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Analysis Methods And Desired Outcomes Of The Analysis Of Intermediate And Process Heat Exchanger Loop Requirements

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Abstract
The components of the intermediate heat transfer loop will be subjected to conditions that may produce time dependent deformation, corrosion and erosion. High temperature strength may also be an issue with many components. A stress analysis will be performed on the intermediate heat exchanger of the printed circuit heat exchanger (PCHE) type and the implications on material requirements will be determined. Potential materials of construction will be identified and evaluated in light of the stress analysis and the available creep data. A concentric or annular pipe design for carrying both the hot and cold fluid streams in the intermediate loop will be modeled to determine the temperature drop between the NGNP and the hydrogen production facility. This design will be compared to separate piping for the hot and cold fluid streams. Finally two designs for the process heat exchangers will be evaluated for catalytic and thermal effectiveness.

All the evaluations mentioned above will be performed for both high pressure helium and liquid salt as the heat transport media. Also, materials and materials issues will be discussed with regard to the evaluations.

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1. Introduction

Heat transport between a high temperature nuclear reactor and the hydrogen production facility is one of the critical systems required for the demonstration of hydrogen production using nuclear heat. Currently the Next Generation Nuclear Power (NGNP) plant is expected to supply heat to the heat transfer loop at temperatures between 900-1000^{o}C. The hydrogen production facility requires a minimum temperature of 800^{o}C for the thermochemical production of hydrogen, i.e. the Sulfur-Iodine cycle, and about 700^{o}C for high temperature electrolysis (HTE) [Independent Technology Review Group, 2004]. Therefore the components of the heat transport system will be subjected to temperatures where high temperature strength and creep will be a concern. Also, current recommendations [Smith. et. al., 2005] site the hydrogen production facility from 60 to 120 meters away from the NGNP, raising concerns about significant heat loss during heat transport. Therefore, this heat transport system will have to receive heat efficiently from the NGNP, transport it over large distances without excessive heat loss and, finally, efficiently transfer it to the hydrogen production facility. Two fluids are currently under consideration for use as the high temperature heat transfer medium, namely high pressure (~1000 psi) helium or liquid salt. A swiftly moving (on the order of 6 m/s) liquid salt raises concerns over high temperature corrosion of loop components. The use of high pressure helium as a heat transfer medium presents less of a corrosion problem but erosion (or, rather the particles and impurities entrained within the helium fluid) may be more of a factor since velocities of 75 m/s are expected. Also the heat transfer system will be supplying heat to decompose concentrated sulfuric acid vapors containing SO_2, SO_3 and water and, therefore, the process heat exchanger will be exposed to highly corrosive conditions.

In general, the major engineering concerns associated with the components of the intermediate heat transfer loop are:

1. High temperature strength - important in off-normal events such as reactor excursions and accidental over-pressurization of the heat transfer loop.
2. Creep resistance – relevant to the long-term day-to-day operation over the design life (>10 years) of heat transfer loop. The creep rate will be especially important if high pressure helium is selected as the heat transfer medium since significant creep will result in failure of the component.
3. Corrosion resistance – the destination of the nuclear heat will be in various hydrogen production processes. In the thermochemical production of hydrogen, e.g. Sulfur-Iodine cycle, the process heat exchanger is exposed to highly corrosive environments while in HTE, the process heat exchanger is exposed to high temperature steam. Corrosion concerns are also associated with the use of liquid salts as a heat transfer medium.
4. Erosion resistance – the heat transfer medium, whether it is liquid salt or high pressure helium, is expected to move at high velocities where erosion may become a concern. Erosion may also strip protective layers from components and allow accelerated corrosion compared to a static or slower moving environment.
5. Heat transport behavior – the thermal properties of the materials used for the heat exchangers and the heat transfer medium will influence the efficiency, size and cost of the heat exchanger. The thermal properties of the material(s) used in the piping and insulation of the heat transfer loop will determine the temperature drop between the NGNP and the hydrogen production facility.

Various components of the heat transfer loop will be affected by a number of the above mentioned engineering concerns.

Although the exact configuration of the intermediate heat transfer loop has not yet been determined [Independent Technology Review Group, 2004 and Davis, 2005] components common to all the proposed configurations include:

- Heat transfer fluid – either high pressure helium or liquid salt
- Intermediate heat exchanger (IHX) – Physically separates the primary coolant from the intermediate heat transfer fluid in addition to allowing the transfer of heat from the nuclear reactor to the intermediate heat transfer loop.
- Heat transfer fluid containment – piping configuration to efficiently transport the heat transfer fluid between the nuclear reactor and the hydrogen production facility without a significant loss of heat over large distances (up to 120 meters [Smith, et. al., 2005]).
- Process heat exchanger – physically separates the intermediate heat transfer fluid from the process fluid for either the thermochemical hydrogen cycle or the HTE process in addition to efficiently transferring heat from the intermediate loop to the hydrogen production process. This heat exchanger must be corrosion resistant to both fluids used in the hydrogen production process and the intermediate heat transfer fluid.
- Heat transfer fluid pumps – circulates the heat transfer fluids through the intermediate loop at velocities on the order of 75 m/s for high pressure helium or 6 m/s for liquid salt.
- High temperature isolation valves –functions to isolate IHX from the primary coolant system in the case of maintenance on the intermediate loop or breach of the IHX.

2. Scope

Work will focus on components (IHX, process heat exchanger and piping) and design options with an emphasis on materials of construction. Previous analyses have focused on configuration options and identification of operating parameters associated with the various configurations [Davis, 2005, Davis, et.. al., 2005 and Smith, et. al, 2005.]. The goal of this work is to identify component parameters (as they are currently known), materials issues, areas of research, active research programs addressing materials issues, component design options, availability of components and, where possible, relative costs of different materials options. The above components will be discussed in light of both heat transfer fluid options. Use of ceramic materials as well as metallic alloys will be considered and discussed. Relevant information will be extracted from past reports, current research projects, related commercial chemical processes and potential vendors of various intermediate loop components as well as modeling of individual components (stress distribution, temperature profile, etc.) where appropriate.

3. Key Requirements and Assumptions

Currently the designs of the NGNP, Intermediate Heat Transfer Loop (IHTL) and the hydrogen production plant have not been finalized and there is considerable discussion on the expected operating parameters. However, Table 1 below has been assembled from various sources and identifies the range of various parameters being discussed.

Table 1. Intermediate Heat Transfer Loop Operating Parameters

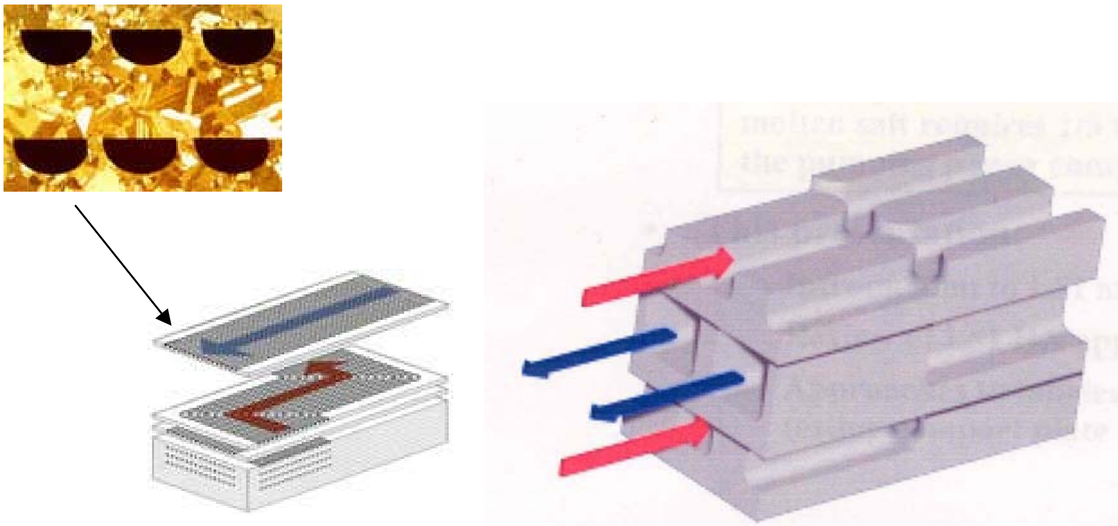
Parameter	Range
IHX – NGNP side	
Inlet Temperature, ^{o}C	900 - 1000
Outlet Temperature, ^{o}C	600-?
Pressure (helium), MPa	7
IHX – Intermediate Loop side	
Inlet Temperature	600 - 800
Outlet Temperature	850 - 950
Pressure –	
Helium, MPa	7
Liquid Salt, MPa	1 - 2
Process HX - Intermediate Loop side	
Inlet Temperature	850 - 950
Outlet Temperature	700 - 500
Pressure –	
Helium, MPa	7
Liquid Salt, MPa	1 - 2
Process HX – Process Side	
Inlet Temperature, ^{o}C	500 - 600
Outlet Temperature, ^{o}C	700 - 900
Pressure , MPa	1.4 - 3.5
*High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, L.C. Brown, G.E. Besenbruch, et. al, General Atomics report #GA-A24285, June 2003	

4. Design Configuration

As mentioned, a number of design configurations have been proposed and evaluated. These configurations include both direct and indirect cycles. Therefore this work will only be concerned with the intermediate heat exchanger and the components required between the IHX and the hydrogen production facility. The components comprising this section are collectively referred to as the intermediate heat transfer loop (IHTL). As a minimum it consists of the IHX, the heat transfer fluid, piping to transport the heat transfer fluid, the process heat exchanger, pumps and isolation valves. A secondary heat exchanger may also be included to enable construction to less stringent code requirements than those imposed on the NGNP. Also, some indirect cycles may require a compressor to compress the cold helium return stream, see Davis, 2005, Figures 6 & 7.

5. Intermediate Heat Exchanger (IHX)

The IHX will be subjected to the highest temperatures of all the IHTL components. The inlet temperature of ~900^{o}C presents a potential for creep since at least one side of the IHX will be exposed to high pressure helium. If the intermediate loop side of the IHX is also pressurized helium the pressure differential across the IHX will be relatively small while a liquid salt heat transfer fluid in the IHTL will result in a relatively large pressure differential. The design of the IHX and the heat transfer fluid will largely define the magnitude of the differential. Current design concepts include printed circuit heat exchangers (PCHE), offset fin heat exchangers, primary surface recuperator-type designs and possibly helical shell and tube designs. The latter two types of heat exchangers are fairly common and have been extensively analyzed. However, PCHEs and offset fin heat exchangers, Figure 1, are relatively new and very compact. A stress analysis of the PCHE type will be included in the final report (thermal stresses will *not* be included). Offset fin heat exchangers are currently being modeled by UNLV and UC- Berkeley and their progress and relevant results also will be reported.



(a) (b)

Figure 1. Proposed compact heat exchanger designs – a) Heatrics and b) offset fin heat exchanger.

Based on the stress analysis for the PCHE, the suitability of various high temperature materials (metallic alloys as well as ceramic materials) for use as materials of construction will be evaluated using standard design criteria (acceptable creep deformation, safety factor, etc.) and available creep data. A similar evaluation will be performed on the offset fin compact heat exchanger if modeling by UNLV and UC-Berkeley has progressed sufficiently. Finally, the maximum allowable erosion/corrosion rate will be calculated for various high temperature materials and will be based on a 10-12 year service life.

6. Piping

Up to this point the piping configuration has been explicitly assumed to be separate hot and cold legs. The concentric or annular design concept for piping, with the hot fluid flowing through the central tube and the cold fluid flowing in the opposite direction in the outer portion, see Figure 2, has been proposed but very little evaluation of the advantages and disadvantages has been performed. This work will evaluate the thermal savings associated with this particular design as a function of separation distance and compared to the single pipe configuration. The evaluation will include pipe (pressure boundary) material parameters and various annular designs, e.g. with and without internal and external insulation, for both high pressure helium and liquid salt heat transfer mediums.

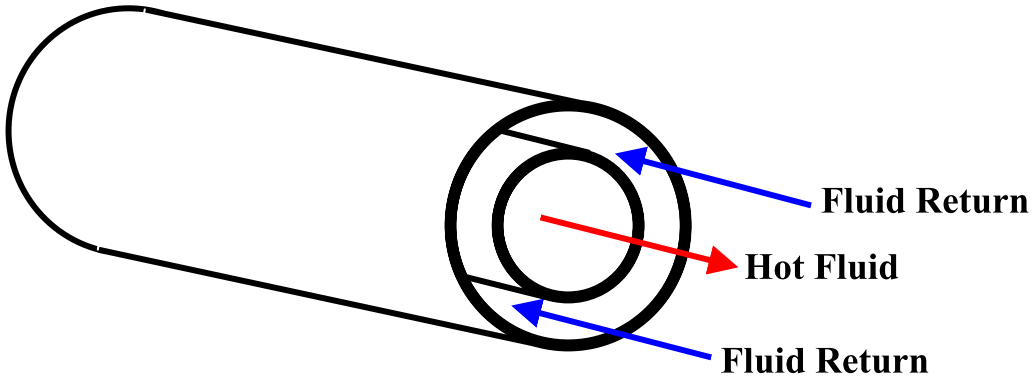


Figure 2. Annular piping design in which the cooler return fluid flows in the opposite direction of the hot fluid in the outer annulus. Insulation may be present on the inside of the inner tube as well as the outside of the outer tube.

7. Process Heat Exchanger

The process heat exchanger also functions as a sulfuric acid decomposition unit. The bulk of the heat energy transported by the intermediate loop will be deposited in the process heat exchanger to accomplish the decomposition of high temperature, pressurized sulfuric acid vapors. The decomposition requires a catalyst. Currently, design options include a PCHE with an internal coating of catalyst on the process channels or a tube in shell heat exchanger containing a packed bed of catalyst-coated beads. The relative size of these two types of heat exchangers will be calculated based on the catalytic surface available for decomposition as well as the catalytic activity of the catalyst in the two different forms (continuous layer versus packed bed of beads). A relative size will also be calculated based on thermal properties and performance. Candidate materials of construction will be used in the evaluation. These materials will possess the required creep resistance, corrosion resistance and erosion resistance for either high pressure helium or liquid salt as the intermediate loop heat transfer fluid.

8. References:

Independent Technology Review Group, 2004, “Design Features and Technology Uncertainties for the Next Generation Nuclear Plant,” INEEL/EXT-04-01816.

Smith, C., S. Beck, and B. Galyean, 2005, “An Engineering Analysis for Separation Requirements of a Hydrogen Production Plant and High-Temperature Nuclear Reactor,” INL/EXT-05-00137 Rev 0, March.

Davis, C.B., 2005, “Analysis Methods and Desired Outcomes of System Interface Heat Transfer Fluid Requirements and Characteristics Analyses”, INL/EXT – 05 – 00228, April.

Davis, C.B. Oh, C.H, Barner, R.B. and Wilson, D.F, 2005, “Thermal-Hydraulic Analyses of Heat Transfer Fluid Requirements and Characteristics for Coupling a Hydrogen Production Plant to a High-Temperature Nuclear Reactor”, INL/EXT – 05 – 00453, June.