage, the electrolysis exit temperature is the same as the inlet temperature. The thermal neutral voltage for this case is 1.286 volts per cell at a current level of 47.5 amperes; therefore the extra voltage and current provided heating to the products of the electrolysis process. This extra

heat can be recovered by preheating the process or sweep streams.

The choice of a sweep gas for the oxygen stream will be determined not only by efficiency considerations, but also by the markets for the recovered oxygen and the availability of materials for oxygen piping, valves and heat exchangers. A corrosion test facility is beginning operation at the INL for the investigation of materials for prototypical oxygen-side service in HTE. For this study, steam was chosen as the sweep gas since it can be readily separated from the oxygen by condensation, allowing pure oxygen to be recovered as a marketable product of the process.

The process model for this particular case has the hydrogen production process coupled to the supercritical CO₂ recompression power conversion cycle with a reactor outlet temperature of 900 °C as described earlier. However, to simplify the flow sheet model for the hydrogen production process, the reactor power cycle portion of the flow sheet (from Figure 4) is modeled as a sub-flow sheet which is not visible in the main flow sheet for the hydrogen production process. Therefore, the flow sheet in Figure 5 shows the reactor power cycle sub-flow sheet represented by a box with the letter “T” (at the bottom left hand corner of the flow sheet). The reactor power cycle sub-flow sheet interfaces with the hydrogen production process through streams 7 and 13, which are the reactor outlet and inlet streams from Figure 4 that provide process heat to the intermediate heat exchanger.

The intermediate heat exchanger transfers its heat to a secondary or intermediate helium loop. The purpose of this loop is to isolate the reactor primary coolant loop from the hydrogen process loops in the event of a breach in the intermediate heat exchanger. The intermediate loop then transfers its heat to the hydrogen process loops through three additional process heat exchangers. Two of the heat exchangers provide heat to the hydrogen/water side of the HTE process and the remaining heat exchanger heats the steam used to sweep the oxygen from the electrolysis process.

The two HTE process loops consist of the hydrogen-steam feed supply loop for the electrolysis stack and the steam sweep loop. In the hydrogen-steam feed supply loop, make-up water is pumped to the electrolysis pressure and is combined with the recycled water. The water is heated to a saturated state through heat exchanger HX1. The heat from heat exchanger HX2 boils off the remaining water after which the desired amount of recycled hydrogen is added to the stream. In this case study, the composition of the stream after the hydrogen addition is 10% hydrogen and 90% steam by mole. The hydrogen is added to the inlet stream in order to maintain reducing conditions at the electrodes of the electrolysis cells. Heat exchanger HX3 raises the temperature of the steam/hydrogen mixture to as close to the desired electrolysis temperature as possible using heat from the helium secondary side. A high-temperature electrical heater (High Temperature Heater) is used to provide the final amount of heat needed for the electrolysis process. This high-temperature electrical heat

is required, even at the higher reactor outlet temperatures, to ensure adequate control of the inlet temperature to the electrolysis process under all operating conditions. The composition of the hydrogen/steam stream leaving the electrolysis process is 90% hydrogen and 10% steam on a mole basis. The water from the hydrogen/steam leaving the electrolysis process is condensed using the heat exchanger HX1. The condensed water is recycled and the hydrogen stream is split into two streams. The first stream is the hydrogen product stream and the second stream is for hydrogen recycling back into the electrolysis process inlet stream.

In the sweep-gas loop, the steam sweep gas is created by pumping water to the electrolysis pressure. The water is boiled and superheated in the heat exchanger HX5 by the sweep steam and oxygen leaving the electrolysis process. The steam is further heated in heat exchanger HX4 to the electrolysis temperature using heat from the helium secondary loop. After the electrolysis process, the steam/oxygen stream composition is 50% steam and 50% oxygen on a mole basis. The steam/oxygen stream is cooled in heat exchanger HX5 to a saturated state. The water is removed at the High Pressure H₂O/O₂ Knockout Tank and then expanded through a turbine to atmospheric pressure. The stream is further cooled in the Low Pressure H₂O/O₂ Knockout Tank to the ambient temperature and the water is removed from the stream.

For the particular conditions shown in Figure 5, the overall hydrogen production efficiency (η_{H_2}) when the HTE process is coupled to a supercritical CO₂ reactor with a recompression power conversion cycle and a reactor outlet temperature of 900 °C is calculated to be 41.52 % using the equation:

$$\eta_{H_2} = \frac{\text{Net Power}_{\text{Turbomach}} + \text{Power}_{H_2} - \text{Net Power}_{\text{Elect}}}{\text{Power}_{\text{Reactor}}} \quad (2)$$

and

$$\text{Net Power}_{\text{Turbomach}} = \sum \text{Turbine Power} - \sum \text{Compressor Power} - \sum \text{Pump Power} \quad (3)$$

$$\text{Power}_{H_2} = \text{Lower Heating Value}_{H_2} \times H_2 \text{ massflow} \quad (4)$$

$$\text{Net Power}_{\text{Elect}} = P_{\text{Electrolysis}} + P_{\text{Heater}} \quad (5)$$

Where $P_{\text{Electrolysis}}$ is the power delivered to the electrolysis stack and P_{Heater} is the power of the high temperature heater that provides the final amount of heat for the electrolysis process.

The above equations assume that the reactor power may be used for both electricity and hydrogen production, and therefore account for the total power produced and used in the reactor primary system and hydrogen process loops.

The calculated power conversion system efficiency (from Equation 1) for the supercritical CO₂ reactor with a recompression power conversion cycle and a reactor outlet temperature of 900 °C is 50.37 %. In this case, the power

conversion cycle efficiency is higher than the hydrogen production efficiency because the electrolysis process is operating above the thermal neutral voltage.

A second model for the HTE process without a steam sweep system was also evaluated, and is shown in Figure 6. For this case, a gas-cooled reactor with a recuperated direct Brayton cycle power conversion system was used as the power source. To simplify the HTE flow sheet, the flow sheet for the reactor system itself was again included as a sub-flow sheet (designated by the box with the “T” in the lower left corner of the HTE flow sheet).

The electrolysis modeling parameters for this case are the same as those used for the HTE process with steam sweep. Heat from the reactor is again transferred to the intermediate heat exchanger and then to the secondary helium loop. However, since there is no steam sweep loop in this model, only one heat exchanger (HX2) is needed to transfer process heat to the hydrogen-steam feed supply loop. Adequate process heat is provided by HX2 to raise the steam feed temperature to close to the desired electrolysis temperature, but a high-temperature electrical heater is still used to reach the final desired electrolysis inlet temperature.

Since the steam-sweep loop has been eliminated in this case, the hot oxygen product gas from the anode side of the electrolysis stack is used to preheat the hydrogen stream that is recycled to feed the electrolysis process. The oxygen product gas is then expanded through a turbine to reduce its temperature and pressure. The energy recovered from the oxygen product gas (in the form of electrical power) can then be used to supply other electrical power needs in the process.

Except for the above changes, the remainder of the HTE process model with no steam sweep is identical to the process model with steam sweep (reference case) that was discussed earlier. For this particular case, the calculated overall thermal-to-hydrogen production efficiency (from Equation 2) is 48.01 % and the power conversion system efficiency for the high-temperature helium-cooled gas reactor with a recuperated direct Brayton cycle (from Equation 1) is 53.86%.

5. PARAMETRIC STUDY RESULTS

To investigate the effect of different advanced reactor concepts, reactor power cycles and reactor outlet temperatures on power cycle and overall thermal-to-hydrogen production efficiencies, a number of parametric studies were performed. These studies were performed for both the HTE hydrogen production process with steam sweep (reference case) and the HTE hydrogen production process with no sweep. For all of these parametric studies, the electrolyzer parameters (number of cells, current density, cell voltage, etc.) were fixed so that overall performance would only be affected by the specific parameters being investigated. In addition, no modifications to the HTE plant configurations shown in Figures 5 and 6 were made. However, for the different reactor power concepts and reactor operating temperatures, flow conditions in the helium intermediate loop and fluid

conditions at various points in the intermediate helium and hydrogen process loops had to change in order to converge to a solution. To obtain realistic results, it was also necessary to constrain the performance of the heat exchangers in the process to what could reasonably be achieved for a reasonable cost and size. For this study, a heat exchanger minimum approach temperature of at least 5 °C and in most cases above 20°C was used. These minimum approach temperatures were specified in order to ensure that heat exchanger effectiveness values did not exceed 95%. In most cases, heat exchanger effectiveness values were kept at or below 95%. The one exception was the feed water heater HX1, which typically had an effectiveness of around 98%. Since the hot side of this heat exchanger provided the cooling to condense and remove steam from the hydrogen product gas, a lower effectiveness could not be achieved without increasing the steam content in the hydrogen product gas or redesigning the process loop. Therefore, a higher effectiveness was accepted for this heat exchanger.

The main parameter varied in this study was the reactor outlet temperature. To maintain a constant reactor primary coolant flow rate and temperature rise across the core, the reactor inlet temperature was also changed to match the change in outlet temperature for each case. Calculations were performed for each of the reactor power cycles described earlier (helium recuperated direct Brayton cycle, supercritical CO₂ recuperated Brayton cycle, and supercritical CO₂ recompression cycle). The reactor power in each of the calculations was 600 MWt. For each of the reactor cycles, the reactor outlet temperature was varied from 500 °C to 950 °C to determine the effect on power conversion system and overall hydrogen production efficiencies.

Figure 7 summarizes the results from all the calculations, showing power conversion system efficiency (Equation 1) and overall hydrogen production efficiency (Equation 2) as a function of reactor outlet temperature for each of the power cycles.

As expected, both the power conversion system efficiencies and hydrogen production efficiencies increase with increased reactor outlet temperatures for each of the power cycles. For each of the power cycles, the hydrogen production efficiency is lower than the power conversion system efficiency since the electrolysis process was operated above the thermal neutral voltage.

To better describe the parametric behavior, the power conversion efficiencies for the three separate cycles are plotted separately in Figure 8. This figure shows that the power conversion efficiency for the helium recuperated direct Brayton cycle is relatively low (~12 %) at a reactor outlet temperature of 500 °C, but increases relatively rapidly as the reactor outlet temperature is increased. A peak power conversion efficiency of ~56 % is reached at a reactor outlet temperature of 950 °C. The efficiency of the helium recuperated Brayton cycle exceeds that of the supercritical CO₂ recuperated Brayton cycle at a reactor outlet temperature of about 600 °C and exceeds that of the supercritical CO₂ recompression cycle at about 750 °C. Therefore, from a power conversion system efficiency point of view, the helium

recuperated Brayton cycle appears to be the preferred cycle at reactor outlet temperatures above 750 °C.

In contrast, the two supercritical CO₂ cycles have higher efficiencies at the lower reactor outlet temperatures but show only a modest increase in efficiency as the reactor outlet temperature is increased. For the supercritical CO₂ recuperated Brayton cycle, the lower power conversion efficiencies may be the result of the large irreversibility in the power conversion system recuperator, which is the result of a pinch point problem described by Dostal, et. al. [5] and others. However, a detailed analysis of the recuperator was not performed as a part of this study.

The supercritical CO₂ recompression cycle was specifically developed to overcome the problems associated with a simple Brayton cycle with supercritical CO₂ as the working fluid. The UniSim-calculated results in Figure 8 indicate that this cycle does indeed produce higher power conversion system efficiencies than achieved with the supercritical CO₂ recuperated Brayton cycle over the full range of reactor operating temperatures. Between 500 °C and 750 °C, the supercritical CO₂ recompression cycle produced the highest power conversion system efficiencies of the three cycles investigated. However, further investigation of the supercritical CO₂ cycles needs to be conducted to better understand these results. In particular, the properties for supercritical CO₂ as defined in UniSim need to be investigated further, since CO₂ properties near the critical point are very sensitive to temperature and pressure.

Hydrogen production efficiencies are plotted as a function of reactor outlet temperature in Figure 9. Since the HTE process coupled to a nuclear reactor relies primarily on the electrical energy supplied by the reactor, with only a small fraction of the total reactor thermal power (~13 %) used as process heat, the general trends in hydrogen production efficiencies in Figure 9 closely follow the power conversion system efficiency trends shown in Figure 8. However, hydrogen production efficiencies in each case are lower than the corresponding power conversion efficiencies for each power cycle because the electrolysis process is operated above the thermal neutral voltage.

Above 700 °C, the helium recuperated direct Brayton cycle had the highest hydrogen production efficiencies. Below 700 °C, the supercritical CO₂ recompression cycle had the highest hydrogen production efficiencies. In general, the supercritical CO₂ recuperated Brayton cycle gave the lowest hydrogen production efficiencies for temperatures between 600 and 950 °C, but its efficiencies did exceed the helium recuperated Brayton cycle hydrogen production efficiencies at temperatures below about 580 °C.

The final sensitivity calculations performed compared the power conversion system and hydrogen production efficiencies for the helium recuperated Brayton cycle coupled to the HTE processes with and without the steam sweep loop. The results of these analyses are shown in Figure 10. The power conversion efficiencies are not

affected by the removal of the steam sweep loop, so the power conversion efficiencies for the helium recuperated Brayton cycle with and without steam sweep are in agreement over the full reactor outlet temperature range. However, the elimination of the steam sweep loop reduces the total energy requirements for the HTE process since irreversible losses and the additional pumping requirements for the steam sweep loop are eliminated. Therefore, Figure 10 shows slightly higher hydrogen production efficiencies (on the order of 1 % to 2 %) for the no-sweep case compared to that for the steam sweep case over most of the reactor outlet temperature range.

6. CONCLUSIONS

Parametric studies were performed to evaluate the performance of HTE hydrogen production processes when coupled to different advanced nuclear reactor power sources. Three different reactor power cycles capable of delivering high-temperature process heat to the HTE hydrogen production processes were investigated. The reactor concepts were (1) a high-temperature helium cooled gas reactor with a direct recuperated Brayton cycle power conversion system, (2) a high-temperature supercritical CO₂ cooled reactor with a direct Brayton cycle, and (3) a high-temperature supercritical CO₂ cooled reactor with a recompression cycle power conversion system.

The reactor power in each case was assumed to be 600 MWt. The majority of the primary coolant flow from the reactor was routed to the power conversion system to produce the required electricity for the high-temperature electrolysis process. However, a portion of the high-temperature primary coolant from the reactor outlet (approximately 13 %) was split from the main stream to provide process heat for the electrolysis process. This heat was transferred through an intermediate heat exchanger to a secondary helium loop, and then to the process loop(s) through various secondary system heat exchangers. The secondary loop was included between the reactor primary system and the hydrogen process loop(s) to preclude the potential for contamination of the hydrogen product gas in the event of a failure/break in the intermediate heat exchanger.

Calculations were performed for each of the reactor concepts over the range of reactor coolant outlet temperatures from 500 °C to 950 °C. The HTE process model for these calculations included a steam sweep loop to remove the oxygen from the electrolyzer anode. Additional calculations were also performed for an HTE process without a steam sweep loop to determine the affect of the steam sweep on hydrogen production efficiencies. These latter calculations were performed using the high-temperature gas reactor with a recuperated direct Brayton cycle as the heat source. The conclusions from these parametric studies are:

- The helium recuperated Brayton cycle produced the highest hydrogen production efficiencies for reactor outlet temperatures between 700 °C and 950 °C.
- The supercritical CO₂ recompression cycle gave the highest hydrogen production efficiencies for reactor outlet temperatures between 550 °C and 700 °C.
- The supercritical CO₂ recuperated Brayton cycle gave the lowest hydrogen production efficiencies

over the range of reactor outlet temperatures investigated.

The removal of the steam sweep system from the hydrogen production process model produced slightly higher hydrogen production efficiencies (1 % to 2 %).

These results are preliminary and do not necessarily represent optimized designs for the concepts investigated. Additional studies are planned to investigate heat exchanger performance and system pressure losses to better characterize the overall system performance. In addition, future work will implement improvements into the electrolyzer model currently incorporated into UniSim and investigate the affect of electrolyzer parameters on system behavior.

REFERENCES

1. Stoots, C. M., Condie, K. G., O'Brien, J. E., Housley, G. K., Herring, J. S., "Integral Laboratory Scale Stack Specification Mechanical Design Report", Idaho National Laboratory, August 15, 2006.
2. O'Brien, J. E., Stoots, C. M., and Hawkes, G. L., "Comparison of a One-Dimensional Model of a High-Temperature Solid-Oxide Electrolysis Stack with CFD and Experimental Results," 2005 ASME International Mechanical Engineering

Congress and Exposition, Nov. 5 – 11, 2005, Orlando.

3. Stoots, C. M., O'Brien, J. E., McKellar, M. G., Hawkes, G. L., and Herring, J. S., "Engineering Process Model for High-Temperature Steam Electrolysis System Performance Evaluation," AIChE 2005 Annual Meeting, Cincinnati, Oct. 30 – Nov. 4, 2005.
4. O'Brien, J. E., Stoots, C. M., Herring, J. S., Hawkes, G. L., "Hydrogen Production From Nuclear Energy Via High Temperature Electrolysis," The 1st Energy Center Hydrogen Initiative Symposium, Purdue University, West Lafayette, IN, April 5-6, 2006.
5. Dostal V., "A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors", Doctoral Dissertation, Massachusetts Institute of Technology, January 2004.
6. Lamarsh, J. R., Baratta, A. J., Introduction to Nuclear Engineering, Third Edition, Prentice Hall, Upper Saddle River, New Jersey, 07458, 2001.
7. O'Brien, J. E., McKellar, M. G., Stoots, C. M., Hawkes, G. L., Herring, J. S., "Analysis of Commercial-Scale Implementation of HTE to Oil Sands Recovery", INERI milestone report, 15 September 2006.

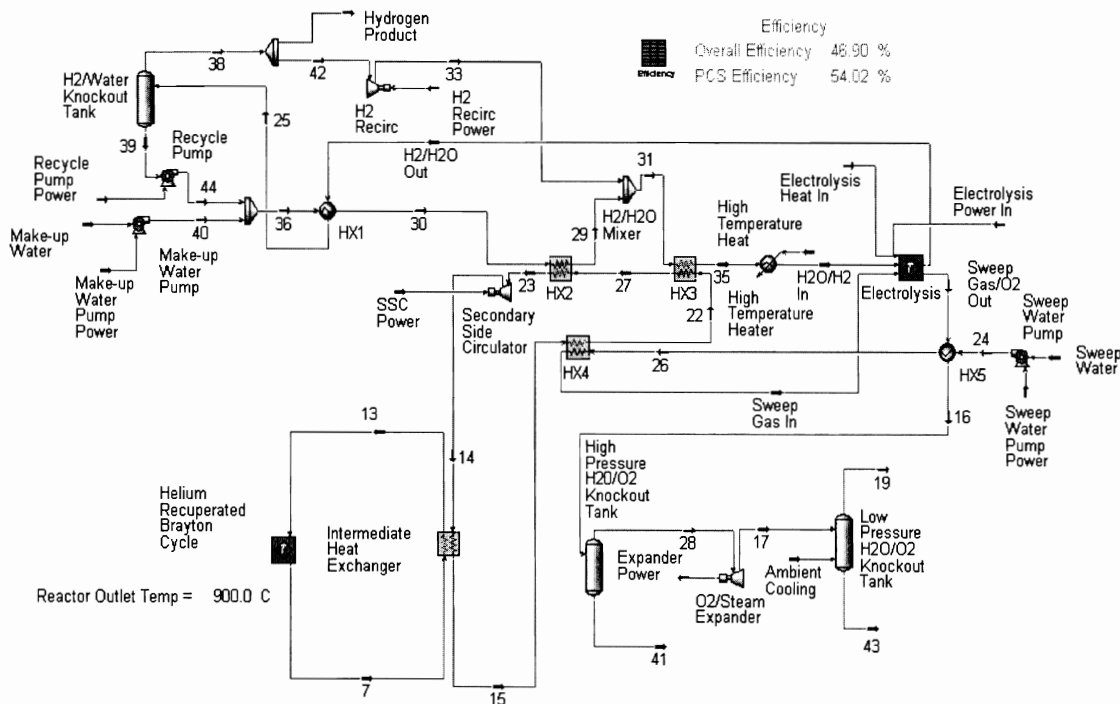


Figure 1. Nuclear-driven HTE process flow sheet.

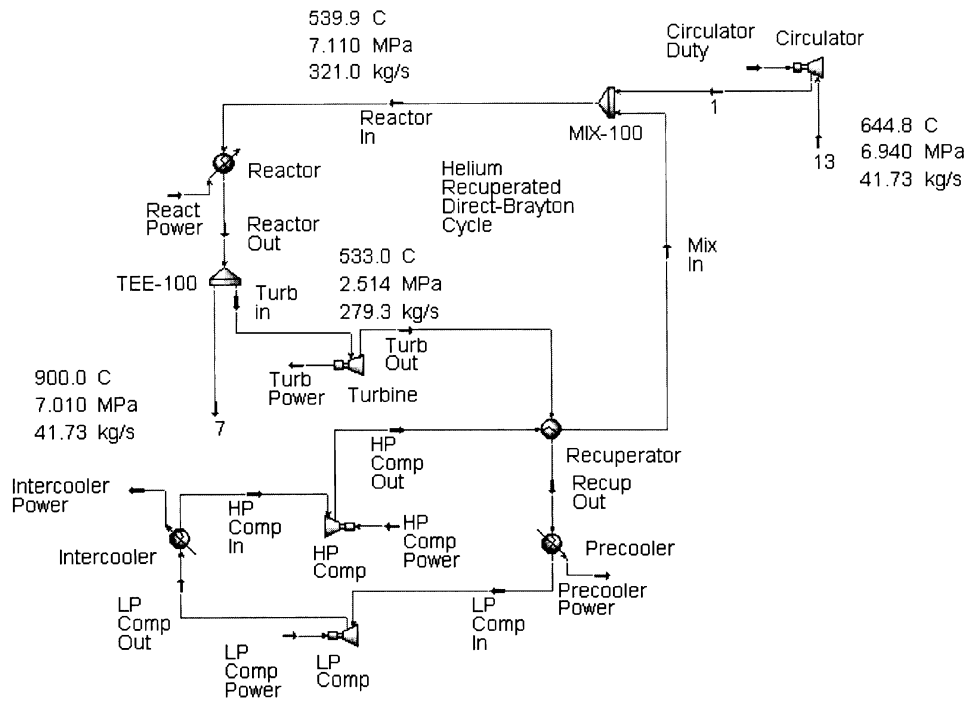


Figure 2. Helium recuperated direct Brayton cycle model.

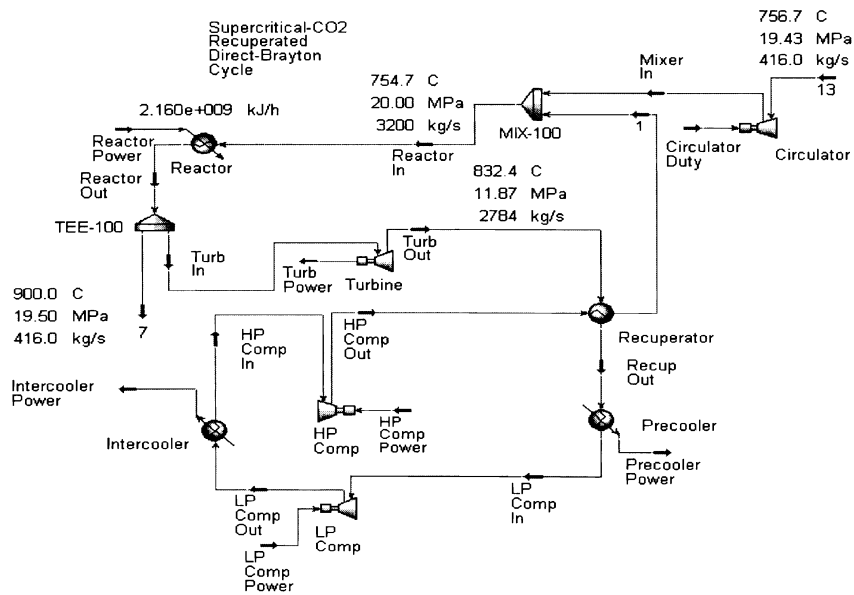


Figure 3. Supercritical CO2 recuperated Brayton cycle model.

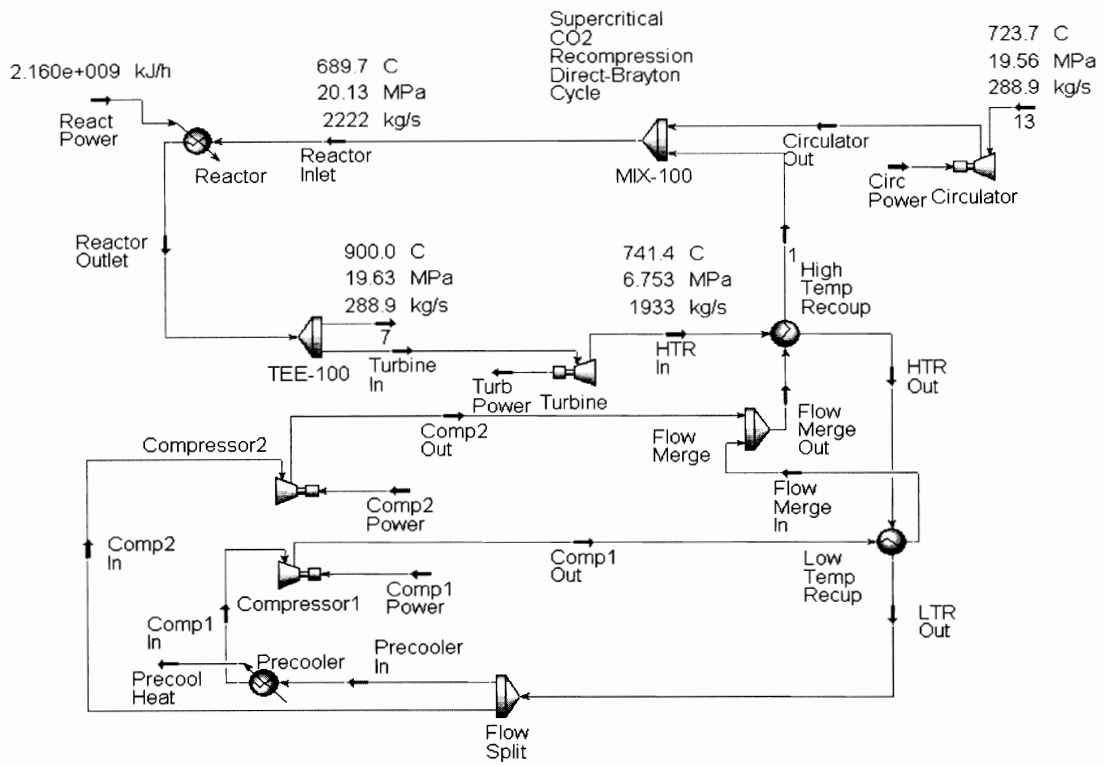


Figure 4. Supercritical CO₂ recompression cycle model.

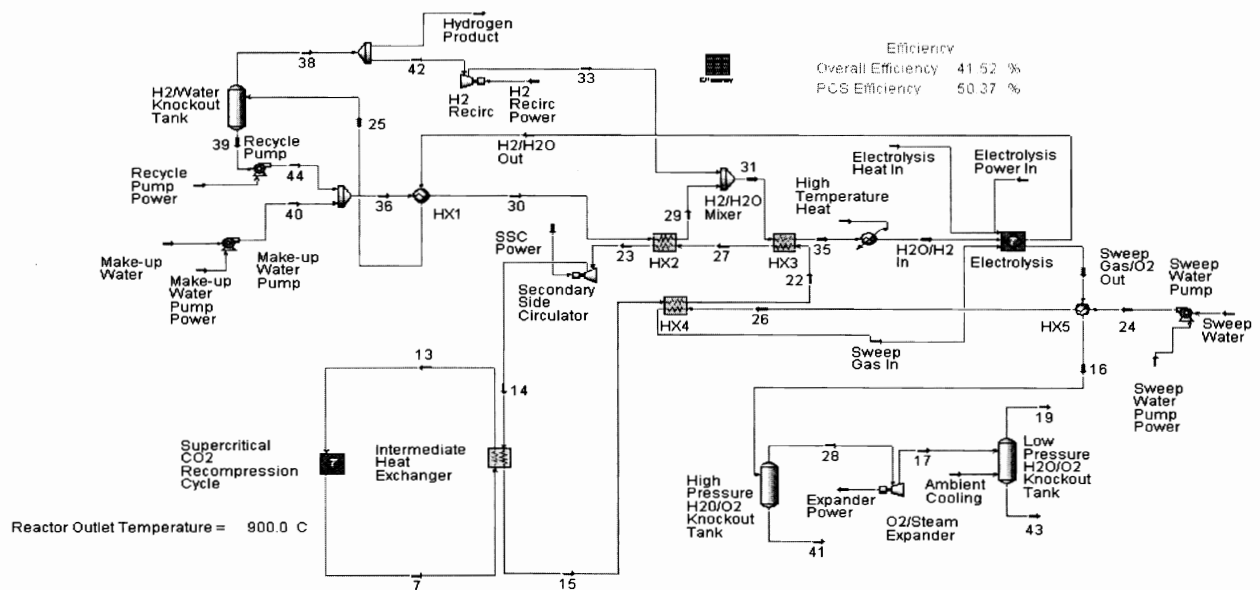


Figure 5. High temperature electrolysis process with steam sweep.

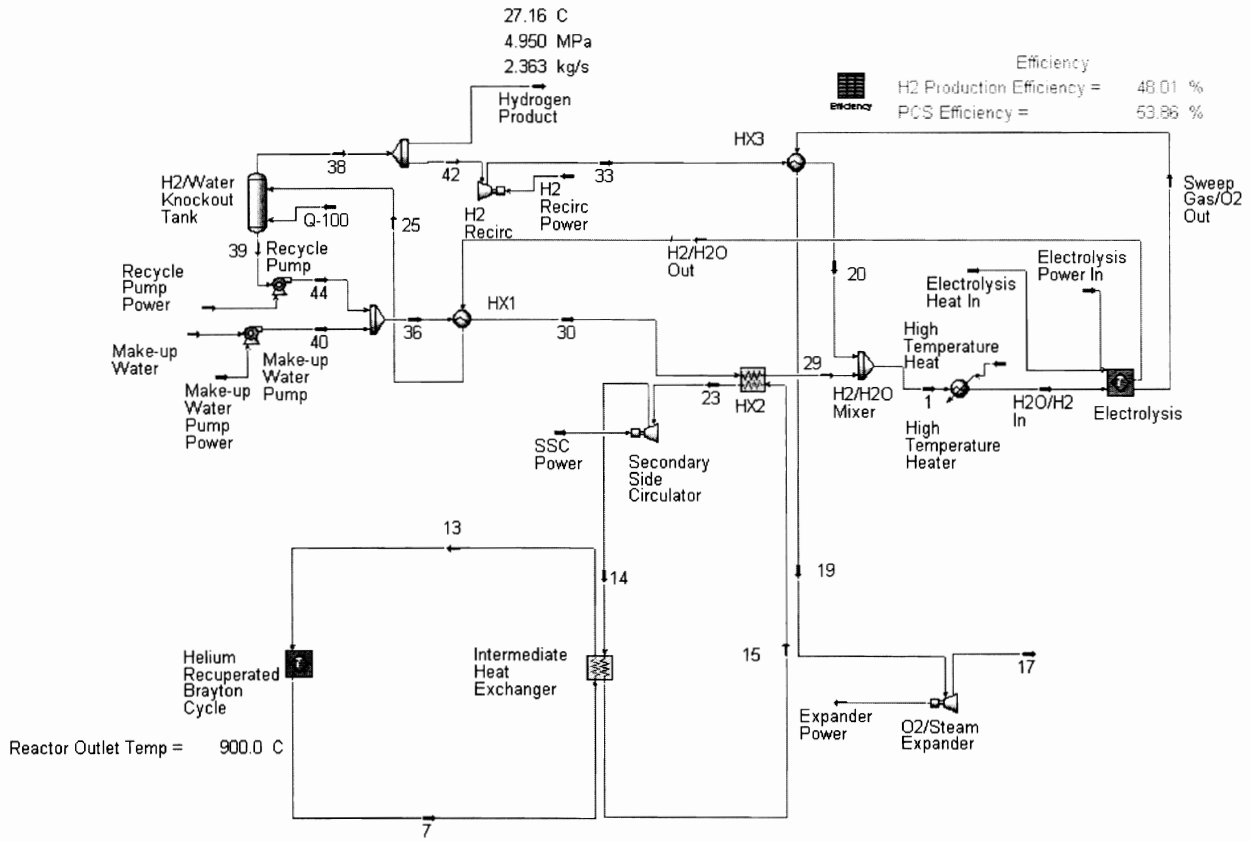


Figure 6. High temperature electrolysis without steam sweep.

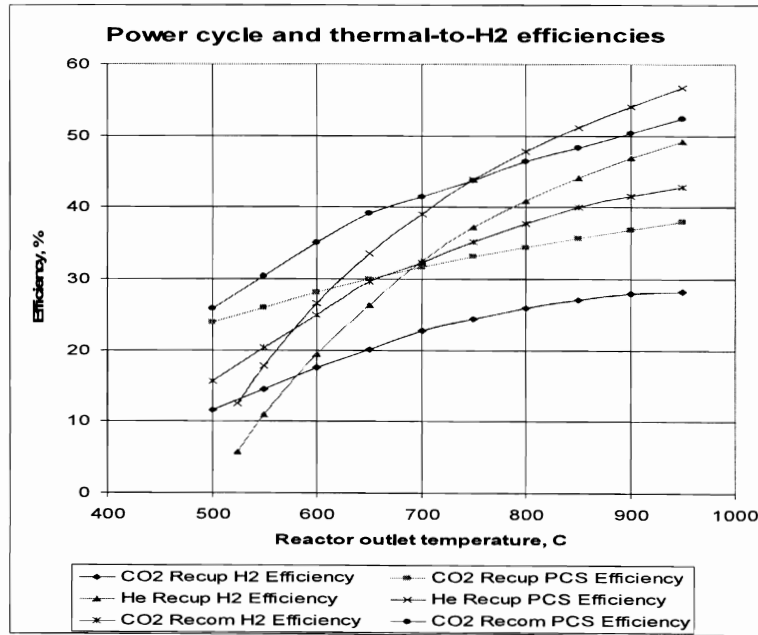


Figure 7. Summary of PCS and hydrogen production efficiencies.

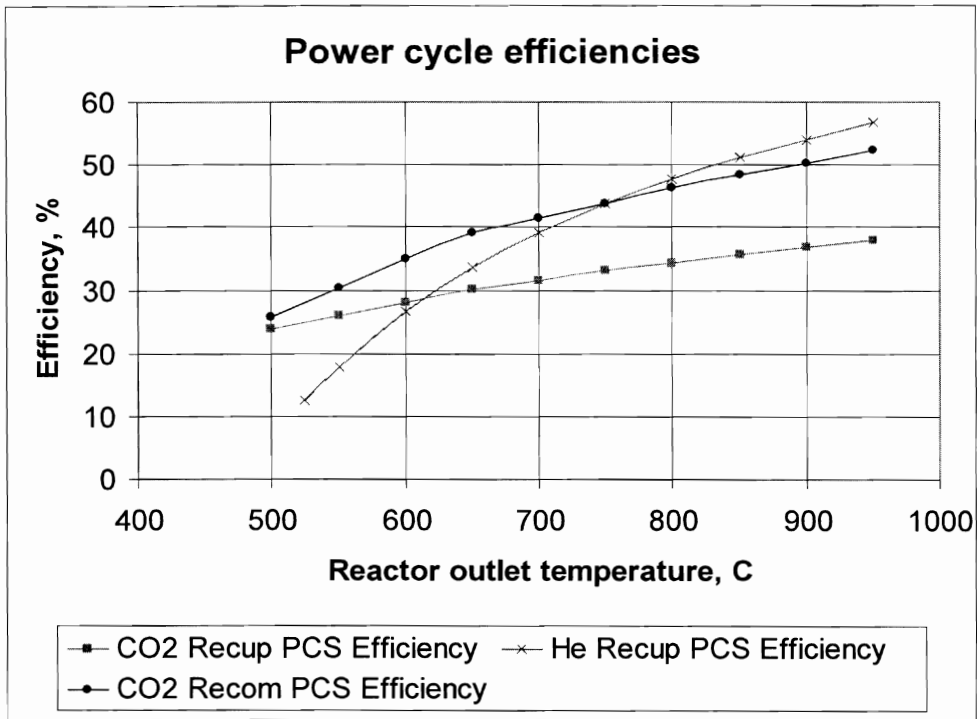


Figure 8. Power conversion system efficiencies as a function of reactor outlet temperature.

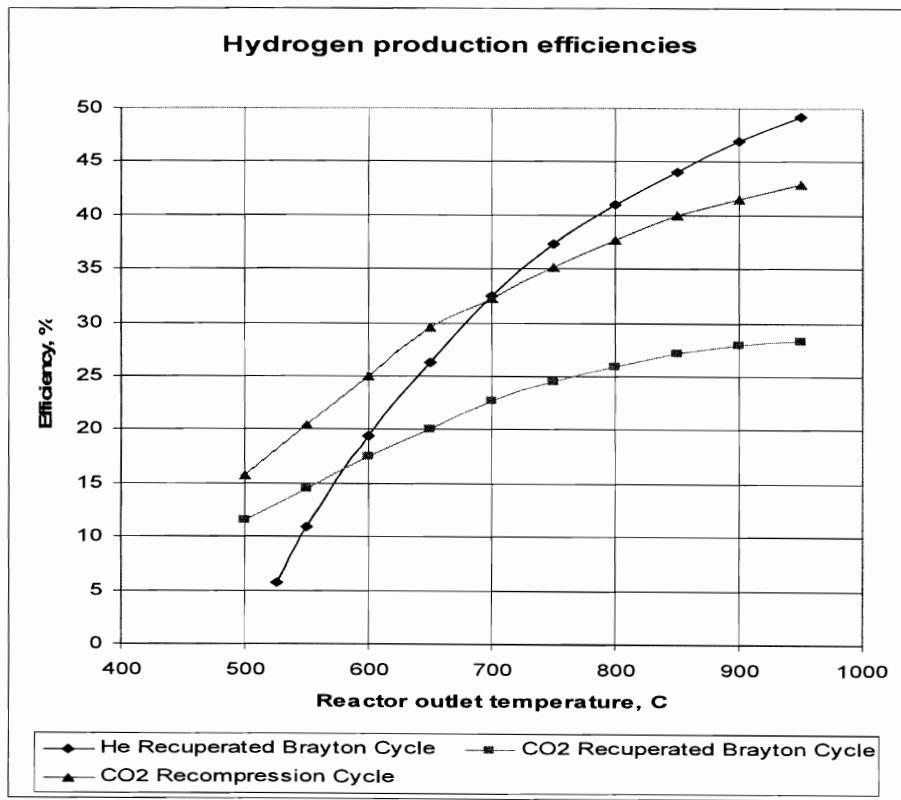


Figure 9. Hydrogen production efficiencies as a function of reactor outlet temperature.

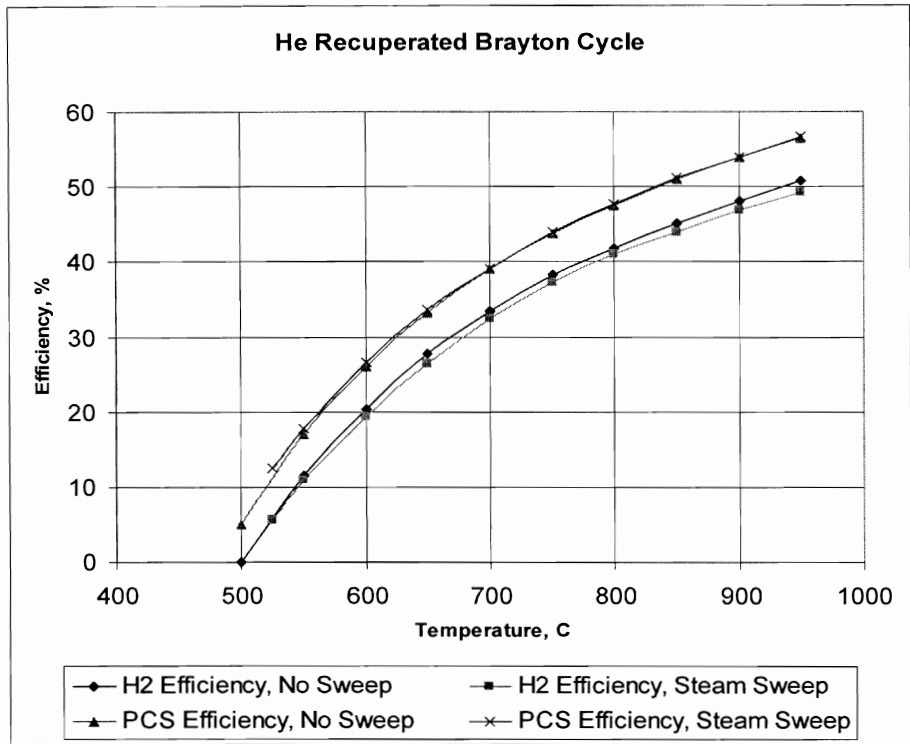


Figure 10. PCS and hydrogen production efficiencies for the helium recuperated Brayton cycle-HTE process with and without steam sweep.