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ANL-GenIV-105

NGNP/HTE Full-Power Operation at Reduced High-Temperature Heat Exchanger Temperatures

Nuclear Engineering Division

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by
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ABSTRACT

Operation of the Next Generation Nuclear Plant (NGNP) with reduced reactor outlet temperature at full power was investigated for the High Temperature Electrolysis (HTE) hydrogen-production application. The foremost challenge for operation at design temperature is achieving an acceptably long service life for heat exchangers. In both the Intermediate Heat Exchanger (IHX) and the Process Heat Exchanger (PHX) (referred to collectively as high temperature heat exchangers) a pressure differential of several MPa exists with temperatures at or above 850 C. Thermal creep of the heat exchanger channel wall may severely limit heat exchanger life depending on the alloy selected. This report investigates plant performance with IHX temperatures reduced by lowering reactor outlet temperature. The objective is to lower the temperature in heat transfer channels to the point where existing materials can meet the 40 year lifetime needed for this component. A conservative estimate for this temperature is believed to be about 700 C.

The reactor outlet temperature was reduced from 850 C to 700 C while maintaining reactor power at 600 MWt and high pressure compressor outlet at 7 MPa. We included a previously reported design option for reducing temperature at the PHX. Heat exchanger lengths were adjusted to reflect the change in performance resulting from coolant property changes and from resizing related to operating-point change. Turbomachine parameters were also optimized for the new operating condition. An integrated optimization of the complete system including heat transfer equipment was not performed. It is estimated, however, that by performing a pinch analysis the combined plant efficiency can be increased from 35.5 percent obtained in this report to a value between 38.5 and 40.1 percent. Then after normalizing for a more than three percent decrease in commodities inventory compared to the reference plant, the *commodities-normalized* efficiency lies between 40.0 and 41.3. This compares with a value of 43.9 for the reference plant. This latter plant has a reactor outlet temperature of 850 C and the two high temperature heat exchangers.

The reduction in reactor outlet temperature from 850 C to 700 C reduces the tritium permeability rate in the IHX metal by a factor of three and thermal creep by five orders of magnitude. The design option for reducing PHX temperature from 800 C to 200 C reduces the permeability there by three orders of magnitude. In that design option this heat exchanger is the single “choke-point” for tritium migration from the nuclear to the chemical plant.

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I. INTRODUCTION

In one deployment scenario the Next Generation Nuclear Plant (NGNP) will provide process heat and electricity to a chemical plant that is to produce hydrogen from liquid-water feedstock. Engineering studies of the coupled nuclear-chemical plant are being performed for two cases, hydrogen production using a high-temperature thermo-chemical process and that using a high-temperature electrolysis process. Both processes require process heat at a temperature of as much as several hundred degrees greater than that found in first-generation gas reactors. The AVR, an example of one such reactor, had an outlet temperature of about 700 C. Key NGNP design features for achieving higher-temperature operation include thermal insulation for lowering the temperature at reactor and heat exchanger structures, cooling flow paths and radiation heat transfer for reducing the temperature at the reactor vessel wall, possibly cooling channels in turbomachine blades, and the use of super-alloys exhibiting relatively low creep at high temperature.

The foremost challenge for operation at these higher temperatures is achieving an acceptably long service life for heat exchangers. Specifically the heat transfer channel in the high-temperature heat exchangers appears to be the limiting element. In both the Intermediate Heat Exchanger (IHX) and the Process Heat Exchanger (PHX) (referred to collectively as high temperature heat exchangers) a pressure differential of several MPa exists combined with temperatures at or above 850 C. Thermal creep in these channels severely limits the heat exchanger life even when the channel walls are fabricated from super-alloys. At this temperature there is the additional problem of high tritium permeability in metals leading to migration of tritium into the chemical plant through the heat exchanger channel wall. The development of ceramic heat exchanger tubes may eventually solve these problems.

In the case of the HTE process, design options appear to exist that will significantly mitigate the creep and tritium problems. In [1] we explored the use of direct heating in the chemical plant to provide the relatively small amount of high-temperature heat that would otherwise come from the reactor outlet by way of the PHX. A low-temperature (< 500 C) heat exchanger then communicates the balance of the chemical plant process heat needs from a heat pump driven off of plant reject heat. Plant efficiency was shown to actually increase under this option with no other identified significant performance consequences.

In this report we describe a design option for reducing the temperature at the IHX. Reactor outlet temperature is reduced from 850 C to 700 C while maintaining reactor power at 600 MWt and high pressure compressor outlet at 7 MPa. The objective is to lower the temperature in the heat transfer channels of the IHX and PHX to the point where existing materials can meet the 40 year lifetime needed for these components. This temperature is believed to be about 700 C. A key issue to be investigated is how coupled-plant efficiency would be affected by such a de-rating. For the case where the PHX solution described above is implemented, tritium migration through the IHX may not be a serious problem since the only path onward to the chemical plant is through a low-temperature heat exchanger. This assumes that tritium accumulation in the PCU is acceptable. The diffusion rate through the low-temperature heat exchanger will be significantly less than through the high-temperature PHX and as a result the tritium concentration in the chemical plant will be significantly smaller. In this report we investigate these issues for coupled plant full power operation at the reduced reactor outlet temperature of 700 C.

II. REFERENCE PLANT

A. Description

The Reference Plant is defined to serve as a baseline against which two reduced temperature plants can be evaluated. The Reference Plant appeared originally as Case 6 of [2]. Subsequently in [3], the HTE plant specification was expanded upon to include more detailed information for configuration of components and for individual component sizes.

The Reference Plant 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 migrating through the IXH heat transfer wall metal to make its way to the HTE plant through the High-Temperature Process Heat Exchanger (PHX).

B. Operating Condition

The performance of the Reference Plant is characterized in [4]. In that work the GPASS 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, MWt	600
Outlet Temperature, C	887
Inlet Temperature, C	490
PCU	
Turbine Inlet Temperature, C	870
HP Compressor Outlet Pressure, MPa	7.4
LP Compressor Outlet Pressure, MPa	4.1
HTE	
Cell Outlet Temperature, C	970
Cell Pressure, MPa	5.0

Figure 1 Reference Plant

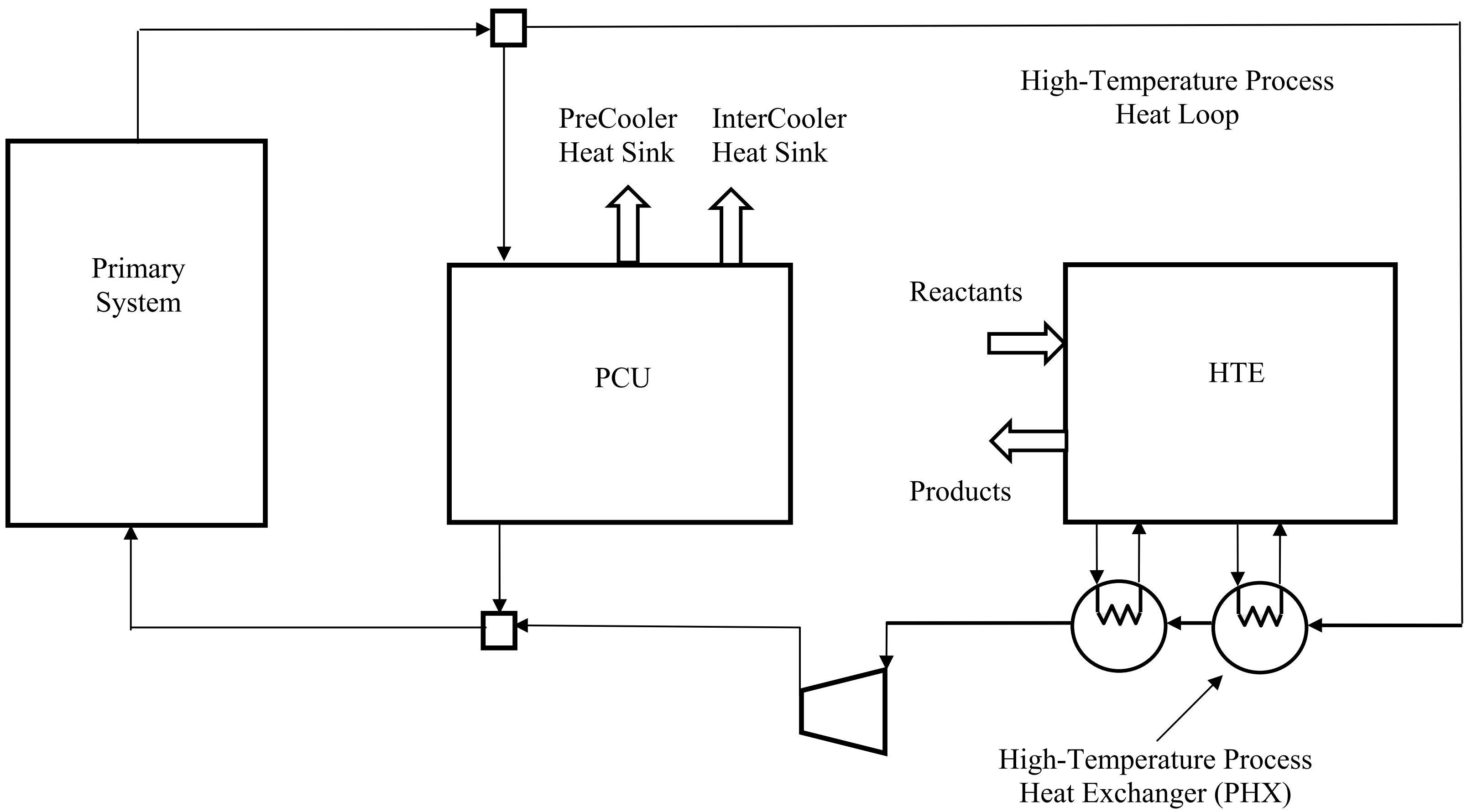


Figure 2 High Temperature Electrolysis Plant

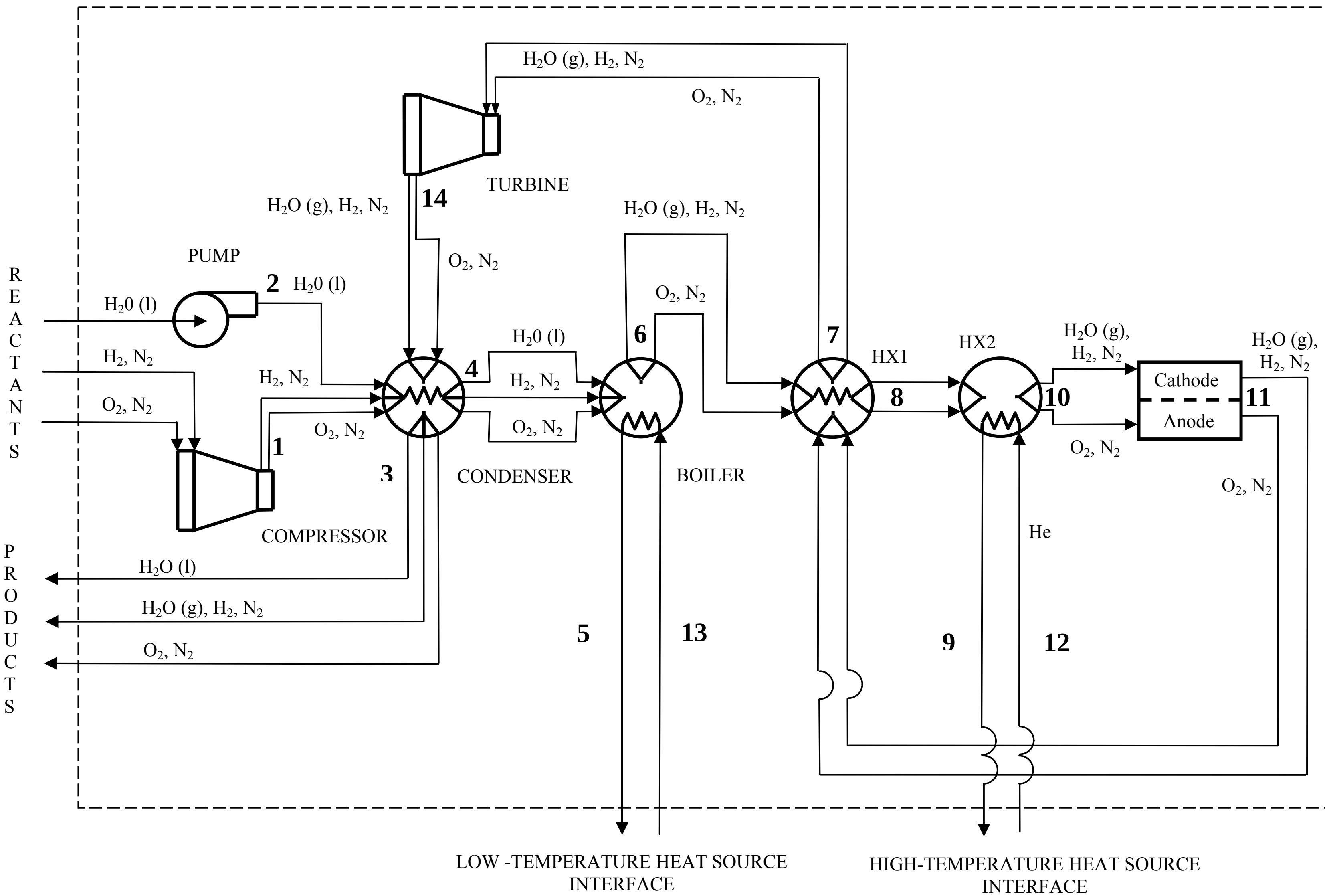


Figure 3 Reference Power Conversion Unit Plant

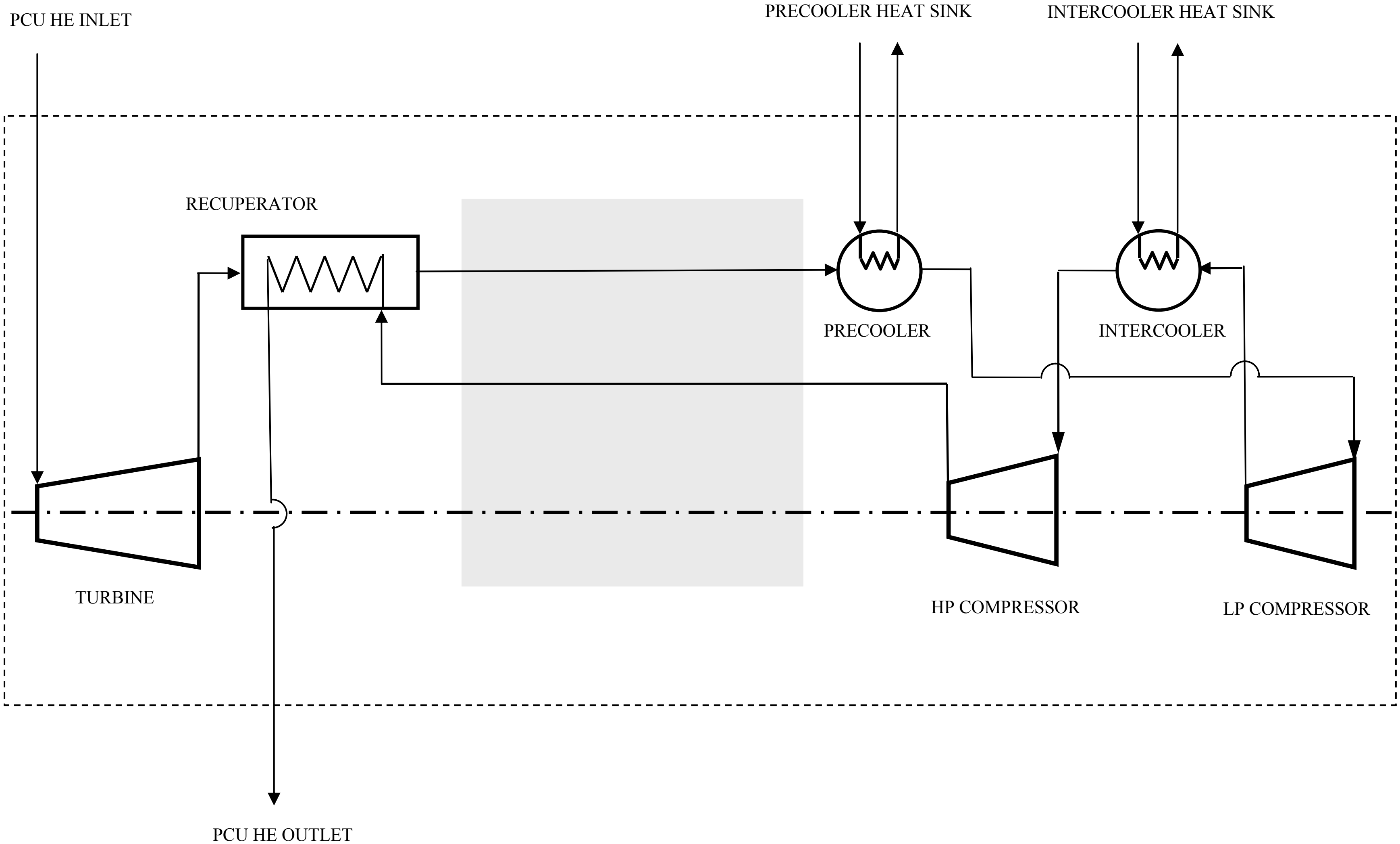
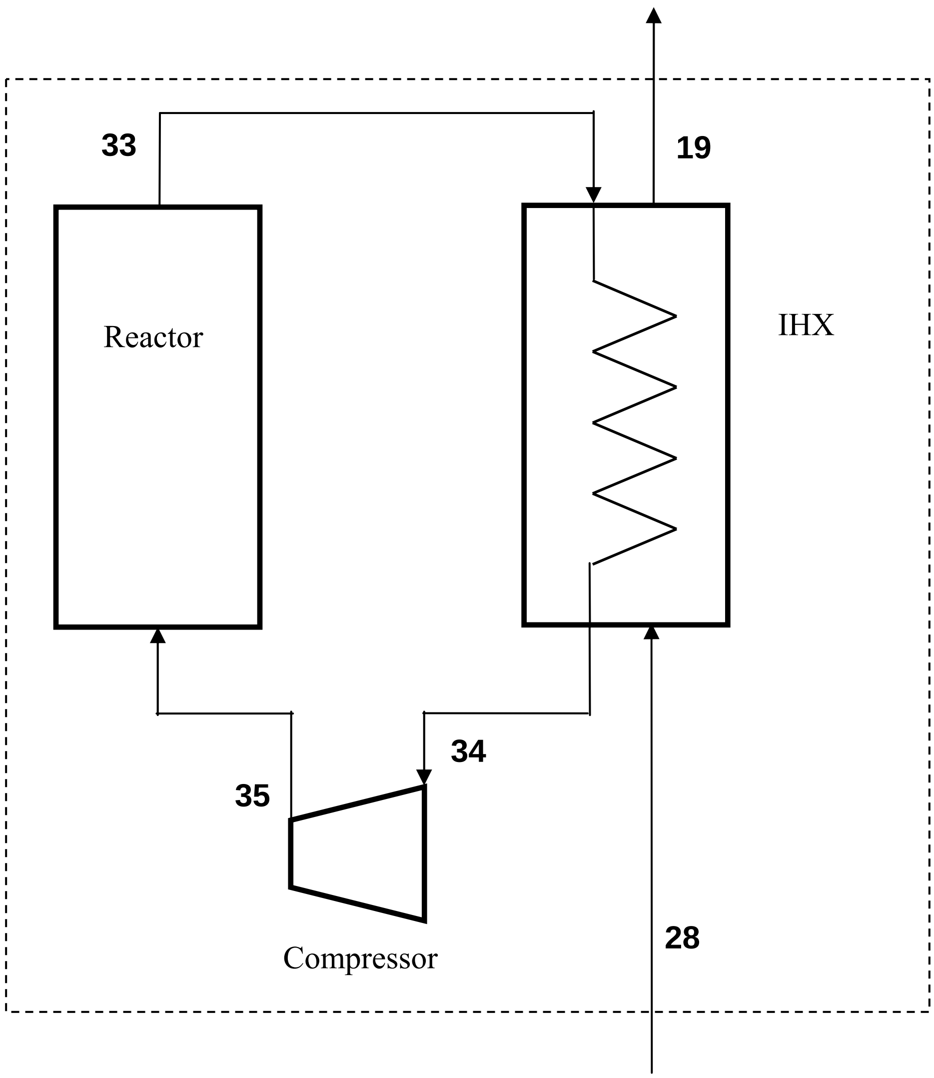


Figure 4 Primary System and Intermediate System Heat Exchanger



III. DESIGN VARIANTS ON REFERENCE PLANT

There are three different plants referred to in this report. Italics are used to make clear when one of these is being referenced. There is the *Reference Plant* described above and its two variants, the *Reduced PHX Temperature Plant* and the *Reduced IHX and PHX Temperature Plant* described below.

A. Reduced PHX Temperature Plant

As the name suggests, the temperature in the PHX of the *Reduced PHX Temperature Plant* is reduced from what it is in the *Reference Plant*. This is achieved through use of the alternate interface for connecting the reactor to the electrolysis plant shown in Figure 5. The key difference 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. Rather it is obtained from hydrogen burners or electrical heaters located in the chemical plant. In place of the High Temperature Process Heat Loop there is a Low Temperature Process Heat Loop linking the electrolysis plant to the reactor. Because it operates at a relatively low temperature, diffusion of tritium from the PCU to the HTE plant and creep of structures are significantly reduced from the *Reference Plant*. This *Reduced PHX Temperature Plant* was examined in [1].

B. Reduced IHX and PHX Temperature Plant

The temperature in the IHX of the *Reduced IHX and PHX Temperature Plant* is less than in the *Reduced PHX Temperature Plant*. This is achieved by lowering the reactor outlet temperature from 850 C to 700 C while maintaining full power values of 600 MWt reactor power and 7 MPa at the outlet of the high pressure compressor in the PCU. The reduction in temperature is achieved solely by resizing equipment; the layout remains the same as in the *Reduced PHX Temperature Plant.*

The following equipment is resized. The precooler and intercooler size is increased to support an increase in heat rejection caused by reduced PCU efficiency at the lower reactor outlet temperature. The recuperator size is decreased as a result of less heat exchanged between cold and hot streams as a result of the temperature difference decrease between heat source and sink. The turbomachine pressure ratios are selected to give maximum PCU efficiency and 7 MPa at the high pressure compressor outlet. An overall optimization of PCU efficiency that takes in heat exchangers was not performed. This is left for a later date when a pinch analysis will be performed.

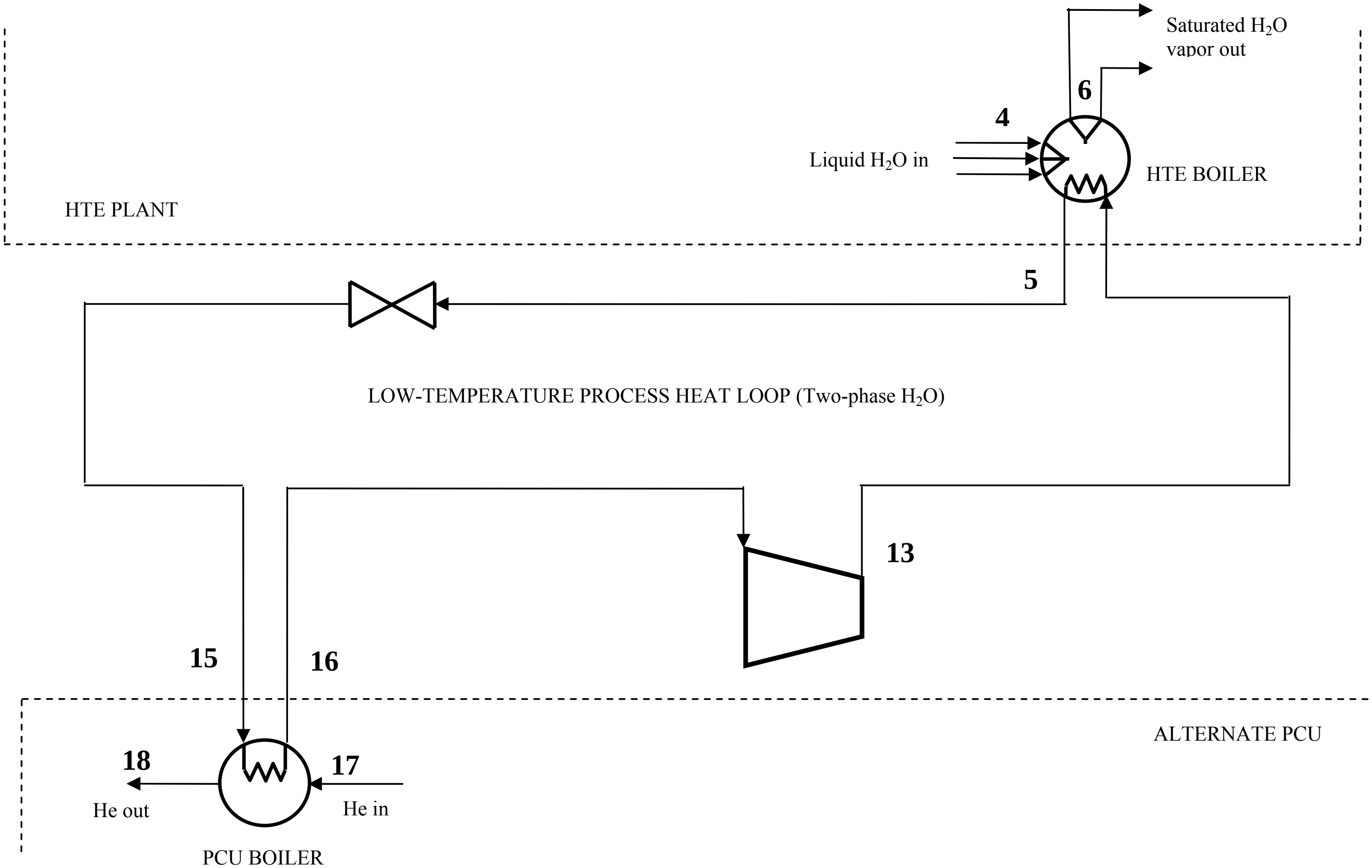
IV. METHODS AND ASSUMPTIONS

A. Prediction of Full-Power Design Point

The GPASS code is used to predict the conditions in the coupled nuclear-hydrogen plant. The code was developed for transient simulation. The user configures components and provides component data through the input deck which minimizes the need to reprogram source code each time a new plant configuration is simulated. Fluid properties in all components are obtained from look-up tables populated off-line (usually only once) using a standalone program that makes calls to the NIST RefProp software. Because NIST supports multiple gases and mixtures, the fluids that can be simulated are limited only by those that appear in NIST RefProp. A multi-node heat exchanger model solves the dynamic conservation equations for a compressible gas where the length has been nodalized and properties are evaluated in each node using local pressure and enthalpy. The model is especially suited for predicting temperature transients in heat exchangers. The status of all models is described in greater detail in [5].

It proved more convenient in this work to obtain steady-state coupled plant solutions using the single-node log-mean temperature model rather than the multi-node model. The values of the

Figure 5 Alternate Interface



overall heat transfer coefficient times area (UA) and the pressure loss coefficient (K) are known for each heat exchanger in the *Reference Plant*. Adjustment of these values for the variants of the *Reference Plant* is described in Section V.A.

B. Dependence of Properties and Loss Mechanisms on Temperature

B.1 Pressure Loss

The thermal efficiency of a closed-loop Brayton cycle is known to be very sensitive to friction losses in the loop. Since we are essentially changing the temperature at which the coolant loops operate while keeping the reactor power constant it is useful to understand the effect of this change on losses and, hence, on net electric power generated. In the simple analysis we assume flow rate remains constant as temperature is changed. The pressure drop in a circular tube is given by

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

where

L	=	length,
D_h	=	hydraulic diameter,
ρ	=	density,
υ	=	velocity, and
f	=	friction factor.

The friction factor is given as a function of Reynolds number *Re* as

$$f = \frac{C}{\mathrm{Re}^n}, \qquad \mathrm{Re} = \frac{w D_h}{\mu A}, \qquad w = \rho v A \tag{2}$$

where

w	=	flowrate,
μ	=	viscosity,
A	=	area, and
C, n	=	empirical constants.

For 30,000 < *Re* < 100,000, a fit to experiment data yields n = 0.2. Eqs. (1) and (2) give

$$\Delta P = \frac{CL}{2} \cdot \frac{\mu^n}{\rho} \cdot \frac{w^{2-n}}{D_h^{1+n} A^{2-n}} \ . \tag{3}$$

Define the *loss coefficient K* for the above equation through

$$\Delta P = K\, w^{2-n} \tag{4}$$

Then for fixed geometry and constant mass flow rate, if we define a reference temperature T_0, the pressure drop at some other temperature is related to that at the reference temperature through

$$\frac{\Delta P}{\Delta P_o} = \frac{K}{K_0} = \left(\frac{\mu}{\mu_o}\right)^n \frac{\rho_o}{\rho} \tag{5}$$

Figure 6 shows the temperature dependence of viscosity and density for helium. One sees from Eq. (3) that the trend in both these variables acts to reduce friction loss with temperature decrease. This appears in Figure 7 where the normalized pressure drop of Eq. (5) has been plotted using the data from Figure 6. This property dependence will be offset to a degree by the reduction in efficiency associated with temperature-dependent Carnot efficiency.

B.2 Temperature Loss

The temperature drop from hot to cold fluid across the heat transfer surface in a heat exchanger is another loss mechanism. It is useful to understand how this loss, in the form of the film temperature drop, varies with coolant temperature for constant mass flow rate and constant heat flux. The heat transfer coefficient is related to the Nusselt number, *Nu*, through the expression

$$h = \frac{k\ Nu}{D_h} \tag{6}$$

where *k* is thermal conductivity. In turn, the heat transfer data for helium are correlated in the form

$$Nu = C_1 \,\mathrm{Re}^p \,\mathrm{Pr}^m \tag{7}$$

where Pr is the Prandtl number

$$\mathrm{Pr} = \frac{Cp\,\mu}{k}. \tag{8}$$

Then for fixed geometry and constant mass flow rate, the heat transfer coefficient at some other temperature is related to that at the reference temperature through

$$\frac{h_0}{h} = \frac{R}{R_o} = \left(\frac{k_o}{k}\right)^{1-m} \left(\frac{\mu}{\mu_o}\right)^{p-m} \left(\frac{C_{p-o}}{C_p}\right)^m \tag{9}$$

where *R* is the reciprocal of the film heat transfer coefficient or the film heat transfer resistance. For 10,000 < *Re* < 120,000, a fit to experiment data yields p = 0.8 and m = 0.4.

Figure 6 shows the temperature dependence of the thermal conductivity, viscosity, and specific heat of helium. Inserting these data in Eq. (9) yields the normalized film heat transfer resistance as a function of temperature shown in Figure 7. A decrease in temperature of 150 C produces an increase in resistance of two percent.

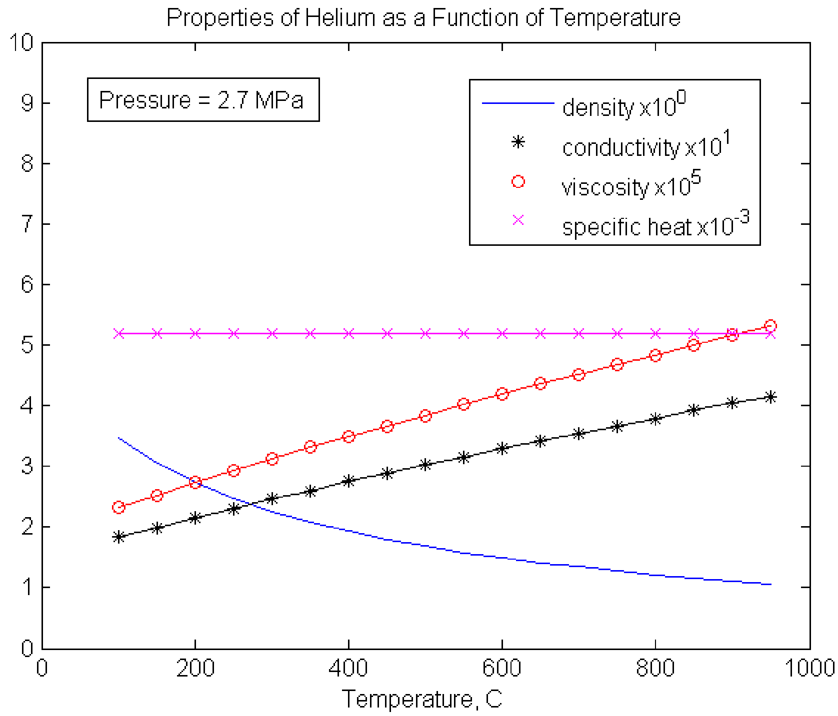


Figure 6a Properties of Helium as a Function of Temperature. 2.7 MPa

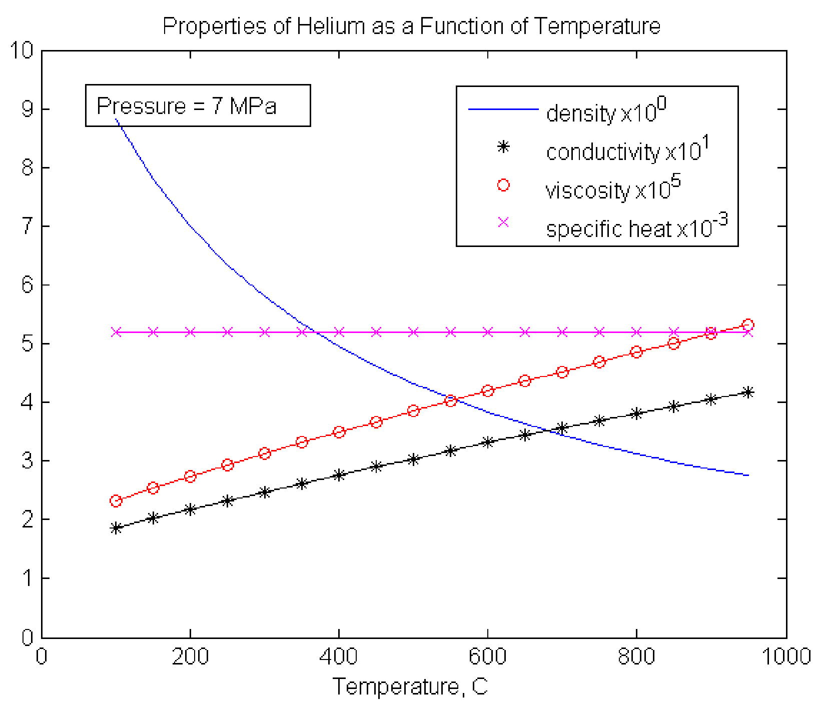


Figure 6b Properties of Helium as a Function of Temperature. 7 MPa

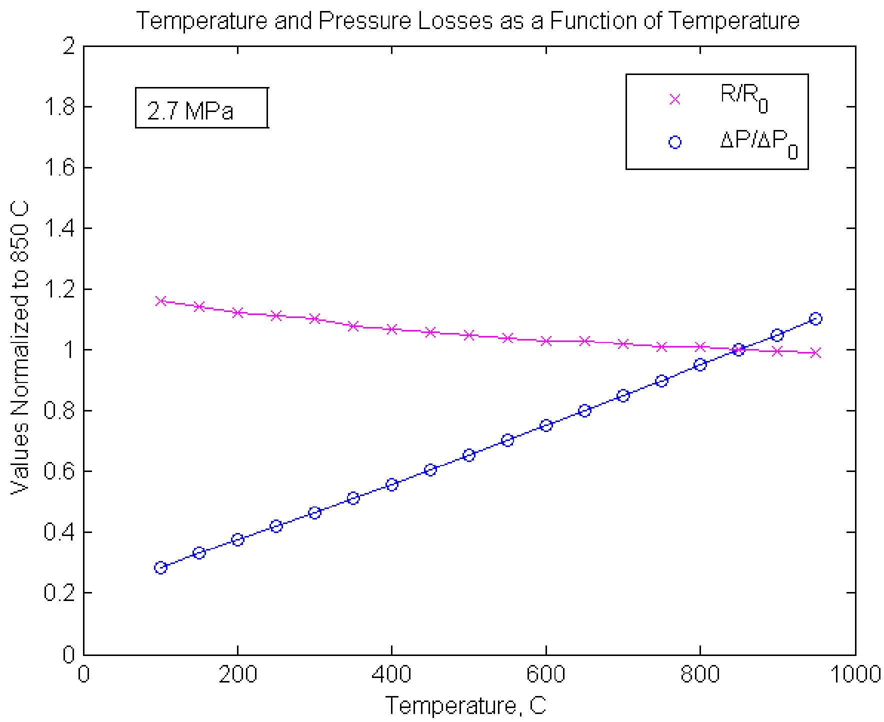


Figure 7a Temperature and Pressure Losses for Helium with respect to 850 C Reference Temperature: 2.7 MPa

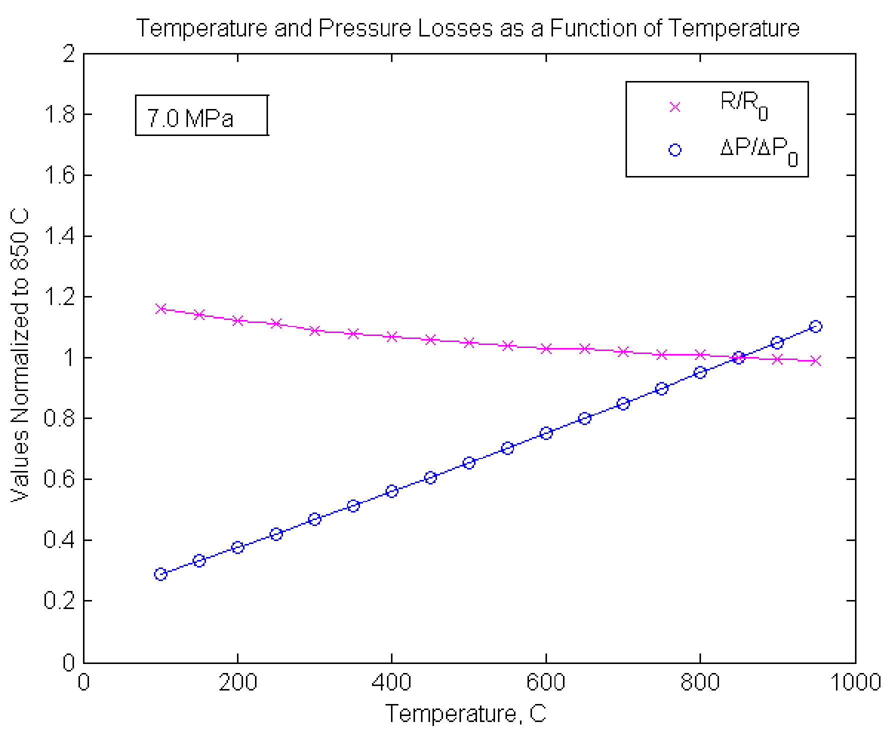


Figure 7b Temperature and Pressure Losses for Helium with respect to 850 C Reference Temperature: 7 MPa

C. Material Creep with Temperature

Thermal creep is a limiting phenomenon for service life of high-temperature heat exchangers under pressure load. Over a 40 year lifetime the creep should not exceed a small percentage of the original dimensions. The creep properties of a metal at its normal service temperature is given by Norton's Law and the Arrhenius function. [6,7] This equation was regressed to experimental data in [8]. The strong dependence of creep rate on temperature is seen in Figure 8. This figure was generated for Alloy 800 H using the regressed equation of [8]. The figure assumes a stress is applied that generates a one percent strain over 40 years at a temperature of 850 C. The resulting dependence of creep with temperature is shown. The creep is exponentially dependent on temperature which is generally true for metals at their normal operating temperature.

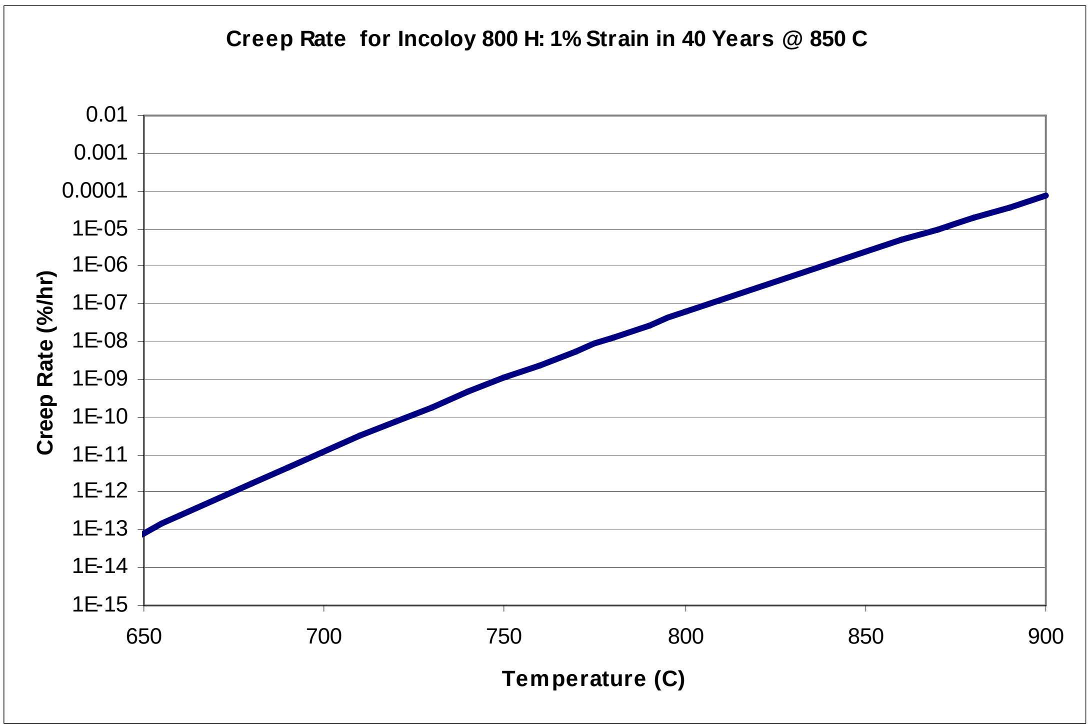


Figure 8 Creep Rate for Incoloy 800 H as a Function of Temperature

D. Tritium Migration with Temperature

The permeability of isotopes of hydrogen in two different metals is shown in Figure 9. The Hastelloy alloy is a high temperature metal for applications near 850 C. The 2-1/4Cr-1Mo alloy is an intermediate temperature metal typically found in liquid-metal reactor applications near 500 C. Both plots show roughly a factor of 10 decrease in permeability for each 200 C reduction in temperature.

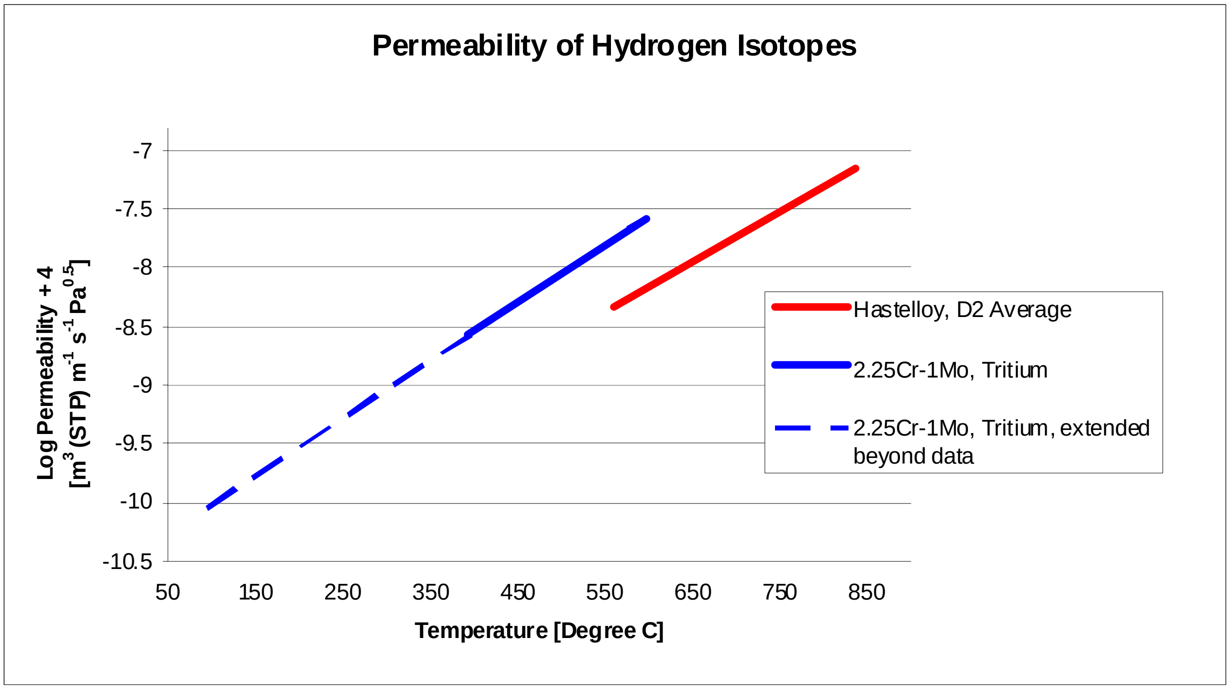


Figure 9 Permeability of Hydrogen Isotopes as a Function of Temperature

V. RESULTS

This section describes results obtained for the *Reduced IHX and PHX Temperature Plant* of Section III.B. This plant is evaluated by comparing its performance against the *Reference Plant* and the *Reduced PHX Temperature Plant*. Results for these latter two were reported in earlier work. [1,4]

A. Plant Efficiency

A consequence of reducing reactor outlet temperature from 850 C to 700 C is lower electric generation efficiency and as a result, lower coupled plant efficiency. The latter is defined as the ratio of thermal energy released by combusting the hydrogen product to the reactor thermal energy that went in to producing the hydrogen. The electric generation efficiency is altered from the *Reference Plant* by several design changes related to operation at reduced high-temperature heat exchanger temperature.

The engineering parameters K and 1/UA which represent pressure and temperature loss mechanisms, respectively, were calculated to reflect the new operating condition. The calculations are shown in Table II. Essentially UA is relatively insensitive to temperature change while K is significantly reduced by temperature decrease.

The precooler and intercooler heat transfer areas were increased to support an increase in heat rejection caused by reduced PCU efficiency at the lower reactor outlet temperature. The increase

Table II Equipment Pressure and Temperature Loss Parameters Adjusted for Temperature Only. Geometry and helium mass flow rate assumed constant. Helium pressure 5 MPa unless otherwise noted. n.a. = not applicable, n.c. = no change.

	Case 1: Alternative Interface Design			Case 2: Alternative Interface Design, Reactor Outlet Reduced by 150 C				
	T_0 ^0C	$(UA)_0$ MW/C	K_0 Pa/(kg-s)$^{1.8}$	T ^0C	R_0/R [Eq. 5] -	UA MW/C	$\Delta P/\Delta P_0$ [Eq. 3] -	K [K_0* $\Delta P/\Delta P_0$] Pa/(kg-s)$^{1.8}$
Reactor Inlet/outlet average	690 [(867+510)/2]	n.a.	1.82	540 [690-150]	n.a.	n.a.	0.826	1.50 [1.82*0.826]
IHX Hot side average	686 [(867+504)]/2	30.0	1.86	536 [686-150]	1.023	30.5 [(1+0.66*0.023)*$(UA)_0$]	0.825	1.53 [1.86*0.825]
Cold side average	665 [(841+489)]/2	n.a.	1.82	515 [665-150]	1.023	n.a.	0.821	1.49 [1.82*0.821]
Recuperator Hot side average@ 2.7 MPa	370 [(233+507)/2]	25.6	1.22	220 [370-150]	1.037	26.2 [(1+0.66* 0.037)*$(UA)_0$]	0.741	0.904 [1.22*0.741]
Cold side average	350 [(489+212)/2]	n.a.	1.22	200 [350-150]	1.038	n.a.	0.734	0.895 [1.22*0.734]
Precooler Hot side average @ 2.7 MPa	80 [(127+32)/2]	6.1	0.619	n.c.	1.0	n.c.	1.0	n.c.
Intercooler Hot side average @ 4.0 MPa	61 [(30+92)/2]	7.0	0.619	n.c	1.0	n.c.	1.0	n.c.
Auxillary Recup. Hot side average @ 2.7 MPa	160 [(213+192+ 127+106]/4]	6.83	0.326	n.c.	1.0	n.c.	1.0	n.c.

Table III Heat Exchanger Pressure and Temperature Loss Parameters Adjusted for Length Change

	Nature of Length Change	Parameters Values Given Coolant Properties at New Operating Point Temperature (from Table VI)		Additional Adjustment for Heat Exchanger Change in Length		
		UA $MW/m^2/C$	K $Pa/(kg\text{-}s)^{1.8}$	New Length as a Fraction of Old	UA $MW/m^2/C$	K $Pa/(kg\text{-}s)^{1.8}$
Recuperator Hot side	Decrease. Less recuperation needed as a result of reduced temperature difference between heat source and sink.	26.2	0.904	0.45 $[(507\text{-}233\text{-}150)/(507\text{-}233)_0]$ [a]	11.8	0.497
Cold side		n.a.	0.895	0.45 $[(507\text{-}233\text{-}150)/(507\text{-}233)_0]$ [a]	n.a.	0.403
Precooler Hot side	Increase. Greater heat rejection needed as a result of decreased plant efficiency.	6.1	0.619	1.1 [(1-0.45)*600/((1-0.5)*600)] [b]	6.71	0.681
Intercooler Hot side	Increase. Greater heat rejection needed as a result of decreased plant efficiency.	7.0	0.619	1.1 [(1-0.45)*600/((1-0.5)*600)] [b]	7.7	0.681

[a] Length of recuperator scaled to inlet-to-outlet temperature drop

[b] Length scaled to plant heat reject rate. Heat reject rate increases as consequence of reduced electrical generation efficiency

was achieved by increasing the length of the units. The new K and UA values are calculated in Table III. An increase in K acts to reduce plant efficiency.

The recuperator heat transfer area was decreased to reflect the fact that less heat is exchanged between cold and hot streams since the temperature difference between heat source and sink is decreased by the reactor outlet temperature decrease. The decrease was achieved by reducing the length of the unit. The new K and UA values are calculated in Table III.

The electric efficiency is altered by the change in component pressure loss characteristics described above, and with it the location of maximum efficiency with respect to pressure ratios. The dependence of efficiency on the turbine pressure ratio and the product of the compressor pressure ratios is shown in Figure 10. The corresponding value of pressure at the outlet of the high pressure compressor is shown in Figure 11. If this pressure is to be 7 MPa, then the corresponding efficiency from Figure 10 is 40.0 percent. Note that the efficiency is not particularly sensitive to the compressor outlet pressure. Note that friction losses increase as a result of coolant density decrease with reduced compressor outlet pressure. Thus there is an incentive to maintain the 7 MPa compressor outlet pressure of the *Reference Plant.*

The coupled-plant efficiency is 35.5 percent. The calculation is shown in Table IV along with individual component powers. Compared to the *Reduced PHX Temperature Plant* the PCU compressor powers have increased while the turbine power has decreased for a net decrease in

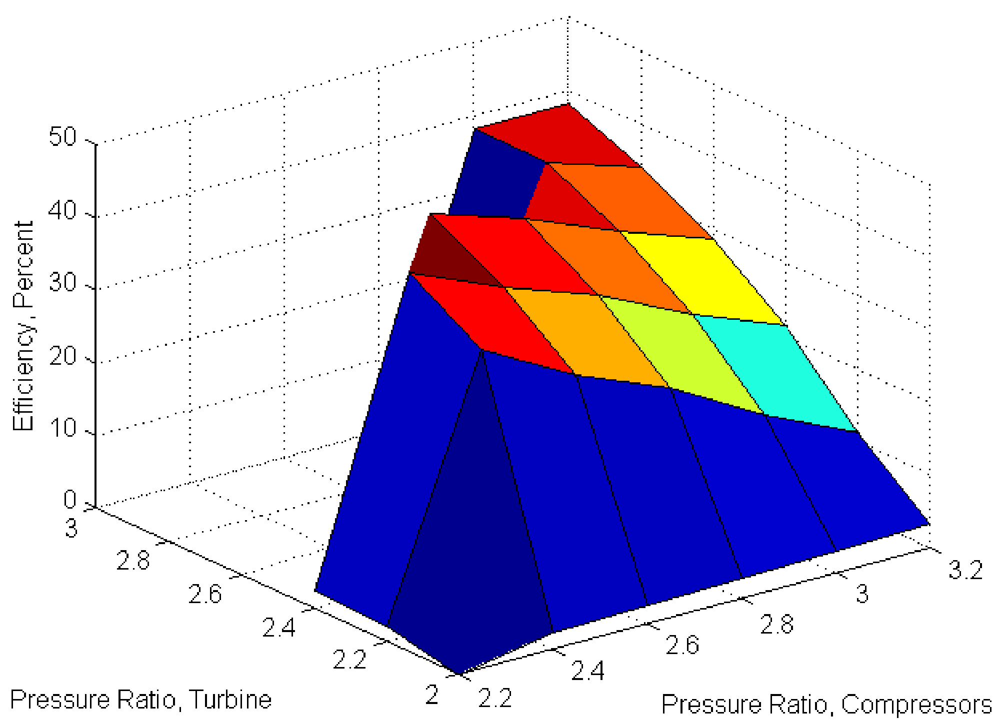


Figure 10 PCU Efficiency as a Function of Turbomachine Pressure Ratios

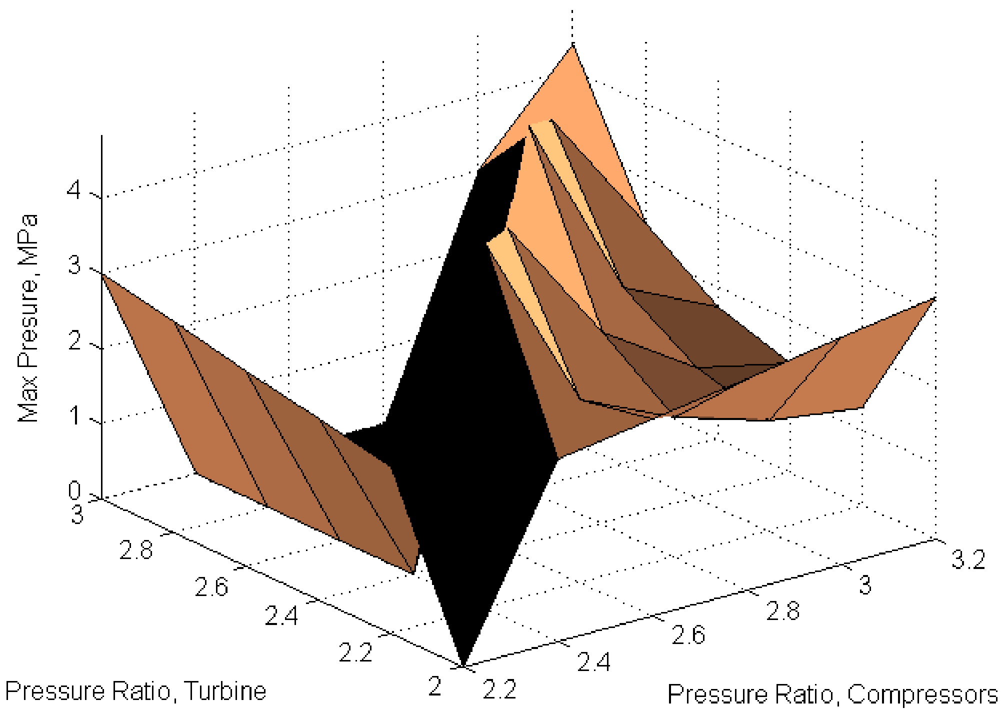


Figure 11 High Pressure Compressor Pressure as a Function of Turbomachine Pressure Ratios

mechanical power production. The dependence of cycle thermodynamic efficiency on heat source and sink temperature is the underlying cause.

In this report optimization of electric generation efficiency was performed with respect to turbomachine pressure ratio but not with respect to heat exchanger thermal-hydraulic parameters. Optimization of heat exchanger size is performed in a way that minimizes temperature and pressure losses for the entire plant subject to an economic constraint on the heat exchanger metal inventory. In the present work the heat exchanger lengths were adjusted only to reflect the change in performance resulting from property changes and resizing related to operating point change. See Table II and III. An integrated optimization of the complete system was not performed.

In the absence of a complete re-optimization at the new operating point, it is still possible to estimate the new efficiency. It is recognized that the actual efficiency obtained for a heat engine falls off with temperature according to the Carnot efficiency times a scaling constant. This empirical relationship, while not rigorously derivable, appears to be a widely accepted rule of thumb. Figure 12 shows the Carnot efficiency plotted as a function of heat source (reactor outlet) temperature. Also shown at 867 C is the *Reduced PHX Temperature Plant* efficiency. This design point is believed optimum since it is based on the *Reference Plant* which was fully optimized with respect to efficiency. Drawn through this point is the Carnot efficiency curve after scaling by a constant of appropriate value. It follows then that at other heat source temperatures, the maximum achievable efficiency lies on this curve. At a temperature of 700 C the value is 40.1 percent. Hence it appears that a pinch analysis performed in the future for the *Reduced IHX and PHX Temperature Plant* might result in the combined plant efficiency rising from 35.5 percent to 40.1 percent.

A second means for estimating an optimized efficiency for the *Reduced IHX and PHX Temperature Plant* is obtained from Figure 13 in [5]. The figure shows the optimized efficiency of a direct cycle helium Brayton loop as a function of reactor outlet temperature. This figure shows a decrease in efficiency of six percent in passing from 850 C to 700 C. If we assume the same decrease in going from the *Reduced PHX Temperature Plant* to the *Reduced IHX and PHX Temperature Plant*, then the plant electric efficiency decreases to 43 percent from 49 percent (Table IV, (-8.1+576-130-105-36)/600=0.49). This provides 258 (=600*0.43) MWe of generated electrical power which is 18 MWe more than appears in the right-most column of Table IV (-8.1+554-151-117-38=240). Then for the *Reduced IHX and PHX Temperature Plant* in Table IV the overall efficiency increases to 38.5 (=0.355+18/600) percent.

In summary, optimized *Reduced IHX and PHX Temperature Plant* efficiency is predicted to lie between 38.5 and 40.1 percent.

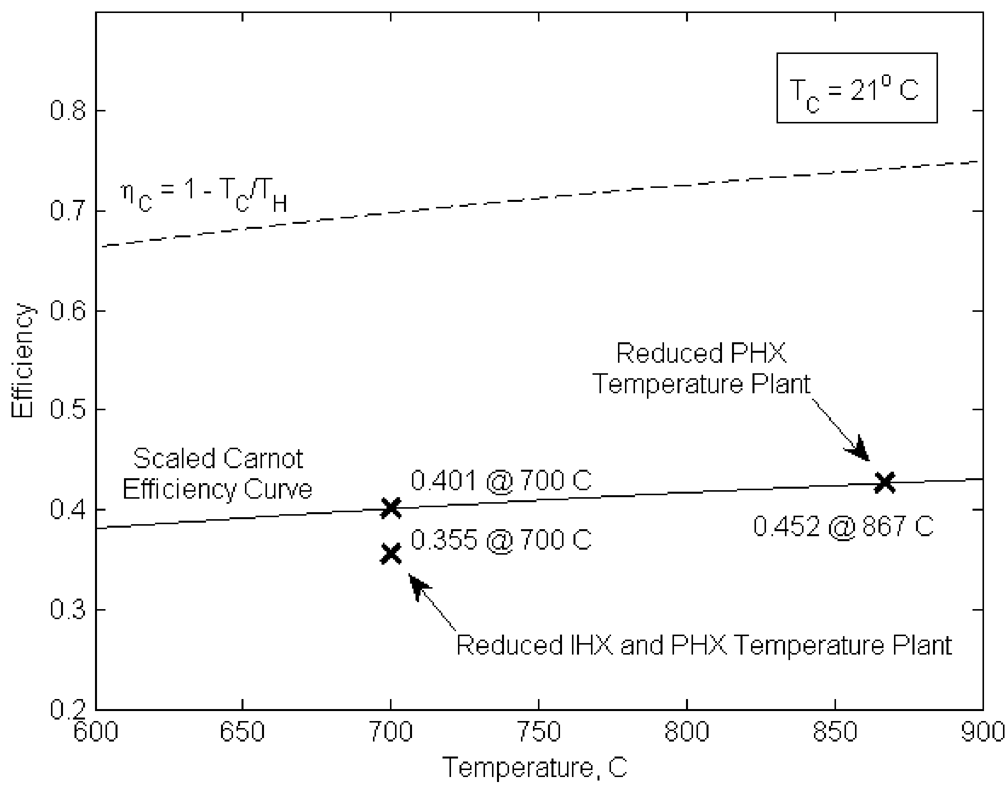


Figure 12 Coupled Plant Efficiency as a Function of Reactor Outlet Temperature

Table IV Coupled Plant Efficiency and Power Inventory by Plant Variant. Powers in MWt

	Plant Variant		
	Reference Plant	*Reduced PHX Temperature Plant.*	*Reduced IHX and PHX Temperature Plant*
Reactor Primary System			
Primary Compressor	-7.0	-8.1	-8.1
Power Conversion Unit and Intermediate System			
Turbine (PCU)	+534	+576	+554
HP Compressor (PCU)	-126	-130	-151
LP Compressor (PCU)	-127	-105	-117
Aux. HP Compressor (PCU)	n.a.	-36	-38
Intermediate System Compressor	-0.9	n.a.	n.a.
Process Heat Loop			
Process Heat Loop Compressor	-7.0	-12	-10
High Temperature Electrolysis Plant			
Cell Electrical Power	-288	unchanged	-288*0.79[c]= -228
Electrical Heating of Reactants (thermal equivalent)	.n.a.	-13.6[b]	-13.6*0.5*0.79/0.4= -13.4[d]
Turbine (HTE)	+11.5	unchanged	11.5*0.79= +9.1
Other Pumps and Compressors	< 0.1	unchanged	unchanged
Hydrogen LHV	+271[a]	unchanged	271*0.79= +215
Q_{net} (sum of above)	+261	+271	+213
Combined Plant Efficiency, $\eta = \frac{Q_{net}}{Q_{reactor}}$	$\frac{261}{594} = 0.439$	$\frac{271}{600} = 0.452$	$\frac{213}{600} = 0.355$

.[a] 2.26 kg/s*120.1 MJoules/kg [b] Assumes electric generation efficiency of 0.5 [c] The factor that the cell power must be scaled by to produce a hydrogen LHV value equal to Q_{net} [d] Factor 0.5/0.4 accounts for reduced electric generation efficiency at reduced reactor outlet temperature

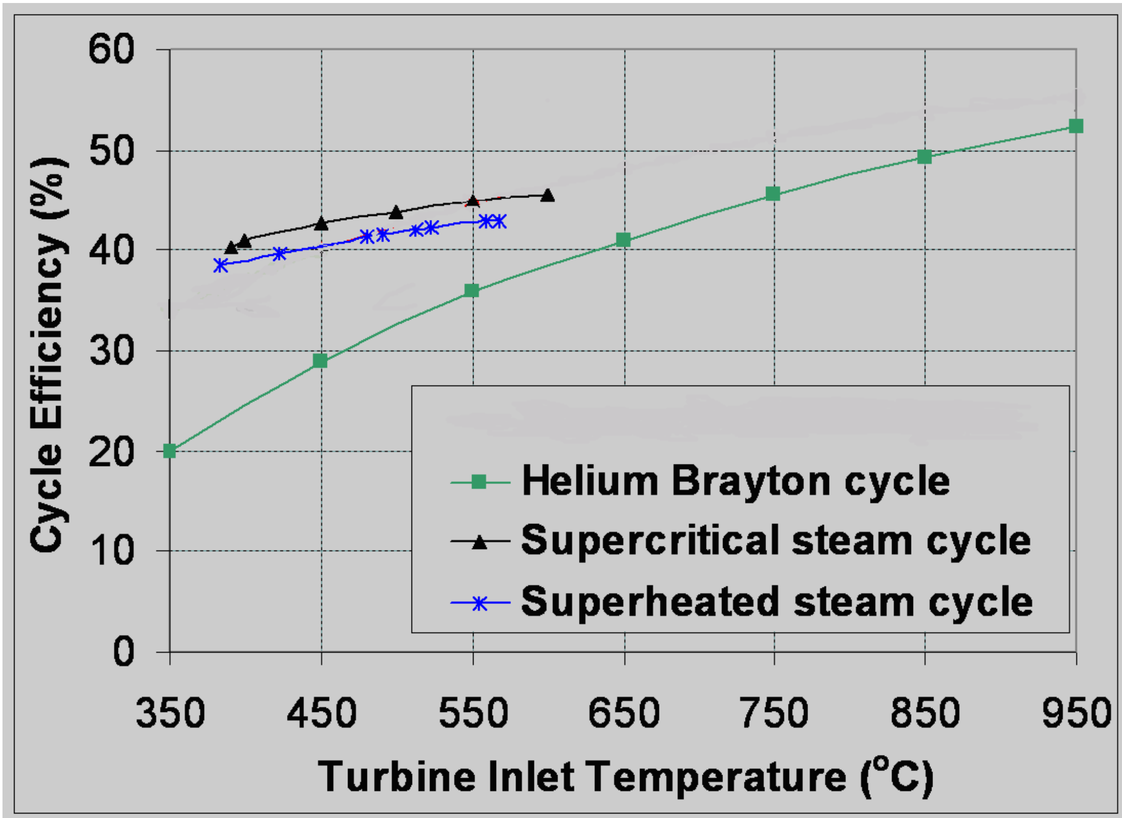


Figure 13 Direct Helium Brayton Cycle Efficiency as a Function of Inlet Temperature [5]

B. Thermal Creep

An indication of the reduced metal capability needed with respect to thermal creep when IHX temperature is lowered by 150 C is provided by Figure 8. This figure assumes that Incoloy 800 H has been loaded with a stress (1.35 ksi) that produces a one percent strain in 40 years at a temperature of 850 C. The figure shows that a reduction in temperature to 700 C reduces the creep rate by approximately five orders of magnitude. Clearly the continued use of Incoloy 800 H at this new condition represents an unnecessary cost. Use instead of a cheaper lower Cr-Ni alloy would be preferred.

C. Economic Performance

C.1 Metal Alloy Inventories as a Function of Creep Capabilities

Thermal creep behavior is important for metals forming a pressure boundary in high-temperature environments. As temperature increases greater fractions of nickel and chromium are needed to maintain creep rate constant under constant mechanical loading. The consequence of this is seen in Table V where the main components in the NGNP system are identified along with normal operating temperature and a representative metal alloy (as identified in the literature). The highest Cr-Ni alloys appear in the high-temperature heat exchangers (IHX and PHX). The mass of these components is derived in Table VI. The trend of Cr-Ni concentration versus temperature seen in Table V (see right-hand column) presents an opportunity for commodities cost savings by reducing reactor outlet temperature to 700 C.

To obtain a measure of the potential commodities cost savings achievable through reactor outlet temperature reduction, the fraction of alloy type by mass for the NGNP plant is shown in the third column from the left side of Table V. One sees that the 23Cr-42Ni-10Mo (Incoloy 800 H) alloy of the high temperature heat exchangers makes up just under five percent of the total metal mass of the NGNP. The next most exotic metal, 19Cr -30Ni (Incoloy 800 H), makes up just under another three percent of the total metal mass. Thus, there appears to be the potential for the highest cost alloys, about eight percent of the NGNP inventory, to be replaced by less expensive alloys upon reduction in temperature to 700 C.

There is potentially an increase in commodities inventory associated with equipment resizing for operation at the lower reactor outlet temperature. There are three separate effects. 1) The right-hand column of Table IV shows compressor power is increased meaning a larger physical unit. The fractional increase in total NGNP inventory associated with this is about 1.5 percent from Tables IV and V. Table V shows the compressors are made of the least-expensive metal commodity in the plant. 2) There is a decrease in recuperator heat transfer area that from Tables II and III amounts to a physical size reduction of 54 percent (i.e. 1- 11.8/25.6). From Table V this amounts to five percent of the total NGNP metal mass inventory. This component is made from an alloy with a Cr-Ni content that is about equal to the plant average. 3) Table III shows the heat transfer area of the coolers increased by ten percent which from Table V amounts to a 0.6 percent increase (i.e. 0.06*0.1) in total NGNP metal mass. Table V shows the coolers are made of the least-expensive metal in the plant. All three effects add up to about a three percent reduction in mass of commodities. The cost savings is even larger as the more costly recuperator metal dominates the reduction in mass.

We compute a *cost-normalized* efficiency where the efficiency has been normalized by equipment cost for comparison with competing designs. Specifically, efficiency is increased to reflect the additional power produced when the plant size is increased by a fraction equal to the commodities cost reduction in going from the *Reference Plant* to the *Reduced IHX and PHX Temperature Plant*. Then the previous estimate for *Reduced IHX and PHX Temperature Plant*.efficiency (between 38.5 and 40.1) becomes between 40.0 and 41.3. This latter range should be compared with the value of 43.9 obtained for the *Reference Plant* in Table IV.

C.2 Energy-Equivalent Product per Unit Cost

A key economic question is how much does reduced commodities cost per unit mass with decreasing temperature offset accompanying loss of product production? The cost of a component is made up of a commodities cost and a labor cost. Hence, the fractional savings above realized through substituting in a less expensive commodity is diminished somewhat as the labor cost remains fixed. Additionally, it is the component cost per unit product produced that is the true measure of economics. If plant efficiency is reduced when temperature is lowered, there is less product produced.

D. Tritium Migration Rate

In [1] we reported that the PHX temperature dropped from an average of 800 C in the *Reference Plant* to 200 C in the *Reduced PHX Temperature Plant*. This heat exchanger is an ultimate barrier to diffusion of tritium from the nuclear plant to the chemical plant. From Figure 9 the permeability of hydrogen isotopes in high temperature and low temperature alloys decreases by three orders of magnitude for this temperature drop. Figure 9 also shows that a temperature reduction of 150 C in the IHX decreases the permeability by a factor of three. Thus the diffusion of tritium is significantly reduced in both the *Reduced PHX Temperature Plant* and the *Reduced IHX and PHX Temperature Plant*

VI. CONCLUSIONS

Operation of the Next Generation Nuclear Plant (NGNP) with reduced reactor outlet temperature at full power was investigated for the High Temperature Electrolysis (HTE) hydrogen-production application. The foremost challenge for operation at design temperature is achieving an acceptably long service life for heat exchangers. In both the Intermediate Heat Exchanger (IHX) and the Process Heat Exchanger (PHX) (referred to collectively as high temperature heat exchangers) a pressure differential of several MPa exists with temperatures at or above 850 C. Thermal creep of the heat exchanger channel wall may severely limit heat exchanger life depending on the alloy selected. This report investigates plant performance with IHX temperatures reduced by lowering reactor outlet temperature. The objective is to lower the temperature in heat transfer channels to the point where existing materials can meet the 40 year lifetime needed for this component. A conservative estimate for this temperature is believed to be about 700 C.

The reactor outlet temperature was reduced from 850 C to 700 C while maintaining reactor power at 600 MWt and high pressure compressor outlet at 7 MPa. We included a previously reported design option for reducing temperature at the PHX. Heat exchanger lengths were adjusted to reflect the change in performance resulting from coolant property changes and from resizing related to operating-point change. Turbomachine parameters were also optimized for the new operating condition. An integrated optimization of the complete system including heat transfer equipment was not performed. It is estimated, however, that by performing a pinch analysis the combined plant efficiency can be increased from 35.5 percent obtained in this report to a value between 38.5 and 40.1 percent. Then after normalizing for a more than three percent decrease in commodities inventory compared to the reference plant, the *commodities-normalized* efficiency lies between 40.0 and 41.3. This compares with a value of 43.9 for the reference plant.

The reduction in reactor outlet temperature from 850 C to 700 C reduces the tritium permeability rate in the IHX metal by a factor of three and thermal creep by five orders of magnitude. The design option for reducing PHX temperature from 800 C to 200 C reduces the permeability there by three orders of magnitude. In that design option this heat exchanger is the single "choke-point" for tritium migration from the nuclear to the chemical plant.

Table V Inventory of Metal Masses for Major NGNP Components

Component	Mass, kg	Fraction of Total	Normal Operating Temperature, C	Representative Alloy	Comments
Reactor					
Vessel	1,200,000	0.26	500	9Cr-1Mo-V (TI-91)	average-cost commodity
Core Barrel	100,000*	0.022	850	19Cr -30Ni (Incoloy 800 H)	high-cost commodity
Core Support Plate	unknown	0.005+	850	19Cr -30Ni (Incoloy 800 H)	high-cost commodity
Heat Exchangers					
IHX	200,000	0.044	850	23Cr-42Ni-10Mo (Hastelloy XR)	very high-cost commodity
Recuperator	450,000	0.10	100-500	8Cr-16Ni-11Mo	-
Precooler	150,000	0.03	130	1/2 Cr-1/2 Mo	low-cost commodity
Intercooler	160,000	0.03	130	1/2 Cr-1/2 Mo	low-cost commodity
PHX	15,000	0.003	850	23Cr-42Ni-10Mo (Hastelloy XR)	very high-cost commodity
Turbomachines					
Turbine	200,000	0.044	-	-	-
Low Press. Comp.	200,000	0.044	30-120	1/2 Cr-1/2 Mo	low-cost commodity
High Press. Comp.	200,000	0.044	30-120	1/2 Cr-1/2 Mo	low-cost commodity
Electric Generator	312,000	0.07	-	-	-
PCU Vessel	1,400,000	0.31	500	9Cr-1Mo-V (TI-91)	average-cost commodity
TOTAL	4,550,000	1.0			

* Δt=0.076m, R=2.42m, L=10.7m + guesstimate

Table VI Estimated Masses for Reference Plant Heat Exchangers*

Parameter	IHX	Recuperator	PHX
Heat Exchanger Type	PCHE	PCHE	PCHE
Outside Dimensions			
Width, m	4.75	6.23	1.52
Height, m	4.75	6.23	1.52
Length, m	2.34	1.62	1.09
Internal Dimensions			
Hot Side Flow Area, m^2	6.48	3.78	0.385
Cold Side Flow Area, m^2	6.48	3.78	0.385
Total Flow Area, m^2	12.96	7.56	0.770
Total Coolant Volume, m^3	30.33	12.25	0.839
Total Metal Volume, m^3	22.47	50.63	1.679
Heat Transfer Surfaces			
Alloy+	Hastelloy XR	Hastelloy XR	Hastelloy XR
Density, kg/m^3	8890	8890	8890
Total Mass, kg	200,000	450,000	15,000

* Active heat transfer region only. Neglects plenum regions.
+ Representative metal.

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REFERENCES

1. R.B. Vilim, "Alternate VHTR/HTE Interface for Mitigating Tritium Transport and Structure Creep," ANL-GenIV-102, March 2008.
2. Davis C.B., Oh C.H., Barner R.B., Sherman S.R., and Wilson D.F., 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 2006.
3. Oh C. H., *et al.*, "HyPEP FY06 Report: Models and Methods," INL/EXT-06-11725, 2006.
4. Vilim R.B., "Power Requirements at the VHTR/HTE Interface for Hydrogen Production," Proceedings of ICAPP 2007 Nice, France, May 13-18, 2007.
5. N. Carstens, "Control Strategies for Supercritical Carbon Dioxide Power Conversion Systems," MIT Department of Nuclear Science and Engineering Ph.D. thesis, June 2007.
6. Natesan, K. "Materials Behavior in HTGR Environments," NUREG/CR-6824, ANL-02/37, July 2003.
7. Blackburn, L.D., Isochronous Stress-Strain Curves for Austenitic Stainless Steels, American Society of Mechanical Engineers, 1972.
8. Booker, M.K. *et al.*, "Survey of Available Creep and Tensile Data for Alloy 800H, Oak Ridge National Laboratory, ORNL/TM-6029, 1978.

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