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# POWER CONVERSION STUDY FOR HIGH TEMPERATURE GAS-COOLED REACTORS

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Abstract – *The Idaho National Laboratory (INL) is investigating a Brayton cycle efficiency improvement on a high temperature gas-cooled reactor (HTGR) as part of Generation-IV nuclear engineering research initiative.*

*There are some technical issues to be resolved before the selection of the final design of the high temperature gas-cooled reactor, called as a Next Generation Nuclear Plant (NGNP), which is supposed to be built at the INEEL by year 2017. The technical issues are the selection of the working fluid, direct vs. indirect cycle, power cycle type, the optimized design in terms of a number of intercoolers, and others.*

*In this paper, we investigated a number of working fluids for the power conversion loop, direct versus indirect cycle, the effect of intercoolers, and other thermal hydraulics issues. However, in this paper, we present part of the results we have obtained. HYSYS computer code was used along with a computer model developed using Visual Basic computer language.*

## I. INTRODUCTION

The HTGR is a graphite-moderated, helium-cooled reactor using a direct or indirect gas cycle to convert the heat generated by nuclear fission into electrical energy by means of a helium Brayton cycle. Since the early 1950's the HTGR technology has been researched and some reactors were built [1]. In the HTGR, the gas coolant is forced to flow through the reactor core where it is heated to a high temperature and then the gas flows directly to a steam generator or a gas turbine. These reactors have been built both in England and Germany. The Arbeitsgemeinschaft Versuchsreactok (AVR), 15-MWe-test reactor located at Forschungszentrum Juelich, Germany. Construction on the reactor started in 1961. Criticality was first achieved in 1966. The AVR was operated for 21 years. In 1974, the reactor outlet temperature was raised to 950°C, which was needed to test very-high-temperature nuclear process heat applications. The most recent HTGR built is the Chinese HTR-10 (10 MW Pebble Bed Reactor), which achieved its first criticality December 2000 [2-4]. The HTR-10 was designed to operate up to 900°C in order to investigate diverse power generation systems (e.g., gas turbine) and nuclear process heat applications [5].

In the mid-1950s, interest in gas-cooled reactor technology was revived in the U.S., United Kingdom, France and Germany. Several of these reactors were built. Recently countries including the U.S, South Africa and the Netherlands [6, 7] renewed their interest in gas-cooled reactor technology, particularly the modular pebble bed reactor.

The only commercial HTGR built in the US was the Fort St. Vrain unit, located at the confluence of the St. Vrain Creek and the South Platte River near Platteville, Colorado. In June 1968 construction began and initial criticality was reached on January 31 1974 [1]. This plant was operated with some technical problems and was eventually shut down due to water leakage into the water-cooled bearings on the circulator, which will not be a problem now thanks to improvements in the circulator design.

[1] Summer Intern

Recently Eskom, a power company based in South Africa, submitted a nuclear installation license application to the National Nuclear Regulator (NNR). It is proposed to locate the installation on Eskom property within the owner-controlled boundary of the Koeberg Nuclear Power Station located in the Western Cape. In the U.S., the Department of Energy (DOE) plans to build a VHTR by 2017.

## II. REFERENCE DESIGN FOR TRADE OFF STUDY

Figure 1 illustrates the reference design of the GTHTR300 [8]. The Japan Atomic Energy Research Institute (JAERI) has been performing the GTHTR300 detailed design evaluation and the development of the necessary component and tests to validate the design.

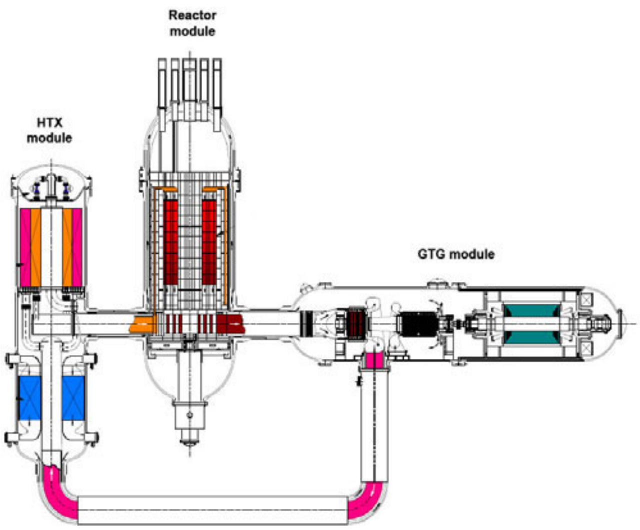



Figure 1. GTHTR reference design.

The GTHTR-300 is a direct-cycle gas cooled reactor that uses a distributed power conversion system with horizontal turbomachinery and heat exchangers located in separate vessels, as shown in Figure 1.

This is basically a horizontal turbomachinery without intercoolers as shown in Figure 2. Helium flows through the reactor and exits at 850°C temperature. The helium flows into the turbine directly, the expanded helium transfers heat to the high pressure side of the recuperator for preheating helium before it enters the reactor. Then the helium is cooled to 28°C before entering the compressor. The pressure ratio across the compressor is 2 resulting in a reported plant efficiency of 47%. The corresponding reactor power and outlet temperature is 600 MW thermal and 850°C respectively. GTHTR-300 design was used to compare the cycle efficiency with various working fluids.

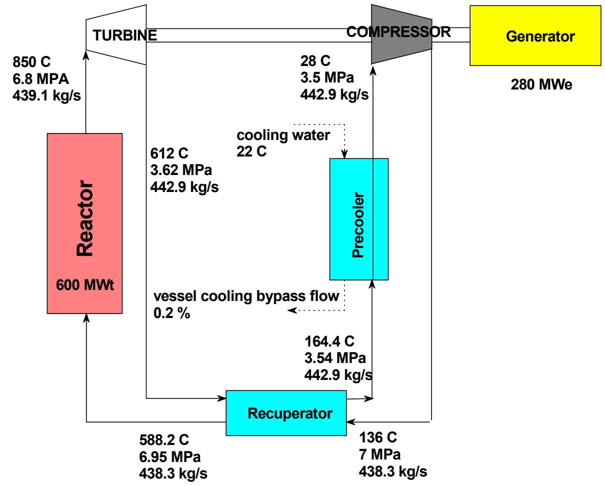



Figure 2. Schematic of GTHTR 300 reference design.

The overall cycle efficiency used in this study is defined as:

$$\eta_{cyc} = \frac{\text{Electric power output}}{\text{Reactor thermal power}} = \frac{\Sigma W_T - \Sigma W_C - W_S - W_{CIR}}{Q_{th}} \qquad (1)$$

where $\Sigma W_T$ is the total turbine workload, $\Sigma W_C$ is the total compressor workload, $W_S$ is the plant stationary load, $W_{CIR}$ is the circulator workload in the primary side, and $Q_{th}$ is the reactor thermal power. For the efficiency calculations, we used the net cycle efficiency, which is the net efficiency and more conservative than the thermal efficiency.

The polytropic efficiency rather than the isentropic efficiency is used for representing the turbo machines efficiency. The expansion and compression processes for a perfect gas are as follows [9].

Expansion:

$$\frac{T_{0,ex}}{T_{0,in}} = \left(\frac{P_{0,ex}}{P_{0,in}}\right)^{\left(\frac{R}{Cp}\eta_{p,e}\right)} \qquad (2)$$

where R is the gas constant, Cp is the specific heat, and $\eta_{p,e}$ is the turbine polytropic efficiency, $T_0$ is the stagnation temperature, and $P_0$ is the stagnation pressure. Subscripts *ex* and *in* refer to exit gas and inlet gas, respectively.

Compression:

$$\frac{T_{0,ex}}{T_{0,in}} = \left(\frac{P_{0,ex}}{P_{0,in}}\right)^{\left(\frac{R}{Cp}\frac{1}{\eta_{p,c}}\right)} \qquad (3)$$

The HYSYS computer code [10]was used for the PCS cycle efficiency calculations. HYSYS is unable to directly calculate the effectiveness of a heat exchanger, because heat exchanger effectiveness is a complex function of the heat exchanger design, and the degree to which the design achieves ideal counterflow conditions. Furthermore, as discussed and modeled in Section 3.1.3, the modular heat exchangers effectiveness is also a function of how uniformly the manifold system distributes flow to each module. For the purpose of system analysis, reasonable values for heat exchanger effectiveness were assumed, and a model to solve for system performance was developed and input into HYSYS. The effectiveness ε of a heat exchanger is defined as the ratio of the actual heat transfer rate to the maximum heat transfer rate.

$$\varepsilon = \frac{q}{q_{max}} \qquad (4)$$

$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) \qquad (5)$$

where $C_{min}$ corresponds to $C_{cold}$ or $C_{hot}$, whichever is smaller.

$$C_{cold} = c_{p,cold}\dot{m}_{cold} \qquad (6)$$

$$C_{hot} = c_{p,hot}\dot{m}_{hot} \qquad (7)$$

The effectiveness is set for each heat exchanger (90% for the intermediate heat exchanger and 95% for the recuperator).

## III. WORKING FLUIDS

The working fluid selection affects the cycle operating condition, the efficiency, and the size of the NGNP components, which will be a major factor for the system cost. Some fluids such as $CO_2$ are not recommended for use in the direct cycle due to chemical reactions with the graphite matrix in the NGNP reactor core at temperatures greater than 550°C, due to heat transfer, neutronics impacts, or activation concerns. The chemical equilibrium of CO and $CO_2$ gases is determined by the following Gibbs free energy equation [11].

$$G = \sum_{\text{ideal gas}} n_i(g_i^0 + R\ln P_i) + \sum_{\text{condensed phase}} n_i g_i + \sum_{\text{solution}} n_i(g_i^0 + R\ln x_i + R\ln\gamma_i) \qquad (8)$$

where $n_i$ is moles, $P_i$ is gas partial pressure, $x_i$ is mole fraction, $g_i^0$ is standard Gibbs free energy, $G$ is the total Gibbs free energy, and $\gamma_i$ is activity coefficient.

The equilibrium is calculated by the combination of $n_i$, $P_i$, and $x_i$, which minimizes the total Gibbs energy, $G$, of the system. An equilibrium calculation based on a chemical reaction of $C + n\,CO_2 \rightarrow 2\,CO + (n-1)\,CO_2$ shown in Figure 3 shows that at low $500^0$ C, the reaction occurs and it produces CO gas at 200 atm (about 20 MPa).

Radiolytic graphite oxidation involves the radiolysis of carbon dioxide by the high intensity gamma field, to produce an ion from the $CO_2$ that is an oxidizing species [12]:

$CO_2 + \gamma \rightarrow Ox$ (+ other products)

where Ox is a short-lived ionized species such as $CO_3$-, $CO_2$+, …. When these reactive oxidizing species impinge on a graphite surface they gasify it to carbon monoxide, equation (9), or, depending upon the rate of diffusion of the oxidizing species within the pores of the graphite, may become deactivated before reacting with carbon atoms in the graphite, equation (10):

$Ox + \text{Graphite} \rightarrow CO$ (9)

$Ox + CO \rightarrow CO_2$ (10)

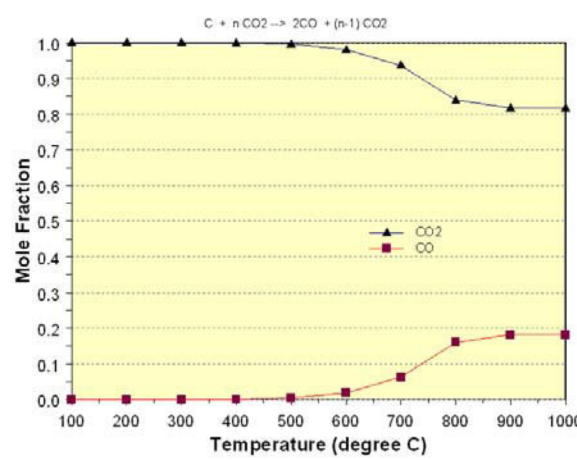



Figure 3. Chemical equilibrium of CO and $CO_2$.

For the indirect cycles, there exists a freedom to examine a number of working fluids. These coolants were examined to see if they provide improved efficiency, cost reduction or reduced development risk when compared to a baseline cycle. Compatibility with intermediate heat exchangers

(IHX), and in particular the potential need to operate metallic IHX's in a pressure-balanced mode, were also considered.

For this study, the effects of the working fluid choice on cost and technical risk measures were examined for the following:

- Helium for both direct and indirect cycle
- Nitrogen indirect cycle
- $CO_2$ for indirect cycle
- $N_2$/He for indirect cycle

## IV. RESULTS

Important parameters for improving the Brayton cycle efficiency are reactor core outlet temperature, efficiencies of the compressors, turbines, intermediate heat exchanger, and others. In this study the reactor core outlet temperature was varied between 850°C and 1000°C. For each of the fixed outlet temperatures (850°C, 900°C, 950°C 1000°C), the inlet temperature to the core was varied between 400°C and 640°C. The results are also based on a three shaft arrangement for the helium Brayton cycle, using an intermediate heat exchanger effectiveness factor of 92 percent, a 90 percent polytropic efficiency for the compressors and turbines, and a 30 degree Celsius cooling temperature to the precooler and the three intercoolers. Figures 4 and 5 are results of sensitivity for the helium Brayton cycle.

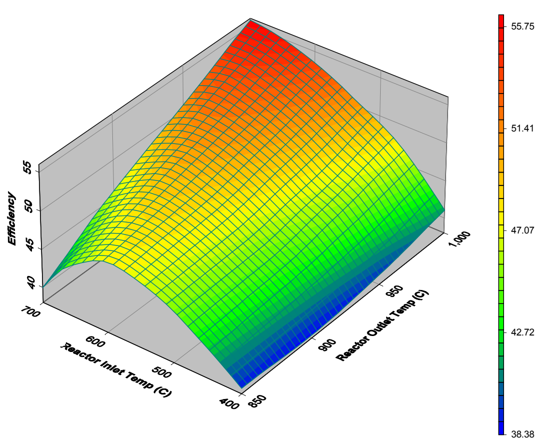



Figure 4. Cycle efficiency as a function of reactor inlet and outlet temperatures.

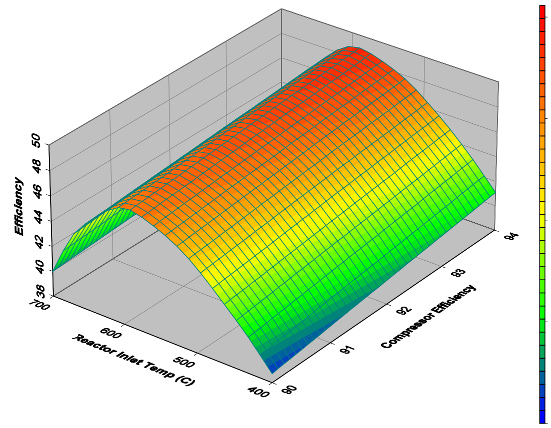



Figure 5. Cycle efficiency as a function of compressor efficiencies and reactor inlet temperatures.

### Helium for both direct and indirect cycle

The direct helium cycle was simulated with an optimal pressure ratio of ~1.93. This gave a cycle efficiency of 50.9%.

The indirect helium cycle was simulated assuming a compressor outlet pressure of 8 MPa. The cycle conditions were optimized with a secondary mass flow rate equal to the primary mass flow (439.1 kg/s) and a pressure ratio of ~2.02. This gave a cycle efficiency of 48.7%.

### Nitrogen for indirect cycle

The indirect Nitrogen cycle was simulated assuming a compressor outlet pressure of 8 MPa. The optimal secondary mass flow rate was 2600 kg/s and the optimal pressure ratio was ~2.37. This gave a cycle efficiency of 45.5%.

### $CO_2$ for indirect cycle

The indirect $CO_2$ cycle was simulated assuming a compressor outlet pressure of 20 MPa. The higher compressor outlet pressure was used to take advantage of compression around the critical point and decrease compressor work. The optimal secondary mass flow rate was 1794 kg/s and the optimal pressure ratio was ~4.76. This gave a cycle efficiency of 50.7%.

The indirect $CO_2$ cycle was also simulated at 8 MPa for comparison. The mass flow rate was unchanged and the optimal pressure ratio was ~6.8. This gave a cycle efficiency of 46.4%. This is closer to the other working fluid efficiencies. The other working fluids are insensitive to system pressure while an efficiency gain can be accomplished by increasing the pressure for $CO_2$.

Assuming similar pressure drops in heat exchangers and the same turbomachinery efficiencies, the helium, nitrogen, and $CO_2$ at 8MPa all have approximately the same cycle efficiency. However, the $CO_2$ at 20 MPa has a ~4% higher efficiency than the other cycles due to the decreased compression work for the cycle as seen in Table 2.1-2. Helium and nitrogen are insensitive to maximum system pressure while an efficiency gain can be accomplished by increasing the pressure for $CO_2$.

The reduced compression work due to compression around the critical point of $CO_2$ makes it an attractive option for a secondary working fluid. However, $CO_2$ is not inert compared with other fluids such as helium and nitrogen and more advanced materials are required to address potential corrosion issues. The tradeoff of increased capital cost and increased cycle efficiency would need to be studied further if a more in-depth economic analysis were to be carried out.

Table 1 compares the cycle efficiency, the work duty of the turbine and compressor, and the total heat transfer area ratio for different working fluids in the power conversion unit. Pressure drops through the IHX and recuperator were calculated for various working fluids using a shell-tube type heat exchanger. Relative total area ratio can be varied depending on the final selection of heat exchanger. Overall heat transfer coefficients, U, were calculated and the ideal heat transfer area (assuming perfect counterflow) of the helium indirect cycle was used as a basis for comparing area ratios for each working fluid. As shown in Table 1, using nitrogen as the working fluid in the power conversion cycle (PCS) requires the largest heat exchanger size compared with those of other fluids studied. Larger heat transfer area can also mean larger pressure drops for flows, not considered here. The Framatome indirect cycle design therefore uses a helium-nitrogen mixture to increase the gas thermal conductivity and reduce the heat exchanger size from these values.

Table 1. Comparison of cycles for different working fluids.

| Working Fluid | Cycle Efficiency | Turbine Work (MW) | Compressor Work (MW) | Total UA[1] (MW/K) | Overall U ($W/m^2K$) | Total Area Ratio[2] |
|---|---|---|---|---|---|---|
| He Direct | 50.9% | 542.9 | 237.7 | Recup: 42.9 | 204.6 | 0.65 |
| He Indirect | 48.7% | 575.4 | 256.5 | IHX: 24.2 Recup: 43.1 | 216.9 204.6 | 1 |
| $N_2$ Indirect | 45.5% | 557.3 | 258.3 | IHX: 13.7 Recup: 58.9 | 186.7 166.6 | 1.32 |
| $CO_2$ (20 MPa) | 50.7% | 497.2 | 167. | IHX: 24 Recup: 35.1 | 170.3 145.3 | 1.18 |

**[1]UA=Universal heat transfer coefficient * heat transfer area, assuming perfect counterflow.**
**[2]Area Ratio: Total Heat Transfer Area of Working Fluid / Total Heat Transfer Area of Helium Indirect.**

HYSYS [9] that is a process optimization computer code used in chemical industry was used to investigate interstage heating and cooling. The component efficiency of turbine, compressor, and primary circulator are 92%, 90%, and 90% respectively with the reactor outlet temperature of $900^0$C.

Interstage Heating and Cooling (IH&C) is an attractive option for improving the efficiency of the NGNP power conversion system. As additional stages are added, the average temperature over which input energy is added stays higher and/or the average temperature over which rejection energy is removed stays lower. If this was the only impact of the IH&C, the cycle efficiency would always increase with more stages. But with each additional stage, pressure drop is present. Additional interstage pumping must be accomplished to make up for this additional pressure drop. Because the pumps are not 100% efficient, eventually the entropy loss during an additional pumping operation results in a smaller total energy input than without that stage. When this occurs, the cycle efficiency actually decreases. When the cycle efficiency improvement is not justified for the additional cost, the additional stage can be assessed based upon achievable component performances.

Cycle efficiencies as well as differential cycle efficiencies (efficiency improvement per stage) were examined as a function of the number of input and rejection stages for several cycles including:

- Recuperated Helium Brayton cycle
- Recuperated 80% $N_2$ 20% He (by weight) Brayton cycle
- Recuperated Supercritical $CO_2$ Brayton with split flow cycle
- Implication of gas or liquid intermediate loop
- Implication of IH&C to system layout

Interstage heating is used to increase the inlet temperature of the turbines resulting in increase turbine work. However, interstage heating with a gas cooled reactor has not been found to be practical due to large pressure loss incurred to perform reheating. For liquid-cooled reactors, such as the reference AHTR system considered in this report, reheating is practical and provides a substantial increase in cycle efficiency [13].

To determine the effects interstage cooling on cycle efficiency 1, 2 and 3 intercoolers were added to the basic indirect recuperated Helium and N2/He mixture cycles. The pressure drop through the precooler was set at 20 kPa. With a 1-intercooler layout the intercooler pressure drop was set to 50 kPa. With 2 intercoolers the first intercooler pressure drop was set to 37 kPa and the second intercooler set to a pressure drop of 50 kPa. With a 3-intercooler layout the first, second and third intercooler pressure drops were set to 30, 40 and 50 kPa, respectively. These pressure drops were chosen because they are representative of pressure drops used by a MIT studied on an indirect Helium Brayton cycle with a maximum system pressure of 8 MPa [14].

A base design for each cycle was determined and input into HYSYS. HYSYS was then used to simulate and optimize each cycle.

- **Recuperated Helium Brayton cycle**

The base cycle used in for this study was the indirect Helium cycle and operating conditions used in this section are summarized in Table 2. The efficiency without intercooling was 45.19%. The efficiency with 1,2 and 3 intercoolers was 48.25%, 48.92% and 49.07%, respectively.

Table 2. Cycle conditions for pressure studies.

| Condition | Value |
|---|---|
| Reactor Power | 600 MW |
| Reactor Outlet Temperature | 900 C |
| Turbine Polytropic Efficiency | 92% |
| Compressor Polytropic Efficiency | 90% |
| IHX Effectiveness | 90% |
| Recuperator Effectiveness | 95% |
| IHX Primary Side Pressure Drop | 150 kPa |
| IHX Secondary Side Pressure Drop | 175 kPa |
| Low Temp. Recuperator Hot Side Pressure Drop | 50 kPa |
| Precooler Pressure Drop | 20 kPa |
| Compressor Inlet Temp | 28 C |
| System Pressure | 20 MPa |
| System Pressure Ratio | 2.1 |

- **Recuperated 80% $N_2$ 20% He (by weight) Brayton cycle**

The base cycle used in for this study was the indirect $N_2$/He cycle [15] and conditions used in this section are shown in Table 2. The efficiency without intercooling was 45.29%. The efficiency with 1,2 and 3 intercoolers was 49.39%, 50.19% and 50.47%, respectively.

- **Recuperated Supercritical $CO_2$ Brayton with split flow cycle**

The base design chosen for the supercritical $CO_2$ was developed at MIT [16]. Split flow is an option for improving cycle efficiency when the working fluid is operated near its critical point. Around the critical point the fluid properties vary greatly. To take advantage of this the flow is split and a portion goes to a precooler before entering the compression stage. By compressing around the critical point the compressor work can be significantly reduced.

The model developed at MIT was repeated in HYSYS to ensure consistency between the two models. The MIT model with a 600 MW(t) reactor power and a 700 °C reactor outlet temperature was simulated in HYSYS. The MIT model gave a cycle efficiency of 51.3% and the HYSYS model gave an efficiency of 51.1%. Since the models were comparable the base model was then modified in HYSYS. The MIT design was modified to be an indirect cycle with a reactor outlet temperature of 867 °C. Next the heat flow in the IHX was set to 600MW(t) to be consistent with the amount of power supplied to the PCS. The design parameters for the modified cycle are detailed in Table 3.

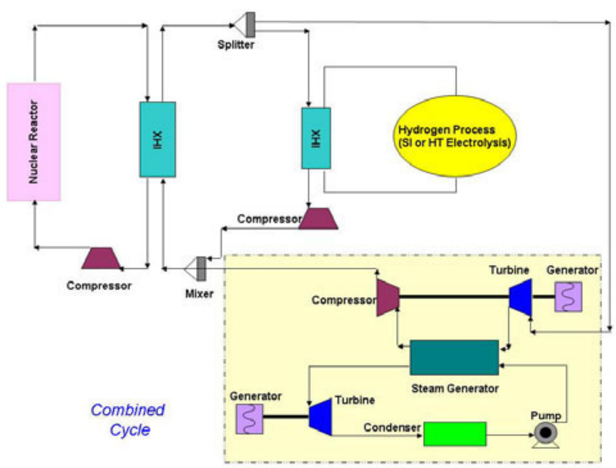
The HYSYS optimized recompression cycle produced a cycle efficiency of 52.09% compared to the 51.1% for the base model. Although this cycle has a slightly higher efficiency, it may not be advantageous from the point of additional capital costs and the potential material problems due to the higher temperatures.

Table 3. Cycle conditions used in $CO_2$ split flow cycle.

| Condition | Value |
|---|---|
| Reactor Power | 600 MW |
| Reactor Outlet Temperature | 900 C |
| IHX Outlet Heat Flow | 600 MW |
| Turbine Polytropic Efficiency | 92% |
| Compressor Polytropic Efficiency | 90% |
| IHX Effectiveness | 90% |
| Recuperator Effectiveness | 95% |

| | |
|---|---|
| High Temp. Recuperator Hot Side Pressure Drop | 140 kPa |
| Low Temp. Recuperator Hot Side Pressure Drop | 50 kPa |
| Precooler Pressure Drop | 50 kPa |
| Compressor Inlet Temp | 31 C |
| System Pressure | 20 MPa |
| System Pressure Ratio | 2.6 |

- **Implication of bottoming cycles**




A steam bottoming cycle can be used to further improve the efficiency of a cycle. The base design studied here was the Framatome cycle [14]. The schematic of this configuration is shown in Figure 6.

Figure 6. A steam bottoming cycle.

The cycle efficiency of the combined cycle produces 44% that did not include the hydrogen generation process. If it is included, the cycle efficiency is about 48%.

One advantage of this configuration is the lower system pressure of 5MPa, which reduces the maximum stress in each component. The mechanical design of the system will be a challenge because the creep rupture strengths of available materials are relatively low for extended operation at 900 °C.

- **Implication of interstage heating and cooling to system layout**

Comparing the results of additional intercoolers as seen in Table 4, after the first intercooling stage is added, additional stages result in much smaller efficiency increases,. This decreasing efficiency gain is due to the additional pressure drop incurred by adding intercoolers. Eventually the efficiency increase from adding an intercooler will be off set by the additional cost of the intercooler. At that point the addition of another intercooler is not feasible.

Table 4. Comparison of cycle implication due to various cycle layouts and intermediate cooling.

| Cycle layout | Cycle Efficiency | Differential Efficiency Gain |
|---|---|---|
| He Indirect no IC | 45.19% | N/A |
| He Indirect 1 IC | 48.25% | 3.06% |
| He Indirect 2 IC | 48.92% | 0.67% |
| He Indirect 3 IC | 49.07% | 0.15% |
| $N_2$/He Indirect no IC | 45.29% | N/A |
| $N_2$/He Indirect 1 IC | 49.39% | 4.10% |
| $N_2$/He Indirect 2 IC | 50.19% | 0.80% |
| $N_2$/He Indirect 3 IC | 50.47 | 0.28 |
| $CO_2$ Split Flow | 52.09 | N/A |
| $N_2$/He Indirect with a Combined Cycle | 49.56 | N/A |

## V. CONCLUSIONS

Among three working fluids studied for the indirect PCS, supercritical $CO_2$ has the highest cycle efficiency due to less compression work caused by higher densities of supercritical CO2 than other fluids used for the indirect cycle. Supercritical CO2 also results in the smallest turbomachinery components.

Helium direct cycle eliminates an IHX and consequently requires the smallest heat transfer area due to the higher heat capacity and thermal conductivity than those of other fluids.

For the final selection of the best working fluid, or fluid mixture, trade-off studies need to be performed for efficiency, capital cost, maintenance cost, the stability of fluids through compressor, potential leakage from PCS, and other relevant issues.

Intercoolers increase the cycle efficiency due to lowering the inlet temperature to the compressor. A single intercooler improves the cycle efficiency by approximately 3 %. Once the first intercooler is used, the second and the third intercooler provide much smaller efficiency increases.

The reheat option was not investigated in this chapter. However, the reheat option needs to be fully investigated for liquid coolants such as molten salts, where the ability to deliver heat with low pumping power allows low-pressure-loss heaters to be used and located close to the turbomachinery.

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REFERENCES

1. IAEA, Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology, IAEA-TECDOC-1198, (Feb. 2001).

2. K. Schleifenheimer, "Steady-State, Transient and Start-up Properties of the AVR Experimental Power Station," Proceedings of a Symposium on the Performance of Nuclear Power Reactor Components. HMSO, London, UK, (1970).

3. R. Gilli, K. Krueger, and W. Dering, "The AVR-Reactor - a Contribution to the Development of the HTR," Transactions of the American Nuclear Society, **Vol. 20**, (1975).

4. E. Zierman, "The AVR Nuclear Power Facility-Progress Report," Nuclear Engineering and Design, **78**, (1984).

5. Z. Wu, D. Lin, and D. Zhong, "The Design Features of the HTR-10," Nuclear Engineering and Design, **218,** (2002).

6. E. C. Verkerk, "Transient Analysis for the High Temperature Pebble-Bed Reactor Coupled to the Energy Conversion System," IAEA TCM 'Safety Related Design and Economic Aspects of High Temperature Gas Cooled Reactors,' Beijing, China, (Nov. 1998).

7. E. C. Verkerk, "Coupling Thermal Hydraulics with Neutronics for Pebble-Bed High Temperature Reactor Calculations," Proc. Int. Conf. On the Physics of Nuclear Science and Technology," Long Island, NY, (Oct. 1998).

8. X. Yan, T. Takizuka, S. Takada, K. Kunitomi, I. Minatsuki, and Y. Mozokami, "Cost and Performance Design Approach for GTHTR300 Power Conversion System," Nuclear Engineering and Design, 226, (2003).

9. H. Saravanamutto, *Gas Turbine Theory*, Pearson Education, 5$^{th}$ Ed., 2006.

10. HYSYS User's Manual V.2.2.2, Aspentech Company, 2001.

11. J. M. Smith and H. C. Van Ness, *Introduction to Chemical Engineering Thermodynamics*, Third Ed., 1975.

12. R.G. Ambrosek and D. J. Utterbeck, "Comparison of Predictive and Experimental Data from Graphite Irradiations in the Advanced Test Reactor Irradiation Test Vehicle, ASME Summer HT Conf., HT2003-40396, Las Vegas, Nevada, July 21-23,2003

13. P. F. Peterson, Multiple-Reheat Brayton Cycles for Nuclear Power Conversion with Molten Salt, Nuclear Technology, vol. 144, December 2003.

14. C. Wang, Design, Analysis and Optimization of the Power Conversion System for the Modular Pebble Bed Reactor System, MIT Ph.D. Thesis, August 31, 2003.

15. B. Copsey, et al., *The Framatome ANP Indirect-Cycle Very High Temperature Reactor*, Proceedings of ICAPP'04, Pittsburgh, PA, June 13-17, 2004.

16. V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, March 10, 2004, MIT-ANP-TR-100.