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ANL-GenIV-102

Alternate VHTR/HTE Interface for Mitigating Tritium Transport and Structure Creep

Nuclear Engineering Division

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ALTERNATE VHTR/HTE INTERFACE FOR MITIGATING TRITIUM TRANSPORT AND STRUCTURE CREEP

R.B. Vilim

ABSTRACT

High temperature creep in structures at the interface between the nuclear plant and the hydrogen plant and the migration of tritium from the core through structures in the interface are two key challenges for the Very High Temperature Reactor (VHTR) coupled to the High Temperature Electrolysis (HTE) process. The severity of these challenges, however, can be reduced by lowering the temperature at which the interface operates. Preferably this should be accomplished in a way that does not reduce combined plant efficiency and other performance measures. A means for doing so is described in this report. A heat pump is used to raise the temperature of near-waste heat from the PCU to the temperature at which nine-tenths of the HTE process heat is needed. In addition to mitigating tritium transport and creep of structures, structural material commodity costs are reduced and plant efficiency is increased by a couple of percent.

1. INTRODUCTION

The production of hydrogen using nuclear power faces two technical challenges that arise at the interface between the chemical plant and the nuclear plant. At the interface as it is presently envisioned, a heat exchanger transfers heat from the reactor system at a temperature of 850 C and a pressure of several MPa to a process heat loop. The process heat loop transports the heat to the chemical plant over a piping run of at least 100 m in length. Recent work has identified two key technical challenges at the interface. The use of metals as structural materials at these elevated service conditions may limit the lifetime of process heat loop components as a consequence of material creep to significantly less than the standard nuclear plant lifetime of 40 years. One possible solution is the use of ceramic materials but their reliability for heat exchangers application is as yet unproven. The second challenge is the migration of tritium from the reactor core through the process heat loop into the chemical plant. It has been suggested that equilibrium levels of tritium in the primary system combined with the high permeability of metals at high temperature may result in tritium migrating to the chemical plant at levels that may trip NRC limits for non-nuclear systems.[1] Ceramic heat exchangers have the potential to significantly limit tritium transport but again the caveat above applies.

In this report an alternative to the Reference Interface from prior work is investigated for solving these challenges in the Very High Temperature Reactor (VHTR) coupled to the High Temperature Electrolysis plant (HTE). The key to mitigating the heat exchanger and tritium transport problems is to lower the temperature of the process heat delivered to the chemical plant and in a way that does not reduce efficiency of the coupled plant. It appears that this may be achievable and without negative impact on other plant performance measures. The alternative configuration proposed centers on the observation that about nine-tenths of the thermal power input to the HTE plant is used to boil water at the relatively low temperature of 247 C. One notes that optimal efficiency of the combined plant is achieved by properly matching the temperature of available heat sources to the temperature at which heat is required. If a process is supplied with heat at a temperature greater than needed to achieve acceptable heat flux, then an unproductive temperature drop occurs and with it a lost ability to do work. In the reference combined plant design, reactor outlet heat at 850 C is used to supply the 247 C heat requirement described above. A more efficient use of reactor heat is to obtain this heat from a point in the cycle better matched in temperature. Then the HTE plant heat requirements are met without significant loss of work potential and as a result increased efficiency. In the VHTR/HTE plant the required temperature is close to the 130 C temperature at which waste heat is rejected by the PCU.

The Alternate Interface (AI) uses a low-temperature process heat loop in place of the high-temperature loop in the Reference Interface. The loop operates in heat-pump mode taking low-quality heat from the PCU and supplying it to the HTE plant to achieve the reactant phase change referred to above. The remaining one-tenth of the needed HTE process heat superheats reactants to about 800 C. In the Alternate Interface in the absence of a high-temperature process heat loop coming from the nuclear plant this heat is supplied by electrical heaters or hydrogen burners. The pumping power in the low-temperature loop is compared to that in the high-temperature loop. An energy budget for the combined plant is developed to find how efficiency compares against the combined plant with the Reference Interface. Also examined are the effects of the Alternative Interface on combined plant availability, reliability, and maintenance costs and on component longevity. The analyses were performed with the GPASS code. [5]

2. REFERENCE INTERFACE

The Alternate Interface is evaluated by comparing the performance of the combined plant against the same plant with an interface that has been extensively studied in earlier work. The Reference Interface was defined in [2] to serve as a baseline against which different combined plant layouts could be evaluated. The Reference Interface appeared originally as Case 6 of [3]. In the work of [2] the HTE plant specification was expanded upon to include more detailed information for configuration of components and for individual component sizes.

The Reference Interface is shown in overview in Figure 1. In this figure the combined plant appears as three modules: the Primary System, the Power Conversion System, and the High Temperature Electrolysis plant. The lines connecting these three modules represent the interface. Each of these three modules is shown in greater detail in Figures 2 through 4. Note the High-Temperature Process Heat Loop shown in Figure 1. The hot side operates at a temperature of about 850 C and provides a path for tritium passing across the IXH to make its way to the HTE plant.

The performance of the Reference Interface is characterized in [4]. In that work the GPASS/H code was used to determine the full power condition, the combined plant efficiency, and the partial power load schedule. The values of the main operating parameters are summarized in Table I.

Table I Conditions in VHTR/HTE Plant with Reference Interface

Reactor	
Power, MW	600
Outlet Temperature, C	887
Inlet Temperature, C	490
PCU	
Turbine Inlet Temperature, C	870
HP Compressor Outlet Pressure, C	7.4
LP Compressor Outlet Pressure, C	4.1
HTE	
Cell Outlet Temperature, C	970
Cell Pressure, MPa	5.0

Figure 1 Combined Plant with Reference Interface

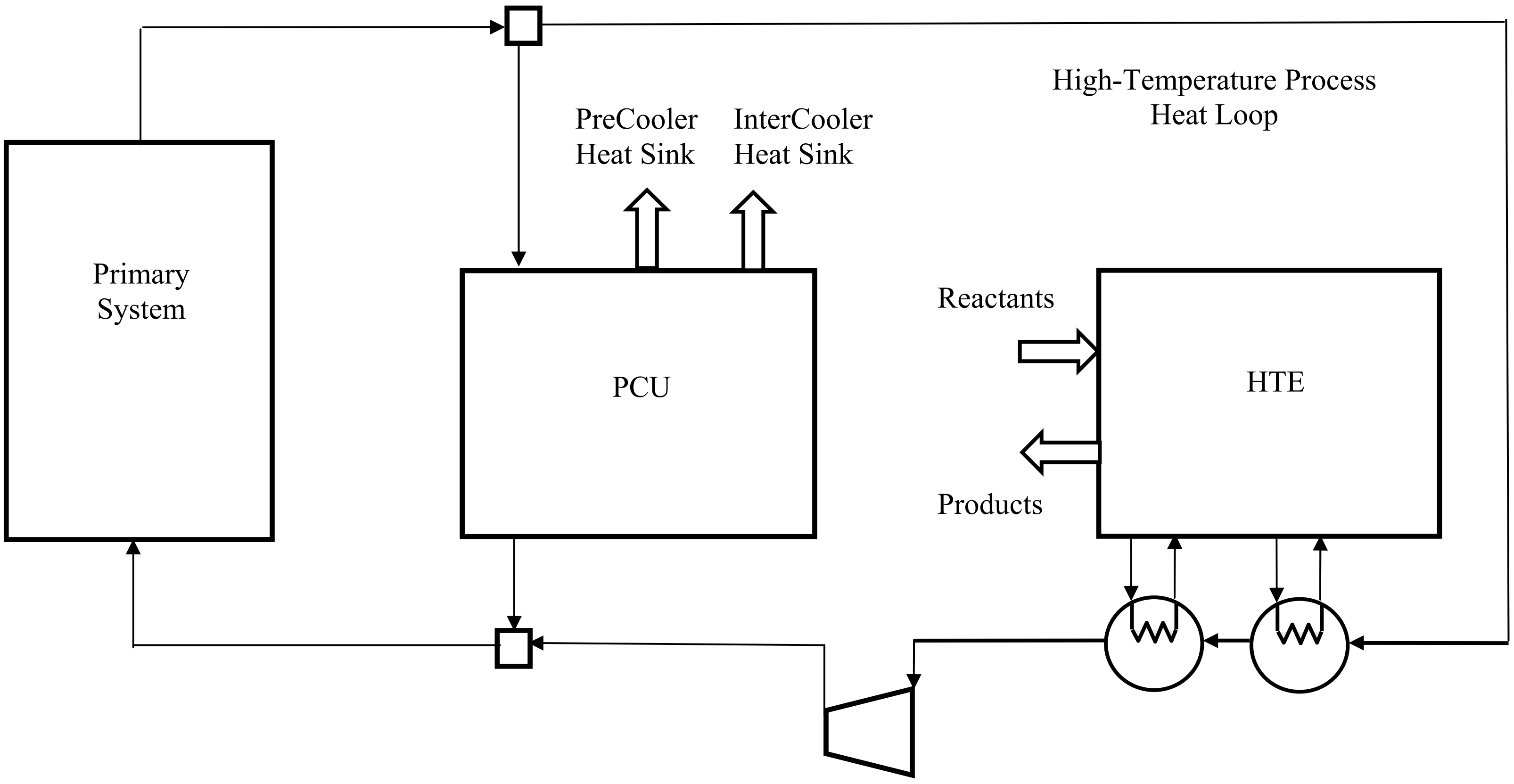


Figure 2 High Temperature Electrolysis Plant

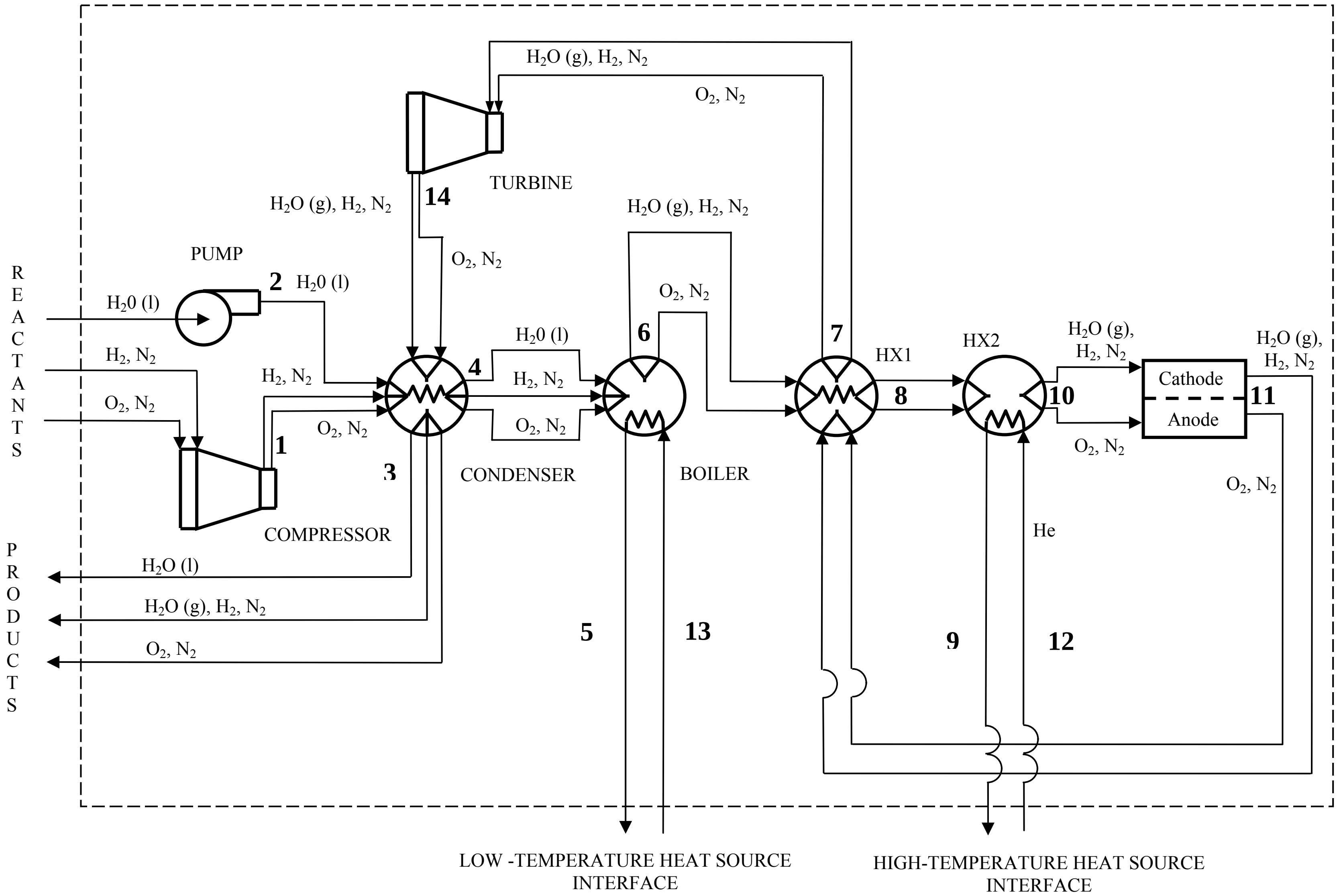


Figure 3 Reference Power Conversion Unit Plant

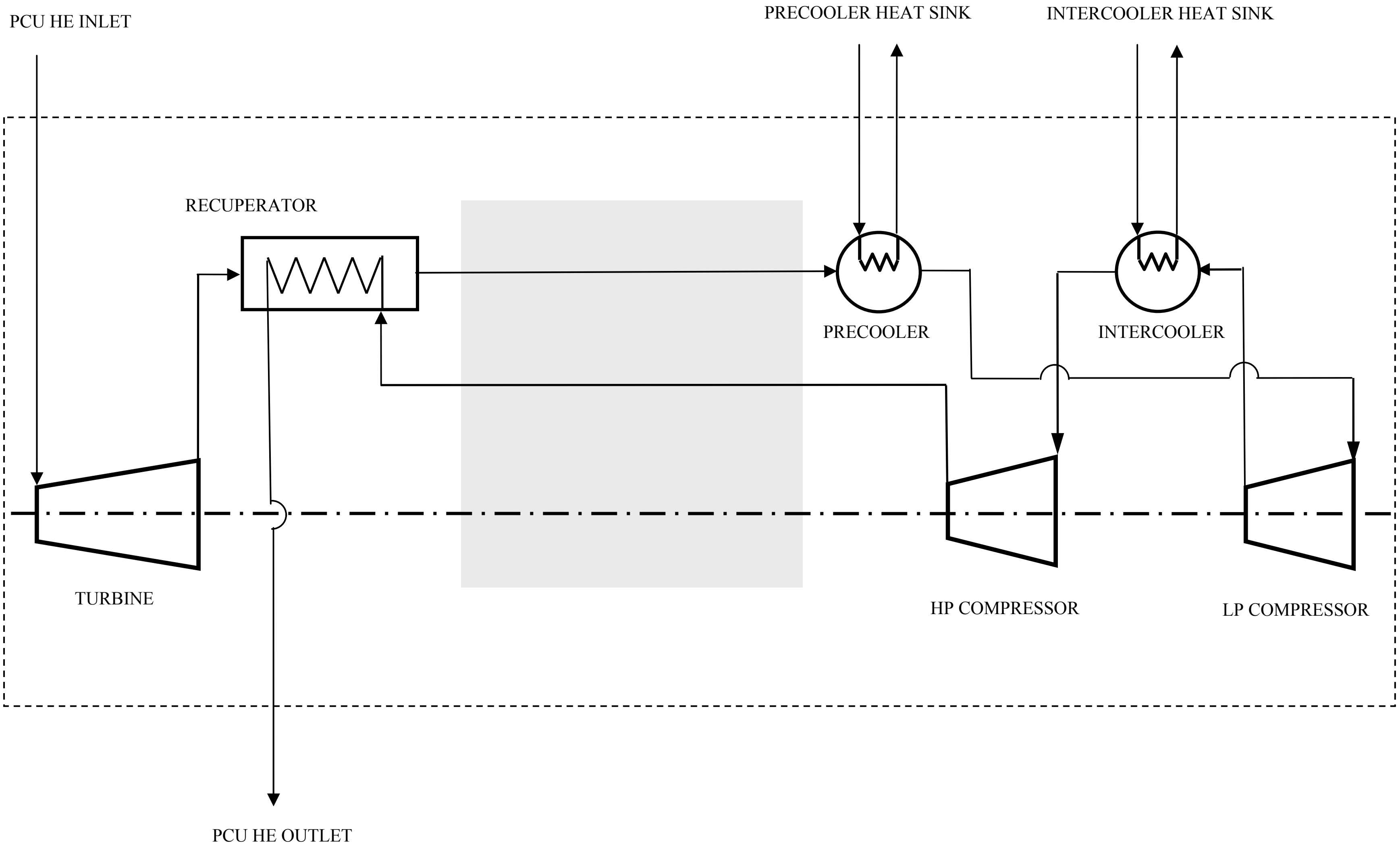
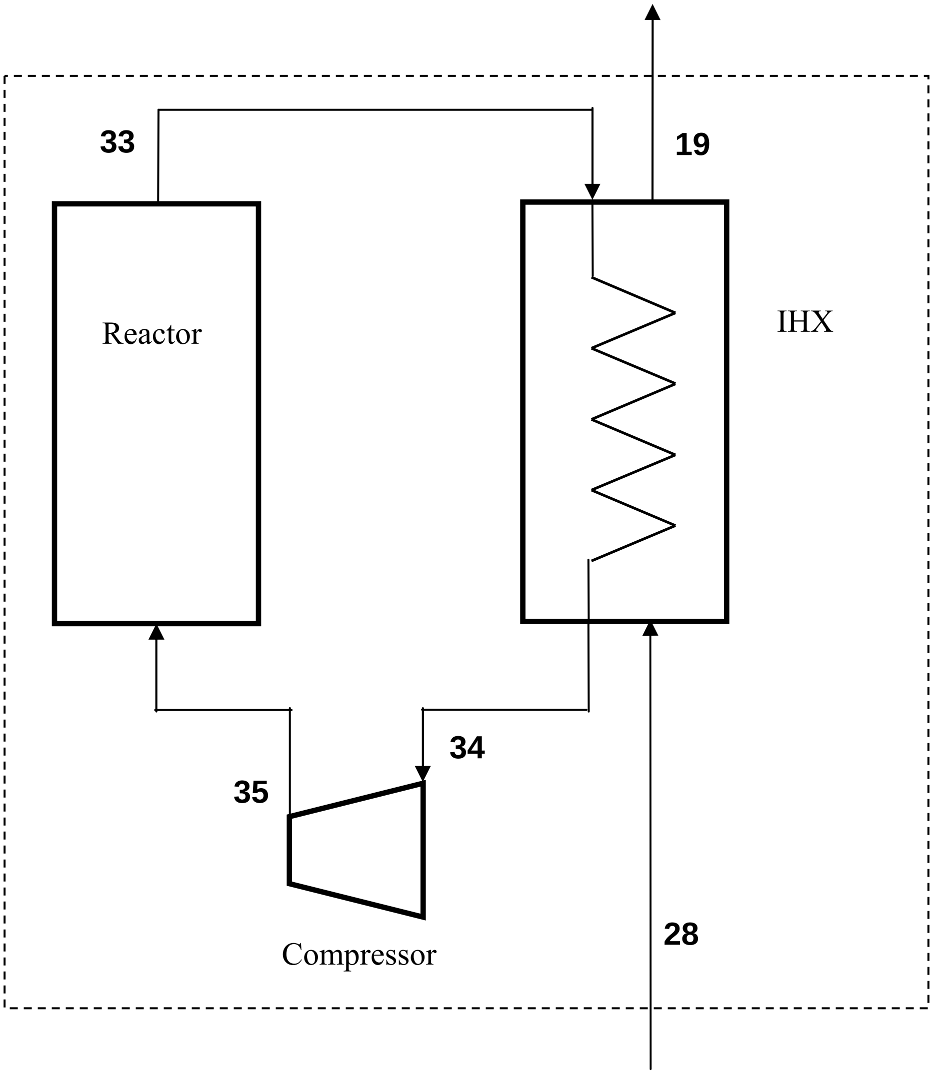


Figure 4 Primary System and Intermediate System Heat Exchanger



3. ALTERNATE INTERFACE

An overview of the Alternate Interface connecting the reactor to the electrolysis plant is shown in Figure 5. The key difference from the Reference Interface of Figure 1 is the absence of the High Temperature Process Heat Loop coupling the electrolysis plant to the reactor. High temperature heat is needed as shown in the figure but it is not obtained from the reactor as described below. There is a Low-Temperature Process Heat Loop linking the electrolysis plant to the reactor. But because it operates at a relatively low temperature diffusion of tritium through structures and creep of structures is significantly reduced from the Reference Interface case.

3.1 Use of PCU Reject Heat

The relatively low temperature heat needed to power the HTE Boiler in the electrolysis plant of Figure 2 is obtained from a point in the PCU where most of the work potential of the working fluid has already been extracted. Figure 6 shows the modification made to the reference plant PCU of Figure 3 to provide the heat. Three new components are needed: a recuperator, a compressor, and a boiler as shown in the shaded region of Figure 6. Their placement and size are such that PCU temperatures outside the shaded region remain essentially unchanged compared to the reference plant. As a consequence to the first order there is minimal disruption to the conditions in the PCU. Then, given that this heat is obtained at only a small amount above reject temperature (80 C), the effect on plant efficiency is minimal.

These three new components operate in combination with the other PCU components as follows. The heat removed by the boiler of Figure 6 is heat that would otherwise be removed by the precooler and intercooler. Since the temperature needed going into the hot side of the boiler is above the helium inlet temperature into these coolers in the reference plant (by about 80 C), the auxiliary recuperator provides the step up in temperature needed. To maintain a constant temperature drop from hot to cold side in the recuperators along their lengths to preserve maximum efficiency, an auxiliary compressor is introduced. It provides a rise in temperature that matches the temperature drop across the auxiliary recuperator. To maintain the same flow rate in the PCU the work done by the HP and LP compressors is reduced by the amount of work done by the auxiliary compressor.

Target temperatures and powers in the PCU were deduced by considering heat transfer and work in the new components of Figure 6 and the goal of keeping temperatures in components outside the shaded region the same as in the reference plant. It was determined in a separate calculation below that a temperature of about 170 C is needed on the cold two-phase side of the boiler. Assuming a film temperature drop of 10 C on the two-phase side, a tube radial temperature drop of 20 C, and a temperature drop from inlet to outlet on the helium side of 20 C, the inlet temperature on the hot side of the boiler should be 220 C. The drop from inlet to outlet on the hot side is obtained from an energy balance. Having established the boiler hot-side temperatures the conditions in the auxiliary recuperator and compressor follow from the goal of keeping all other conditions the same as in the reference plant and in keeping the radial temperature drop along the recuperators constant.

3.2 Low-Temperature Process Heat Transport Loop

Figure 7 shows the process heat loop for transporting heat from the cold side of the PCU boiler to the hot side of the HTE boiler. This loop operates as a heat pump transferring heat from a cold source to a hot sink. Heat transfer with phase change is used at both the source and sink to achieve high heat fluxes and, hence, compact heat exchangers. A key question is the mechanical power consumption of the compressor and how it compares to the overall heat transfer rate. The compressor serves to boost the temperature of the near-waste heat and to circulate the fluid in the loop. The heat transported from the He/H_2O boiler is essentially low-cost heat as its work potential is small. It is conceivable that an efficiency gain relative to the reference plant might

Figure 5 Combined Plant with Alternate Interface

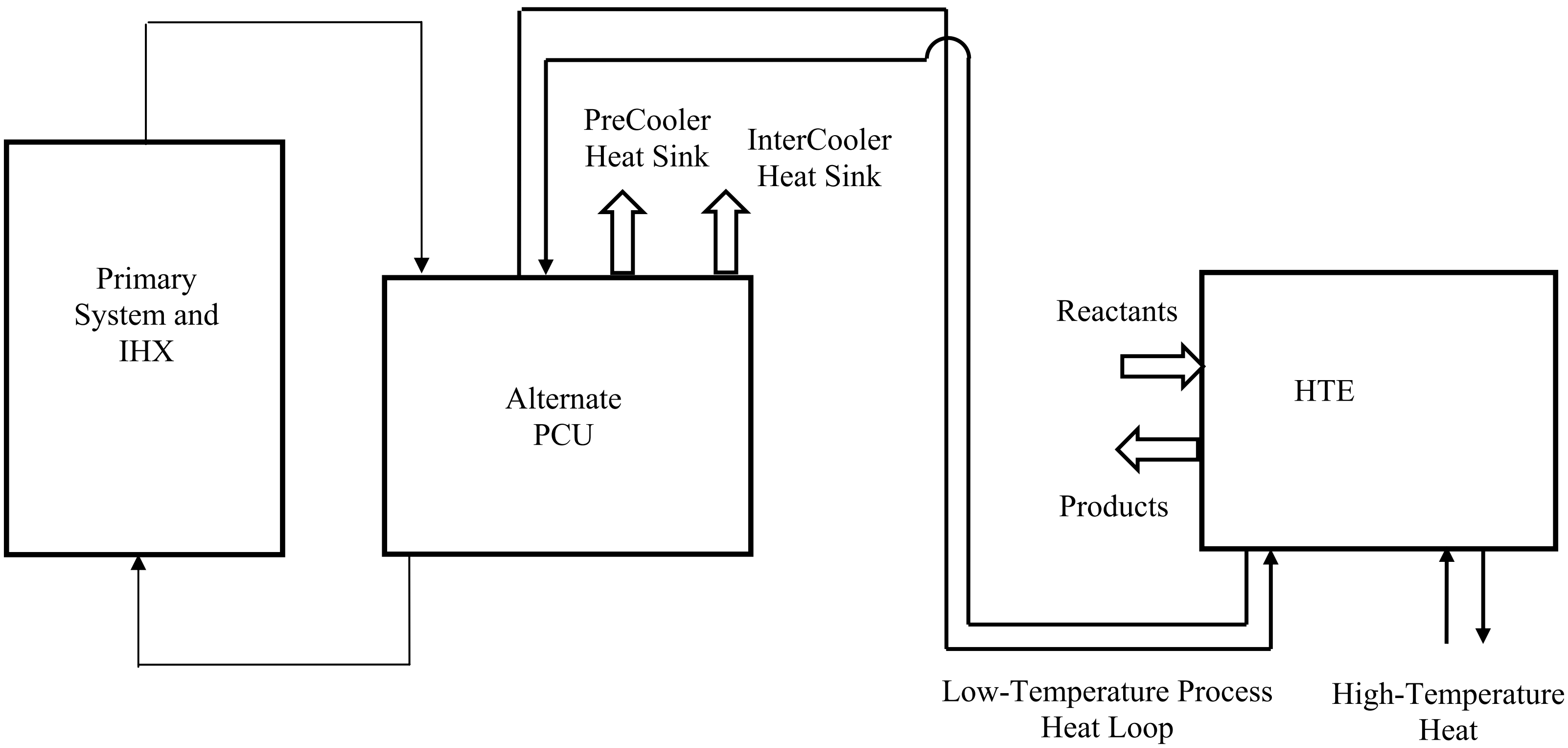


Figure 6 Alternate Power Conversion Unit Plant

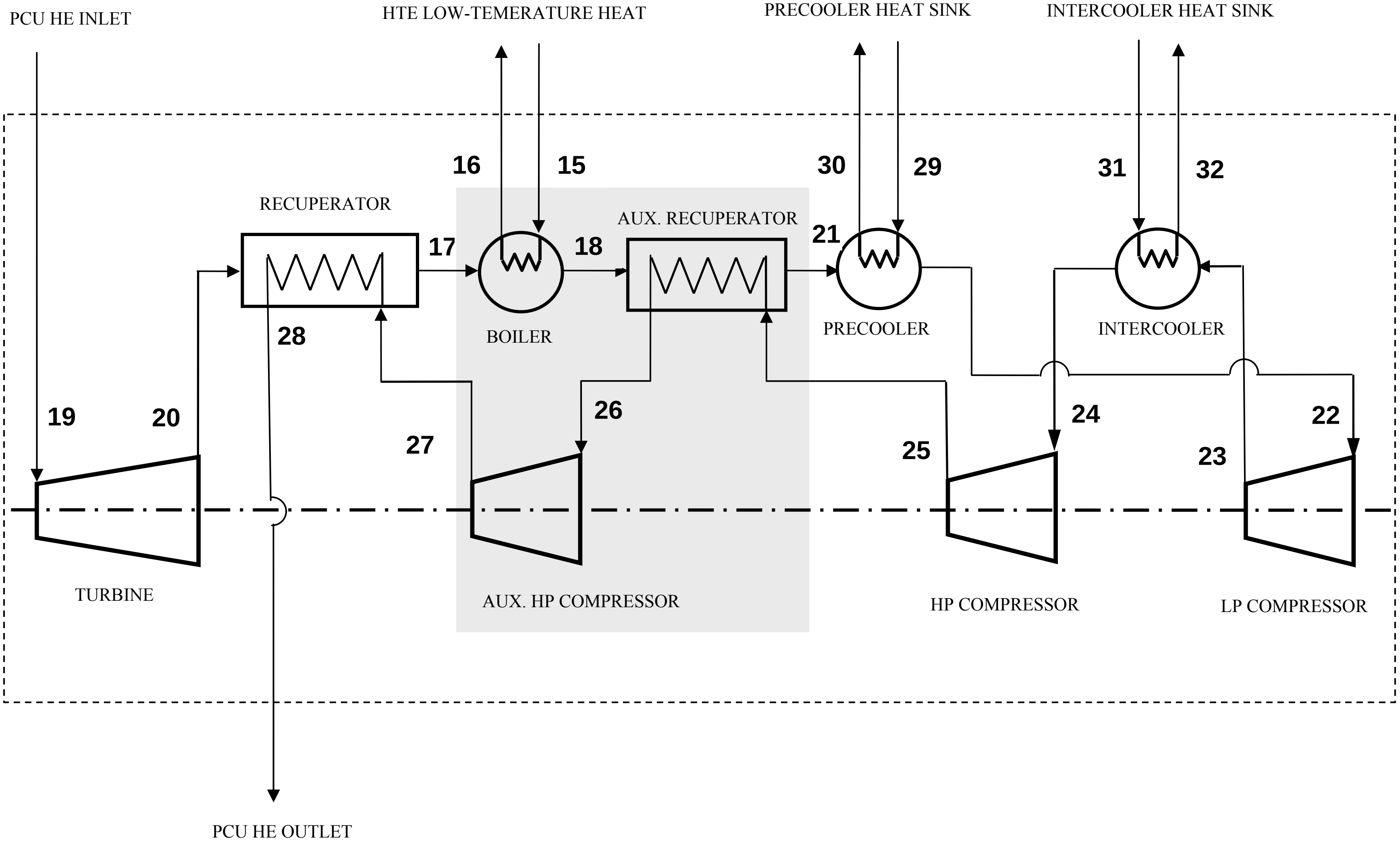
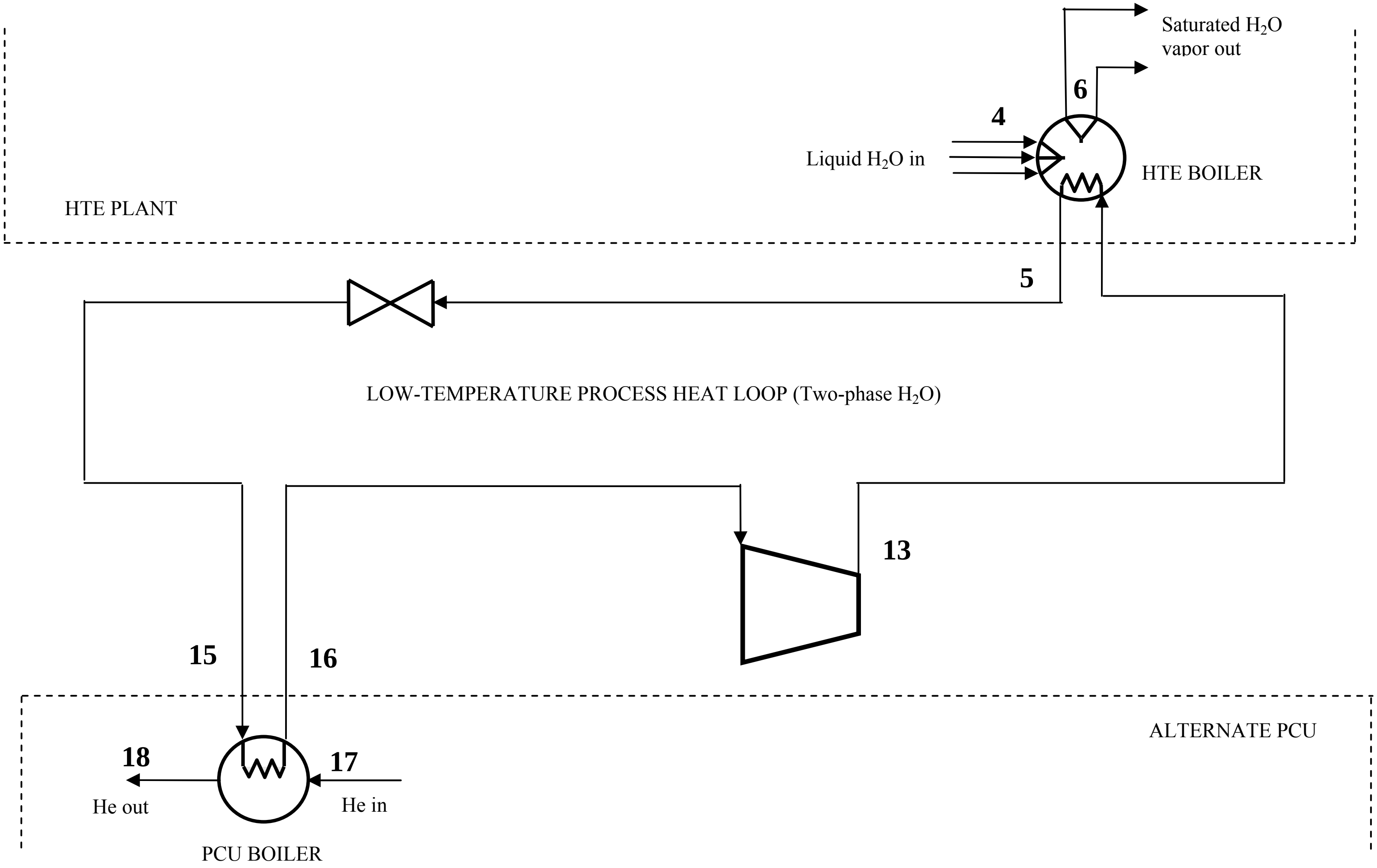


Figure 7 Alternate Interface



be achieved if the power input to the compressor can be limited to a small fraction of the heat transported. Scoping calculations to estimate the compressor power are described below.

The conditions in the low-temperature process heat loop such that it transfers the requisite amount of heat and within a narrow temperature range were obtained from consideration of the following principles. The loop heat transfer fluid is water, selected mainly for its heat transfer properties in the temperature range of interest. In the two-phase regime very high heat fluxes can be obtained with minimal temperature change. On the cold-side of the PCU boiler water is assumed to exist as a two-phase mixture at a temperature of 160 C (see above) and, hence a pressure of 0.6 MPa. A low quality two-phase mixture enters the cold aide and higher quality mixture exits. The reverse is arranged for at the HTE boiler. The goal is for a saturation temperature of 247 C on the cold side of the boiler, the same value as is present in the reference plant. Given a film temperature drop of 10 C on both sides of the HTE boiler and a tube radial temperature drop of 20 C, a saturation temperature of 286 C is needed on the hot side which corresponds to a pressure of 7.0 MPa.

Two variations on the loop just described were evaluated using the heat pump representation shown in Figure 8. First the loop is operated so the fluid leaving the compressor is saturated vapor. In practice this design would require a pump and a compressor operating in parallel. The inlet two-phase mixture would be separated into liquid and vapor streams, both streams would be compressed in a manner such that the outlet streams combined to give saturated vapor. In the second operating variation of the loop the compressor inlet is saturated vapor while the outlet is superheated vapor. Both loops analyzed with the goal of estimating compressor power.

3.2.1 Loop Conditions: Saturated-Vapor Compressor Outlet

The energy requirements and the operating conditions of the heat transport loop of Figure 8 were estimated under the assumption that the compressor operates to deliver saturated vapor at the outlet of the compressor. This stream feeds the hot side of the HTE boiler. Pressure drop through components is ignored in the analysis. It is assumed the loop operates at two pressures, the low side to the left of the compressor and valve and the high side to the right. On the high side saturation conditions are designated by the subscript *H* and on the low side by the subscript *L*.

The conditions in the loop at the full power condition were computed using the thermodynamic model in Section A.1 of Appendix A. The results are shown in Table II. Note that the saturation temperatures and loop power are boundary conditions whose values were selected based on the discussion above. The compressor shaft mechanical power is 13.6 MW and compares with a loop heat transport power of 43.3 MWt. The shaft power needs to overcome frictional losses is not included but it is shown below that the value is insignificant compared to the compression power.

3.2.2 Loop Conditions: Saturated-Vapor Compressor Inlet

Operation of the loop with saturated conditions at the compressor outlet as above implies two-phase conditions at the inlet and the consequent need for a steam separator and an

Figure 8 Heat Pump Representation of Low-Temperature Process Heat Loop

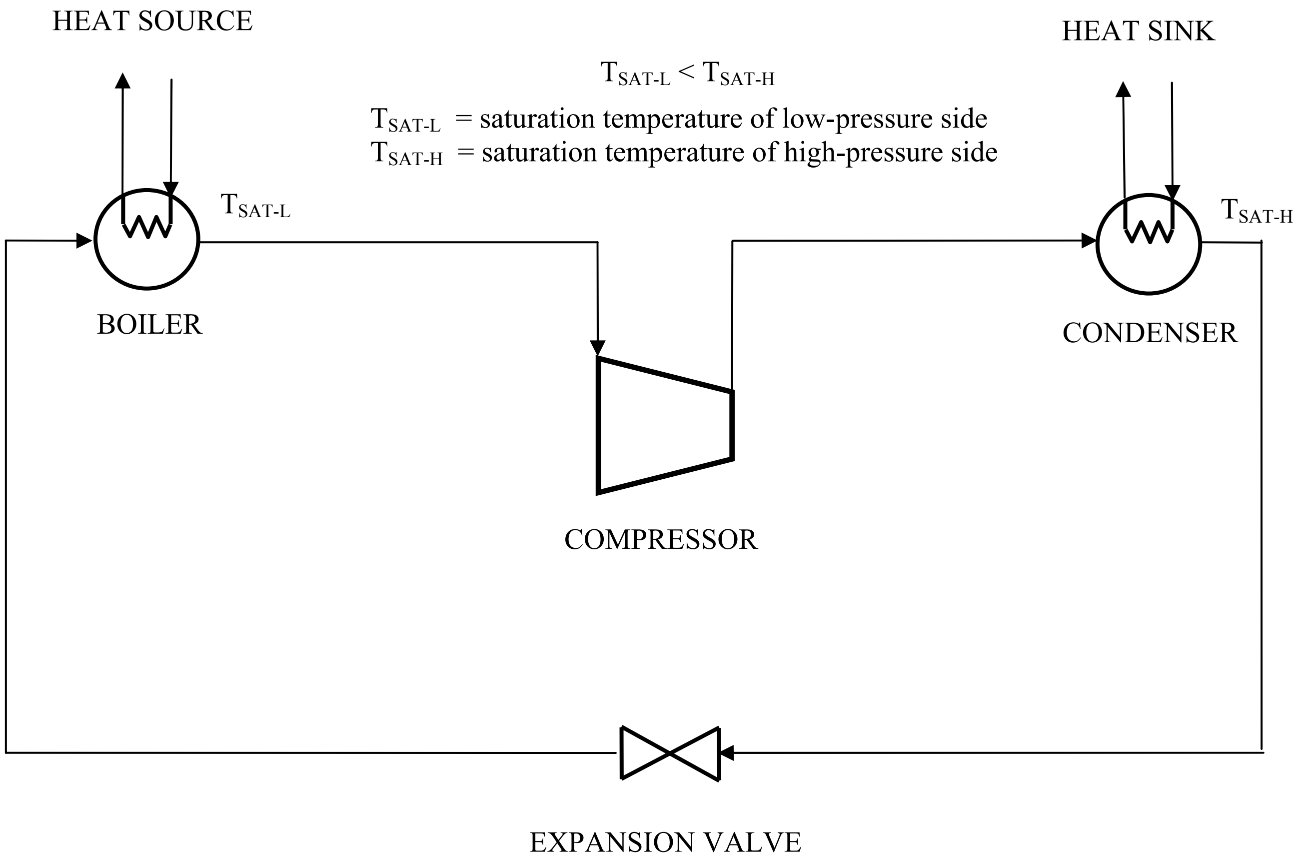


Table II Low-Temperature Process Heat Loop: Saturated-Vapor Compressor Outlet

		PCU Boiler	Compressor	HTE Boiler	Valve
Power (MW)	Hot Side	29.7	13.6	43.3	-
	Cold Side	29.7		43.3	
Outlet Temperature (°C)	Hot Side	-	286	286	160
	Cold Side	160		-	
Outlet Pressure (MPa)	Hot Side	-	7.0	7.0	0.62
	Cold Side	0.62		-	
Mass Flow Rate (kg/s)	Hot Side	-	28.8	28.8	28.8
	Cold Side	28.8		-	
Outlet Quality	-	0.780	1.0	0	0.284

incompressible pump in addition to a compressor. A potentially more attractive option from the standpoint of equipment count is to present saturated vapor at the compressor inlet to obtain superheated conditions at the exit of the compressor. In this case only the compressor is needed to take the fluid from the low to high pressure condition.

The conditions in the loop at the full power condition were computed using the thermodynamic model in Section A.2 of Appendix A. The results are shown in Table III. Note that the

Table III Low-Temperature Process Heat Loop: Saturated-Vapor Compressor Inlet

		PCU Boiler	Compressor	HTE Boiler	Valve
Power (MW)	Hot Side	31.5	11.7	43.2	-
	Cold Side	31.5		43.2	
Outlet Temperature (°C)	Hot Side	-	510	286	160
	Cold Side	160		-	
Outlet Pressure (MPa)	Hot Side	-	7.0	7.0	0.62
	Cold Side	0.62		-	
Mass Flow Rate (kg/s)	Hot Side	-	21.3	21.3	21.3
	Cold Side	21.3		-	
Outlet Quality	-	1.0	superheat	0	0.291

saturation temperatures and loop power are boundary conditions whose values were selected based on the discussion above. The compressor shaft mechanical power is 11.7 MW and compares with a loop heat transport power of 43.2 MWt. The shaft power needs to overcome frictional losses is not included but it is shown below that the value is insignificant compared to the compression power. This option of saturated vapor inlet rather than outlet conditions requires less compressor power. Combined with the reduced equipment count this makes it the preferred option.

3.2.3 Loop Pumping Power

In addition to the shaft power needed to raise the water heat transfer medium from the low to high loop pressure, additional compressor power is needed to overcome frictional pressure-drop around the loop. The power associated with this loss has been compared with that of the high-temperature process loop in the reference design. To understand the role of the different heat transport fluid – water in the alternate design versus helium in the reference design – the pumping power is expressed as a fraction of the pumping power per unit thermal power transported. This permits a consistent comparison between the two loops even if they differ in total thermal power transported.

The pumping power for a water-based versus helium-based loop was calculated at the full power condition using the thermodynamic model of Appendix B. The fluid properties in the respective loops are shown in Table IV. These data were used to calculate the friction loss power per unit megawatt of thermal power transported for the water-based loop as a fraction of the same in the helium-based loop. The calculation was performed using Eq. (23). The result in Table V shows that the power in the water loop is insignificant to the power in the helium loop. In the helium loop the circulating power needed is about 7MWe or 14 MWt out of a reactor thermal capacity of 600 MWt. Thus an advantage of a water-based loop is that the pumping power to overcome frictional losses is significantly less and results in an efficiency increase.

3.3 HTE Reactant Super-Heating

By eliminating the high-temperature process heat loop one eliminates the source in the reference design of the relatively small thermal power (approximately 7 MWt) used to pre-heat reactants before they enter the electrolytic cell. In considering alternative means for supplying this power it is important to realize that alternative means can be used to address an issue unrelated to tritium transport or structure creep. The developers of the High Temperature Electrolysis cycle at INL have cited electrolytic cell temperature change over time as a factor in limiting cell lifetime. Temperature variation during operation has been shown in experiments to accelerate degradation in cell performance. An important goal then is to operate electrolytic cell so that temperature remains unchanged, even during reactor shutdown. Clearly, the high-temperature process heat loop alone cannot provide this capability. Other means such as electrical heaters or combustion of hydrogen are needed. Thus, whether the high-temperature loop is present or not, a final design will require some back-up means for heating reactants. In the alternate plant configuration proposed in this work we assume some combination of electric heaters and hydrogen burners.

Table IV Properties of Fluids in Process Heat Loops

Property	High-Temperature Helium Loop		Low-Temperature Water Loop	
	1.7 MPa, 850 C (supply line)	1.7 MPa, 525 C (return line)	7.0 MPa, 500 C. vapor (supply line)	0.62 MPa sat. liquid (return line)
ρ [kg/m^3]	0.73	1.0	21	909
μ [Pa-s]	47e-06	40e-06	29e-06	1070e-06

Table V Friction Pumping Power in Low-Temperature Process Heat Loops. Normalized to High-Temperature Process Heat Loop

Eq. (23)	Supply Line	Return Line
$\dfrac{\left.\dfrac{\Delta P\, w}{Q\, \rho}\right\|_{H_2O}}{\left.\dfrac{\Delta P\, w}{Q\, \rho}\right\|_{He}}$	$(29/47)^{0.2}(0.73/21)^2$ = 1.1e0-3 *	$(1070/40)^{0.2}(1.0/909)^2$ = 2e-06 *

* Assumes $w_{He} = w_{H2O}$ and $Q_{He} = Q_{H2O}$. Error introduced is less then 25 percent

4. AT-POWER OPERATION

The performance of the coupled plant with the Alternate Interface is compared with that of the Reference Interface. Reactor power and outlet temperature were held constant to allow for a consistent comparison. Similarly, the conditions in the HTE plant were maintained the same. The conditions in the combined plant for the Reference Interface are given in [4]. The Alternate Interface is shown in Figure 7. By following the number labels on this figure one sees the exact manner by which the HTE plant of Figure 2 and the PCU of Figure 6 are coupled together. The at-power operating conditions of the VHTR/HTE with the Alternate Interface were estimated using the Gas Plant Analyzer and System Simulator (GPASS) code. At full power one is interested in knowing the efficiency of the combined plant and the temperatures at the interface. At partial power one is interested in how temperatures change with load.

4.1 Full Power

The temperatures and pressures in the low-temperature process heat loop of the Alternate Interface are compared in Table VI with those in the high-temperature process heat loop of the Reference Interface. One sees that for the heat exchanger coupling the process heat loop to the source of heat in the nuclear plant the temperatures have been significantly reduced. They have dropped on average from 800 C to 200 C. The reduction decreases the diffusion rate of tritium through the heat exchanger heat transfer surfaces by about a factor of 100. One also sees that all temperatures in the low-temperature loop are below 500 C. As a consequence more

Table VI Comparison of Conditions in Main Process Heat Loops

Condition	Source Heat Exchanger		Sink Heat Exchanger	
	RI [6] (HTLHX)	AI (PCU Boiler)	RI [6] (HTE Boiler)	AI (HTE Boiler)
Temperature, C				
Hot side in	870	231	488	480
Hot side out	611	214	332	286
Cold side in	515	160	184	184
Cold side out	849	179	247	247
Pressure, MPa				
Hot side	7.2	2.6	1.8	7.0
Cold side	1.8	0.6	5.0	5.0

economical steels can be used in place of those alloys needed in the case of the high-temperature loop that operates at 850 C.

The Alternate Interface still requires a high-temperature heat source to power the heat exchanger HX2 in Figure 2. However, this heat source is now envisioned to be electrical heaters or a hydrogen or natural gas combustor in place of reactor heat. The link to the reactor has been broken allowing for improved temperature control and limiting HX2 to a role as an accident initiator in the chemical plant rather than the combined plant.

The efficiency of the plant with the Alternate Interface is at least one and a half percent higher. The increase is a consequence of better matching of heat source temperature to HTE plant heat requirements. The power sources and sinks that combine to determine the overall efficiency are shown in Table VII. It is noted that substituting combustion of a synthetic organic created from the plant hydrogen stream in place of electric heating might raise the efficiency of the Alternate Interface plant another one percent.

4.2 Control System

A principle objective in developing a control strategy for partial-load operation is to maintain temperatures constant with power over the normal-operation power range, particularly hot-end temperatures. Another consideration is that peak efficiency should by design occur at full power since the plant is to operate there for the largest fraction of life. While partial-load efficiency is important, maintaining constant temperatures over load at the hot end is probably more important since material capabilities at 900 C are a limiting factor in plant lifetime. The focus of the control strategy in this work was therefore on maintaining constant hot-end temperatures.

Partial power operation takes place over a continuum and is constrained by the *load schedule*. The load schedule specifies the value of each process variable as a function of plant power. Good operability as characterized by minimal thermal stresses during power change is achieved by developing a load schedule that maintains temperatures constant with respect to load at the hottest points in the plant (e.g. reactor outlet).

Table VII Summary of Power and Efficiency by Interface Type. Powers in MWt.

	Plant Interface	
	Reference	Alternate
Reactor Primary System		
Primary Compressor	-7.0	-8.1
Power Conversion Unit and Intermediate System		
Turbine (PCU)	+534	+576
HP Compressor (PCU)	-126	-130
LP Compressor (PCU)	-127	-105
Aux. HP Compressor (PCU)	n.a.	-36
Intermediate System Compressor	-0.9	n.a.
Process Heat Loop		
Process Heat Loop Compressor	-7.0	-12
High Temperature Electrolysis Plant		
Cell Electrical Power	-288	unchanged
Electrical Heating of Reactants	.n.a.	-13.6[b]
Turbine (HTE)	+11.5	unchanged
Other Pumps and Compressors	< 0.1	unchanged
Hydrogen LHV	+271[a]	unchanged
Q_{net} (sum of above)	+261	+271
Combined Plant Efficiency, $\eta = \frac{Q_{net}}{Q_{reactor}}$	$\frac{261}{594} = 0.439$	$\frac{271}{600} = 0.452$

[a] 2.26 kg/s*120.1 MJoules/kg [b] Assumes electric generation efficiency of 0.5

The control strategy developed in this work makes use of the principle that the temperature change from inlet to outlet in a heat exchanger remains constant when the mass flow rate and power are varied in the same proportion. This is true for ideal-like gases such as helium, hydrogen, oxygen, and nitrogen and for the liquid and gas phases of water. It is not true, however, for water when there is a phase change.

In the HTE plant and the process heat loop that connects it to the nuclear plant there is a pump or compressor in each flow circuit providing the capability to independently vary mass flow rate in each circuit as the power in heat exchangers varies (to the first order heat exchanger power varies linearly with hydrogen production rate). This provides significant operational flexibility to control temperature drops across heat exchangers. In the electrolytic cell the control system maintains constant current density as hydrogen production rate is varied. Then ohmic heating is proportional to mass flowrate and the cell temperature rise from inlet to outlet remains constant. Constant current density can be achieved by maintaining constant active cell area per unit hydrogen production (i.e operate fewer cells as production rate decreases).

In the PCU and primary system, however, there is only one compressor to manage mass flow rate while there are several different circuits. To achieve the desired control of helium mass flow rate compressor control provides little flexibility. Rather inventory control is used to obtain flow rate proportional to heat exchanger power. Because density is proportional to pressure for fixed temperature, by varying pressure and maintaining constant speed turbomachinery, gas velocity remains constant and mass flow rate (proportional to the product of density and velocity) is linear with pressure. Thus, pressure is manipulated through coolant mass inventory so that it is proportional to heat exchanger power so that in turn mass flow rate is proportional to heat exchanger power. Results obtained for this control scheme are described below.

The load schedule as presented gives process variables in terms of fraction of full power hydrogen production rate. All controlling process variables (i.e. forcing functions) are expressed as a function of fraction of full power hydrogen production rate which is taken as the independent variable (or equivalently, electrolyzer electrical current where it has been assumed all current goes to decompose water). The following controlling process variables were selected: reactor power, mass flow rates, and the electrolyzer current. Other sets of variables could be used but the above set is appealing based on the discussion above. Each of these forcing functions was linearly ramped from its full power value at one end to a value of 60 percent of this at the other end. Hence, the load schedule covers the range of operation from 60 to 100 percent of the full power hydrogen production rate.

4.3 Partial Power

The load schedule performance is assessed in terms of how well temperatures on the hot side of the combined plant are maintained constant. Also of interest are the pressures on the helium side for assessment of creep under pressure load. The pressures in the HTSE plant were maintained at 5 MPa over the load schedule from the point downstream of where the reactant water is fed in up to the point where the products enter the pressure-work recovery turbine.

The end results appear in Figures 9 through 11. The first figure shows temperatures in the VHTR plant. The reactor outlet temperature varies by approximately 130 C over the load range, perhaps larger than desirable. This change can be reduced by modifying how the primary system inventory changes with reactor power. The second figure shows temperatures in the HTE plant. The electrolytic cell inlet and outlet temperatures are essentially constant which is important to achieve maximum cell life. Helium loop pressures are shown in Figure 11. Pressure is to a first order proportional to hydrogen production rate, a consequence of inventory control. Also shown is the pressure out of the low-temperature process heat loop compressor. This value is maintained constant to obtain a near-constant saturation pressure on the cold side of the HTE boiler.

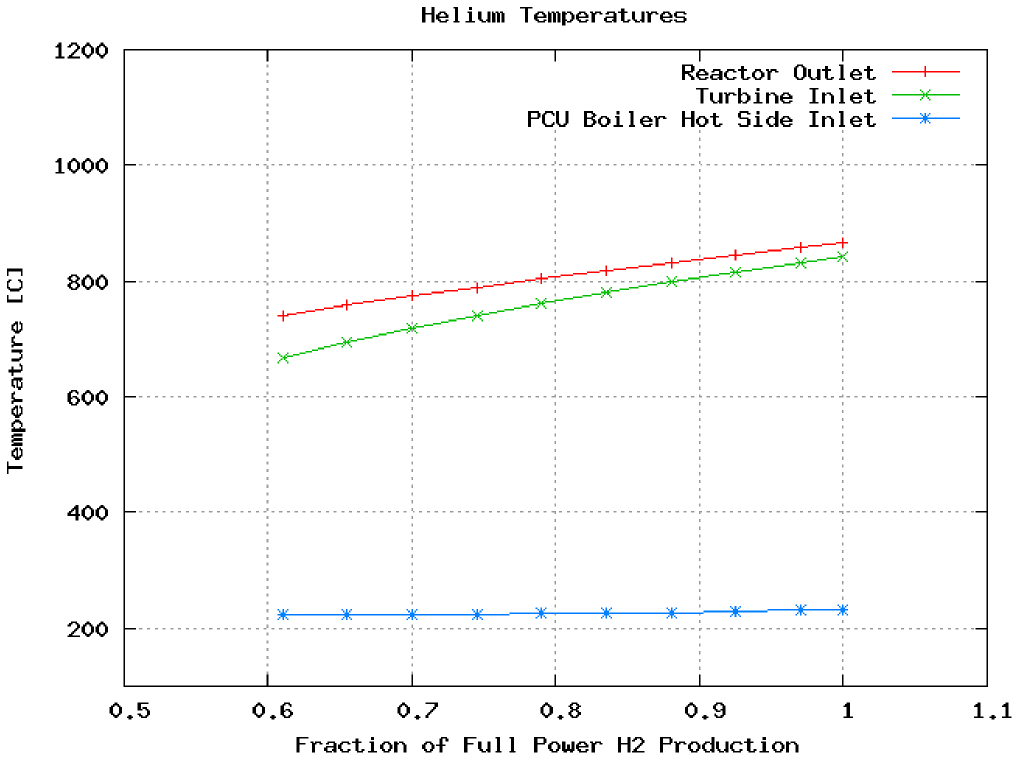


Figure 9 Partial Load Helium Temperatures for Alternate Interface

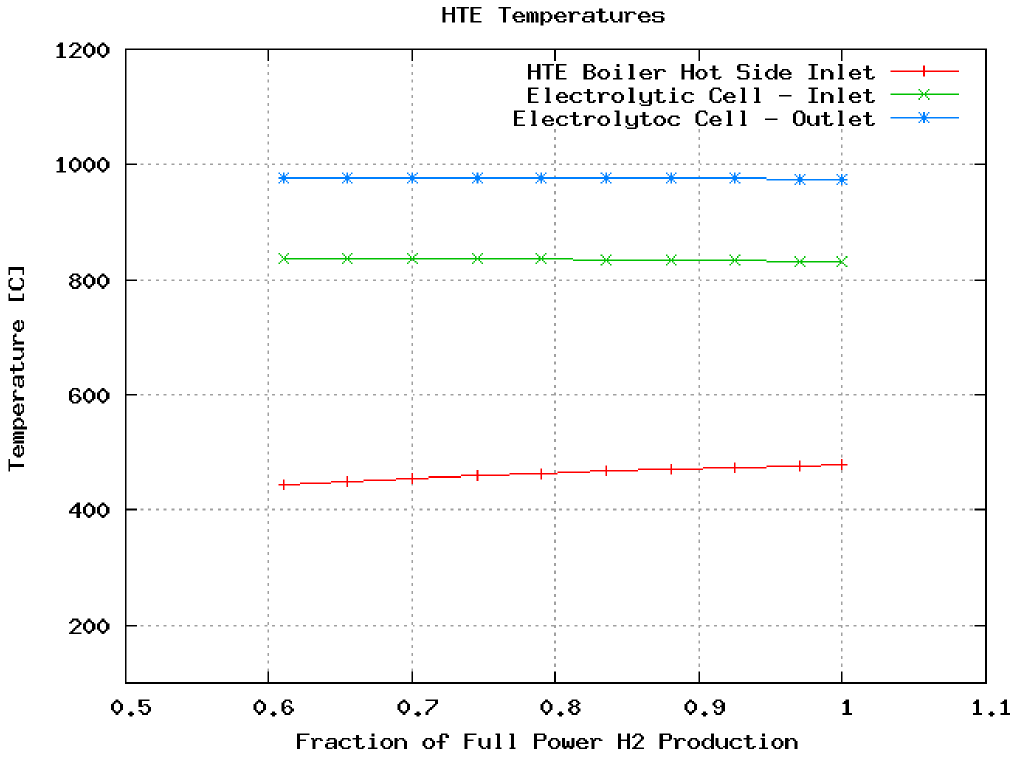


Figure 10 Partial Load HTE Temperatures for Alternate Interface

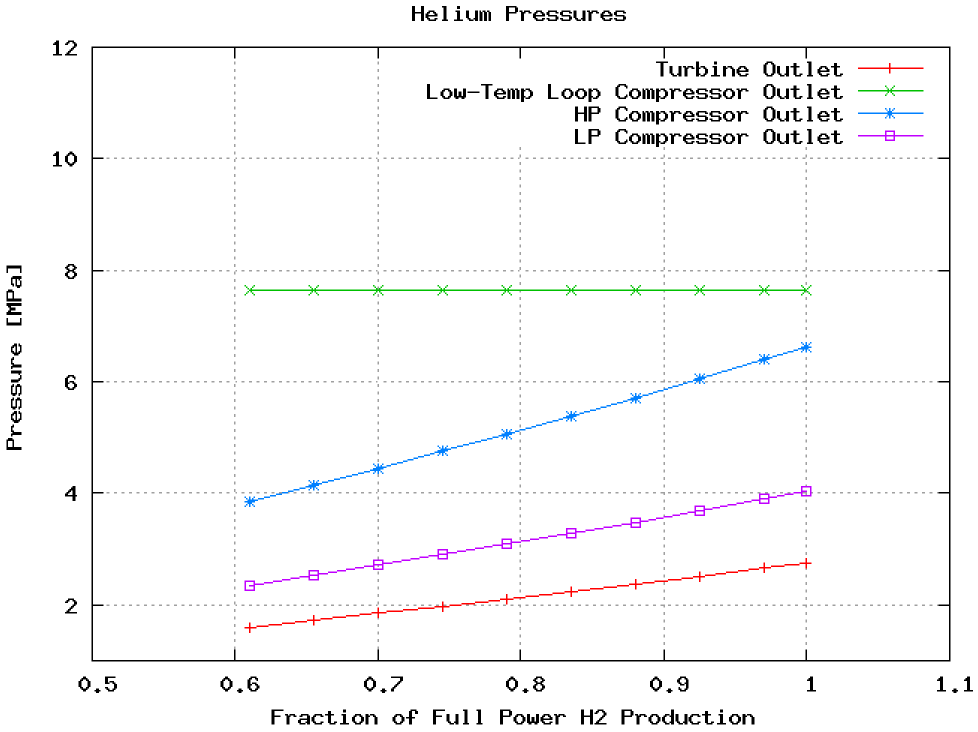


Figure 11 Partial Load Pressures for Alternate Interface

5. ASSESSMENT

While the primary focus of this report was on mitigation of structure creep and tritium transport in the VHTR/HTE high-temperature process heat loop, any potential design solution needs to be evaluated in the wider context of the economics, operability, and safety of the plant. Table VIII presents nine different measures of performance. In this table the Reference Interface is taken as the standard against which the proposed Alternative Interface is compared. The table suggests that overall there are significant advantages to adopting a low-temperature process heat loop in place of a high-temperature loop. However, additional work is required to characterize how the extraction of heat from the PCU might affect operability of the combined plant, especially during upsets in the hydrogen plant.

6. CONCLUSIONS

High temperature creep in structures at the interface between the nuclear plant and the hydrogen plant and the migration of tritium from the core through structures in the interface are two key challenges for the Very High Temperature Reactor (VHTR) coupled to the High Temperature Electrolysis (HTE) process. The severity of these challenges, however, can be reduced by lowering the temperature at which the interface operates. An alternate interface design was investigated as a means for doing so.

Table VIII Overall Assessment of Low-Temperature Process Heat Loop

Performance Measure	**Assessment with Respect to Reference Design**
Structural Materials Longevity/Cost	Superior. Standard reactor-grade stainless steels for low-temperature loop will perform acceptably over 30 year life and at lower cost compared to high-temperature loop.
Equipment Count	
Efficiency	Superior. Coupled plant overall efficiency is several percent greater.
Reliability	Superior. Material problems including creep and corrosion not expected at 200 C.
Availability	Not Clear. Process heat loop is on back side of PCU farther from reactor core but is tightly coupled to PCU. So disturbance in process heat loop affects PCU directly and could cause turbine to trip leading to reactor shutdown.
Maintenance	Superior: In-service inspection easier as a result of better access to heat exchangers and piping. Service work simpler as a consequence of improved access and lower temperature.
Operability	Not clear. Answer awaits transient simulation studies.
Investment Protection	Superior. The need to keep electrolytic cells at temperature even during reactor shutdown is more easily met if cells are heated by electrical heaters or hydrogen combustion products as is proposed for plant design that uses low-temperature process heat loop.
Safety	Perhaps Superior. 1) PCU and process heat loop have no role in heat removal safety systems. Safety system heat removal provided by Shutdown Cooling System and Reactor Cavity Cooling System. 2) Rate of transport of tritium to chemical plant is reduced.

In the alternate interface a heat pump raises the temperature of near-waste heat from the PCU to the temperature at which nine-tenths of the HTE process heat is needed. The decrease in temperature at the heat exchanger that links the HTE plant with the nuclear plant reduces the tritium migration rate by about a factor of 100. In addition to mitigating tritium transport and creep of structures, structural material commodity cost is also reduced.

The efficiency of the plant is increased by one and a half percent. The increase is a consequence of better matching of heat source temperature to HTE plant heat requirements. The efficiency might be increased by another one percent if a small fraction of a synthetic organic created from the plant hydrogen stream for commercial sale were diverted for high-temperature heating in place of electric heating.

There are other advantages which include reduced maintenance cost due to greater accessibility and less severe operating conditions. There may also be a plant investment advantage. In the alternate interface the high-temperature heat is obtained from electrical heaters or hydrogen combustion. This is judged more reliable than process heat used in the reference interface. In the event the reactor trips it would be difficult to maintain the electrolytic cells at temperature using process heat. But off-site power or hydrogen burners would still be available. Temperature changes in the cells are known to significantly shorten cell lifetime and so maintaining constant temperature even when the plant shuts down will be important.

Dynamic simulations should be performed to assess the role of this alternate interface in plant nuclear safety. It is not expected to be a significant issue because the interface links with the nuclear plant at the PCU, a non-safety grade system. Additionally, the heat removed is near reject heat conditions and is just ten percent of the total heat rejected by the nuclear plant.

7. REFERENCES

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APPENDIX A THERMODYNAMIC ANALYSIS OF LOW-TEMPERATURE PROCESS HEAT LOOP

The development below references the heat pump circuit shown in Figure 8. Pressure losses are ignored. The loop is assumed to operate at two pressures, a high-side pressure from compressor outlet to valve inlet and a low side pressure from valve to compressor inlet. When saturation conditions are referenced the index *L* designates low side pressure and index *H* high side pressure.

A.1 Saturated-Vapor Compressor Outlet

An energy balance on the HTE boiler gives

$$Q_{HTE} = w\,(h_{g-H} - (h_{f-H} + x_{HTE}\,(h_{g-H} - h_{f-H}))) . \tag{1}$$

An energy balance on the valve gives

$$0 = (h_{f-L} + x_{VALVE}\,(h_{g-L} - h_{f-L})) - (h_{f-H} + x_{HTE}\,(h_{g-H} - h_{f-H})) . \tag{2}$$

In modeling the compressor it is assumed the outlet condition is saturated vapor at a fixed pressure. In this case the inlet conditions will be a function of the compressor efficiency. If we consider reversible expansion, then the inlet conditions are related to the outlet through

$$S_{f-L} + x_{He/H2O-rev}\,(S_{g-L} - S_{f-L}) = S_{g-H} . \tag{3}$$

The reversible work done is then given by

$$W_{comp-rev} / w = h_{g-H} - (h_{f-L} + x_{He/H2O-rev}\,(h_{g-L} - h_{f-L})) . \tag{4}$$

But from the definition of efficiency the actual work is related to the reversible work through

$$W_{comp-act} = W_{comp-rev} / \eta \tag{5}$$

An energy balance on the compressor gives

$$W_{comp-act} + w\,(h_{f-L} + x_{He/H2O}\,(h_{g-L} - h_{f-L})) = w\,h_{g-H} . \tag{6}$$

where the inlet quality is now the actual rather than reversible.

An energy balance on the He/H2O boiler gives

$$Q_{He/H2O} = w\,(h_{f-L} + x_{He/H2O}\,(h_{g-L} - h_{f-L})) - w\,(h_{f-L} + x_{VALVE}\,(h_{g-L} - h_{f-L})) . \tag{7}$$

Also required is

$$Q_{He/H2O} + W_{comp-act} = Q_{HTE} \tag{8}$$

In the loop of Figure 8 as it is to be operated, the high and low pressure and the power of the HTE boiler, Q_{HTE}, are assumed known. The unknowns to be solved for in order using the above equations are:

$$x_{HTE}, x_{VALVE}, x_{He/H2O-rev}, W_{comp-rev}, W_{comp-act}, x_{He/H2O}, Q_{He/H2O}, w\,.$$

To solve these equations, guess at *w* and then solve in succession Eq. (1) through (7) for the single unknown. Then iterate on *w* repeatedly solving these equations until Eq. (8) is satisfied.

A.2 Saturated-Vapor Compressor Inlet

If the compressor inlet condition is assumed saturated vapor at a fixed pressure, then the outlet condition will be a function of the compressor efficiency. If we consider reversible expansion, then the outlet conditions are related to the inlet through

$$S_{g-L} = S(P_{sat-H}, T_{sh-comp-rev})\,. \tag{9}$$

The reversible work done is then given by

$$W_{comp-rev}/w = h_{g-H} + \bar{C}_{p-g}\,(T_{sh-H-rev} - T_{sat-H}) - h_{g-L}\,. \tag{10}$$

But from the definition of efficiency the actual work is related to the reversible work as previously

$$W_{comp-act} = W_{comp-rev}/\eta \tag{5}$$

An energy balance on the compressor gives

$$W_{comp-act} + w\,h_{g-L} = w\,(h_{g-H} + \bar{C}_{p-g}\,(T_{sh-comp} - T_{sat-1H})) \tag{11}$$

where the superheat temperature is now the actual rather than reversible.

An energy balance on the HTE boiler gives

$$Q_{HTE} = w\,(\,h_{g-H} + \bar{C}_{p-g}\,(T_{sh-H} - T_{sat-H}) - (h_{f-H} + x_{HTE}\,(h_{g-H} - h_{f-H}))\,)\,. \tag{12}$$

An energy balance on the valve remains as previously

$$0 = (h_{f-L} + x_{VALVE}\,(h_{g-L} - h_{f-L})) - (h_{f-H} + x_{HTE}\,(h_{g-H} - h_{f-H})\,)\,. \tag{2}$$

An energy balance on the He/H2O boiler gives

$$Q_{He/H2O} = w\,(h_{g-L} - (h_{f-L} + x_{VALVE}\,(h_{g-L} - h_{f-L})))\,. \tag{13}$$

Also required is

$$Q_{He/H2O} + W_{comp-act} = Q_{HTE} \tag{14}$$

In the loop of Figure 8 as it is to be operated, the high and low pressure and the power of the HTE boiler, Q_{HTE}, are assumed known. The unknowns to be solved for in order using the above equations are:

$$T_{sh-comp-rev}, W_{comp-rev}, W_{comp-act}, T_{sh-comp}, x_{HTE}, x_{VALVE},\ Q_{He/H2O}, w\,.$$

APPENDIX B PUMPING POWER IN HIGH- AND LOW-TEMPERATURE PROCESS HEAT LOOPS

In the analysis below it is assumed that the majority of the pressure drop arises in the pipe runs rather than the heat exchangers. It is also assumed that the mass flux in the low-temperature loop is the same as the high-temperature loop of the reference design. Good engineering practice places a limit on the range of acceptable values in pipe runs. By choosing the same mass flux we are assuring that a comparison is made on a consistent basis.

The friction losses in the proposed low-temperature water loop compared to the helium high-temperature loop are derived as follows. From energy balances for the two loops we have

$$Q_{He} = w_{He}\, C_{p-He}\, \Delta T_{He} \qquad \text{and} \qquad Q_{H2O} = w_{H2O}\, C_1 \tag{15}$$

where C_1 is a constant. The first equation reflects the change in temperature in the high-temperature loop due to sensible heat while the second equation reflects the fact that for phase change at fixed pressure the energy transport rate in the low-temperature loop is mainly linear with flow rate. The flow rates are then related by

$$\frac{w_{H_2O}}{w_{He}} = C_2\, \frac{Q_{H2O}}{Q_{He}}\,. \tag{16}$$

where

$$C_2 = \frac{C_{p-He}\, \Delta T_{He}}{C_1}\;. \tag{17}$$

It is assumed that the flow in each leg of the low-temperature loop is predominantly saturated vapor or saturated liquid and that the supply and return lines are sized so ρv has the same value as in the high-temperature loop. Then since $A = w/(\rho v)$ for the cross-sectional area of a pipe

$$\frac{A_{H_2O}}{A_{He}} = \frac{w_{H_2O}}{w_{He}} \tag{18}$$

and from this for the pipe diameters

$$\frac{D_{H_2O}}{D_{He}} = \left(\frac{A_{H_2O}}{A_{He}}\right)^{1/2}\;. \tag{19}$$

In the above it is assumed that in comparing the low-temperature case with the high-temperature case the comparison is between supply pipes and return pipes.

The pressure drop is

$$\Delta P = f\,\frac{L}{D}\,\frac{1}{2}\,\rho\, v^2 \tag{20}$$

or given $f = C/Re^n$

$$\Delta P = \frac{CL}{2}\cdot\frac{\mu^n}{\rho}\cdot\frac{w^{2-n}}{D^{1+n}\;A^{2-n}}\,. \tag{21}$$

Eq. (21) yields after substituting in Eqs. (16), (18), and (19)

$$\frac{\Delta P/Q\,|_{H_2O}}{\Delta P/Q\,|_{He}} = \left(\frac{\mu_{H_2O}}{\mu_{He}}\right)^n \frac{\rho_{He}}{\rho_{H_2O}} \left(\frac{w_{He}}{w_{H_2O}}\right)^{\frac{1+n}{2}} \left(\frac{Q_{He}}{Q_{H_2O}}\right) \tag{22}$$

The pumping power per unit of process heat transported is then

$$\frac{\left.\dfrac{\Delta P\, w}{Q\,\rho}\right|_{H_2O}}{\left.\dfrac{\Delta P\, w}{Q\,\rho}\right|_{He}} = \left(\frac{\mu_{H_2O}}{\mu_{He}}\right)^n \left(\frac{\rho_{He}}{\rho_{H_2O}}\right)^2 \left(\frac{w_{He}}{w_{H_2O}}\right)^{(n-1)/2} \left(\frac{Q_{He}}{Q_{H_2O}}\right). \tag{23}$$

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