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NGNP High Temperature Process Heat Transfer and Transport Study

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ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
DOE	(United States) Department of Energy
FLiNaK	LiF, NaF, KF Molten Salt
GA	General Atomics
H2-MHR	Hydrogen – Modular Helium Reactor
HTE	High Temperature Electrolysis
HTTR	High Temperature Test Reactor
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
JAEA	Japan Atomic Energy Agency
L/D	Length Divided by Diameter
MHR	Modular Helium Reactor
MS	Molten Salt
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
ORNL	Oak Ridge National Laboratory
PCHE	Printed-Circuit Heat Exchanger
PHX	Process Heat Exchanger
SI	Sulfur-iodine
VHTR	Very High Temperature Reactor

1 SUMMARY

The objective of the trade study is to evaluate the design options and impacts of using either high-pressure helium or FLiNaK molten salt as the working fluid for the NGNP Heat Transport System Design. The evaluation in the trade study focuses on economics and technical risk to arrive at a recommendation on working fluid selection.

Sizing of components was performed as part of an NGNP secondary loop design in order to determine costs and cost discriminators between the helium and molten salt heat transport loops. Both heat transfer loops were assumed to be 90 meters in length. Both the helium and molten salt intermediate heat exchangers (IHXs) are about the same size and are made of the same material – alloy 617. The total cost for the 50 MWt IHX assumed in this study is around $12 million. The cost of the IHX is not a discriminator between the helium and molten salt (MS) working fluids. The total cost of the He piping including valves is about $3 million. The total cost for the MS piping including valves is almost $5 million. The size and cost of the circulator in the helium transport loop is determined by its power consumption. The circulator is sized at 757 kW. The estimated cost of this circulator is $19 million. The molten salt pump is sized at only 11 kW. The estimated cost of the MS pump is $1 million. The He secondary heat transport system has a higher capital cost by about $16 million primarily due to the cost of the circulator.

The operating cost of the He secondary heat transport system is dominated by the cost to operate the circulator which is sized at 757 kW. Assuming a 90% capacity factor, the circulator would use 6 million kW-hrs per year. At an average 2005-2006 electricity price in Idaho of 5¢/kW-hr, the circulator operating cost would be $300,000. The molten salt pump is sized at only 11 kW so that its operating cost is much lower. Replacement cost of the IHX is much more significant. The annualized replacement cost is $2 million for the He-He IHX and $10 million for the He-MS IHX. These replacements costs do not include labor or other costs associated with reactor downtime. The pressure difference between the primary and secondary sides of the He-MS IHX significantly degrades the operating lifetime of the metallic IHX due to creep stress. The replacement costs of the PHXs are also expected to be significant if they are made of metallic materials though ceramic materials may be a cost-effective alternative.

The difference in capital costs is significant relative to the total cost of the secondary heat transport system, but is insignificant compared to the total NGNP cost. Similarly, the operating cost for the He circulator represents about a 0.3% reduction in available electrical output, which is also insignificant.

The technical risks associated with molten salts relative to those associated with helium remain significant at the present time. The principal technical risks with molten salt are high-temperature corrosion, freezing protection, and drainage of molten salt from the IHX and process heat exchangers (PHXs). While technical solutions appear possible, there does not

appear to be a compelling reason to choose molten salt over high-pressure helium, particularly in view of the high-level NGNP Project requirement to use the lowest-risk technology consistent with satisfying the NGNP objectives.

The technical risks associated with high-pressure helium are much more manageable and understood. Gas circulator technology has been proven on numerous reactor applications including the High Temperature Test Reactor (HTTR) in Japan. HTTR also has experience in using helium as a secondary coolant to transfer heat from the reactor to process heat exchangers.

Therefore, it is the recommendation of this study that the secondary heat transfer loop use high-pressure helium as the working fluid. Further design analysis is needed to determine the optimal pressure for the heat transfer loop which balances the design challenges on the IHX against the design challenges and performance objectives of the PHXs and hydrogen production processes.

2 INTRODUCTION AND SCOPE

2.1 Introduction

The Energy Policy Act of 2005 (H.R. 6), which was signed into law by the President in August 2005, required the Secretary of the U.S. Department of Energy (DOE) to establish a project to be known as the Next Generation Nuclear Plant (NGNP) Project. According to the Energy Policy Act, the NGNP Project shall consist of the research, development, design, construction, and operation of a prototype plant (to be referred to herein as the NGNP) that (1) includes a nuclear reactor based on the research and development activities supported by the Generation IV Nuclear Energy Systems initiative, and (2) shall be used to generate electricity, to produce hydrogen, or to both generate electricity and produce hydrogen. The NGNP Project supports both the national need to develop safe, clean, economical nuclear energy and the Bush Administration's National Hydrogen Fuel Initiative, which has the goal of establishing greenhouse-gas-free technologies for the production of hydrogen. The DOE has selected the helium-cooled Very High Temperature Reactor (VHTR) as the reactor concept to be used for the NGNP because it is the only near-term Generation IV concept that has the capability to provide process heat at sufficiently high temperatures for highly-efficient production of hydrogen. The DOE has also selected the Idaho National Laboratory (INL), the DOE's lead national laboratory for nuclear energy research, to lead the development of the NGNP under the direction of the DOE.

In support of the hydrogen production mission, the NGNP shall have a secondary heat transport system for transporting at least 50 MW of thermal energy transferred from the primary coolant via the Intermediate Heat Exchanger (IHX) to the hydrogen production system (Ref. 1). The secondary heat transport system shall deliver the process heat at the temperature conditions required by the hydrogen production process and at pressure conditions which minimize the technical risk associated with the IHX, the process heat exchanger (PHX) and the hydrogen production processes. Heat losses to the environment from the secondary heat transport system shall be limited to less than 1% of the 50 MW(t) being transferred.

Design options for the secondary heat transport system were previously examined by General Atomics (GA) as part of a Nuclear Energy Research Initiative (NERI) project. The NERI project produced two documents on the pre-conceptual design of a commercial-scale H2-MHR plant. One of the plant designs used the Sulfur-Iodine (SI) hydrogen production process (Ref. 2). The other plant design used the High Temperature Electrolysis hydrogen production process (Ref. 3).

INL has also studied issues associated with the secondary heat transport system and possible design configurations (Ref. 4) as part of the NGNP project. Recent INL focus (Ref. 5) has been on the Intermediate Heat Exchanger (IHX) design in support of NGNP and the NERI project led by GA.

2.2 Scope

The scope of this trade study is to evaluate design options for the NGNP Heat Transport System Design. In particular, the study evaluates the design options and impacts of using either high-pressure helium or molten salt as the working fluid for the secondary loop. The trade study limited its evaluation of molten salts to FLiNaK which is a mixture of lithium fluoride, sodium fluoride and potassium fluoride. FLiNaK is one of the leading molten salt candidates based on assessments prepared by Oak Ridge National Laboratory (ORNL) and studies being performed at University of California at Berkeley and University of Wisconsin.

The evaluation criteria of the trade study are divided into two areas: economics and technical risk. The evaluation criteria are discussed in Section 3. Section 4 presents the heat transfer and transport properties of helium and FLiNaK. Secondary heat transport loop designs using either high-pressure helium or FLiNaK are presented in Sections 5 and 6, respectively. The secondary loop designs provide the technical basis of the economic evaluation. The economic and technical risk evaluations are presented in Section 7. Section 8 is the recommendation for working fluid selection.

3 EVALUATION CRITERIA

3.1 Economics Criteria

One objective of the trade study is to evaluate the relative economics of the two leading candidates for the working fluid for the secondary heat transport loop. The two leading candidates for working fluid are high-pressure helium and moderate-pressure molten salt. The molten salt with the best heat transfer performance is a ternary mixture of LiF, NaF, and KF commonly referred to as FLiNaK.

The economic evaluation examines sizing of the Intermediate Heat Exchanger (IHX), Process Heat Exchangers (PHXs), piping, and pump or circulator. The sizing of these components was used to determine the quantity of construction materials and their cost, which is a determining factor in the relative capital cost of a helium versus molten salt secondary heat transport loop.

Operating cost is an additional factor in the economic evaluation. The operating cost for the secondary heat transport loop includes power usage, component replacement, and working fluid leakage. Power usage by the pump or circulator in the secondary heat transport loop is the primary component of operating cost. Additional operating cost is due to possible replacement of components which have limited operating life. Leakage of working fluid, especially in the case of high-pressure helium, is an additional contributor to operating cost.

3.2 Technical Risk Criteria

The second objective of the trade study is to evaluate the technical risk associated with the working fluid options of high-pressure helium and moderate-pressure molten salt. The qualitative evaluation of technical risk includes consideration of the following: high-temperature corrosion, coolant purification requirements, radionuclide (including tritium) control, maintenance, worker safety, technology development, licensing, code qualification and decommissioning.

As part of the technical risk evaluation, commercial applications and scalability was qualitatively assessed. Commercial applications of the NGNP will include not only electricity production and hydrogen production, but also other process heat applications.

4 WORKING FLUID CHARACTERISTICS

Two working fluids were evaluated in this study: high-pressure helium and the molten salt commonly referred to as FLiNaK. An alternate high-pressure gas, nitrogen, and alternate molten salts were initially considered but were not evaluated because they have lower heat transfer performance, especially in the case of nitrogen. The major reason for considering alternate molten salts would be a lower melting temperature. However, this benefit was considered to be outweighed by the higher technical risk associated with most other molten salts due to their inadequate databases, especially for high-temperature corrosion.

4.1 Helium Characteristics

Helium is the primary coolant of the NGNP due to it being chemically inert and neutronically invisible, and having relatively high thermal conductivity and specific heat. The correlations used at GA, which closely approximate the data given in Reference 6, are given as follows. For thermal conductivity, k, the correlations for helium in English and metric units are given by the following equations:

$$k[\text{Btu/hr-ft-°F}] = 1.29 \times 10^{-3} (T[\text{R}])^{0.674}$$
$$k[\text{W/m-K}] = 3.32 \times 10^{-3} (T[\text{K}])^{0.674}$$

where T is absolute temperature in either Rankine or Kelvin.

For dynamic viscosity, μ, the English and metric correlations are as follows:

$$\mu[\text{lbm/ft-hr}] = 6.9 \times 10^{-4} (T[\text{R}])^{0.674}$$
$$\mu[\text{kg/m-s}] = 4.24 \times 10^{-7} (T[\text{K}])^{0.674}$$

Specific heat, c_p, for helium is constant at 1.242 Btu/lbm-°F (5.200 kJ/kg-K).

The density, ρ, of a pure helium coolant is determined by the ideal gas law as shown below in English and metric units.

$$\rho\left[\text{lbm/ft}^3\right] = \frac{P\left[\text{lbf/ft}^2\right]}{386.25\, T\left[\text{R}\right]}$$

$$\rho\left[\text{kg/m}^3\right] = \frac{P\left[\text{Pa}\right]}{2079\, T\left[\text{K}\right]}$$

where P is pressure in either pounds force per square foot or pascals.

4.2 FLiNaK Characteristics

The molten salt, FLiNaK, is a ternary eutectic mixture of LiF, NaF, and KF. The molar composition of FLiNaK is 46.5% LiF, 11.5% NaF, and 42% KF. On a mass basis, the composition is 29 wt.% LiF, 12 wt.% NaF, and 59 wt.% KF (Ref. 7). The molecular weight of FLiNaK is 41.3 g/mole.

One of the most critical parameters for any molten salt is its melting (or freezing) temperature. For FLiNaK, the melting temperature is 454°C. For a reactor outlet temperature of 950°C, the reactor inlet temperature could be as high as 590°C. Under these conditions, the minimum loop temperature would be as high as 565°C which provides adequate margin to freeze for normal operating conditions. For lower reactor inlet temperatures, a molten salt with a lower melting temperature would be preferable in order to increase the margin to freezing. Alternate fluoride, chloride and fluoroborate molten salts have been considered. Some of these alternates have melting temperatures below 400°C which is highly desirable. However, these alternates have poorer heat transfer characteristics and higher technical risks compared to FLiNaK (Ref. 8).

The maximum temperature being considered for the NGNP reactor outlet / IHX inlet is 950°C which could easily produce a maximum molten salt temperature of 925°C. At 900°C, the vapor pressure of FLiNaK is only 0.5 mm Hg and the boiling point is estimated to be 1570°C. Vapor and two-phase flow concerns are not applicable to FLiNaK at the maximum expected NGNP temperature.

The thermal conductivity correlations for FLiNaK in English and metric units are shown below:

$$k[\text{Btu/hr-ft-°F}] = 0.00016\ T[\text{R}] + 0.1234$$
$$k[\text{W/m-K}] = 0.0005\ T[\text{K}] + 0.2135$$

The dynamic viscosity, μ, of FLiNaK is given in English and metric units by the following correlations:

$$\mu[\text{ lbm/ft-hr}] = 0.097 \exp(7506/T[\text{R}])$$
$$\mu[\text{kg/m-s }] = 4 \times 10^{-5} \exp(4170/T[\text{K}])$$

The specific heat, c_p, of FLiNaK is given by the following correlations in English and metric units:

$$c_p[\text{Btu/lbm-°F}] = 0.0521 + 1.32 \times 10^{-4}\ T[\text{R}]$$
$$c_p[\text{kJ/kg-K}] = 0.912 + 9.92 \times 10^{-4}\ T[\text{K}]$$

The density, ρ, of FLiNaK is given by the following correlations in English and metric units:

$$\rho[\text{lbm/ft}^3] = 158.8 - 0.0253\ T[^\circ\text{F}]$$
$$\rho[\text{gm/cm}^3] = 2.530 - 0.00073\ T[^\circ\text{C}]$$

5 SECONDARY LOOP DESIGN FOR HELIUM

The secondary loop design assumes that the reactor outlet temperature is 950°C and the reactor inlet temperature is 590°C. Design optimization studies are being performed to lower the reactor inlet temperature in order to provide additional margin for vessel and other metallic component temperatures. The IHX assumed in this study was designed and sized to remove 50 MWt using these helium temperatures on the primary side. The secondary side helium temperatures were assumed to be 925°C and 565°C, which are consistent with the temperatures used in the H2-MHR design using the SI hydrogen production process (Ref. 2). Reactor operation at lower reactor outlet and/or inlet temperatures would be less limiting and provide additional design margin on vessel and metallic component temperatures. The sizing of the IHX is based on the Heatric-style printed-circuit heat exchanger (PCHE). The arrangement of the PCHE submodules is illustrated in Figure 5-1.

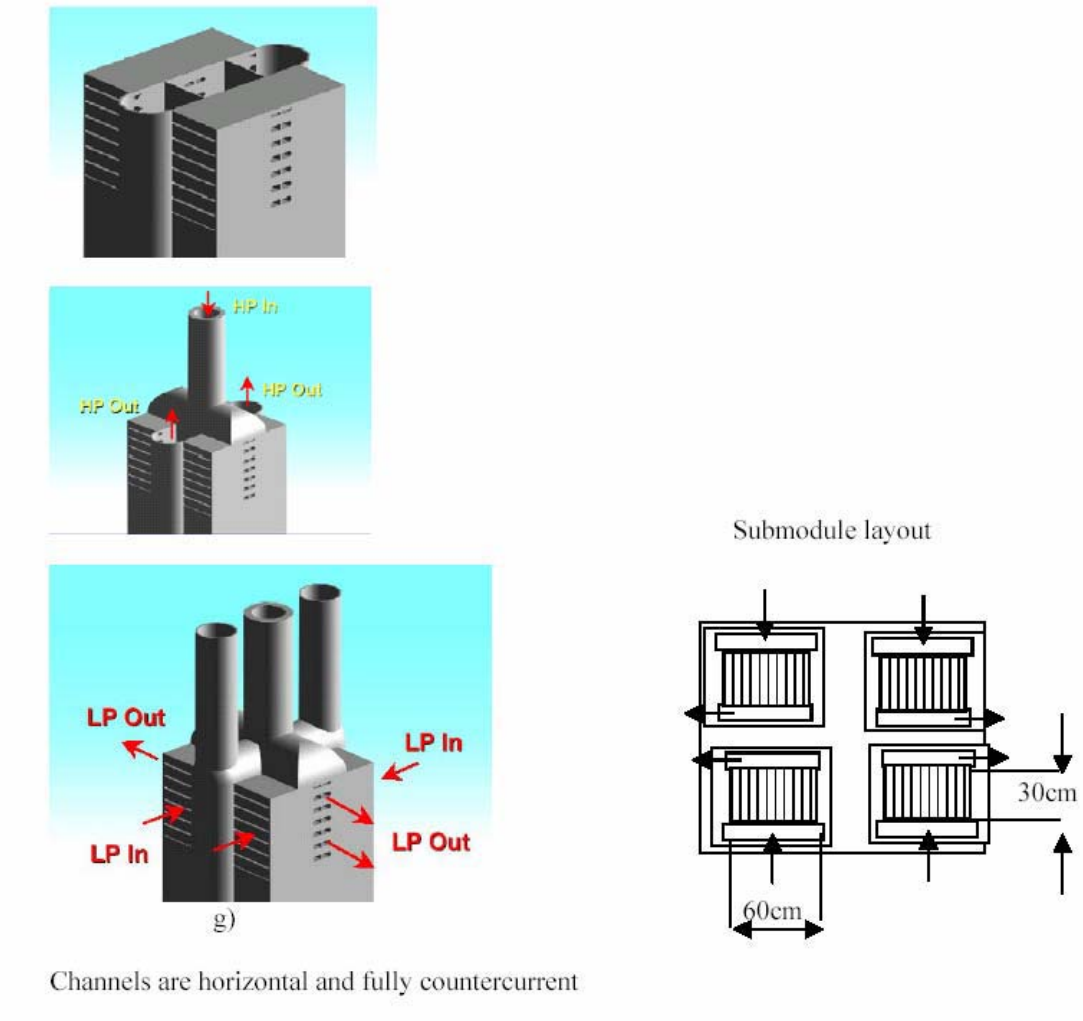

Figure 5-1: True Counter Flow Heatric[R] Heat Exchanger

The basic geometric parameters of the He-He IHX are as follows:

Table 5-1: Basic Geometric Parameters of He-He IHX

Parameter	Value
Number of Modules	4
Module Height	1.4 m
Total Module Width (includes edges)	1.026 m
Edge Distance	13 mm
Total Module Length	0.902 m
Radius of Helium Channels	1.5 mm
Channel Center to Center Spacing	3.9 mm
Channel Offset Pitch	12.7 mm
Height of Offset	2.286 mm
Layer Thickness	2.4 mm
Flow Area per Module	0.2517 m^2
Heat Transfer Area per Module	523 m^2

Both the primary side and secondary side IHX flow channels are the same size. For each coolant, there are 286 PCHE layers per module. Each layer has 249 coolant channels. The flow area per module is 0.2517 m^2 (2.709 ft^2) for each coolant. The LMTD of the heat exchanger is 25°C (45°F) and its effectiveness is 93.5%. The primary and secondary side heat transfer coefficients are both just over 2215 W/m^2-K (390 Btu/hr-ft^2-°F). The overall heat transfer coefficient is 954 W/m^2-K (168 Btu/hr-ft^2-°F). The flow rates on the primary and secondary sides are both 26.71 kg/s (58.88 lb/s). The pressures on the primary and secondary sides are also essentially the same at 7 MPa (1015 psia). The pressure drop on the primary side is 27.8 kPa (4.03 psi). The pressure drop on the secondary side is essentially the same at 27.0 kPa (3.92 psi). The metal volume before etching the flow channels is 5.18 m^3 (183 ft^3), which has a mass of 44,000 kg (96,000 lb) and will be used to evaluate the material cost of the IHX.

Parallel hot leg and cold leg piping is assumed to run 90 m in length between the IHX and PHXs of either the SI or HTE hydrogen production demonstration plant. Concentric piping was considered since this would reduce the heat loss to the environment. However, as noted in References 2 and 3, a parallel pipe configuration is less complex and is more amenable for interfacing with secondary loop isolation valves. The parallel pipe configuration is also a simpler design to accommodate the design features necessary to address thermal expansion. A schematic of the secondary loop configuration is presented in Figure 5-2.

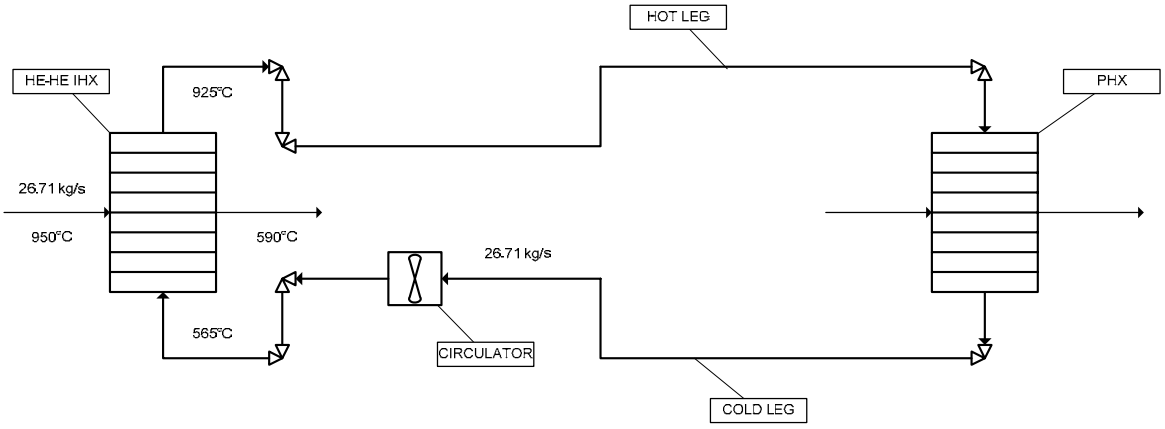

Figure 5-2: Schematic of Helium Secondary Heat Transport Loop

In order to reduce the pipe wall temperature and the heat loss to the environment, internal insulation is proposed for both the hot leg and cold leg piping. The internal insulation would be made of kaowool with cover plates holding it in place. The same design approach was used in the Fort St. Vrain HTGR and is proposed for the hot duct and cross vessel of the NGNP primary system. External insulation is also proposed to further reduce the heat loss to the environment. The addition of external insulation raises the pipe wall temperature.

Insulated system performance was analyzed under two extreme weather conditions: a hot day with no wind, and a cold windy day. The air temperature for the hot day was 38°C (100.4°F). The hot day determines the maximum pipe wall temperature which is used to determine the minimum allowable pipe wall thickness to be within the stress allowables using the ASME process piping standard B31.3 (Ref. 9). The air temperature for the cold day was -30°C (-22°F) with a wind speed of 22.4 m/s (50 mph). The cold day determines the insulation thicknesses necessary to meet the requirement of ≤1% heat loss to the environment. In order to simplify the pipe design and manufacturing, the hot and cold leg pipes were designed to be the same size, same diameter, and same wall thickness, and to have the same internal and external insulation thicknesses. One advantage of this approach is that any transient that raises the cold leg temperature would not exceed allowable stresses at the elevated pipe wall temperatures associated with the transient.

Table 5-2 summarizes the geometric parameters of the helium piping. The results of the one-dimensional thermal analysis are shown in the following table for the hot and cold leg pipes operating on hot and cold days. For the cold day, the total temperature drop is 3.6°C which is 1% of the 360°C temperature rise within the IHX. The total temperature drop on the hot day is 3.0°C.

Table 5-2: Basic Geometric Parameters of the He Piping

Parameter	Metric Value	English Value
Pipe Inside Diameter	0.76 m	30 in.
Pipe Wall Thickness	35.6 mm	1.4 in.
Pipe Outside Diameter	0.83 m	32.8 in.
Internal Insulation Thickness	127 mm	5 in.
External Insulation Thickness	15.2 mm	0.6 in.

Table 5-3: Thermal Analysis Results for the He Piping

Parameter	Temp. on Hot Day	Temp. on Cold Day
Hot Pipe		
- Inside Surface of Internal Insulation	924°C (1696°F)	924°C (1696°F)
- Inner Pipe Wall	482°C (899°F)	371°C (700°F)
- Outer Pipe Wall	480°C (896°F)	369°C (697°F)
- Outside Surface of External Insulation	277°C (530°F)	-10°C (14°F)
- Temperature Drop in Hot Pipe	2.0°C (3.6°F)	2.4°C (4.3°F)
Cold Pipe		
- Inside Surface of Internal Insulation	565°C (1048°F)	565°C (1048°F)
- Inner Pipe Wall	299°C (570°F)	203°C (398°F)
- Outer Pipe Wall	298°C (569°C)	203°C (397°F)
- Outside Surface of External Insulation	163°C (325°F)	-20°C (-4°F)
- Temperature Drop in Cold Pipe	1.0°C (1.8°F)	1.2°C (2.2°F)
Air Temperature	38°C (100.4°F)	-30°C (-22°F)

The maximum pipe wall temperature on the hot day is 482°C (899°F). The material chosen for the pipe wall is 2¼Cr-1Mo which is fully qualified to 590°C under Section III, Subsection NH of the ASME code and is allowed to reach 650°C for short times. The advantage of this material over other high temperature alloys is its low cost. At 482°C (900°F), the stress allowable is 94 MPa (13,600 psi). The stress in the pipe wall is less than the stress allowable if the wall thickness is 35.6 mm (1.4 in.). The resulting volume of pipe material is 16.04 m^3 (566.4 ft^3) which has a mass of 130,000 kg (280,000 lb).

The total pressure drop in the secondary heat transport loop is the sum of pressure drops in the IHX, PHXs and piping system. A design of the PHX for either the SI or HTE hydrogen production process was not available for this study, so the pressure drop in the PHX was assumed to be the same as the pressure drop in the IHX. The secondary heat transport loop

was assumed to have three isolation valves on each leg – two near the IHX and one near the PHX. Isolation valves are necessary to prevent events in the NGNP reactor from propagating to the hydrogen production plant or events in the hydrogen production plant from propagating to the reactor. Isolation valves are also necessary to perform maintenance on the heat transport loop. Each valve is assumed to be similar to the high temperature isolation valve discussed in References 2 and 3, which would have a pressure loss L/D of 55. Figure 5-3 presents a diagram of a potential high temperature isolation valve being developed for the Japan Atomic Energy Agency (JAEA). Each leg of the secondary loop was also assumed to have five bends with a pressure loss L/D of 18 and an entrance/exit K_{loss} of 1.5. The hot leg has a pressure loss of 21.8 kPa (3.2 psi). The cold leg has a pressure loss of 15.1 kPa (2.2 psi). The total pressure drop in the secondary loop is estimated to be 92 kPa (13.3 psi). Assuming the circulator has an 80% efficiency, the total system pumping power would be 757 kW (1015 hp).

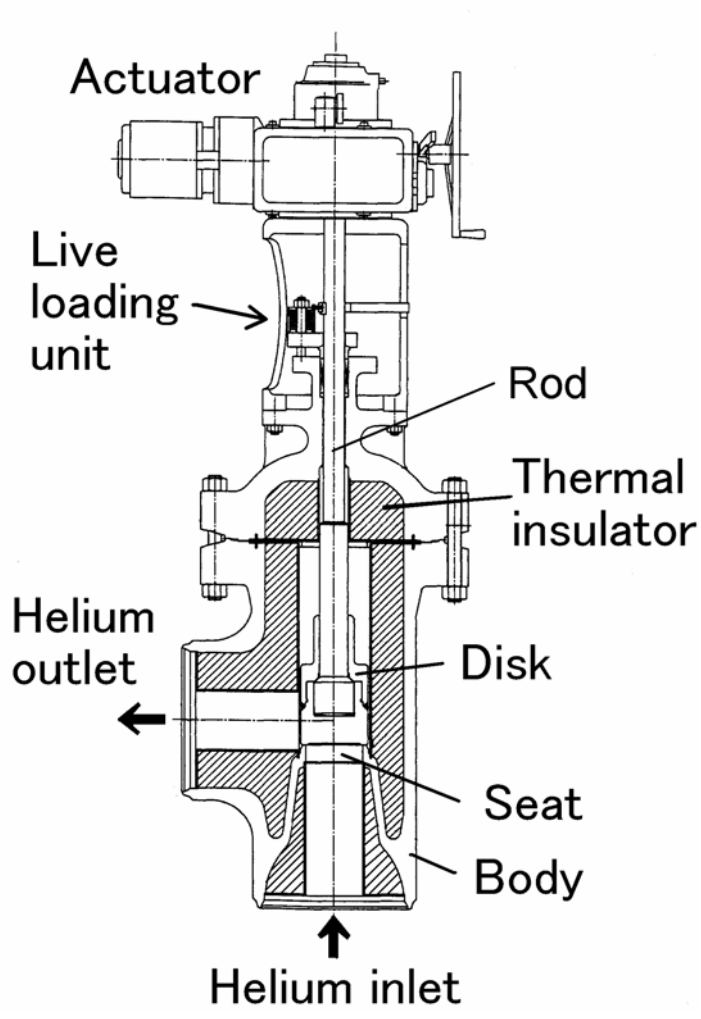

Figure 5-3: Diagram of High Temperature Isolation Valve

6 SECONDARY LOOP DESIGN FOR FLINAK

Previous secondary loop configurations (Ref. 4) have used a minimum steady-state loop temperature of 680°C which allows for a wide range of molten salt choices. However, such a minimum loop temperature will result in an unacceptably high helium temperature being returned from the IHX to the reactor.

Initial reactor operation at 850°C would involve a reactor inlet temperature of 490°C. A reactor inlet temperature that is lower than 590°C during 950°C operation would improve performance of metallic materials within the primary system. An IHX using FLiNaK would be unacceptably close to freezing if it was required to cool reactor helium down to 490°C. For a cogeneration plant like the NGNP, a reactor inlet temperature of 490°C could be maintained even with the molten salt IHX returning helium at 590°C by mixing the IHX helium with the much larger amount of helium being returned from the electricity power production portion of the NGNP.

The secondary loop design assumes that the reactor outlet temperature is 950°C and the reactor inlet temperature is 590°C. The IHX was designed and sized using these helium temperatures on the primary side. The secondary side FLiNaK temperatures were assumed to be 925°C and 565°C which are consistent with the temperatures in the SI-based H2-MHR design (Ref. 2). The sizing of the IHX is based on the Heatric-style printed-circuit heat exchanger (PCHE). The arrangement of the PCHE submodules was illustrated in Figure 5-1 in the previous section.

The relative size of the helium and molten salt channels (3:1) is based on a conceptual IHX design prepared by University of California – Berkeley as part of a DOE Nuclear Energy Research Initiative (NERI) project (Ref. 10). Assuming the molten salt is at 2 MPa and the helium is at 7 MPa, a finite element stress analysis as reported in Reference 10 indicated stresses within allowables for less than 0.5% creep over 10,000 hours using either Haynes Alloy 214 or alloy 800H. The pressure difference between the primary and secondary sides of the IHX significantly reduces the lifetime of the He-MS IHX. Materials such as alloy 617 or as alloy 230, which have better high temperature stress allowables and are generally more corrosion resistant, might also be acceptable in an HE-MS IHX. Alloys 617, 230, and 800H have relatively high Cr content of 19 – 23%, which is relatively high compared to the Cr content of 7% for Hastelloy N and 16% for Alloy 214. The corrosion characteristics of high Cr alloys may be unacceptable or require maintenance of a reducing environment. Efforts are underway to update ASME Nuclear Code Case N-201 to accommodate the needs of the VHTR to include candidate materials such as alloy 617. The draft code case for alloy 617 will cover temperatures up to 982°C and maximum service life of 100,000 hrs at temperatures greater than 427°C under Subsection NH of the ASME Code. Other non-nuclear sections of the code already allow the use of alloy 617 up to 982°C.

The basic geometric parameters of the He-molten salt (MS) IHX are as follows:

Table 6-1: Basic Geometric Parameters of He-MS IHX

Parameter	Value
Number of Modules	4
Module Height	2.25 m
Total Module Width (includes edges)	0.626 m
Edge Distance	13 mm
Total Module Length	0.902 m
Radius of Helium Channels	1.5 mm
Radius of Molten Salt Channels	0.5 mm
Channel Center to Center Spacing	3.9 mm
Channel Offset Pitch	12.7 mm
Height of Offset	2.286 mm
Layer Thickness	2.4 mm
He Flow Area per Module	0.2389 m^2
MS Flow Area per Module	0.02654 m^2
He Heat Transfer Area per Module	493 m^2
MS Heat Transfer Area per Module	164 m^2

For each coolant there are 463 PCHE layers per module. Each layer has 146 coolant channels. The flow area per module is 0.2389 m^2 (2.5716 ft^2) for the helium coolant and 0.02654 m^2 (0.2857 ft^2) for the molten salt coolant. The LMTD of the heat exchanger is 25°C (45°F) and its effectiveness is 93.5%. The primary side heat transfer coefficient is 2294 W/m^2-K (404 Btu/hr-ft^2-°F) and the secondary side heat transfer coefficient is 8404 W/m^2-K (1480 Btu/hr-ft^2-°F). The overall heat transfer coefficient is 1016 W/m^2-K (179 Btu/hr-ft^2-°F). The helium flow rate on the primary side is 26.71 kg/s (58.88 lb/s). The FLiNaK flow rate on the secondary side is 72.16 kg/s (159.1 lb/s). The pressure on the primary and secondary sides are 7 MPa (1015 psia) and 2 MPa (290 psia), respectively. The pressure drop on the primary side is 30.5 kPa (4.4 psi). The pressure drop on the secondary side is 252.4 kPa (16.6 psi). The metal volume before etching the flow channels is 5.08 m^3 (179 ft^3), which has a mass of 43,000 kg (94,000 lb) and will be used to evaluate the material cost of the IHX.

Parallel hot leg and cold leg piping is assumed to run 90 m in length between the IHX and PHXs of either the SI or HTE hydrogen production demonstration plant. A parallel pipe configuration was selected because it is less complex and is more amenable for interfacing with secondary loop isolation valves. The parallel pipe configuration is also a simpler design to accommodate the design features necessary to address thermal expansion. A schematic of the secondary loop configuration is presented in Figure 6-1.

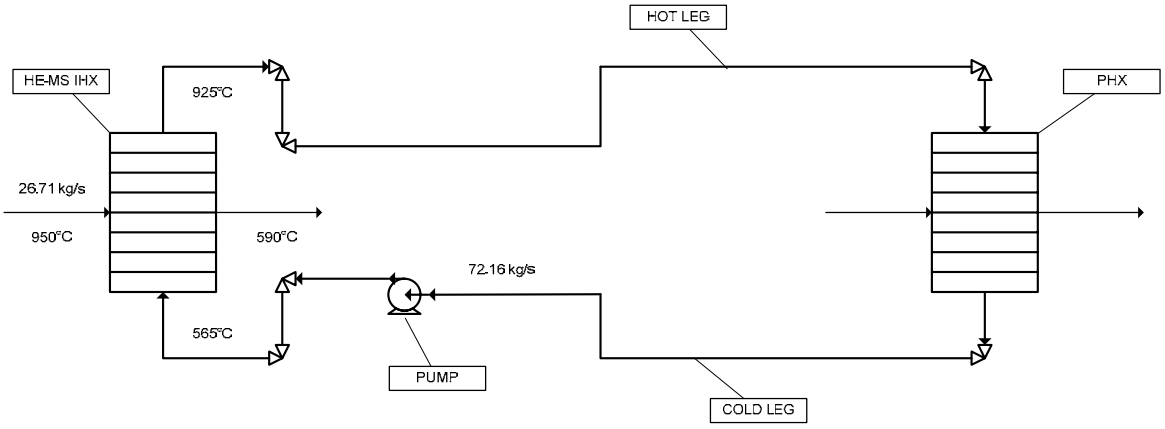

Figure 6-1: Schematic of Molten Salt Secondary Heat Transport Loop

Unlike the He secondary loop, no internal insulation was uncovered in the literature which would be compatible with FLiNaK. Most insulations are porous and would absorb the molten salt, which would compromise the heat transfer resistance of the insulation. Because of freezing concerns with molten salt, the pipe wall would have to be maintained at greater than 500°C. External insulation is proposed to reduce the heat loss to the environment. The addition of external insulation does not raise the pipe wall temperature since there is no internal insulation.

Insulated system performance was analyzed under two extreme weather conditions: a hot day with no wind, and a cold windy day. The air temperature for the hot day was 38°C (100.4°F). The hot day determines the maximum pipe wall temperature which is used to determine the minimum allowable pipe wall thickness to be within the stress allowables using the ASME process piping standard B31.3 (Ref. 9). The air temperature for the cold day was -30°C (-22°F) with a wind speed of 22.4 m/s (50 mph). The cold day determines the insulation thickness necessary to meet the requirement of ≤1% heat loss to the environment. In order to simplify the pipe design and manufacturing, the hot and cold leg pipes were designed to be the same size, same diameter, and same wall thickness, and to have the same external insulation thickness. One advantage of this approach is that any transient that raises the cold leg temperature would not exceed allowable stresses at the elevated pipe wall temperatures associated with the transient.

Table 6-2 summarizes the geometric parameters of the molten salt piping. The results of the one-dimensional thermal analysis are shown in the Table 6-3 for the hot and cold leg pipes operating on hot and cold days. For the cold day, the total temperature drop is 3.0°C which is 1% of the 360°C temperature rise within the IHX. The total temperature drop on the hot day is 2.5°C.

Table 6-2: Basic Geometric Parameters of the MS Piping

Parameter	Metric Value	English Value
Pipe Inside Diameter	0.20 m	8 in.
Pipe Wall Thickness	27.9 mm	1.1 in.
Pipe Outside Diameter	0.26 m	10.2 in.
External Insulation Thickness	25.4 mm	1 in.

The maximum pipe wall temperature on the hot day is 924°C (1695°F) which is also the maximum pipe wall temperature on the cold day. The material chosen for the pipe wall is alloy 617, which is qualified to 982°C under Section III, Class 2 & 3, Section VII, Div. 1, and Section XII of the ASME code. Efforts are underway to update ASME Nuclear Code Case N-201 to accommodate the needs of the VHTR to include candidate materials such as alloy 617. At 924°C (1695°F), the stress allowable is only 10 MPa (1,450 psi). The stress in the pipe wall is less than the stress allowable if the wall thickness is 27.9 mm (1.1 in.). The resulting volume of pipe material is 3.65 m^3 (129 ft^3) which has a mass of 31,000 kg (67,000 lb).

Table 6-3: Thermal Analysis Results for the MS Piping

Parameter	Temp. on Hot Day	Temp. on Cold Day
Hot Pipe		
- Inner Pipe Wall	924°C (1695°F)	924°C (1695°F)
- Outer Pipe Wall	920°C (1688°F)	919°C (1686°F)
- Outside Surface of External Insulation	463°C (865°F)	14°C (58°F)
- Temperature Drop in Hot Pipe	1.7°C (3.1°F)	2.0°C (3.6°F)
Cold Pipe		
- Inner Pipe Wall	564°C (1047°F)	564°C (1047°F)
- Outer Pipe Wall	562°C (1044°F)	561°C (1042°F)
- Outside Surface of External Insulation	218°C (425°F)	-13°C (9°F)
- Temperature Drop in Cold Pipe	0.8°C (1.4°F)	1.0°C (1.8°F)
Air Temperature	38°C (100.4°F)	-30°C (-22°F)

The total pressure drop in the secondary heat transport loop is the sum of pressure drops in the IHX, PHXs and piping system. A design of the PHX for either the SI or HTE hydrogen production process was not available for this study, so the pressure drop in the PHX was assumed to be the same as the pressure drop in the IHX. The secondary heat transport loop was assumed to have three isolation valves on each leg – two near the IHX and one near the PHX. Each valve is assumed to be similar to the high temperature isolation valve discussed in References 2 and 3, which would have a pressure loss L/D of 55. Each leg of the secondary loop was also assumed to have five bends with a pressure loss L/D of 18 and an entrance/exit K_{loss} of 1.5. The hot leg has a pressure loss of 17.1 kPa (2.5 psi). The cold leg has a pressure loss of 17.8 kPa (2.6 psi). The total pressure drop in the secondary loop is estimated to be 264 kPa (38.3 psi). Assuming the pump has an 80% efficiency, the total system pumping power would only be 11.2 kW (15 hp) which is almost 1000 times lower than the circulator power for the He secondary loop.

7 EVALUATION OF WORKING FLUID

7.1 Economic Evaluation

The difference in capital cost of the secondary heat transport loop using high-pressure helium or moderate-pressure FLiNaK is based on the size of components and the quantity and cost of construction materials. Sizing of the IHX and piping were explicitly determined for both working fluids in Section 5 and 6. The size and cost of the PHXs for the SI and HTE hydrogen production processes were assumed to be similar regardless of the secondary system working fluid. Based on results presented below on the IHX, the design of the PHXs will be primarily a function of the fluid properties within the hydrogen production process. The PHX for the SI process would vaporize and decompose sulfuric acid at either 2 MPa or 7 MPa depending on the working fluid pressure. If the decomposer is made of a ceramic material, then it should be capable of fully absorbing any pressure difference between the secondary heat transport loop and the sulfuric acid. With a ceramic decomposer, there would be no reason to reduce the secondary coolant pressure. The PHX for the HTE process would superheat steam at pressures also dependent on the working fluid pressure. The optimal pressure condition of the secondary heat transport loop that minimizes the technical risk associated with IHX, PHXs, and hydrogen production process design will need to be determined. This technical risk minimization process requires iteration between the heat transport system design and hydrogen production system design. The size and cost of the circulator or pump for the secondary heat transport loop is based on the pumping power required to deliver 50 MWt of heat from the reactor to the hydrogen production processes.

The size of the Heatric-style PCHE IHX is limited by the heat transfer performance on the primary side, which is why the He-He IHX and the He-MS IHX are essentially the same size. The metal volume and mass of the He-He IHX and He-MS IHX before etching of the flow channels are shown in Table 7-1. Both IHXs are assumed to be made of alloy 617 in order to withstand the maximum primary side helium temperature of 950°C (1742°F).

Table 7-1: Intermediate Heat Exchanger Size Comparison

Parameter	He-He IHX	He-MS IHX
Metal Volume	5.18 m^3 (183 ft^3)	5.08 m^3 (179 ft^3)
Mass	44,000 kg (96,000 lb)	43,000 kg (94,000 lb)

The alloy 617 material costs around $48/lb so the material cost of the He-He IHX would be $4.608 million and the He-MS IHX would be $4.512 million. The material cost of either IHX is essentially the same. The manufacturing of the Heatric PCHE is estimated to cost $7.7 million based on prior communication with Heatric, Inc. on other projects. The total cost for the 50 MWt IHX is around $12.3 million. The cost of the IHX is not a discriminator between helium and molten salt working fluids. The same conclusion should apply to the PHXs.

The size of the 90-m long piping used to transport the working fluid between the IHX and the PHXs is primarily determined by the goal of minimizing pressure drop within a reasonably sized pipe. The pipe material, inner diameter, wall thickness, metal volume and mass are summarized in Table 7-2 for the He and MS secondary heat transport systems.

Table 7-2: Piping Size Comparison

Parameter	He Working Fluid	FLiNaK Working Fluid
Material	2¼Cr-1Mo	Alloy 617
Inner Diameter	0.76 m (30 in.)	0.20 m (8 in.)
Wall Thickness	35.6 mm (1.4 in.)	27.9 mm (1.1 in.)
Metal Volume	16.04 m^3 (566.4 ft^3)	3.65 m^3 (129 ft^3)
Mass	130,000 kg (280,000 lbm)	31,000 kg (67,000 lbm)

The alloy 617 material costs around $48/lb plus a 30% cost adder for pipe manufacturing. The 2¼Cr-1Mo material costs around $2/lb plus a 40% cost adder for pipe manufacturing. The pipe cost for the He working fluid is $0.78 million, and for the FLiNaK working fluid, it is $4.18 million. The cost of insulation was not estimated because it is relatively inexpensive compared to the piping cost. High temperature isolation valves for the MS system are estimated to cost a total of $0.42 million. For the He system, the isolation valves are estimated to cost a total of $2.16 million. The valves for the He system are much more expensive due to their larger size. Internal valve insulation for the He system could reduce the cost by allowing less expensive materials of construction. The total cost of the He piping including valves is $2.94 million. The total cost for the MS piping including valves is $4.60 million. If the length of piping was doubled, then the cost of the MS piping and valves would nearly double while the cost of the He piping and valves would increase from about $3 million to less than $4 million.

The remaining cost discriminator is the circulator/pump. The circulator is assumed to be an axial flow machine with a variable speed motor. The shaft and impeller would be supported by magnetic bearings similar to the primary helium circulator, IHX loop circulator, and shutdown cooling circulator. The size and cost of the circulator is determined by its power consumption. The circulator is sized at 757 kW. The estimated cost of this circulator is $19 million. The MS pump is sized at only 11.2 kW. The estimated cost of the MS pump is $1 million.

Based on these estimates, the He secondary heat transport system would cost about $34 million including the IHX cost. The MS secondary heat transport system would cost $18 million. Both of these estimates exclude several auxiliary systems associated with the secondary heat transport system. Any cost differential among the auxiliary systems would be minor relative to the major cost items. It is evident that the He secondary heat transport system has a higher capital cost by about $16 million.

The operating cost of the He secondary heat transport system is dominated by the cost to operate the circulator which is sized at 757 kW. Assuming a 90% capacity factor, the circulator would use 6 million kW-hrs per year. At an average 2005-2006 electricity price in Idaho of 5¢/kW-hr, the circulator operating cost would be $300,000. As a percentage of the NGNP's electrical output, the circulator uses less than 0.3%. Therefore, the operating cost is relatively insignificant for the NGNP.

An additional capital cost and operating cost is associated with the cost of the working fluids. The quantity of working fluid was simply estimated by calculating the internal volume of the piping. For the helium piping, the volume used by the internal insulation is ignored because of its high void fraction. The helium volume is 82 m^3 (2900 ft^3) and the FLiNaK volume is 5.8 m^3 (206 ft^3). The helium mass is 270 kg (600 lb) and the FLiNaK mass is 11,500 kg (25,400 lb). The initial cost of the working fluid would be $13,500 for helium. Based on the cost data in Reference 8, the initial cost for FLiNaK is $89,900. A recent price quote from American Elements for 99% pure anhydrous fluorides powders adds up to a total initial cost of $960,000. The price quote further suggests it would take 5 years to produce the required amount of sodium fluoride. Both of these costs are relatively insignificant. Annual helium leakage is expected to be less than 10% so that the annual helium replacement cost is only $1,350. Leakage of FLiNaK is expected to be minimal.

Potentially the largest contributor to operating cost for either the He or MS heat transport loops is the periodic replacement of the IHX and PHXs due to limits on allowable operating life. Whereas Subsection NH of the ASME code is limited to 300,000 hrs, the draft code case for alloy 617 is limited to design lives of 100,000 hrs or less. The main reasons for this shorter design life are (1) the uncertainties of data extrapolation at very high temperatures, and (2) at long times, the allowable stresses are less than 1,000 psi at the highest temperature. There is a lack of experience in designing reliably at such low allowable stresses. The 100,000 hr limit corresponds to an 11-12 year lifetime for the He-He IHX. In the case of the He-MS IHX, creep stress and corrosion would likely limit the lifetime to 10,000 hrs. The total cost for replacing the IHX was not quantified but the IHX itself would cost $12-13 million which corresponds to an annual replacement cost of about $2 million for the He-He IHX and $10 million for the He-MS IHX. The PHXs are likely to have similar life limiting issues.

A commercial scale plant using the HTE hydrogen production process would use an IHX and secondary heat transport system of about the same size as in the NGNP. In contrast, a commercial scale plant using the SI process would use an IHX and secondary heat transport system that is 12 times larger and transfers 600 MWt instead of only 50 MWt. The flow areas and heat transfer surface areas of the IHX and PHX would increase by a factor of 12 so that the pressure drop through these components would be the same as the NGNP. Increasing the pipe diameter by a factor of 12 is not practical. A more realistic pipe size would be limited to an inner diameter of 1.52 m (60 in.). To further manage the increased mass flow rate, the secondary loop would probably have two hot pipes and two cold pipes. In such a configuration, the pressure drop in the piping system would decrease by a factor of 0.65 and the total system pressure drop would decrease by a factor of 0.86. The circulator power would increase from one circulator at 0.75 MWe to two circulators at 4 MWe each. The primary helium circulator is expected to use 10 MWe and the SI hydrogen production plant would use 178 MWe on a per module basis. The 8 MWe of electricity usage by the secondary loop circulators is relatively minor but not insignificant.

7.2 Technical Risk Evaluation

High-temperature corrosion is an issue with molten salts that is being researched. This issue will be a concern with licensing and code qualification. Past experience with FLiNaK at Oak Ridge National Laboratory led to the development of Hastelloy N. The NGNP and its secondary heat transport loop will operate at temperatures that will not allow the use of Hastelloy N as a structural material. For this reason, it has been proposed that the IHX be made of alloy 617 instead of Hastelloy N. Whether alloy 617 will have acceptable resistance to high-temperature corrosion has yet to be proven. The high Cr content of alloy 617 may be unsuitable without the benefit of a reducing environment. For the He-MS IHX, the combination of high-temperature corrosion and high-temperature creep may limit its operating life. For the MS piping, the alloy 617 pipe could include an internal liner of Hastelloy N as a corrosion barrier. This design approach would be similar to the stainless steel liner on light water reactor pressure vessels.

Helium purification and radionuclide control (including tritium) can be maintained in a He transport system using similar equipment as in the helium purification system for the NGNP primary coolant system. Such a system can remove particulates, carbon monoxide, carbon dioxide, and tritium through the use of filters, oxidizers and dryers. Unlike the primary system purification train, the transport loop would not need low-temperature absorbers for removing nitrogen, xenon and krypton. A coolant purification and radionuclide control solution for a molten salt transport system has not been developed. One possibility is to process the cover gas on the pressurizer used to maintain the transport system at 2 MPa.

Freeze protection on the molten salt system is an additional technical risk which adds complexity to system design and operation, maintenance, and inspection. The external insulation on the piping system should reduce the risk but some heat tracing will be necessary.

The heat tracing for the piping would be able to keep the molten salt at ≥565°C if it is sized to add 240 kW of heat. For maintenance and shutdown, the molten salt would have to be drained into a storage tank where it can either be maintained at liquid temperatures or allowed to freeze. Helium could be used to aid in the drainage of the molten salt. Of particular concern is the drainage of molten salt out of the IHX and PHXs. The IHX with the 0.5 mm radius channels may be extremely difficult to drain. There would be insufficient margin to freezing of FLiNaK if the reactor inlet temperature was lowered to 490°C with a corresponding decrease in the cold leg temperature in the transport system down to 465°C. The minimum secondary loop temperature should be keep above 500°C to provide adequate margin.

Code qualification and licensing issues are a concern with the high temperatures imposed on the IHX and with the use of a Heatric-style PCHE. Alloy 617 is already allowed at temperatures up to 982°C in non-nuclear sections of the ASME code. The draft code case for Alloy 617 will extend its use under Subsection NH to 982°C with a maximum service life of 100,000 hrs at temperatures greater than 427°C. The ASME code issues for Heatric-style PCHE deal with the use of diffusion bonding between the PCHE plates. Alternate IHX designs based on existing practice are possible but would significantly increase the size of the IHX. The IHX and PHXs are the primary areas of technical risk that require technology development regardless of the working fluid selection for the heat transport loop. Using a pressure-balanced IHX will lessen these concerns but not eliminate them. Worker safety and decommissioning do not appear to impose any significant technical risk regardless of the working fluid selection. One particular safety issue involving molten salt is its interaction with the process fluid in the hydrogen production plant if the PHX develops a leak. Such a leak could form highly corrosive HF, especially in the steam generators of the HTE process.

8 CONCLUSIONS AND RECOMMENDATION

The economic evaluation clearly shows that an NGNP secondary heat transport system using molten salt FLiNaK as the working fluid would have lower initial capital and operating costs, excluding IHX replacements costs, relative to a system using helium as the working fluid. IHX replacement costs are much more significant especially for the molten salt heat transport system. The difference in capital costs is significant relative to the total cost of the secondary heat transport system but is insignificant compared to the total NGNP cost. Similarly, the operating cost for the He circulator represents about a 0.3% reduction in available electrical output, which is also insignificant.

However, the technical risks associated with molten salts relative to those associated with helium remain significant at the present time. The principal technical risks with molten salt are high-temperature corrosion, freezing protection and drainage of molten salt from the IHX and process heat exchangers (PHXs). Also, the pressure difference between the primary and secondary coolants significantly degrades the operating lifetime of a metallic IHX due to creep stress. While technical solutions appear possible, there does not appear to be a compelling reason to choose molten salt over high-pressure helium, particularly in view of the high-level NGNP Project requirement to use the lowest-risk technology consistent with satisfying the NGNP objectives.

The technical risks associated with high-pressure helium are much more manageable and understood. Gas circulator technology has been proven on numerous reactor applications including the High Temperature Test Reactor (HTTR) in Japan. HTTR also has experience in using helium as a secondary coolant to transfer heat from the reactor to process heat exchangers.

Therefore, it is the recommendation of this study that the secondary heat transfer loop use high-pressure helium as the working fluid. Further design analysis is needed to determine the optimal pressure for the heat transfer loop which balances the design challenges of the IHX against the design challenges and performance objectives of the PHXs and hydrogen production processes. For a commercial scale SI plant, the helium circulator power for a secondary heat transport system consisting of two loops is estimated to increase electrical power use by 4.3% and results in an overall hydrogen production efficiency of 45.6%. The increased electricity usage by the secondary loop circulators is relatively minor and does not change the recommendation that the secondary heat transfer loop use high-pressure helium.

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