LM-05K184
January 24, 2006

Prometheus Hot Leg Piping Concept

AM Girbik and PA DiLorenzo

Prometheus Hot Leg Piping Concept

Anastasia M. Gribik[1] and Peter A. DiLorenzo[2]

[1]Bechtel Bettis, Inc., Bettis Atomic Power Laboratory, West Mifflin, PA 15122, USA
[2]KAPL, Inc., Knolls Atomic Power Laboratory, Schenectady, NY 12301, USA

Abstract. The Naval Reactors Prime Contractor Team (NRPCT) recommended the development of a gas cooled reactor directly coupled to a Brayton energy conversion system as the Space Nuclear Power Plant (SNPP) for NASA's Project Prometheus. The section of piping between the reactor outlet and turbine inlet, designated as the hot leg piping, required unique design features to allow the use of a nickel superalloy rather than a refractory metal as the pressure boundary. The NRPCT evaluated a variety of hot leg piping concepts for performance relative to SNPP system parameters, manufacturability, material considerations, and comparison to past high temperature gas reactor (HTGR) practice. Manufacturability challenges and the impact of pressure drop and turbine entrance temperature reduction on cycle efficiency were discriminators between the piping concepts. This paper summarizes the NRPCT hot leg piping evaluation, presents the concept recommended, and summarizes developmental issues for the recommended concept.

Keywords: Gas reactor piping, internal insulation, Prometheus
PACS: Replace this text with PACS numbers; choose from this list: http://www.aip.org/pacs/index.html

BACKGROUND

The SNPP design incorporates a piping system which circulates He-Xe gas through the reactor and closed Brayton energy conversion system. The piping is comprised of high pressure (~2 MPa) and low pressure (~1 MPa) sections. The high pressure sections include piping from the reactor to the turbine inlet, piping from the compressor outlet to the recuperator, and piping from the recuperator to the reactor. The low pressure sections include piping from the turbine outlet to the recuperator, piping from the recuperator to the gas cooler, and piping from the gas cooler to the compressor inlet. The heat balance shown in Figure 1 was generated from the NASA Glenn space reactor power system optimization spreadsheet, and depicts the nominal operating conditions for the multi-Brayton plant piping used in the hot leg piping analysis.

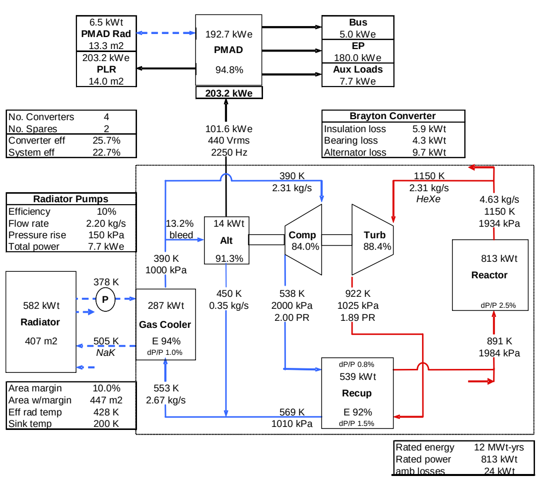

FIGURE 1. Direct Gas Concept System Schematic with Nominal Operating Conditions.

Nominal values of operating pressure, temperature, and flow are shown in Table 1.

TABLE 1. Nominal Piping Operating Parameters.

Piping Run		**Pressure**	**Gas Temperature**	**Flow**
From	**To**	**(MPa)**	**(K)**	**(kg/s)**
Reactor	Turbine	1.93	1150	4.63
Turbine	Recuperator	1.02	922	2.32
Recuperator	Cooler	1.01	569	2.32
Cooler	Compressor	1.00	390	2.32
Compressor	Recuperator	2.00	538	2.32
Recuperator	Reactor	1.98	891	4.63

The baseline material for the plant piping is Inconel 617, a nickel superalloy. Nickel superalloys were the primary piping material candidates due to their structural performance at high temperatures and compatibility with atmospheric constituents. The hot leg piping contains the highest temperature gas and is located in the high pressure section of the system. In the absence of a heat transfer barrier, the pipe metal temperature would approach the temperature of the gas in contact with the piping. According to currently available materials test data at temperatures above ~900K the thermal creep resistance of Inconel 617 decreases significantly (Bassford , 1982) and (Corum, 1991). As a result, the hot leg piping required unique design features to control pressure boundary temperature which did not apply to the rest of the piping sections. It should be noted that the turbine to recuperator piping section also contains gas at a temperature in excess of 900 K. However, the lower gas temperature and pressure (relative to the hot leg piping) and the ability to increase the wall thickness of this piping section likely preclude the need for additional control of pressure boundary temperature.

HOT LEG PIPING REQUIREMENTS

The hot leg piping contains He-Xe gas at a nominal operating temperature and pressure of approximately 1150K and 1.9 MPa. However, hot leg piping operating pressures from 1.4 MPa to 4 MPa are being evaluated. While refractory metal alloys such as Mo-47.5Re, Nb-1Zr, and Ta-10W offer better high temperature creep resistance than nickel superalloys, it was preferred that the piping material be a nickel superalloy to maximize mission extensibility and to minimize material compatibility issues, cost, and uncertainties associated with the development and use of refractory metals. Key challenges associated with a refractory metal hot leg pipe include:

- A bimetallic pressure boundary joint would be required between the refractory outer pipe and the cast nickel superalloy turbine housing.
- Surface mission extensibility would be decreased since refractory metals can not be exposed to atmospheric constituents.
- Refractory piping requires the reactor pressure vessel to be constructed of a refractory metal or the addition of a second bimetallic pressure boundary joint between the refractory outer pipe and the reactor pressure vessel.
- A controlled environment is necessary for testing refractory metals at elevated temperature (i.e. a high purity vacuum).
- There is an increased risk of failure for long term operation of the ground test reactor due to the potential for loss of high purity vacuum (external to the reactor primary pressure boundary).
- There is a possibility of exposure to contaminants from micrometeoroid impacts and gas particles in planetary orbits which are incompatible with refractory metals at high temperatures.

A variety of materials were considered and three wrought nickel superalloys were identified as leading candidate materials for the hot leg piping: Inconel 617, Haynes 230, and Nimonic PE-16. Inconel 617 was used as the baseline material throughout the concept evaluation to provide a common comparison; however, all three nickel superalloys were considered equal candidates. Inconel 617 was chosen as the baseline because significant material test data and analysis had already been compiled for Inconel 617 at high temperature in an ASME code case.

Superalloy Pressure Boundary Temperature Requirement

To maintain sufficient material strength and creep resistance with a reasonable wall thickness, analyses determined that the nickel superalloy pressure boundary should be maintained at a maximum of ~900K. This is a reference value which could have changed as the design evolved and more material data became available. The 900K piping limit was selected as described below.

Material properties of the candidate nickel superalloy (Inconel 617) were not fully characterized due to insufficient material test data. Uncertainties in the material properties were related to creep-fatigue interaction, strain ratcheting, irradiation effects, and high temperature effects which were not quantified. There were also uncertainties with the operational conditions of the piping including cyclic and thermal stresses in addition to the piping arrangement. The 900K maximum usage temperature was judged to provide adequate margin for a sufficient design space until these uncertainties became better defined. For Inconel 617, the time dependent stress design limit (S_{mt}) for general primary membrane stress intensity was ~101 MPa, at a temperature of 900K and a mission lifetime of 135,000 hours (~15 years), see Figure 2. This figure also depicts an exponential decrease in S_{mt} at temperatures greater than ~900K as a result of thermal creep (Bassford, 1982) and (Corum, 1991).

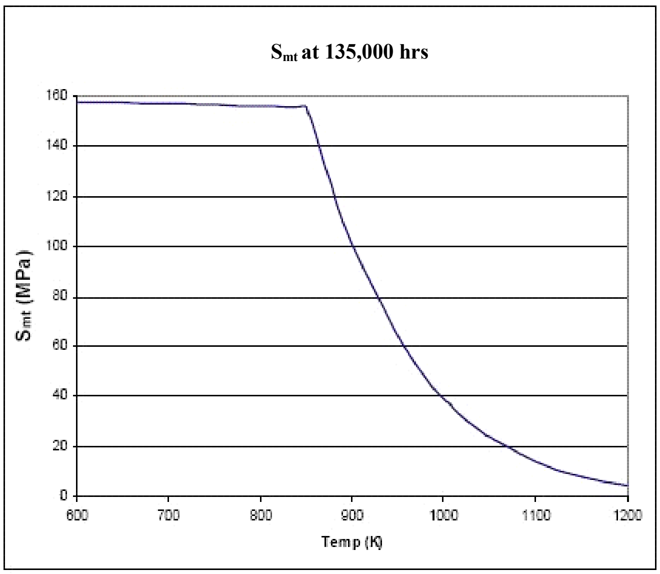

FIGURE 2. Inconel 617 S_{mt} as a Function of Temperature at 135,000 hours.

Additionally, nickel superalloys decarburize, if water vapor is present, at elevated temperatures (>1073K) which could contaminate the rest of the SNPP as well as weaken the piping (Graham, 1985). Reduction of metal temperature decreases this risk.

Another consideration is that the reactor inlet piping operates at approximately 900K. It may be advantageous to design the hot leg piping and reactor inlet piping to operate at or near the same temperature to minimize potential issues related to differential thermal expansion of these two piping sections.

Hot Leg Pipe Sizing

The hot leg piping must travel around or through the reactor shielding. In order to constrain neutron and gamma streaming through the piping, the piping outer diameter was limited to 16 cm. This limit would have been revisited and optimized as the design matured.

The nominal values of operating pressure, temperature, and flow and the piping diameter specified above were used to calculate pipe wall thicknesses. The calculated pipe wall thicknesses were used in conjunction with the operating conditions to perform thermal and hydraulic analyses of the various hot leg piping concepts.

Pipe wall thickness calculations were performed for both straight and bent piping to provide a preliminary estimate of acceptable pipe wall thicknesses. Wall thicknesses required for straight pipe were calculated based on the ASME Boiler and Pressure Vessel (B&PV) Code (ASME, 2004). Wall thicknesses required prior to bending were estimated by multiplying the wall thicknesses required after bending, as calculated per the ASME B&PV Code for straight pipe, by a factor to account for wall thinning caused by the bending process (Nayyar, 1992). For the thermal and hydraulic analyses, wall thicknesses were conservatively based on the pipe wall thickness prior to bending.

Space Temperature Assumption

According to SRPS-opt (space reactor power system optimization) tool, the nominal space environment temperature the Prometheus spaceship was expected to see was 200K. To account for hot components in the vicinity of the hot leg piping, the space temperature was increased to 400K for the thermal analyses of the hot leg piping concepts. This may not be an accurate assumption, but further analysis of the thermal behavior for the entire system was needed before a more refined assumption for the space temperature could be made.

HOT LEG PIPING CONCEPT DESCRIPTIONS

In order to maintain the hot leg piping wall temperature at 900K, several concepts were developed which would reduce the wall temperature by adding additional layers of heat transfer resistance and/or cooling while protecting the pressure boundary from direct contact with the high temperature gas. The hot leg piping concepts compared include four main variations termed *internally insulated*, *counter flow*, *bypass flow*, and *stagnant gas layer* which are described in further detail in the following sections.

Recommended Concept – Internally Insulated Hot Leg Piping

In the internally insulated concept shown in Figure 3, the hot reactor outlet gas flows within a lined layer of ceramic or metallic insulation. The insulation is lined to prevent the hot gas from flowing through the insulation, which would increase pressure drop by increasing the relative roughness of the piping, to prevent erosion, and to prevent the release of insulating material particulates. The insulation liner operates at the hot leg gas temperature but does not act as a pressure boundary since small amounts of coolant flow through the liner slip fits, see Figure 4. This allows the liner material to be either a nickel superalloy or a refractory metal depending upon other material selections in the SNPP.

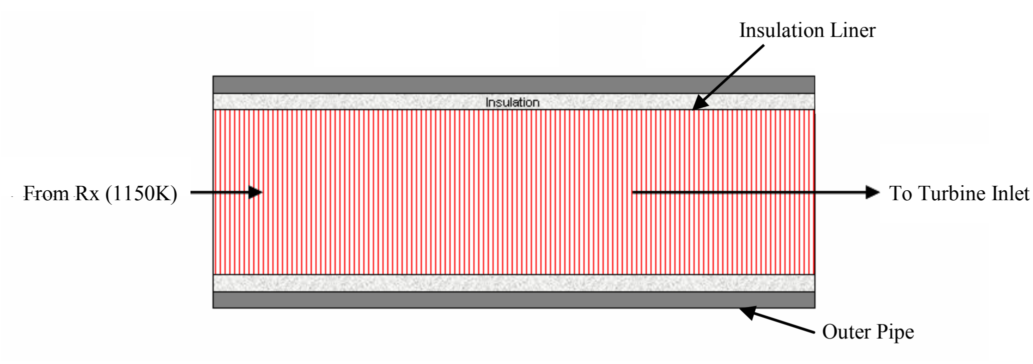

FIGURE 3. Internally Insulated Concept.

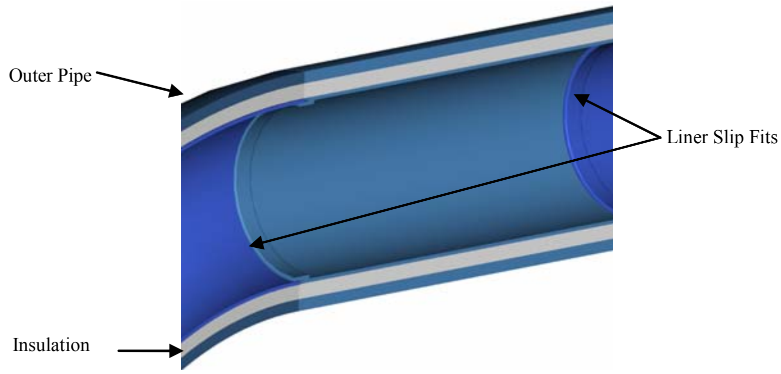

FIGURE 4. Liner Slip Fits.

Insulation is required in the internally insulated concept to maintain the temperature of the pressure boundary at or below 900K. This insulation would be designed to provide sufficient support to maintain concentricity of the liner and outer pipe. The maximum operating temperature of the insulation is approximately 1150K. In addition, it is desirable that the insulation not outgas contaminates or become friable after long periods at high temperature. With respect to these requirements, promising insulating materials for this application are ceramic or metallic foams comprised of hollow bonded microspheres. Metallic foams are preferred due to increased compatibility with the SNPP components. Figure 5 depicts Inconel 617 hollow sphere foam.

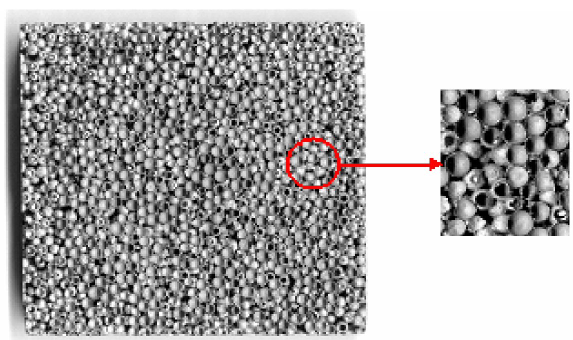

FIGURE 5. Inconel 617 Hollow Sphere Foam.

Alternate Concepts

The other concepts evaluated were intended to reduce the pressure boundary temperature by using primary coolant or a stagnant gas as a resistance layer. These concepts proved non-viable unless an insulating layer was added, similar to that used in the internally insulated hot leg concept. This would add complexity to the alternative concepts with no advantage over the internally insulated concept, while also decreasing the hot leg area for gas flow which ultimately increases pressure drop and decreases system efficiency.

Counter Flow Concept

In the counter flow concept (Figure 6), the hot reactor outlet gas flows through the inner pipe, and the cooler reactor inlet gas flows in the opposite direction from the recuperator discharge through the annular space between the inner pipe and outer pipe. Two separate counter flow hot leg pipes were used to decrease the pressure drop through the piping. There may be a lined insulation layer between the flowing gas sections. A support structure, such as stents, would be necessary in the annular spaces between the inner pipe and outer pipe to maintain concentricity. Because the inner pipe and liner are not pressure boundaries, they could be constructed from either a nickel superalloy or a refractory metal depending upon other material selections in the SNPP.

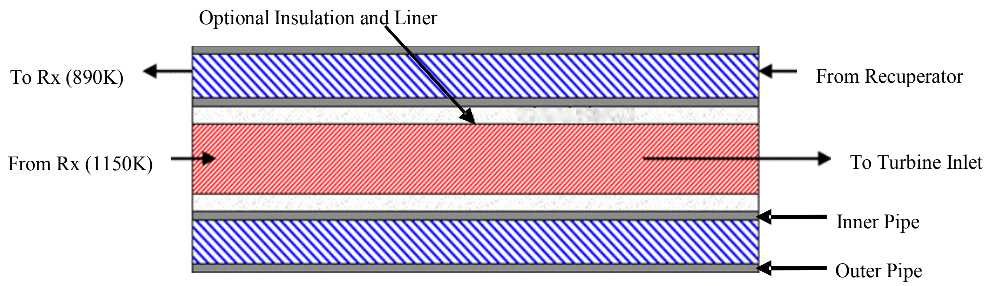

FIGURE 6. Counter Flow Concept (Pictured with Inner Insulation).

Bypass Flow Concept

In the bypass flow concept (Figure 7), the reactor outlet gas flows in the inner pipe and a small quantity (~1%) of the cooler reactor inlet gas flows in the same direction in the annular space between the inner and outer pipe. The bypass gas flow rejoins the main gas flow at the turbine outlet. There may be a lined insulation layer within the inner pipe. Some type of support structure, such as stents, would be necessary in the annular spaces between the inner pipe and outer pipe to maintain concentricity. Because the inner pipe and liner are not pressure boundaries, they could be constructed from either a nickel superalloy or a refractory metal depending upon other material selections in the SNPP.

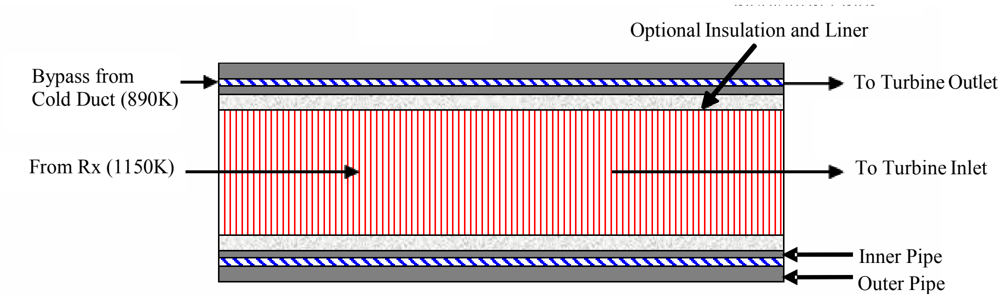

FIGURE 7. Bypass Flow Concept (Pictured with Inner Insulation).

Stagnant Gas Layer Concept

In the stagnant gas layer concept (Figure 8), the hot reactor outlet gas flows in the inner pipe and a stagnant layer of He-Xe gas is contained in the annular space between the inner and outer pipe. There may be a lined insulation layer within the inner pipe. Some type of support structure, such as stents, would be necessary in the annular spaces between the inner pipe and outer pipe to maintain concentricity. Because the inner pipe and liner are not pressure boundaries, they could be constructed from either a nickel superalloy or a refractory metal depending upon other material selections in the SNPP.

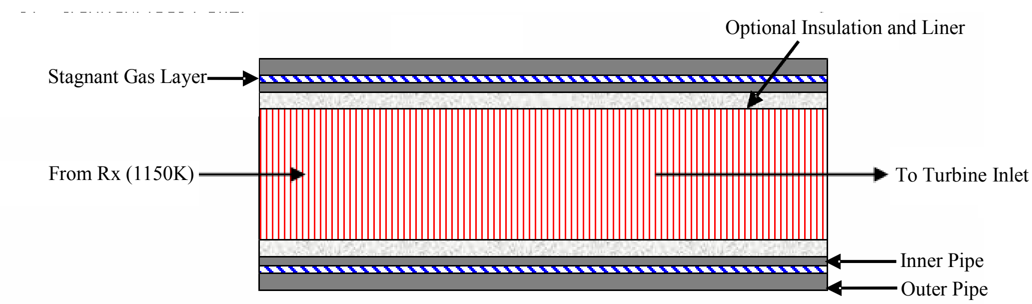

FIGURE 8. Stagnant Gas Layer Concept (Pictured with Inner Insulation).

HOT LEG PIPING CONCEPT COMPARISON

Thermal and hydraulic analyses were performed for the internally insulated and stagnant gas layer concepts. The counter flow and bypass flow concepts were excluded as discussed below in the omitted concepts section. The analyses were performed based on an arrangement which utilized a three Brayton configuration having a shared gas cooler with two Braytons operating. The concepts were compared based on thermal performance, hydraulic performance, manufacturing simplicity, and past commercial HTGR practice.

Thermal Analysis Approach

To assess the hot leg piping concepts, a detailed thermal analysis was performed for the internally insulated concept and the stagnant gas layer concepts (both with and without internal insulation). The thermal analysis was set up in a manner which equalized the thermal performance of the concepts by requiring that the outer pipe inner wall temperature not exceed 900K. As a result, only the insulating and/or stagnant gas layer thicknesses were varied, and the concepts could be directly compared by their hydraulic performance.

Internally Insulated Concept

For the internally insulated concept, there are five heat transfer paths in series:

1. Forced convection from the hot gas to the liner
2. Conduction through the liner
3. Conduction through the insulation
4. Conduction through the outer pipe
5. Radiation from the outer pipe to space

The total heat transferred through each path and from the piping to space is equal to the heat lost from the hot gas. Based on these heat transfer paths, an Excel model was developed which determined the temperature profile (axial and radial) for each resistance layer of the piping. This was accomplished by setting the heat losses per length of piping equal for the flowing gas and for each of the five heat transfer paths in series. The temperature profile that satisfied this requirement was calculated iteratively with the space temperature held constant at 400K. After the radial energy balance converged, the insulation thickness was adjusted in order to achieve an outer pipe inner wall temperature of 900K ± 0.5K, and the energy balance was recalculated. The model also automatically divided piping sections into successively smaller equal segments until the exit gas temperature from the current iteration differed by less than 0.1K from the previous iteration. In addition, all gas and material properties were adjusted for temperature.

Stagnant Gas Layer Concepts with Internal Insulation

For the stagnant gas layer concepts with internal insulation, there are seven heat transfer paths in series:

1. Forced convection from the hot gas to the liner
2. Conduction through the liner
3. Conduction through the insulation
4. Conduction through the inner pipe
5. Conduction and radiation through the stagnant gas layer
6. Conduction through the outer pipe
7. Radiation from the outer pipe to space

The total heat transferred through each path and from the piping to space is equal to the heat lost from the hot gas. Based on these heat transfer paths, an Excel model was developed which determined the temperature profile (axial and radial) for each resistance layer of the piping. This was accomplished by setting the heat losses per length of piping equal for the flowing gas and for each of the seven heat transfer paths in series. The temperature profile that satisfied this requirement was calculated iteratively with the space temperature held constant at 400K. After the radial energy balance converged, the insulation thickness and stagnant gas layer thickness were adjusted in order to achieve an outer pipe inner wall temperature of 900K ± 0.5K, and the energy balance was recalculated. The stagnant gas layer thickness was set to be ¼ of the insulation thickness since insulation is more effective at limiting heat transfer than the stagnant gas layer due to radiant heat transfer through the stagnant gas. The model also automatically divided piping sections into successively smaller equal segments until the exit gas temperature from the current iteration differed by less than 0.1K from the previous iteration. All gas and material properties were adjusted for temperature.

Stagnant Gas Layer Concepts without Internal Insulation

The stagnant gas layer concepts without insulation analyses were performed using the same method presented for the internally insulated concept. However, in the stagnant gas layer concepts, convection occurs from the hot gas to the inner pipe and the heat transfer paths of conduction through the liner and insulation layers no longer exist, rather conduction and radiation occur through the stagnant gas layer. Also, instead of adjusting the insulation thickness to achieve an outer pipe inner wall temperature of 900K, the stagnant gas layer thickness was adjusted through iteration.

Hydraulic Analysis Approach

Pressure drop calculations were performed to provide an estimate of the percentage ΔP/P for the concepts analyzed. The pressure drop in the hot leg was determined, using an Excel spreadsheet analysis, by combining the pressure drops due to friction, dividing and combining flows, and pipe bends (ESDU, 1990). In addition, the effect of heat transfer on gas properties and pressure drop was taken into account. The pressure drops were then converted to a percentage ΔP/P by dividing the total pressure drop by the compressor inlet pressure and multiplying by 100.

Concepts Omitted from Thermal and Hydraulic Analyses – Counter Flow and Bypass Flow

The counter flow concept with two separate pipe-in-pipe sections was eliminated as a viable concept due to the high rate of heat transfer from the hot gas to the cold gas. This heat transfer results in an unacceptable decrement to cycle efficiency. The decrease in turbine entrance temperature is ~150K. See Table 2 for the hot gas and cold gas axial temperature profiles for a 6 m pipe length divided into 1 m increments.

TABLE 2. Axial Temperature Profile for the Counter Flow Concept

		Reactor Outlet →						*Turbine Inlet*
Hot Leg	**(K)**	1150	1123	1097	1070	1044	1017	991
Cold Leg	**(K)**	890	864	839	813	788	762	736
		Reactor Inlet ←						*Recuperator Outlet*

If internal insulation is utilized to reduce heat transfer between the two flows, the pressure drop becomes significantly higher than in the other concepts analyzed. The combined hot and cold leg pressure drop is ~7 %ΔP/P for the counter flow option versus ~2 %ΔP/P for the internally insulated concept.

The bypass flow concept utilizes a fractional cooling flow (~1% of total gas flow) in parallel with the hot leg gas. The bypass flow is supplied from the recuperator outlet and is discharged into the turbine outlet. The bypass flow concept was evaluated with and without internal insulation. The un-insulated option was not viable due to excessive cold gas temperature increase, as illustrated by the results of the counter flow thermal analysis presented above. In the un-insulated bypass flow configuration, this will cause the cold gas temperature to exceed the temperature limit of the piping material. In order to maintain an outer wall temperature of 900K in the insulated bypass flow concept, the insulation thickness must approach that of the internally insulated concept. The addition of insulation will significantly increase pressure drop due to a reduction in the area available for gas flow and will also increase manufacturing complexity.

For both the insulated and un-insulated bypass flow concepts, there is a loss of electric generation as a result of gas bypassing the turbine. At nominal operating conditions, turbine output is approximately 348 kW. A 1% bypass flow would reduce turbine output by ~3.5 kW, thereby reducing net Brayton output (~102 kW nominal) by ~3.4%.

Thermal and Hydraulic Analysis Results

Because the thermal performances of the concepts analyzed were equalized, the discriminating variable between concepts was the resulting hot leg inner diameter. Hydraulically, the concept with the largest inner diameter will have the best performance. The internally insulated concept had the largest diameter as a result of having only one insulating layer. A summary of the thermal and hydraulic performance of the analyzed concepts is presented in Table 3.

TABLE 3. Thermal and Hydraulic Analysis Results.

Concept	Turbine Entrance Temperature (K)	Hot Gas ΔT (K)	Heat Loss Through Stagnant Gas Conduction (kW)	Heat Loss Through Stagnant Gas Radiation (kW)	Total Heat Loss (kW)	Insulation Thickness (cm)	Stagnant Gas Thickness (cm)	%ΔP/P	Hot Leg ID (cm)
Stagnant Layer w/ Insulation - Ni Liner	1143.5	6.5	14.3	1.5	15.8	0.86	0.22	1.45	11.6
Stagnant Layer w/ Insulation - Refractory Liner	1143.5	6.5	13.7	2.1	15.8	0.88	0.22	1.46	11.5
Internally Insulated	**1143.5**	**6.5**	**NA**	**NA**	**15.8**	**1.20**	**NA**	**1.26**	**12.1**
Stagnant Layer w/o Insulation - Ni Liner	1143.5	6.5	4.5	11.3	15.8	NA	2.77	4.49	8.4
Stagnant Layer w/o Insulation - Refractory Liner	1143.5	6.5	4.5	11.3	15.8	NA	2.03	4.58	8.3

Supplemental Results – Space Temperature Sensitivity

A space temperature sensitivity analysis was performed for the analyzed concepts in order to assess the impact of increasing space temperature on the hot leg inner diameter. As the space temperature increases, a larger thermal barrier to heat transfer is required to maintain the pressure boundary temperature at 900 K. The increase in the thickness of the insulation and/or the stagnant gas layer decreases the diameter of the inner pipe for a fixed outer diameter.

The internally insulated concept continues to have the largest flow area of the analyzed concepts as the space temperature is increased. This is because, with other parameters fixed, the resistance to heat transfer of a conduction path is directly proportional to the length of the conduction path. To reduce the conductive heat transfer through the insulation or stagnant gas layer, the separation between the liner and pipe must be increased.

In contrast, for radiation between surfaces through a non-absorbing gas (e.g. He-Xe), the surface areas, rather than the separating distance, impact heat transfer. To reduce the radiant heat transfer through the stagnant gas layer between the inner and outer pipe, the surface area of the inner pipe must be reduced. For the stagnant gas layer without insulation concepts, radiation accounts for approximately 70 to 75 percent of the heat transfer; therefore, in order to suppress heat transfer, the area for radiation, rather than the thickness of the gap is controlling. Whereas, for the stagnant gas layer with insulation concepts, the insulating layer reduces the inner pipe wall temperature, thereby reducing the amount of radiant heat transfer between the inner and outer pipe.

As a result, the internally insulated and the stagnant layer with internal insulation concepts are less sensitive to increases in space temperature. However, the internally insulated concept is the least sensitive of all the analyzed concepts. See Figure 9 for a comparison of the space temperature sensitivity for the analyzed concepts. Increasing space temperature from 200K to 800K causes the inner diameter of the internally insulated concept to decrease by ~25% versus ~30% for the stagnant gas with insulation concepts and 77% for the stagnant gas without insulation concepts.

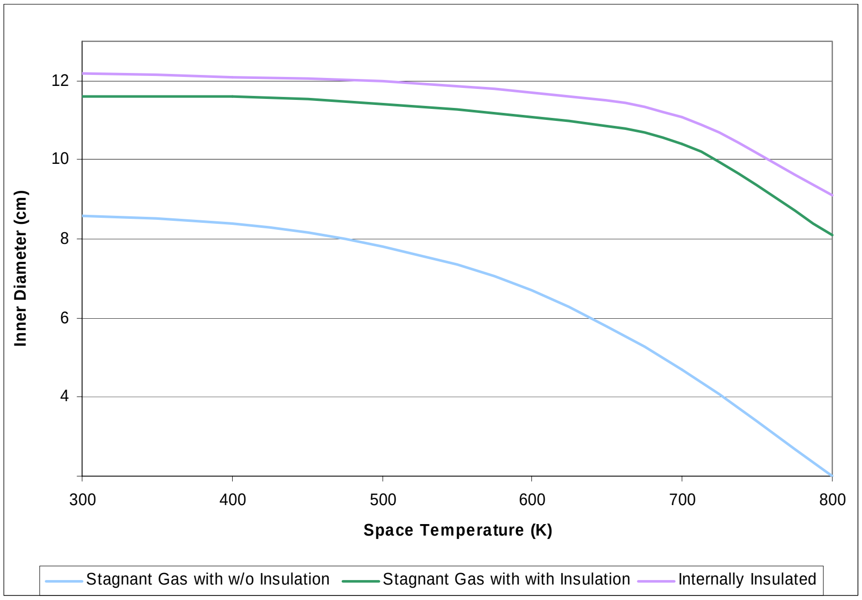

FIGURE 9. Inner Diameter as a Function of Space Temperature.

Commercial HTGR Practice

Commercial HTGRs have used a number of engineering techniques to maintain desired pressure boundary temperature in the hot leg piping. Table 4 summarizes these approaches, as well as piping materials, piping dimensions, and plant operating parameters. These commercial reactors either utilized counter flow or internal insulation as the method for maintaining the pressure boundary temperature. However, the concepts which utilized the counter flow approach had significantly larger piping diameters than the SNPP. It should be noted that there are additional HTGRs not presented in this table due to insufficient primary piping information.

TABLE 4: Commercial HTGR Experience for Maintaining Pressure Boundary Temperature.

Reactor Plant, Country, and Dates of Operation	Temperature Control Approach	Piping Materials (If Applicable)	Piping Dimensions (cm)	Operating Parameters		
				Power (MW_t)	Coolant Temperature (K)	Coolant Pressure (MPa)
HTTR Japan 1998 – Present	Counter Flow with Internal Insulation	Outer Pipe – SB42 (Mild Steel) Inner Pipe and Liner – Hastelloy X Insulation – Kaowool	Outer Pipe Diameter – 152 Inner Pipe Diameter – 36	30	1223	4
Peach Bottom US 1966 – 1974	Counter Flow with Internal Insulation	Outer Pipe – Carbon Steel Inner Pipe – 304 Stainless Steel Insulation – 304 Stainless Steel Honeycomb Panels	Outer Pipe Diameter – 91 Inner Pipe Diameter 52	115	998	2.2
HTR-10 China 2000 – Present	Counter Flow with Internal Insulation	Outer Pipe – Nickel Superalloy Inner Pipe – Not Available Insulation – Not Available	Outer Pipe Diameter – 90 Inner Pipe Diameter- 27	10	1000	3
GTMHR US Planning Phase	Internal Insulation	Outer Pipe – Alloy 800H (Nickel Superalloy) Insulation – Ceramic Fiber	Outer Pipe Diameter – 152 Inner Pipe Diameter – 104	600	1120	0.7
UHTREX US 1966 – 1970	Internal and External Insulation	Piping – 304SS/106 Carbon Steel Internal Insulation – Stainless Steel Foil Reflector External Insulation – Calcium Silicate	Pipe Diameter – 36	3	1590	3.4
Dragon UK 1964 – 1989	Internal Insulation	Piping – Not Available Insulation – Multilayer Nimonic Liners (Nickel Superalloy)	Pipe Diameter – 19	20	1020	2.2
Fort Saint Vrain US 1974 – 1989	Internal Insulation	Outer Pipe – Carbon Steel Insulation – Ceramic Fiber	Not Available	842	1050	4.8

HTTR, Peach Bottom, and Dragon (Simnad, 1991) and (Brey, 2001); HTR-10 (Xu, 2000), GTMHR (Potter, 1996); UHTREX (Simnad, 1991) and (Simnad, 1971); and Fort Saint Vrain (Simnad, 1991), (Brey, 2001), and (IAEA, 2001).

Manufacturability Assessment

All of the concepts considered would have required some level of manufacturing development, such that all required development for the assembly process of the internal insulation and/or concentric piping/liner within the outer pipe. However, the internally insulated concept was the most straightforward to manufacture. This concept only has one outer pressure boundary and internal insulation with a slip fit liner. The remaining concepts utilize concentric welded pipes with an optional lined insulation layer. The process to fabricate concentric welded pipes would require significant development. Additionally, examination of the piping welds would be more difficult for multiple concentric pipes as well as increased complexity for component interfaces.

Concept Comparison Discussion

Hydraulic performance, thermal performance, and manufacturability proved to be the major concept discriminators between the four concepts under comparison. Given the constraint of a fixed maximum allowable hot leg pipe outer diameter, the internally insulated hot leg piping concept had significant advantages over the other concepts considered. The counter flow and bypass flow concepts were eliminated due to inferior thermal and hydraulic performance. The un-insulated stagnant gas layer concept achieved equivalent thermal performance to the internally insulated concept, but with a pressure drop penalty. The insulated stagnant gas layer concept achieved equivalent thermal and hydraulic performance to the internally insulated concept, but with a manufacturability penalty. Table 5 presents a summary of the primary grounds for concept elimination.

TABLE 5: Eliminated Concepts.

Eliminated Concept	Primary Reason for Elimination	Secondary Reason for Elimination
Counterflow without Insulation	Decrease in Cycle Efficiency	Manufacturing Complexity
Counterflow with Insulation	Pressure Drop	Manufacturing Complexity
Bypass Flow without Insulation	Decrease in Cycle Efficiency	Manufacturing Complexity
Bypass Flow with Insulation	Decrease in Cycle Efficiency	Manufacturing Complexity
Stagnant Gas Layer without Insulation	Pressure Drop	Space Temperature Sensitivity
Stagnant Gas Layer with Insulation	Manufacturing Complexity	N/A

Hydraulic calculations, based on early arrangement studies, indicated that pressure losses within the SNPP piping systems were significant enough to have a major impact on cycle efficiency. Although the results were based on preliminary piping arrangements, the magnitude of the calculated losses indicated that piping pressure drops would continue to be a major driver in arrangements and system design and performance. The internally insulated concept provided the largest design space, since it resulted in the lowest pressure drop while maintaining the required pressure boundary surface temperature of 900K. In addition, there is greater fabrication complexity with the alternate designs with no benefits.

DEVELOPMENT EFFORTS

The internally insulated nickel superalloy hot leg concept presented a number of significant development issues including: material selection, manufacturability, modeling and testing, and placement of the turbine entrance temperature sensor. The following sections briefly describe the development efforts that the NRPCT would have focused on to deliver the hot leg piping.

Material Selection

In order for the internally insulated hot leg piping concept to have adequately performed hydraulically, thermally, and structurally, appropriate materials would need to have been selected. In addition, the chosen materials would need to have met all system requirements and constraints. Final selection for the reactor plant materials would not have occurred for several years due to radiation testing and other long term materials testing; however, preliminary material selection would have been required in the near term to support conceptual design and proof of principal testing. Material development efforts would have been required for outer pipe, insulation, and liner.

Manufacturability

The purpose of a manufacturability study would have been to determine the feasibility of acquiring and assembling the hot leg piping. Manufacturability issues for the internally insulated nickel superalloy hot leg piping include material availability, piping assembly, and component interfaces which include insulation containment and issues associated with joining the hot leg piping to both the turbine inlet and reactor pressure vessel outlet.

Modeling and Testing

Analytical models would have been utilized to further develop the internally insulated nickel superalloy hot leg piping concept. Testing would have been used to qualify these analytical models. The initial testing would have focused solely on a straight section of piping, followed by introducing bends and tees into the test section. Thermal, hydraulic, and structural performance would have been qualified by these tests.

Turbine Entrance Temperature Sensor Placement

The temperature of the gas in the hot leg piping may have to have been monitored to supply feedback for reactor control. It was desired that the sensors making this measurement be as non-invasive as possible in order to minimize flow disruptions and discontinuities in the pressure boundary. The inherent response times of all sensors which were under consideration for measuring the coolant are on the order of several milliseconds. Placing them outside the gas stream would have introduced a finite delay time for the temperature at the sensor location to reach equilibrium during a transient. This delay time would have depended primarily on the heat transfer properties of the piping configuration and would dominate the response time of the hot leg temperature sensor.

The non-invasive requirement for the hot leg temperature sensor must therefore be evaluated against impacts on reactor control response time. Other factors affecting sensor placement include sensor accuracy and resolution, temperature tolerance, sensor size, and feasible attachment methodologies. The sensor technologies under consideration for measuring the hot gas were ultrasonics, thermocouples, resistance temperature devices (RTDs), optical pyrometry, and fiber Bragg grating.

CONCLUSIONS

The baseline SNPP incorporates a piping system which circulates He-Xe coolant through the reactor and closed Brayton energy conversion system. Due to the elevated gas temperature in the section of piping between the reactor and the turbine; the hot leg piping, additional design features were required to allow the use of a non-refractory metal pressure boundary. In order to maintain the hot leg piping wall temperature at 900K, several concepts were developed which would reduce the wall temperature by adding additional layers of heat transfer resistance and/or cooling while protecting the pressure boundary from direct contact with the highest temperature gas. The hot leg piping concepts compared include four main variations termed *internally insulated*, *counter flow*, *bypass flow*, and *stagnant gas layer*.

The hot leg piping concepts were compared based on thermal and hydraulic performance and manufacturing complexity. Based on these comparison criteria, the NRPCT recommended continued development of a nickel superalloy pipe with lined insulation on the inner surface of the piping. The internally insulated hot leg piping concept proved equivalent or superior to the other concepts considered, with respect to the selection criteria. This concept resulted in the least complex design and the largest gas flow area while maintaining the required pressure boundary temperature. However, further development efforts would have been required to overcome challenges in material selection, manufacturability, modeling, testing, and the placement of the turbine entrance temperature sensor for the recommended hot leg piping concept.

NOMENCLATURE

S_{mt} = Time dependent stress design limit
$\Delta P/P$ = Piping pressure drop divided by the compressor outlet pressure

ACKNOWLEDGMENTS

The NRPCT acknowledges the support received from NASA Glenn Research Center.

REFERENCES

ASME, *ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB,* The American Society of Mechanical Engineers, New York, 2004, pp. 114-116.

Bassford, T.H., "Inconel Alloy 617 Data Package," INCO Alloys International, Huntington, 1982.

Brey, H.L., "Development History of the Gas Turbine Modular High Temperature Reactor" in *IAEA-TECDOC-gtpc,* edited by Dutch Uselton, International Atomic Energy Agency, Vienna, 2001, pp. 25-44.

Corum, J.M., "Rules for Design of Alloy 617 Nuclear Components to Very High Temperatures," in *PVP,* Vol. 215 (1991).

ESDU, *Engineering Sciences Data, Fluid Mechanics, Internal Flow, Vol. 2 Bends, Branches, and Junctions,* London, 1990, Items 73022, 73023, and 83037.

Graham, L.W. "High Temperature Corrosion in Impure Helium Environments," in *High Temperature Technology,* Vol. 3, No. 1 (1985).

IAEA, "The HTTR and HTR-10 Test Reactors" in *IAEA-TECDOC-1198,* edited by IAEA, International Atomic Energy Agency, Vienna, 2001, pp. 115-140.

Nayyar, M.L., *Piping Handbook,* McGraw-Hill, Inc., New York, 1992, pp. A305.

Potter, R.C., *Gas Turbine-Modular Helium Reactor (GT-MHR) Conceptual Design Description Report,* General Atomics, San Diego, 1996, pp. 4.1-4.164.

Simnad, M.T., *Fuel Element Experience in Nuclear Power Reactors,* Gordon and Breach, New York, 1971.

Simnad, M.T., "Early History of High Temperature Helium Gas-Cooled Nuclear Power Reactors," in *Energy*, Vol. 16, No. 1/2 (1991),

Xu, Y., *High Temperature Gas Cooled Reactor Programme in China,* Institute of Nuclear Energy Technology – Tsinghua University, Beijing, 2000, pp. 1-7.