Functional Requirements Overview For a 50-MW(t) Liquid-Salt Intermediate Loop for NGNP

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INTRODUCTION

Liquid salts (LS) provide an important candidate fluid for high-temperature heat transport for hydrogen production and other applications, due to their high volumetric heat capacities and boiling temperatures. This report discusses functional requirements for a 50 MW(t) LS intermediate loop, designed for heat transfer between high-temperature, high-pressure helium and process heat exchangers for hydrogen production, for the Next Generation Nuclear Plant (NGNP) [1]. Figure 1 provides a preliminary flow diagram for a liquid-salt intermediate heat transport system for the NGNP. This work extends previous UCB development and design for a 50 MW(t) intermediate heat exchanger (IHX) for the NGNP [2], by identifying key functional requirements for the intermediate loop.

The design goal for the LS intermediate loop is to achieve the same hydrogen production efficiency that would be reached using a high-pressure, high-temperature helium intermediate loop. The advantages of the LS intermediate loop, compared to helium, are then: (1) lower reactor core outlet temperature, due to lower temperature drop across heat exchangers, reduced pumping power, and reduced hydrogen process pressures; (2) larger spacing between nuclear and hydrogen plants for safety; (3) elimination of intermediate loop stored energy from pressurized helium; and (4) potentially reduced capital costs due to smaller and lower pressure piping system and smaller and more compact heat exchangers. Disadvantages include (1) increased complexity due to requirements for LS freezing control and draining; and (2) safety and corrosion issues associated with process fluid in-leakage into the LS loop.

In order to identify functional requirements and design goals for the LS intermediate loop, the approach taken here is to first identify the set of operating, transient and accident conditions that the loop is required to operate under. The loop is divided into its major subsystems, and each subsystem is examined to identify key functional requirements for these operating, transient and accident conditions.

The major subsystems of the liquid-salt intermediate loop are:

- He-to-LS intermediate heat exchanger (IHX)
- He supply and return lines

- LS transfer lines
- LS pumps
- LS throttling and shut-off valves
- LS drain and chemistry/volume control system (CVCS)
- LS instrumentation and control system
- Process heat exchangers

The primary focus of this report is on the IHX. The LS intermediate loop, including the IHX, is designed to accommodate the following normal operation, transient, and accident conditions:

- Normal operation for 60 years (component creep/corrosion rates acceptable or replacement frequency specified)
- Loss or rapid change of helium flow, loss of LS flow, loss of process fluid flow, and thermal transients changing the helium or process fluid inlet temperatures.
- IHX leaks and breaks (helium manifolds, IHX modules, LS manifolds)
- Process HX leaks and breaks
- LS pipe small and large breaks
- Intermediate loop filling and draining transients

By dividing the intermediate loop system up into subsystems, and by defining the normal operation, transient, and accident conditions the intermediate loop system must perform under, the phenomena identification and ranking process can then be applied to determine the specific phenomena which must be understood to predict system performance.

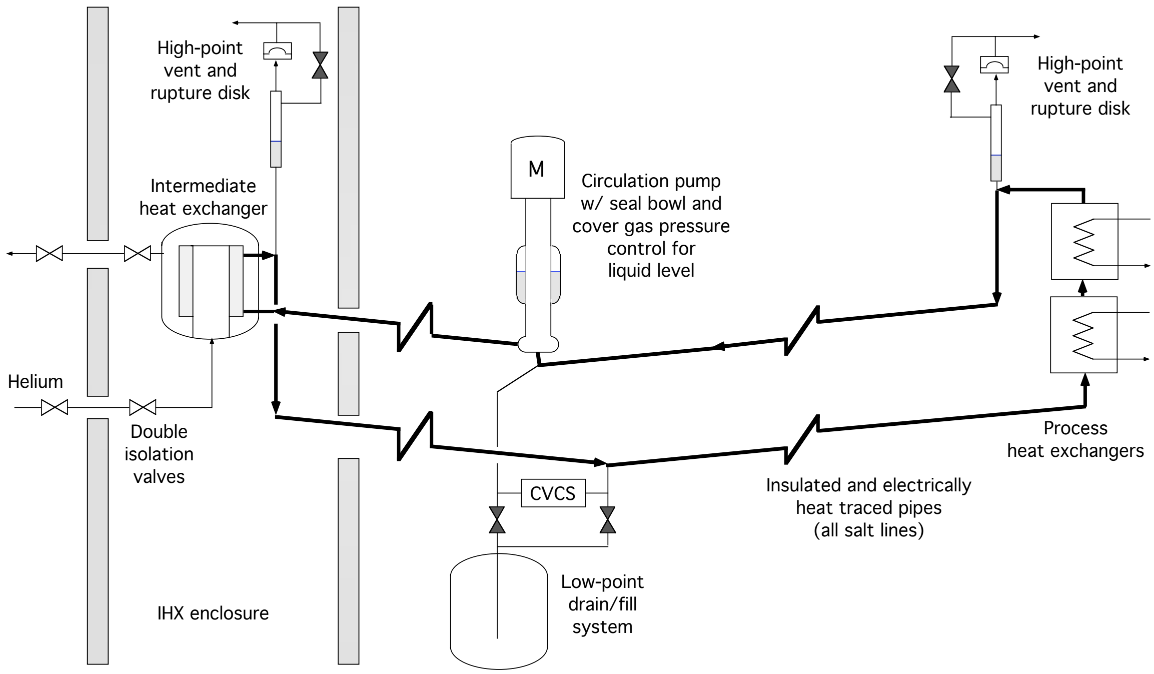

Fig. 1 NGNP LS intermediate loop flow diagram.

The primary focus of this report is on the design of the intermediate heat exchanger for the NGNP. However, the other elements of the intermediate loop system must be specified and understood in sufficient detail to permit the IHX to be designed. The following sections review requirements for the intermediate loop LS pump; drain and chemistry/volume control systems; shut-off and throttling valves; and the IHX itself.

Intermediate loop pump

A large-scale pump development program occurred for centrifugal liquid salt pumps, which share many design requirements with centrifugal pumps for sodium. Liquid salt pump technology is reviewed in Chapter 6 of the UCB AHTR design report issued at the same time as this report [3]. Liquid seals were not developed for the primary and secondary liquid salt pumps for the Molten Salt Reactor (MSR), and instead seal bowls have been used, with the shaft passing through a free liquid surface with an inert gas cover, and a gas seal on the shaft, as shown schematically in Fig. 1 and in detailed figures in Ref. [3]. In the design of earlier LS systems, the pump bowl was also used to accommodate thermal expansion, as does the pressurizer in a pressurized water reactor (PWR). In this design, additional small gas volumes, and liquid free surfaces, exist at the high-point vents, where gas is removed during loop filling and injected during loop draining (Fig. 1). Further development work for high temperature pumps has occurred for industrial nitrate salt heat transfer systems (for example for solar power towers), including the demonstration of salt-lubricated bearings for long-shaft pumps [8].

Several important phenomena occur in the pump seal bowl. These include the prevention of gas entrainment under the liquid surface and the control of transport, condensation, and freezing of vapor (dominantly the most volatile component of the salt, which when condensed will have a higher freezing temperature than does the mixture utectic—this is an issue mainly for zirconium-based salts due to the relatively high vapor pressure of ZrF_4).

In the loop, caution is necessary when multiple free surfaces are present, because flow transients can create pressure distributions that drive LS from one volume to the other. In the case of the 50 MW(t) LS loop, a single pump is used, and the free volume associated with the vent system is small compared to the free volume of the pump bowl. Commonly, LS pumps are located at the high point of loops. However, because the intermediate loop must be designed to drain over long distances, and to drain heat exchangers first (these have the largest surface area to volume and thus the highest risk for freezing), in this intermediate loop design the pump bowl is designed to be pressurized to provide positive pressure throughout the loop. This approach has been used in other high-temperature loop designs [4].

Drain and CVC systems

The intermediate loop uses electric trace heating to thermally precondition piping and components prior to filling, and to prevent freezing. But, due to the high freezing temperature of the salt, the loop is also designed to drain. As shown in Fig. 2, in the base-line design both the supply and the return lines are designed to drain to a single low point, which allows both lines to be run at equal elevations between the IHX and the process heat exchangers.

In the baseline design, the chemistry and volume control system is also located at the low point, so that it can be used for chemistry control of the drained salt, as well as chemistry control of salt in the intermediate loop. Here it is assumed that chemistry control is performed by the CVCS on a side-stream taken from the loop, which is then reinjected into the loop, as shown in Fig. 2. Chemistry control focuses on the filtering of solids, and the control of the fluorine and oxygen potential of the salt [5]. In general, these processes are best performed at the coldest location in the loop, because this is where the solubility of solid and immiscible liquid phases is the lowest. Thus in the baseline design, flow to the CVCS system is extracted at the discharge of the circulation pump in the return line, and is reinjected into the lower-pressure supply line.

LS throttling and shut-off valves

Limited work was performed to develop LS valves under the MSR program. Plans were in place to develop shut-off valves in sizes up to 6 inches, and throttling valves up to 24 inches [6]. Large throttling valves are not likely to be required for intermediate loop applications, because variable-speed pump motor technology now provides an preferable method for LS flow control.

For shut-off, freeze valves were developed and provided high reliability for pipe sizes up to 1-1/2 inches [6]. These valves used a flattened section of pipe and heaters and coolers to induce freezing and thawing, and provided response times of several minutes and highly reliable operation. Throttling valves for flow control, using bellows seals, were also tested in sizes up to 4 inches and provided reliable service [6]. For shut-off service, the principal challenge was considered to be the development of appropriate seat materials, because liquid salts effectively flux passivating coatings from surfaces and thus can permit self-welding to occur. Limited experience using cermets was obtained.

For operation at 3 m/s flow velocity, the baseline 50 MW(t), 0.4 m^3/s LS intermediate loop uses a 0.4 m (10 inch) diameter supply and return pipes. This exceeds the limit of available throttling and shut off valves. However, flow control for the loop can be obtained by using variable pump speed. Throttling valves can then be used for bypass flow control, if required for some process heat exchangers, and freeze valves can be used for fill and drain control. For a total salt volume of 50 m^3 (200 m separation between the reactor and hydrogen plant) fill and drain times would be approximately 4 hours using 1-1/2 inch freeze valves.

Intermediate heat exchanger

Figure 2 shows a scaled figure for the baseline 50 MW(t) IHX design, using Heatric-type heat exchanger modules. For this baseline design the primary side inlet temperature is 900ºC and outlet temperature is 635ºC, and secondary side inlet temperature is 615ºC and outlet temperature is 880ºC [2]. With these temperatures, the LMTD for the counter flow IHX is 20ºC and the thermal effectiveness for a perfect counter flow IHX is 0.93. Table 1 compares this He-to-LS IHX with a corresponding He-to-He IHX.

Actual temperatures used for the NGNP IHX require coordination with reactor and hydrogen system designers, to select acceptable maximum and minimum temperatures for the intermediate loop operation.

The baseline design uses a sufficiently low reactor outlet temperature to permit metallic materials to be used for the heat exchangers, fabricated using diffusion bonding of chemically etched plates. This baseline design meets a number of key functional requirements, as summarized below.

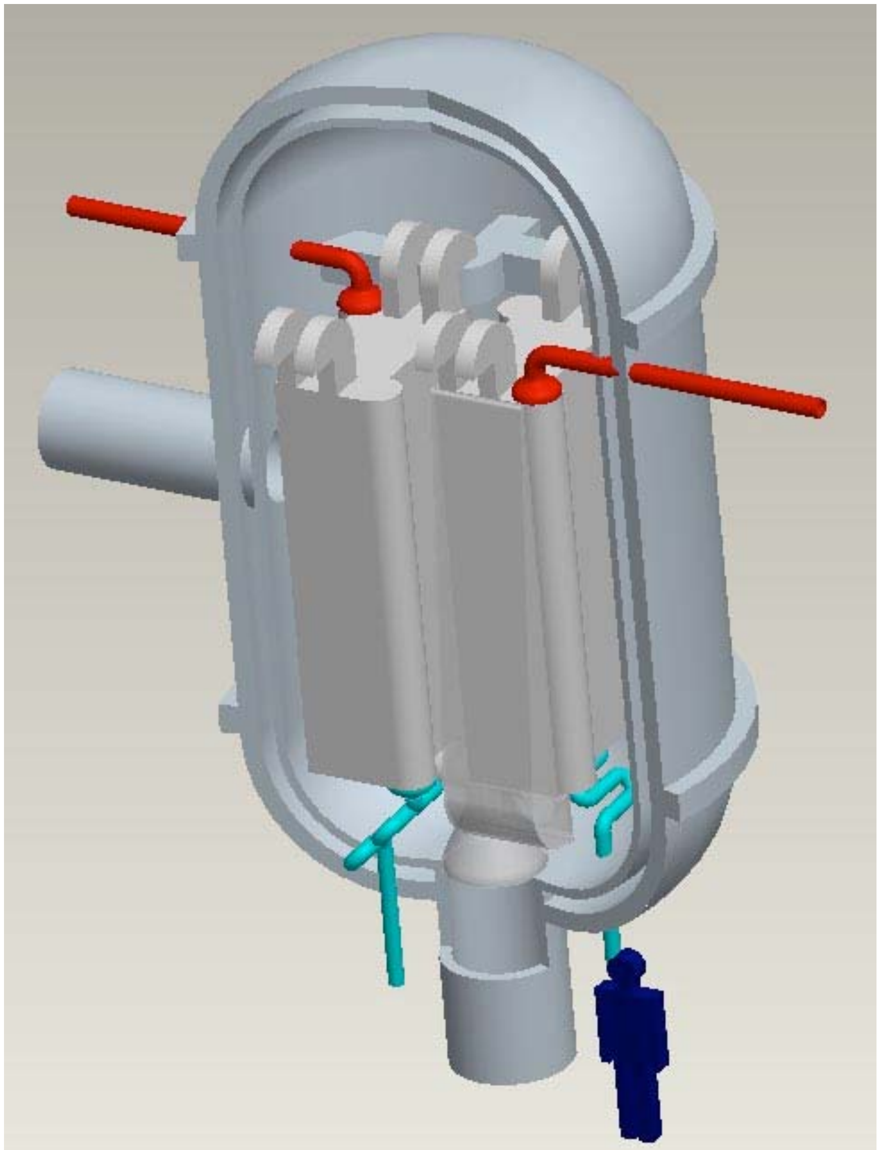

Fig. 2 Baseline 50 MW(t) IHX design. Hot, high-pressure helium enters from the bottom and exits from the side of the IHX pressure vessel.

Structural design for pressure loads. The baseline IHX immerses the heat exchanger modules in the helium environment, which places the heat exchangers and LS manifold piping dominantly into compressive stress. Hot helium flows to the IHX through a hot duct that operates with relatively small tensile stresses, and the IHX vessel is insulated and actively cooled so that the tensile stresses from the helium are carried dominantly As shown in Fig. 3, the baseline IHX uses very small LS flow channels, compared to those that would be required for to carry helium with acceptable pumping power. This in turn reduces the compressive stresses in the metal, allowing the IHX to accommodate the pressure differential between the helium and salt with acceptable creep deformation, while maximizing the peak temperature.

Table 1. Thermal design results for a 50 MW(t) He-to-MS PCHE IHX and He-to-He PCHE IHX [2]

	He-to-MS PCHE IHX	He-to-He PCHE IHX
Core volume, m^3	11	21
Frontal area, m^2	8.5	16
Core flow length, m	1.3	1.3
Total pumping power, W	9.6×10^4	9.7×10^4
Hot side counter flow region pressure loss, Pa	6.7×10^3	3.8×10^3
Cold side counter flow region pressure loss, Pa	1.2×10^5	3.6×10^3
Total core weight, metric tons	79	131
Core thermal density, MW/m^3	4.4	2.4

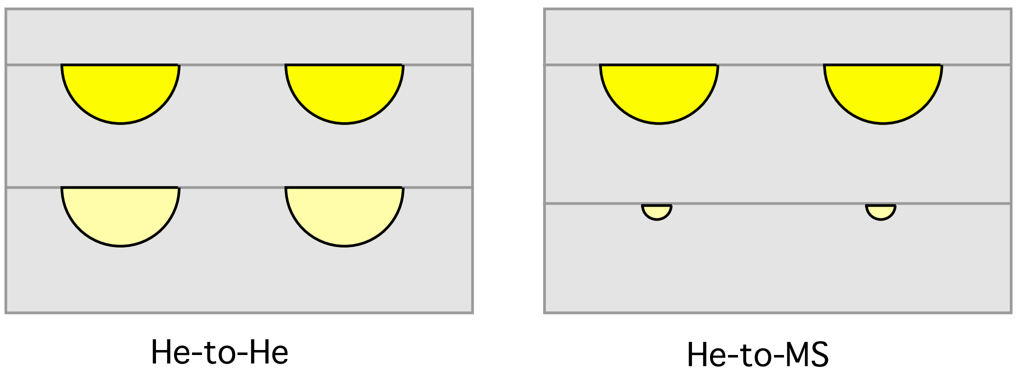

Fig. 3 Schematic of He-to-He and He-to-MS Heatric IHX flow channels.

Thermal expansion. The IHX modules will undergo thermal expansion, relative to the IHX vessel. As shown in Fig. 4, the modules are supported from the top, and the bottoms of the modules are allowed to move freely due to thermal expansion. The hot LS outlet pipe establishes the position of the IHX module, so that the hot pipe operates with low stresses. Figure 5 shows that the cold LS inlet pipe is designed to flex with low stress, to accommodate the movement of the bottoms of the IHX modules. The helium hot duct requires expansion joints and seals to allow for differential movement; this requirement is similar to that for other hot duct designs.

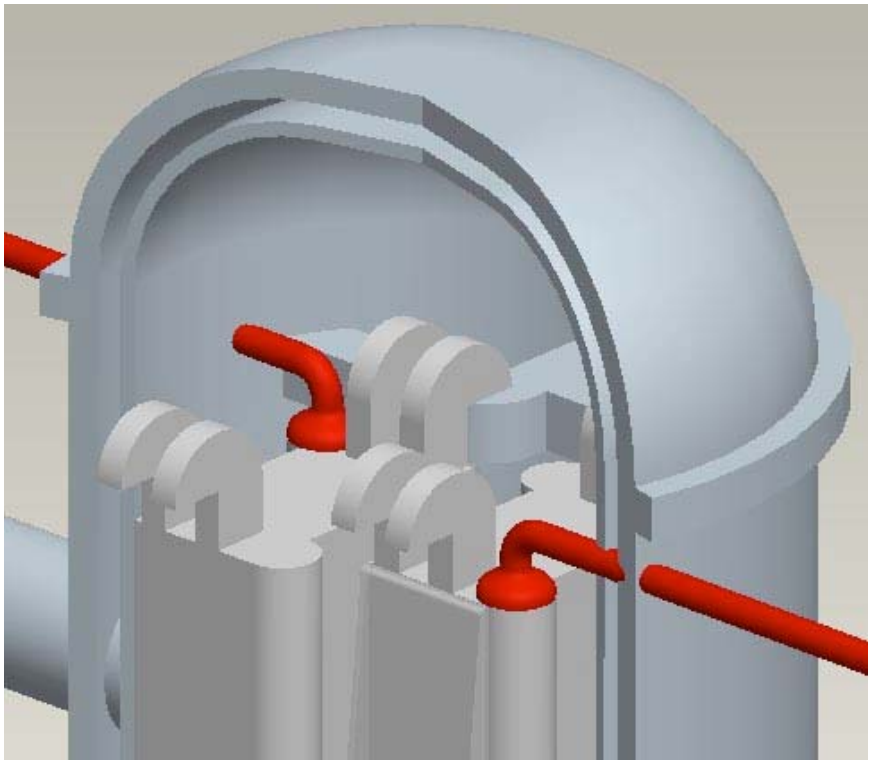

Fig. 4 Baseline 50 MW(t) IHX design, top view.

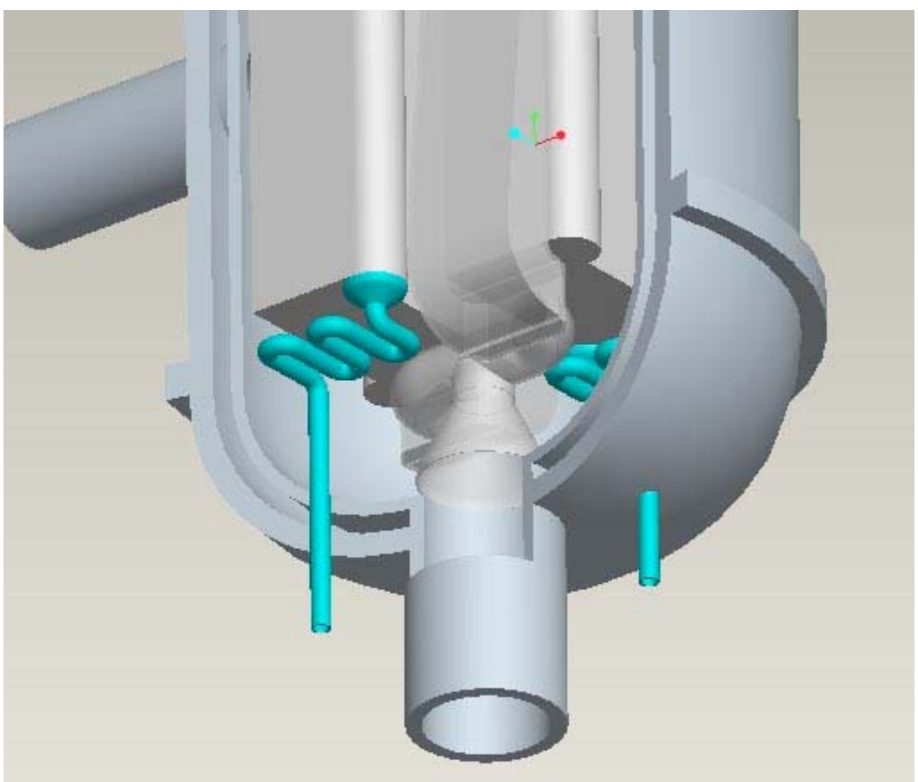

Fig. 5 Baseline 50 MW(t) IHX design, bottom view.

Helium flow distribution control. The surface area and log mean temperature difference (LMTD) required to transfer heat from the helium to the LS is sensitive to the distribution of the helium and LS flows, which determines the effectiveness of the heat exchanger. For a fixed area, increased flow maldistribution requires increased LMTD, and thus increased reactor outlet temperature. Because the LS pumping power is small, orifices can be used effectively to control flow distribution. Therefore the major issue is to obtain a uniform flow distribution of helium while minimizing pressure losses, which create large pumping power requirements due to the very large volumetric flow rate of helium. Figure 5 shows the symmetric hot-duct arrangement entering the IHX, which is designed to provide equal flows to each IHX module with low pressure loss. In general, IHX modules should be arranged to be axially symmetric, no matter what their number. Because a 90 degree bend is likely to be required in the hot duct entering the IHX, turning vanes should be considered in the bend to reduce secondary flows in the helium entering the IHX.

An advantage of gas-to-liquid heat transfer comes from the fact that the high volumetric flow of gas can occur through simple, relatively short and straight flow channels of roughly equal length, so that the pressure loss of the flow channels also serves to encourage uniform flow distribution between the channels. This is similar, in principal, to the flow distribution that occurs for air flow through car radiators. However, it is important that the pressure distribution across the face of the heat exchanger be uniform. Acceleration and deceleration in the supply manifold cause changes in dynamic pressure that can create flow maldistribution. Therefore, in the helium hot duct the flow area is tapered to maintain constant helium velocity, as shown in Fig. 5, to provide a uniform helium pressure distribution at the entrance to the IHX modules. Because the flow area for helium exiting the modules is large, uniform pressure distribution also exists at the exits of the modules.

Maintenance, in-service inspection, leaks and pipe breaks. Access to components for maintenance and in-service inspection is an important design requirement. For this reason, a vertical, cylindrical vessel is used for the IHX, with the gas inlet flow into the bottom of the vessel and the gas exit flow from the side of the vessel. This provides access inside the vessel from the top, permitting the use of a crane for maintenance.

In service inspection (ISI) is an important activity to confirm that materials degradation processes (corrosion, cracking, creep) have not reached limits which could affect the IHX safety or reliability. Because the IHX heats the LS, which increases the solubility of chromium and other metals, the primary corrosion effect expected is the removal and gradual thinning of the walls of the LS channels. Material removed from the IHX would then be expected to deposit in process heat exchangers where the LS is cooled, where channel plugging could become an issue. It is expected that chemistry control will be used to keep the LS fluorine potential very low, which will result in very low solubility for IHX materials. Therefore cracking damage due to cyclic thermal stresses, and metal creep, may be the most important phenomena requiring detection by ISI.

For shell-and-tube heat exchangers (such as PWR steam generators) ISI can be performed by visual and eddy-current testing of tubes. In contrast, compact heat exchangers do not permit similar access to inspect all heat transfer surface, but the maximum leak area and resulting implications for safety are also much smaller than they are for a tube burst in a PWR steam generator (thus, for example, more extensive corrosion is permitted in steam generators in locations where the tube sheet or support plates would confine a burst tube and limit the maximum flow rate). ISI requirements have not, as yet, been defined for the NGNP IHX. However, it is noted that in the baseline design the helium flow paths are relatively large (3-mm hydraulic diameter) and straight, and are readily accessible from the exit side. Likewise, the LS manifolds and inlet and outlet holes are also accessible after the IHX has been drained.

From a safety perspective, the very small flow required for the LS, compared to the helium flow area (Fig. 2), limits the maximum helium flow that could occur if a LS manifold line were to break. The resulting overpressure of the LS line would be relieved by a rupture disc, shown in Fig. 1, that would vent into the IHX enclosure area and would discharge a mixture of helium and LS. Critical flow of helium would play an important role in limiting maximum helium flow rates. Design and safety analysis of this IHX pressure relief system is required.

LS draining and filling. In the IHX, the LS flow path is designed to flow continuously downward, to assist in draining and filling of the IHX with liquid salt. It is noted that the IHX must be preheated to above the LS freezing temperature prior to filling. Because the IHX is at one of two high points in the intermediate loop (Fig. 1), it is the first component to drain after draining is initiated. Extensive experience with industrial applications of nitrate salts (for example for solar power towers) can be applied in designing approaches and systems to control freezing.

Thermal transients. The IHX will be subjected to a variety of thermal transients that will create transient stresses in the heat exchanger modules and their inlet and outlet manifolds. Such transient stresses can be highly challenging for Heatric type heat exchangers, because their monolithic construction constrains transient thermal expansion. Thermal transients can be generated by changes in the flow rates and inlet temperatures of the fluids entering the heat exchanger manifolds and modules. In addition, the IHX pressure vessel, insulation system, and hot ducts may be subjected to thermal transients. Modeling of such transients, to predict the peak stresses induced by changes in fluid flow rates and temperatures, requires further development. This is a major issue affecting the potential viability of the baseline IHX design.

Additional applications. In addition to the use as an IHX for transferring heat from high-pressure helium to LS, similar systems may be useful for transferring heat from liquid coolants to gases for power conversion systems. For example, Fig. 7 shows a recent conceptual design for a multiple reheat gas Brayton cycle system, that would use gas heaters very similar to the NGNP IHX. Similar heat exchangers would also be required for supercritical CO_2 power cycles for sodium fast reactors. The IHX design supports these potential applications as well.

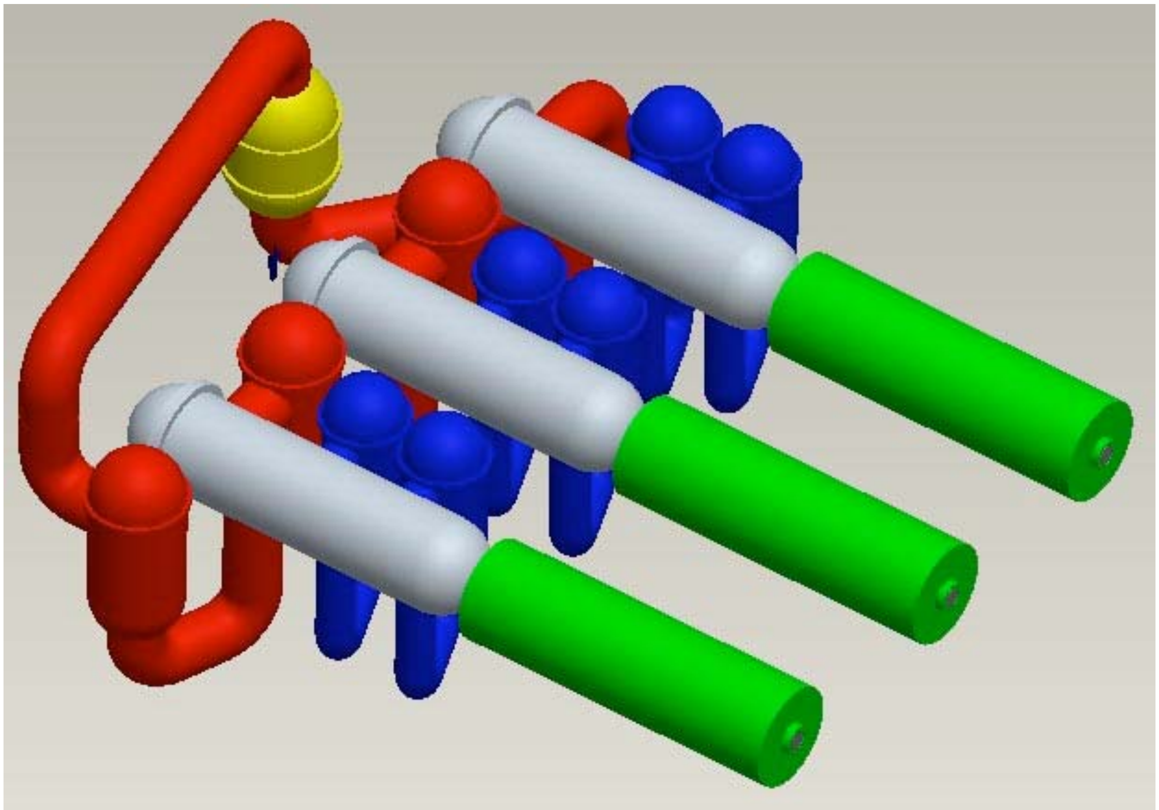

Fig. 6 Example of a multiple-reheat gas Brayton cycle system with a distributed configuration of heaters (red), coolers (blue), recuperator (yellow) and turbomachinery (grey) [7].

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