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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.*

Three configurations of the power conversion unit were demonstrated in this study. A three-shaft design with three turbines and four compressors, a combined cycle with a Brayton top cycle and a Rankine bottoming cycle, and a reheated cycle with three stages of reheat were investigated. An intermediate heat transport loop for transporting process heat to a High Temperature Steam Electrolysis (HTSE) hydrogen production plant was used. Helium, CO_2, and a 80% nitrogen, 20% helium mixture (by weight) were studied to determine the best working fluid in terms cycle efficiency and development cost. In each of these configurations the relative component sizes were estimated for the different working fluids. Parametric studies were carried out on reactor outlet temperature, mass flow, pressure, and turbine cooling. Recommendations on the optimal working fluid for each configuration were made.

Engineering analyses were performed for several configurations of the intermediate heat transport loop that transfers heat from the nuclear reactor to the hydrogen production plant. The analyses evaluated parallel and concentric piping arrangements and two different working fluids, including helium and a liquid salt. The thermal-hydraulic analyses determined the size and insulation requirements for the hot and cold leg pipes in the different configurations. Mechanical analyses were performed to determine hoop stresses and thermal expansion characteristics for the different configurations. Economic analyses were performed to estimate the cost of the various configurations.

I. INTRODUCTION

This paper describes various power conversion unit (PCU) configurations coupled to a HTSE plant by means of an intermediate heat transport loop (IHTL)[1,2] and more details of analyses can be found in References 1 and 2. The key issues that are addressed in this document are:

1. PCU configuration options
2. Coupling of the HTSE to the reactor
3. Working fluids in the PCU and IHTL
4. Efficiency
5. Component sizing
6. IHTL thermal-hydraulic and economic performance
7. IHTL piping mechanical performance

The commercial process code HYSYS[3,4] was used to model three configurations of the PCU coupled to a HTSE plant. A three-shaft design with three turbines and four compressors, a combined cycle with a Brayton top cycle and a Rankine bottoming cycle, and a reheated cycle with three stages of reheat were investigated. An IHTL was used for transporting heat to the HTSE plant. This IHTL was taken from configuration 6 from a report by Davis et al.[5] The HTSE plant was adapted from work by Stoots et al.[6]

Helium, CO_2, and an 80% nitrogen, 20% helium mixture (by weight) were studied to determine the best working fluid in terms cycle efficiency and development cost. Helium is a well understood fluid and has been used in numerous studies pertaining to nuclear power. CO_2 has been slow in developing due to material concerns with the fluid. CO_2 does possess some advantages over helium such as a higher density allowing for smaller velocities than helium for the same pressure drops (Perry et al.[7]). Despite the lower specific heat, the volumetric flow rates are smaller for CO_2 than for a helium cycle generating equivalent power. Therefore, the turbomachinery sizes are smaller for CO_2. Copsey et al.[8] used the nitrogen-helium mixture for the working fluid in a combined cycle. Helium and a liquid salt ($NaBF_4$-NaF) as recommended by Davis et al.[5] were studied in the IHTL.

In each of these configurations relative component sizes were estimated for the different working fluids. The relative size of the turbomachinery was measured by comparing the power input/output of the component. For heat exchangers the volume was computed and compared.

Parametric studies away from the baseline values of the systems were performed to determine the effect of varying conditions in the cycle. This gives some insight into the sensitivity of these cycles to various operating conditions. The parametric studies were carried out on reactor outlet temperature, mass flow in the PCU, pressure in the PCU, and turbine cooling.

Thermal-hydraulic, mechanical, and economic analyses of the IHTL were performed for different piping configurations and working fluids. The piping configurations included parallel and concentric arrangements. Parallel arrangement means separate cold and hot legs while concentric arrangement means hot leg inside and cold leg outside.

II. SYSTEM INTEGRATION

The HTSE plant was coupled to the reactor and the PCU by means of the IHTL. Helium and liquid salt were investigated as working fluids in the IHTL. Figure 1 depicts the HYSYS simulation of the entire plant including a three-shaft PCU and the HTSE plant. The overall efficiency was calculated for the various PCU and IHTL working fluids and PCU configurations. Table 1 summarizes the overall efficiency of the plant for the various configurations and working fluids. The overall efficiency of the facility is ~4-5% lower than the PCU efficiency. This is due to the addition of the pumping power in the IHTL and HTSE.

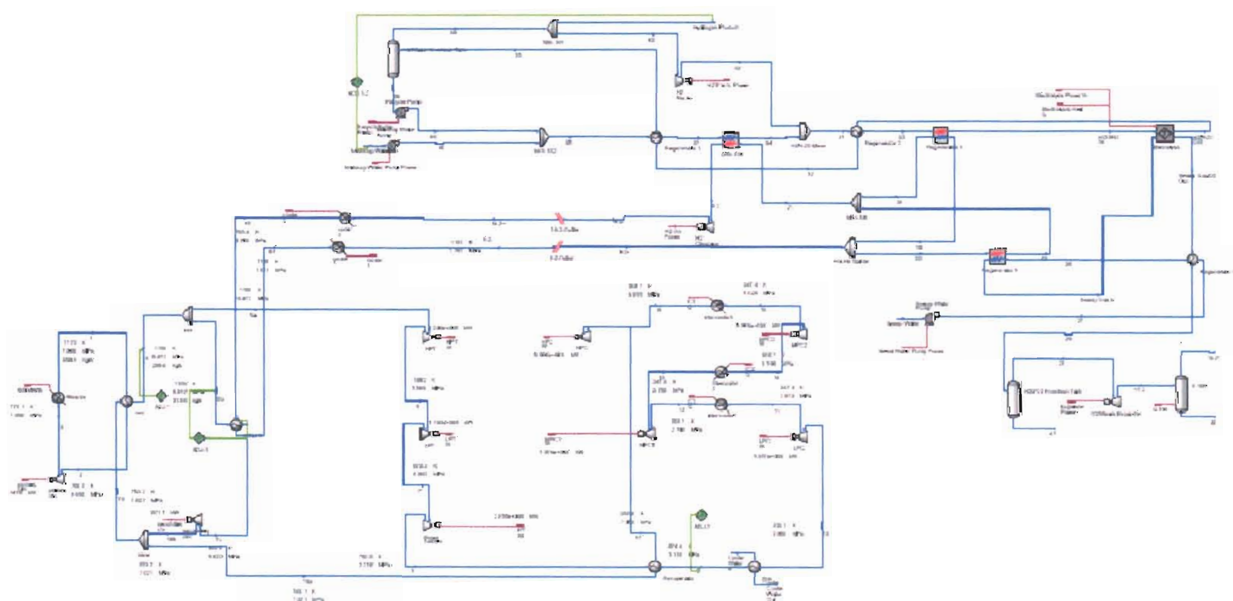

Figure 1. HYSYS model of entire plant with a three-shaft PCU and HTSE plant.

The HTSE facility requires electrical power from the PCU to operate the electrolysis cell. Therefore much of the electrical power produced by the PCU is required by the HTSE. The excess power from the PCU can be used for electrical generation. The amount of excess power available for electrical generation varies for each configuration. Table 2 summarizes the electrical power generation for each configuration. When using a helium working fluid in the IHTL, hydrogen can be produced at a rate of 113.7 kg/hr, while using the liquid salt working fluid produces 96.42 kg/hr of hydrogen. The difference in these values is due to the amount of heat that is being transferred to the HTSE facility by the working fluids. This is due to the assumptions made in the design of the IHTL. The amount of hydrogen produced can be adjusted by increasing the heat flow through the IHTL and increasing the electrical power sent to the electrolysis cell. These are competing values, as the heat transfer to the IHTL increases the power to PCU and electrical generation decreases.

Table 1. Summary of overall plant efficiency for each PCU configuration and IHTL working fluid.

PCU configuration and working fluid	Efficiency (Helium)	Efficiency ($NaBF_4$-NaF)
3-Shaft		
He	44.83	46.02
CO_2	41.09	42.26
N_2-He	44.78	45.94
Combined		
He	43.07	44.40
CO_2	44.35	45.69
N_2-He	42.69	44.02
Reheat		
He	50.80	51.99
CO_2	47.45	48.64
N_2-He	50.52	51.71

Table 2. Excess power available for electrical generation for each PCU configuration and IHTL working fluid.

PCU configuration and working fluid	Electrical Power (Helium)	Electrical Power ($NaBF_4$-NaF)
3-Shaft	MW	MW
He	43.29	84.62
CO_2	20.87	62.07
N_2-He	42.97	84.12
Combined		
He	32.71	74.91
CO_2	40.43	82.63
N_2-He	30.45	72.65
Reheat		
He	79.13	120.45
CO_2	59.03	100.35
N_2-He	77.43	118.75

III. THERMAL HYDRAULIC ANALYSES

Thermal-hydraulic conditions for the IHTL for four separate cases are shown in Figures 2 through 5. Figures 2 and 3 are for a working fluid of helium at loop thermal powers of 50 and 600 MW, respectively. The 600MW_t cases are designed for S-I plants and the entire 600 MW energy can not be applicable for a HTSE plant because the HTSE requires an electricity to operate the HTSE plant. Figures 4 and 5 are for a working fluid of $NaBF_4$-NaF. The minimum loop temperatures shown in Figures 4 and 5 exceed the freezing temperature of $NaBF_4$-NaF by nearly 90 °C, which should provide a reasonable margin for operation. Although the figures show various components of the PCU, only the compressor would actually be required for the 600-MW cases because all of the reactor power was transported to the hydrogen production plant, with none left for electricity production.

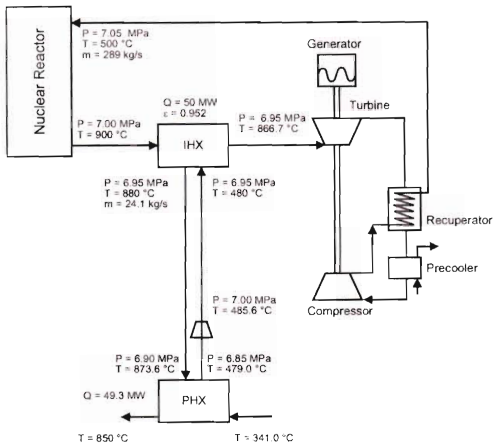

Figure 2. Thermal-hydraulic conditions for a 50-MW loop with helium working fluid.

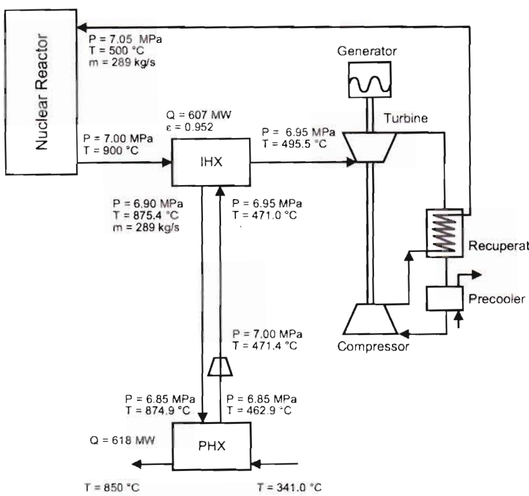

Figure 3. Thermal-hydraulic conditions for a 600-MW loop with helium working fluid.

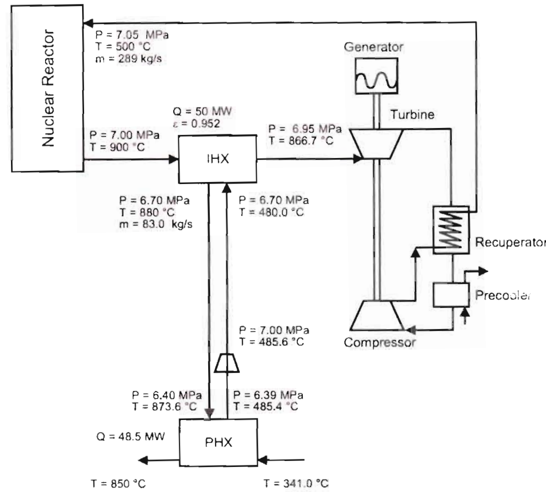

Figure 4. Thermal-hydraulic conditions for a 50-MW loop with $NaBF_4$-NaF working fluid.

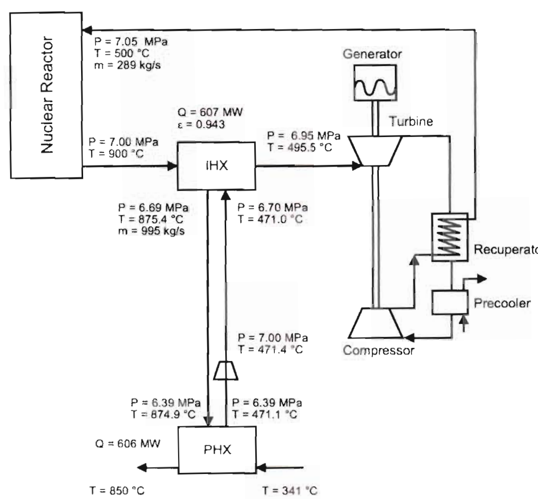

Figure 5. Thermal-hydraulic conditions for a 600-MW loop with $NaBF_4$-NaF working fluid.

Figure 6 shows the calculated inner diameter of the cold leg as a function of separation distance for both the parallel and concentric configurations with helium as the working fluid. The diameter required to provide a given pressure drop increased with separation distance, loop power, and when the configuration changed from parallel to concentric. Increasing the separation distance from 90 to 500 m increased the diameter by

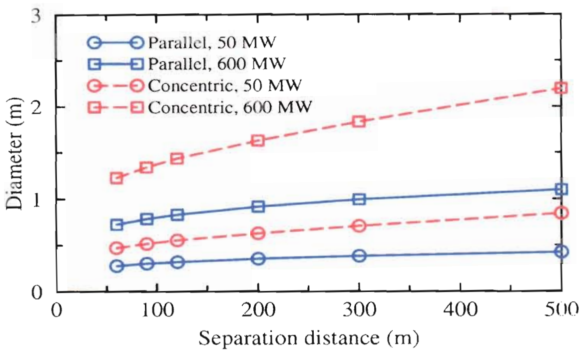

Figure 6. The effect of configuration, power, and separation distance on cold leg diameter with helium as the working fluid.

40% in the parallel configuration and by 60% in the concentric configuration. Increasing the loop power from 50 to 600 MW increased the diameter by a factor of 2.6. The diameter was 70 to 100% larger with the concentric configuration. These results show that all three parameters have a significant effect on the size of the piping and, as will be shown later, on the cost. Although not shown, the diameter of the hot leg was about 10% greater than the diameter of the cold leg in the parallel configuration.

The amount of insulation required to meet the heat loss and metal temperature criteria was a strong function of the separation distance and, to a lesser extent, power. Figure 7 shows the effects of various parameters on the required insulation in the cold leg. Increasing the separation distance from 90 to 500 m increased the insulation thickness by a factor of 20 while increasing the power from 50 to 600 MW caused the thickness to increase by a factor of three. Slightly less insulation was required with the concentric configuration. Although the total heat loss was the same in both configurations, the heat loss was divided between the hot and cold legs in the parallel configuration whereas the entire heat loss passed through the cold leg wall in the concentric configuration. Thus, the heat loss through the cold leg was nearly two times higher in the concentric configuration. The larger heat loss resulted in less insulation and more than compensated for the additional insulation required because of the larger diameter in the concentric configuration. Note that the thickness required for the hot leg in the parallel configuration was more than twice the thickness shown for the cold leg. The amount of insulation required was relatively modest except for the cases at high power and large separation distances. For these cases, more reasonable thicknesses could be achieved by relaxing the heat loss criterion. The heat loss could be increased by a factor of four and still represent only 1% of the 600 MW of loop power.

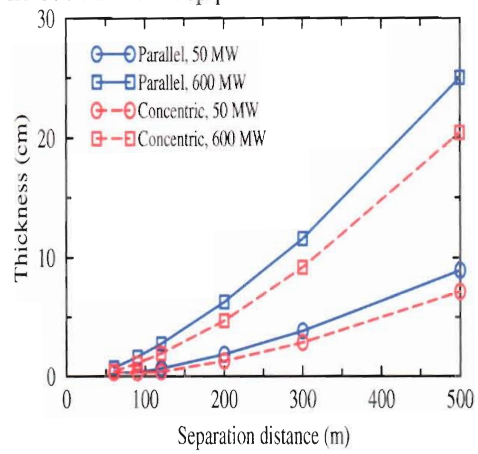

Figure 7. The effect of configuration, power, and separation distance on the cold leg insulation thickness with helium as the working fluid.

IV. MECHANICAL ANALYSES

Simple stress calculations were performed for three configurations of the IHTL piping. The configurations included parallel, concentric and jacketed arrangement.

The stress evaluations were based on the case with helium working fluid, 50-MW of loop power, and a separation distance of 90 m. The evaluations determined the hoop stress arising from the maximum pressures. The evaluations used thin-walled approximations in the metal and neglected the strength of the insulation. The assumed conditions and geometry are summarized in Table 3. In the jacketed configuration, one assumption made was that the pressure in the jacket was half of that of the hot leg. The thickness-to-diameter ratios of the hot leg and the jacket were half of the value used for the legs in the parallel configuration.

Table 3. Stress analysis parameters.

Parameter	Value
Hot / cold leg pressure, MPa	6.95 / 7.0
Metal temperature, °C	355
Metal material	Carbon steel
Parallel configuration:	
Hot / cold leg inner diameter, m	0.330 / 0.304

Hot / cold leg insulation thickness, m	0.0125 / 0.00305
Metal thickness-to-inner-diameter ratio	0.06
Concentric configuration:	
Hot / cold leg inner diameter, m	0.3300 / 0.5186
Hot / cold leg insulation thickness, m	0.00920 / 0.00305
Hot leg metal thickness-to-inner-diameter ratio	0.02
Cold leg metal thickness-to-inner-diameter ratio	0.06
Jacketed configuration:	
Jacket pressure, MPa	3.45
Hot leg inner diameter, m	0.330
Hot leg insulation thickness, m	0.0125
Hot leg metal thickness-to-inner-diameter ratio	0.03
Jacket inner diameter, m	0.400
Jacket metal thickness-to-inner-diameter ratio	0.03

The hoop stress calculated for each configuration was then compared to 132 MPa, the allowable value for Class C carbon steel seamless pipe at 355 °C (ASME[9]). Ratios of the allowable stress to the calculated stress are presented in Table 4. In each case, the allowable stress was slightly more than two times the calculated stress. The difference between the allowable and calculated values provides some margin for increases in stress at elbows and fittings and reductions in strength at welds.

Table 4. Stress analysis results.

Configuration	Allowable stress/ calculated stress
Parallel configuration:	
Hot leg	2.16
Cold leg	2.14
Concentric configuration:	
Cold leg	2.14
Jacketed configuration:	
Hot leg	2.22
Jacket	2.22

The stress evaluation indicates that the design appears feasible if the insulation is effective in reducing the temperature of the metal to 355 °C.

V. CONCLUSIONS

The use of an IHTL and HTSE plant allows the simultaneous production of hydrogen and electricity. With approximately 50 MW of process heat being transferred to the HTSE facility, hydrogen can be produced at a rate of 96.42 to 113.7 kg/hr. The use of a liquid salt in the IHTL increases the overall cycle efficiency by about 1% by lowering the pumping power required in the loop. Some of the electrical power generated by the PCU must be used to power the electrolysis cell, thus decreasing the net electrical output.

The concentric pipe configuration requires the greatest quantity of pipe due to the higher operating temperature of the hot leg metal. The carbon steel and the Inconel are reasonably comparable for the jacketed configuration. The concentric configuration also has disadvantages in terms of installation and inspection.

This pipe stress analysis did not account for any dynamic loads such as earthquake or wind loads, deadweight or supports. Furthermore, spacers may be necessary to maintain the spacing in the concentric and jacketed pipe configurations.

ACKNOWLEDGMENTS

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REFERENCES

1. C. H. Oh, R. B. Barner, C. B. Davis, B. D. Hawkes, and J .D. Morton, Energy Conversion Advanced heat Transport Loop and Power Cycle, INL/EXT-06-11681, August, (2006).

2. C. H. Oh, C. B. Davis, J. Han, R. Barner, S. R. Sherman, R. Vilim, Y. Lee, and W. Lee, HyPEP FY06 Report: Models and Methods, INL/EXT-06-11725, September, (2006).

3. Aspen Technology, *HYSYS Simulation Basis Manual*, www.aspentech.com, (2002).

4. Aspen Technology, *HYSYS Simulation Basis Manual*, www.aspentech.com, (2002).

5. C. B. Davis, C. H. Oh, R. B. Barner, S. R. Sherman, and D. F. Wilson, *Thermal-Hydraulic Analyses of Heat Transfer Fluid Requirements and Characteristics for Coupling a Hydrogen Production Plant to a High-Temperature Nuclear Reactor*, INL/EXT-05-00453, June (2005).

6. C. M. Stoots, J.E. O'Brien, M. G. McKellar, and G. L. Hawkes, *Engineering Process Model for High-Temperature Electrolysis System Performance Evaluation*, AIChE 2005 Annual Meeting, Cincinnati, OH, October 30 – November 4, (2005).

7. R. D. Perry, and J. Maloney, *Perry's Chemical Engineer's Handbook*, Sixth Edition, McGraw-Hill, (1984).

8. B. Copsey, M. Lecomte, G. Brinkmann, A. Capitaine, and N. Deberne, *The Framatome ANP Indirect-Cycle Very High Temperature Reactor*, Proceedings of ICAPP '04, Paper 4201, June (2004).

9. ASME, *ASME Boiler and Pressure Vessel Code*, Section II, Part D (2001 with 2002 Addenda).