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Comparison of Direct and Indirect Gas Reactor Brayton Systems for Nuclear Electric Space Propulsion

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Abstract – *Gas reactor systems are being considered as candidates for use in generating power for the Prometheus-1 spacecraft, along with other NASA missions as part of the Prometheus program. Gas reactors offer a benign coolant, which increases core and structural materials options. However, the gas coolant has inferior thermal transport properties, relative to other coolant candidates such as liquid metals. This leads to concerns for providing effective heat transfer and for minimizing pressure drop within the reactor core. In direct gas Brayton systems, i.e. those with one or more Brayton turbines in the reactor cooling loop, the ability to provide effective core cooling and low pressure drop is further constrained by the need for a low pressure, high molecular weight gas, typically a mixture of helium and xenon. Use of separate primary and secondary gas loops, one for the reactor and one or more for the Brayton system(s) separated by heat exchanger(s), allows for independent optimization of the pressure and gas composition of each loop. The reactor loop can use higher pressure pure helium, which provides improved heat transfer and heat transport properties, while the Brayton loop can utilize lower pressure He-Xe. However, this approach requires a separate primary gas circulator and also requires gas to gas heat exchangers. This paper focuses on the trade-offs between the direct gas reactor Brayton system and the indirect gas Brayton system. It discusses heat exchanger arrangement and materials options and projects heat exchanger mass based on heat transfer area and structural design needs. Analysis indicates that these heat exchangers add considerable mass, but result in reactor cooling and system resiliency improvements.*

I. INTRODUCTION

In a direct cycle gas Brayton system the reactor coolant also serves as the working fluid in the Brayton thermodynamic cycle. In an indirect system the reactor coolant is coupled to the Brayton working fluid through an intermediate heat exchanger. High temperature gas reactors coupled with a Brayton thermodynamic cycle provide a potentially viable heat source/power conversion system for space power applications. In Reference 1 a high temperature gas cooled reactor directly coupled to a Brayton energy conversion system was proposed for 20 kWe space lander application. The coolant in this concept is a mixture of helium/xenon.

II. COMPARISON OF DIRECT AND INDIRECT OPTIONS

An indirect gas Brayton cycle offers both advantages and disadvantages relative to a direct gas Brayton system for space propulsion applications. Figure 1 illustrates the main components of both direct and indirect gas Brayton systems. An indirect gas Brayton system provides the following benefits over a direct gas system:

1. The intermediate heat exchangers isolate the reactor from the energy conversion units providing potential improvements in system resiliency. Through this isolation the Brayton units in the secondary system are isolated from

potential primary contamination. For systems with multiple Brayton units the Brayton units are also isolated from one another making the system more fault tolerant to catastrophic Brayton failures.

2. The primary coolant can be optimized to provide more ideal conditions for core cooling and the secondary gas can be optimized to provide more ideal conditions for Brayton power conversion. Higher primary pressures with pure helium gas provide better thermal hydraulic characteristics for core cooling. For the Brayton energy conversion, a gas mixture of helium and xenon provides a more efficient Brayton unit due to the higher molecular weight of the xenon gas, and the pressure of the helium/xenon can be set to optimize system performance. References 3 and 4 provide various system trade sensitivities as a function of helium/xenon composition and pressure.

An indirect system also results in disadvantages relative to the direct Brayton cycle for space propulsion applications. The following provides a summary of the main disadvantages:

1. The isolation of the primary and secondary coolants requires independent coolant circulation mechanism for both the primary and secondary loops. In a direct cycle Brayton system the turbine compressor unit circulates the coolant. In an indirect cycle a gas circulator is required in the primary loop. This circulator adds additional system complexity and additional pumping power/mass requirements on the system.

2. Although the intermediate heat exchanger provides isolation it also results in additional system mass and adds a significant amount of surface area and welds (potential leakage paths) to the primary and secondary loops. Some of this additional area is operated at or near the outlet temperature of the reactor.

The remainder of this paper focuses on sizing considerations for intermediate heat exchangers at the temperatures and conditions envisioned for a Prometheus1 space mission with indirect gas-Brayton energy conversion system. The operating power level assumed in these sizing estimates is approximately 200 kWe. This power level is twice the design point power for planetary missions described in Reference 2. For the studies in this paper, four Brayton units each sized to provide half of the mission power requirements form the power plant baseline. Two of the units are operated continuously and two additional units are retained as back-up for redundancy.

In an indirect Brayton system intermediate heat exchangers provide isolation between the primary and secondary fluids. This isolation comes at the expense of system mass and places a strong dependence on the structural integrity of the heat exchangers to maintain primary/secondary fluid isolation through mission life. For projected missions of 15 years material creep becomes a critical parameter in the successful operation of the heat exchangers. For other components in the power system (i.e. piping, vessels, etc …) various engineering solutions can be employed to reduce structural boundary temperatures and mitigate the effects of creep. One such example is the primary pipe in pipe configuration shown in Figure 2. In this piping configuration the cooler primary fluid passes through the outer annulus and allows the structural boundary between space and structural piping boundary to be operated at the inlet temperature of the reactor. For the intermediate heat exchangers, separation of the primary and secondary fluids must be maintained while also maintaining elevated temperatures across this same structural boundary to achieve the necessary heat transfer.

This paper summarizes relevant literature for heat exchangers designed to similar temperature limits and provides an intermediate heat exchanger sizing estimate for a fifteen year space mission. Table I provides a summary of the system conditions for an indirect gas Brayton design for a Prometheus1 mission. At the reactor outlet temperatures (~877^{o}C) and mission life (~15 years) envisioned for an indirect Brayton concept material strengths and creep resistance of non-refractory materials are marginal at best. Several non-refractory material options have been evaluated in the past for similar temperature ranges as documented in Reference 5 and 6. Figure 3 depicts a notional allowable stress for the more promising non-refractory alloys as a function of temperature over a 15 year mission.

III. INTERMEDIATE HEAT EXCHANGER DESIGN OPTIONS

Various heat exchanger designs have been evaluated at similar temperatures required by an intermediate heat exchanger for a Prometheus1 mission. The heat exchanger designs considered can be grouped into the following three categories: (1) compact brazed plate-fin designs, (2) diffusion bonded designs and (3) shell and tube designs. The compact brazed design is commonly used in a multitude of applications including air craft applications, commercial and residential cooling and chemical/food processing. These designs typically result in the most compact, lowest mass heat exchangers for a given power rating and desired coolant temperature conditions. The operating conditions of these heat exchangers are usually limited to temperatures of 600°C or less (see Reference 7). The rectangular geometry and braze materials typically limit the operating temperatures of these designs. Due to the operating temperature limits for these heat exchangers, they were not considered as candidates for an intermediate heat exchanger design. Compact plate fin designs have been proposed at temperatures of 800 – 900°C per Reference 8; however, these heat exchangers have not been built or tested. A significant amount of development work would be required to fabricate a plate fin design in this temperature range.

Brazed plate fin recuperators have been operated at temperatures in excess of 600°C. Unlike the intermediate heat exchanger for the indirect-Brayton cycle, some minor leaks between the hot and cold fluids can be tolerated in a recuperator with minimal impact on overall system performance. Reference 9 summarizes the fabrication and testing of a brazed plate-fin recuperator with a hot gas inlet temperature of 722°C.

Shell and tube designs are also widely used in a variety of chemical and power generation applications. These designs tend to be more robust than compact brazed plate-fin heat exchangers. At similar operating temperatures envisioned for Prometheus1 mission, a shell and tube design has been built and is currently being operated in the Japanese High Temperature Test Reactor (see Reference 10). The high temperature components of this heat exchanger were fabricated from Hastelloy XR. A schematic of this design is provided in Figure 4. In the HTTR design the primary fluid flows on the shell side and the secondary fluid flows on the tube side. The tubes are helically arranged to improve heat transfer. The heat exchanger flow path is designed so that the ambient pressure boundaries are maintained at the cold temperatures of the primary and secondary fluids (378°C for primary helium and 283°C for the secondary helium). The pressure difference between the primary and secondary systems is maintained at approximately 0.1 MPa to minimize the pressure stresses in the heat exchanger. Another helium cooled reactor, the German AVR, used a shell and tube boiler design to extract the heat from the primary coolant. Primary outlet temperatures for this reactor were as high as 950°C. Reference 11 provides a summary of the plant layout and operating conditions for the AVR design.

Diffusion bonded heat exchanger designs have also been evaluated at temperatures similar to Prometheus1 reactor outlet temperatures. Reference 12 provides a summary of the design and testing of heat exchanger submodules for potential use in the Japanese HTTR. Diffusion bonded heat exchangers designed by Heatric of Dorset England operate at temperatures up to ~800°C. In these designs flat plates are chemically etched using printed circuit board technology. The plates are then stacked and diffusion bonded at elevated temperatures. The improved heat transfer from the micro-channels of these heat exchangers results in compact heat exchanger cores. The diffusion bonding results in a more structurally robust design relative to brazed plate fin designs at the expense of greater heat exchanger mass. In Reference 8, diffusion bonded heat exchangers fabricated from high temperature Nickel superalloys have been proposed for operating temperatures up to 900°C. A significant development effort would be required to design and qualify this heat exchanger at these temperatures.

IV. NOMINAL HEAT EXCHANGER SIZING ESTIMATES

The following calculations provide sizing estimates for a notional shell and tube heat exchanger illustrated in Figure 5. In this counter flow pipe in pipe design, the primary helium coolant from the reactor outlet passes on the tube side of the heat exchanger and then makes a 180 degree turn and flows upward through the outer annulus of the heat exchanger. The secondary helium xenon gas passes on the outside of the tube bundle and turns 180 degrees and flows downward through an inner pipe. Similar to the pipe in pipe configuration shown in Figure 4, this heat exchanger is configured so that the structural boundaries between the primary and secondary fluids (other than the tube bundle and tube sheet) and the primary fluid and space are maintained at T_{cold} of each of the fluids. The tube bundle length and number of tubes were sized to meet the design parameters outlined in Table I. Equations 1 and 2 provide the heat transfer correlations used for the helium and helium xenon fluids. The fully developed turbulent equation is based on the Dittus-Boelter correlation and the laminar correlation is based on the Nusselt number for fully developed laminar flow in a circular cross section.

$$h = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{n} \cdot \frac{k}{D_h} \qquad \mathit{for}\ \mathrm{Re} > 2300 \tag{1}$$

$$h = 3.66 \cdot \frac{k}{D_h} \qquad \mathit{for}\ \mathrm{Re} \le 2300 \tag{2}$$

Where: n = 0.3 for the primary fluid (helium)

n = 0.4 for the secondary fluid (HeXe)

The straight section of the tube bundle is sized based on the standard heat exchanger sizing equation from Reference 13 provided in Equations 3 and 4 below.

$$U_{He} = \left[\frac{ID_{tube}}{h_{HeXe} \cdot OD_{tube}} + \ln\left(\frac{OD_{tube}}{ID_{tube}}\right) \cdot \frac{ID_{tube}}{2\pi \cdot k_{tube}} + \frac{1}{h_{He}} \right]^{-1} \quad (3)$$

$$L_{tubebundle} = \frac{Q}{N_{tubes} \cdot \pi \cdot ID_{tube} \cdot U_{He} \cdot \Delta T_{lm}} \quad (4)$$

Where:

$$\Delta T_{lm} = \frac{(T_{hot.He} - T_{hot.HeXe}) - (T_{cold.He} - T_{cold.HeXe})}{\ln\left(\frac{T_{hot.He} - T_{hot.HeXe}}{T_{cold.He} - T_{cold.HeXe}}\right)} \quad (5)$$

The inner diameter of the tubes for this heat exchanger have been set to 2.8 millimeters. The relatively small flow passages provide improved heat transfer similar to the micro-channel features in the diffusion bonded heat exchangers. These small tube diameters may pose some tube vibration concerns and require structural supports located periodically along the tube lengths. Potential flow induced vibration modes were not evaluated in this paper.

The structural materials evaluated for the heat exchanger are Haynes 230 and Hastelloy X. The mass of the tube bundle and heat exchanger structural components have been sized based on the nominal temperatures in Figure 5. The effects of microstructural phase stability on the material properties was not considered in the sizing estimates and would need to be studied further for a mission duration of 15 years at temperatures of 877^{o}C.

Table II provides a summary of the heat exchanger dimensions and corresponding mass to meet the operating parameters in Table II. Only primary pressure stresses were considered for the sizing estimates. From this table the higher creep resistance of Haynes 230 provides a weight reduction of approximately 360 kg relative to the Hastelloy X design on a single heat exchanger basis. However, even for the Haynes 230 design, the heat exchanger mass represents a significant fraction of the total estimated propulsion plant mass for an envisioned 15 year Prometheus mission. Assuming four independent Brayton loops and four intermediate heat exchangers an additional 2280 – 3720 kg of heat exchanger mass is required relative to a direct gas Brayton system with total propulsion plant mass in the range of 6500 – 7000 kg. The reductions in core mass associated with the improved coolant properties in an indirect gas Brayton system are expected to be minimal relative to the additional heat exchanger mass.

Another design option for potential reductions in heat exchanger mass is to raise the reactor outlet temperature and design the heat exchanger with refractory materials while keeping the turbine inlet temperature the same. This would increase the log mean temperature difference and reduce the heat exchanger size at the expense of higher primary operating temperatures. Due to the higher fuel temperatures and the more difficult primary piping/circulator material options this design case was not pursued.

IV. CONCLUSIONS

For space applications, an indirect Brayton system provides both benefits and drawbacks relative to a direct Brayton system. The indirect Brayton system isolates the energy conversion units from the primary loop at the expense of a primary gas circulator and increased system mass. Shell and tube and diffusion bonded designs have been evaluated for operation in the envisioned temperature range of a Prometheus mission. A shell and tube helical design for the intermediate heat exchanger in the Japanese HTTR was constructed from Hastelloy XR and has been operated at temperatures between 850 and 950^{o}C. Sizing estimates have been provided for a counterflow shell and tube heat exchanger design for both Hastelloy X and Haynes 230 materials. The resulting heat exchanger mass estimates are significant fraction of the total propulsion plant mass for a similar direct gas Brayton system (~ 32 - 57%). The importance of mass in space applications and the addition of primary circulators is expected to outweigh the potential resiliency benefits of primary/secondary isolation offered by an indirect gas system.

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The views expressed in this document are those of the author and do not necessarily reflect agreement by the government.

NOMENCLATURE

h – heat transfer coefficient (W/(m^2 K))
Re – Reynolds number (-)
Pr – Prandtl number (-)
k – thermal conductivity (W/(m K))
D_h – hydraulic diameter (m)
U_{He} – overall heat transfer coefficient (W/(m^2 K))
OD_{tube} – outer diameter of tubes (m)
ID_{tube} – inner diameter of tubes (m)

$L_{tubebundle}$ – length of the straight section of the tube bundle (m)
Q – heat load rating of the heat exchanger (W)
N_{tubes} – number of tubes (-)
T – helium and helium/xenon temperatures (K)
ΔT_{lm} – log mean temperature difference (K)

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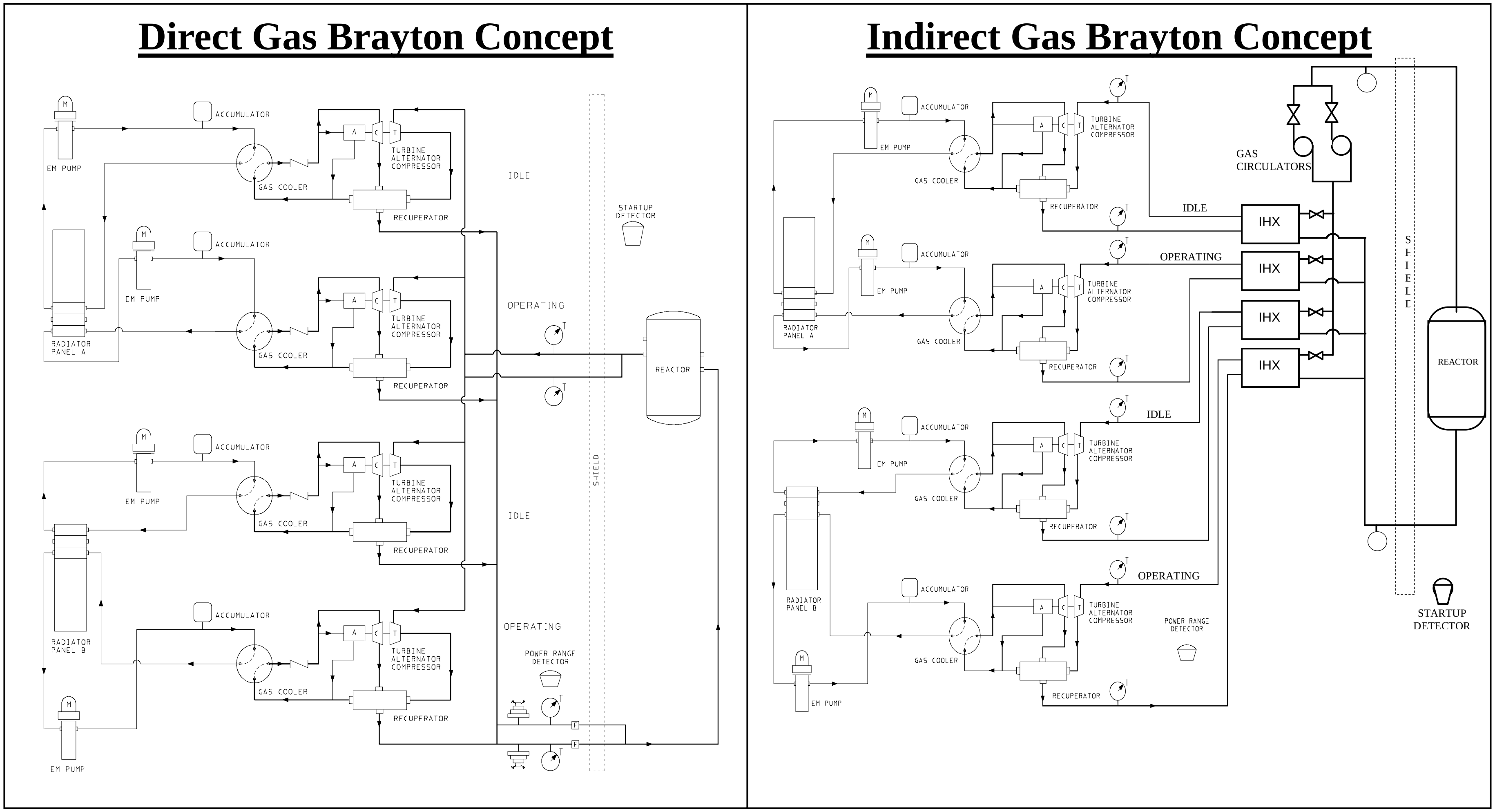

Figure 1: Comparison of system layouts for direct and indirect gas Brayton systems assuming 2 operating and 2 idled Brayton units in each system.

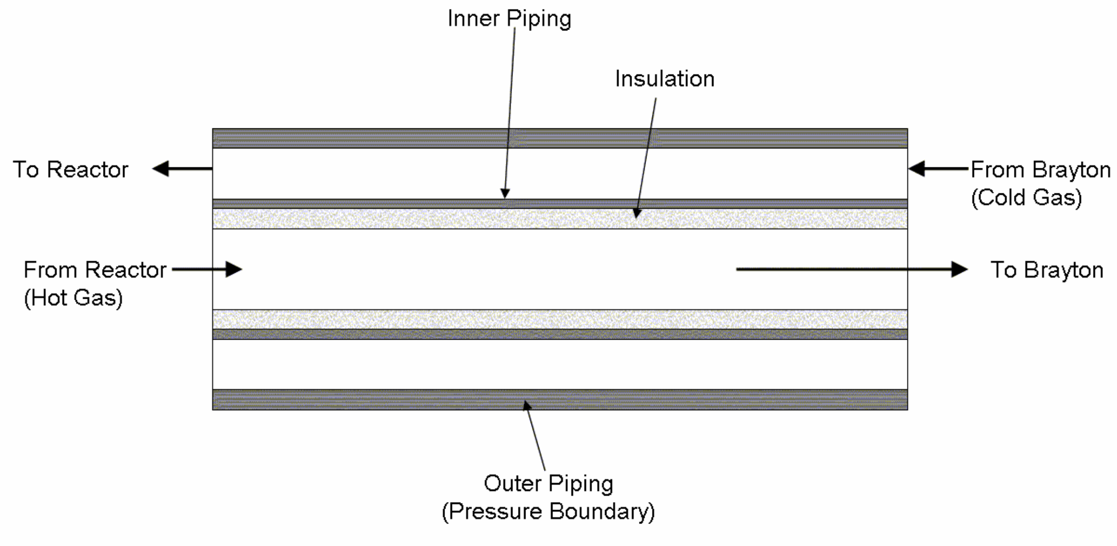

Figure 2: Schematic illustrating the pipe in pipe concept.

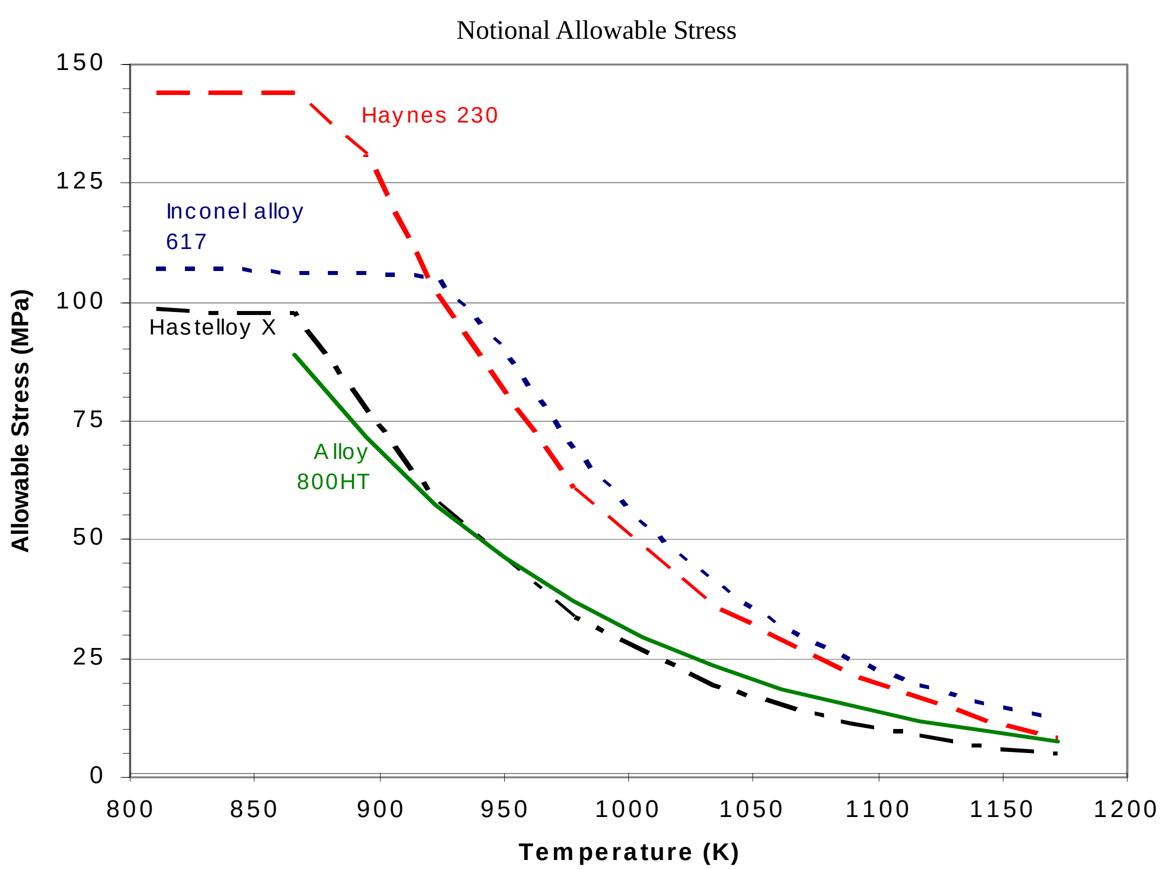

Figure 3: Notional allowable stress plot of the more promising non-refractory alloys. The allowable stress is evaluated to be the minimum of the ASME Vessel Code allowable stress, 1% creep strain stress, and 2/3 of the creep rupture stress based on References (14–18). The creep strain stresses are extrapolated to the mission time of 135,000 hours.

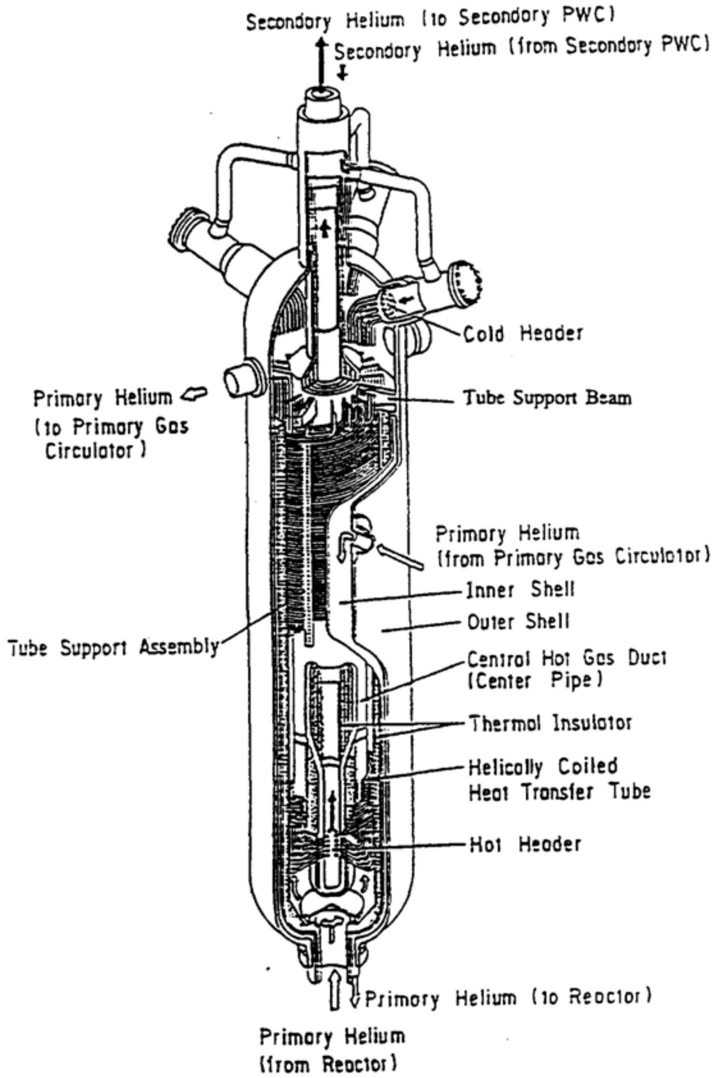

Figure 4: Cross sectional view of the Japanese HTTR helically coiled intermediate heat exchanger (from Reference 12).

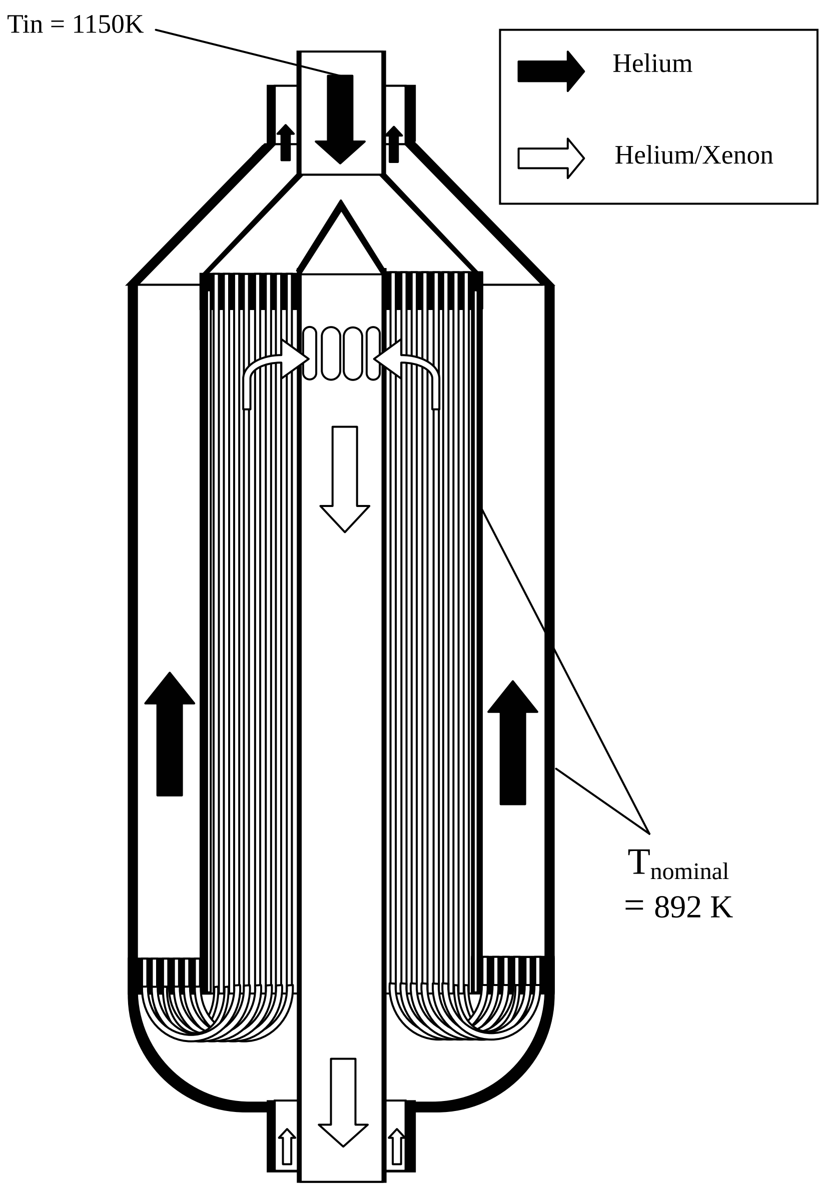

Figure 5: Intermediate heat exchanger concept for indirect gas Brayton heat exchanger sizing estimates.

Table I: Summary of intermediate heat exchanger operating conditions assumed for a 15 year Prometheus mission.*

Parameter	Primary Side of the Heat Exchanger	Secondary Side of the Heat Exchanger
Working Fluid	Helium	Helium/Xenon (0.7177/0.2823 on a mole fraction basis)
Pressure (MPa)	4	1.4
Heat Exchanger Inlet Temperature (^{o}C)	877	572
Heat Exchanger Outlet Temperature (^{o}C)	619	827
Target Heat Exchanger Pressure Drop Ratio ($\Delta P/P$)	0.01	0.015
Total Heat Transfer/Heat Exchanger (kW)	392.5	

* The parameters listed in this table represent a point design and not an optimized overall system design.

Table II: Summary of heat exchanger performance/sizing estimates for a single heat exchanger.

Parameter	Haynes 230 Design	Hastelloy X Design
Tube Inner Diameter (mm)	2.8	
Tube Wall Thickness (mm)	0.386	0.82
Tube Bundle Length - straight section (m)	1.384	1.21
Number of Tubes	3248	
Tube Bundle Mass (kg) Includes tubes, tube sheets, and tube bends	237	453
Shell and Ducting Mass (kg)	333	477
Total Heat Exchanger Mass (kg)	570	930