Comparison of Molten Salt and High-Pressure Helium for the NGNP Intermediate Heat Transfer Fluid

Per F. Peterson, H. Zhao, and G. Fukuda
U.C. Berkeley
Report UCBTH-03-004

December 5, 2003

INTRODUCTION

The Next Generation Nuclear Plant (NGNP) will employ a 50 MW(t) intermediate loop to transfer heat from the primary coolant to demonstrate the production of nuclear hydrogen using thermochemical and high-temperature electrolysis processes. To achieve high efficiency (>50%), high temperatures are expected to be required for the baseline sulfur-iodine thermochemical process, so the functional requirements for the NGNP include a 1000°C core outlet temperature. This high temperature creates substantial technical challenges for the intermediate heat exchanger (IHX) and process heat exchangers, as well intermediate heat transfer loop components.

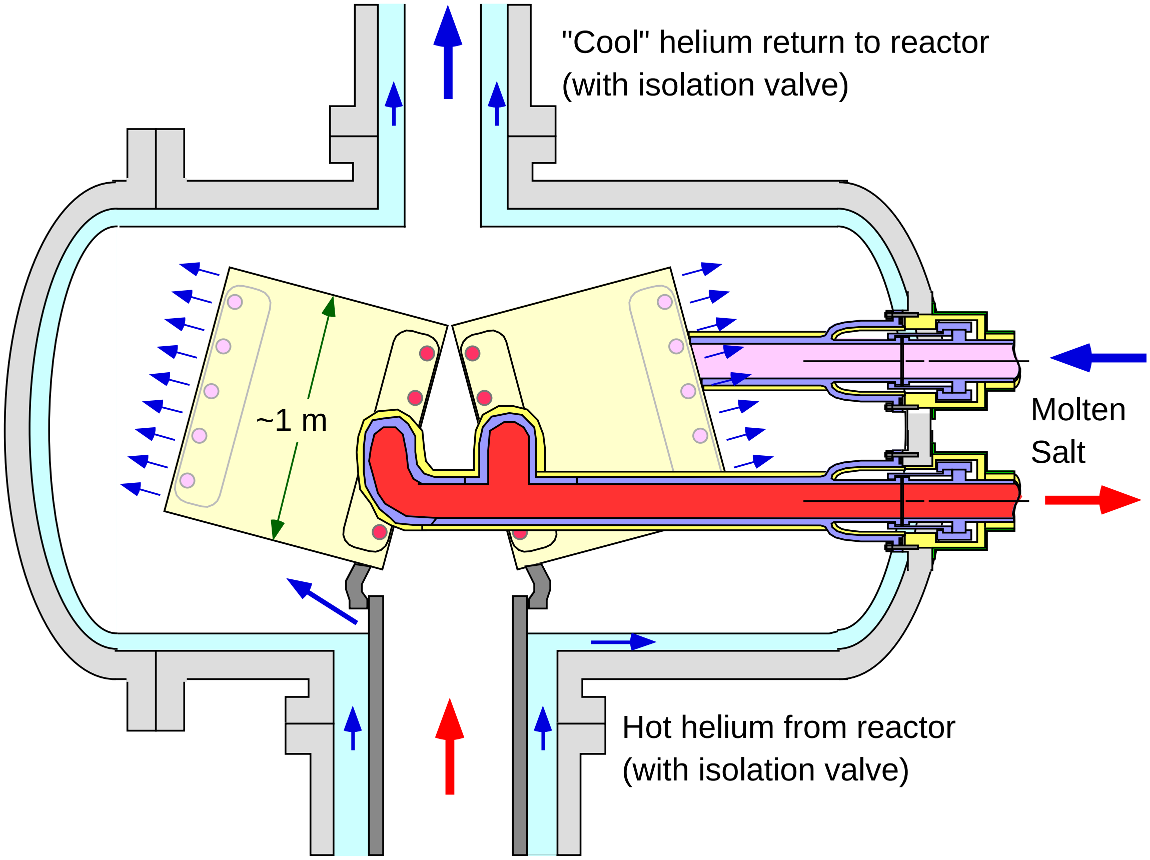


Fig. 1 Pre-conceptual design for a 50 MW(t) intermediate heat exchanger for the NPNG, based on a plate-type, compact high-temperature composite design now

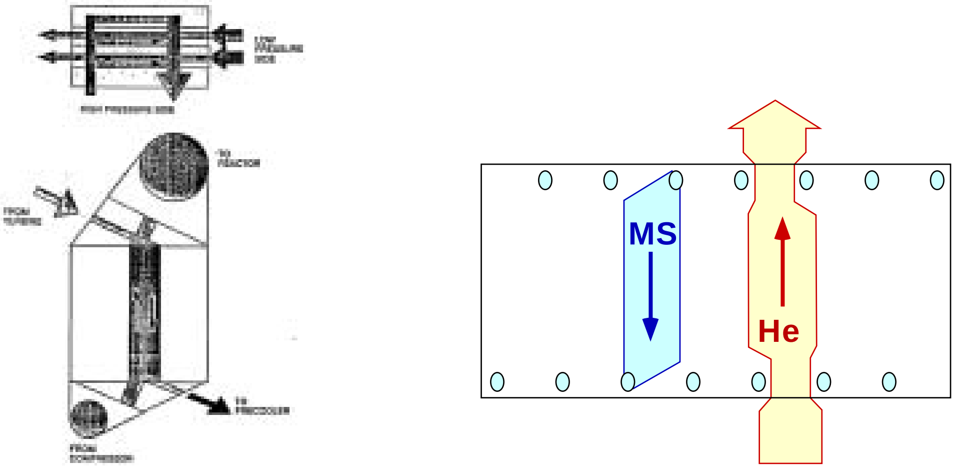
being developed [4]. Primary helium and intermediate MS inlet and outlet headers are shown to scale, with active cooling of pressure boundary.

The two candidate fluids for the NGNP intermediate loop are intermediate-pressure molten salt (MS), and high-pressure helium (He). Figure 1 shows a scaled cross section of a pre-conceptual design for a 50 MW(t) MS IHX for the NGNP.

Table 1 summarizes the thermophysical properties for high-pressure helium and three typical molten fluoride salts. Two key differences are seen. First, the volumetric heat capacity, ρc_p, of molten salts is over two orders of magnitude greater than that of high-pressure helium. Second, the thermal conductivity of molten salts is several times greater than helium. The very low volumetric heat capacity of helium has important effects on the design of headers to feed flow to and from heat exchanger flow channels; for example, Fig. 2 shows typical configurations for gas-to-gas and gas-to-liquid heat exchangers

Table 1. Comparison of thermophysical properties of helium and three reference molten salts (approximate values at average intermediate loop temperature of 700°C), (ρ-density, c_p -specific heat, k-thermal conductivity, ν-viscosity).

Material	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m^3)	c_p (kJ/kg°C)	ρc_p (kJ/m^3°C)	k (W/m°C)	$\nu \times 10^6$ (m^2/s)
$^7Li_2BeF_4$ (Flibe)	459	1,430	1,940	2.34	**4,540**	**1.0**	2.9
$0.58NaF\text{-}0.42ZrF_4$	500	1,290	3,140	1.17	**3,670**	**2.1**	0.53
$0.42LiF\text{-}0.29NaF\text{-}0.29ZrF_4$	460	?	2706	1.47	**3,978**	**2.1**	1.64
Helium (7.5 MPa)	—	—	3.8	5.2	**20**	**0.29**	11.0



(a) (b)

Fig. 2 Comparison of typical header configurations for (a) He-to-He (a GT-MHR recuperator module) and (b) He-to-MS plate type heat exchangers. In the He-to-MS exchanger the He flow path resembles the air-flow path of an automobile radiator.

Substantial differences and tradeoffs exist between molten salts and high-pressure helium for use in the NPNG intermediate loop. This report summarizes the key differences in thermal performance, materials compatibility, and safety, which must be considered in selecting the NPNG intermediate heat transfer fluid. Based on this discussion, it can be concluded that the use of either fluid carries technical risks, and that both should be retained and studied until these technical issues are resolved and an optimal choice can be made.

Thermal Performance

The much higher volumetric thermal capacity (ρc_p) of intermediate-pressure molten salts, compared to high-pressure helium, has an obvious and large effect upon the relative heat transfer capability. In general, a molten salt loop will use piping of 1/5 the diameter, and pumps 1/20 the power, of those required for high-pressure helium. These large differences in pumping power and pipe size reduce the capital cost of the piping system, and allow the arrangement of process equipment to be optimized more easily since process heat can be delivered over larger distances easily.

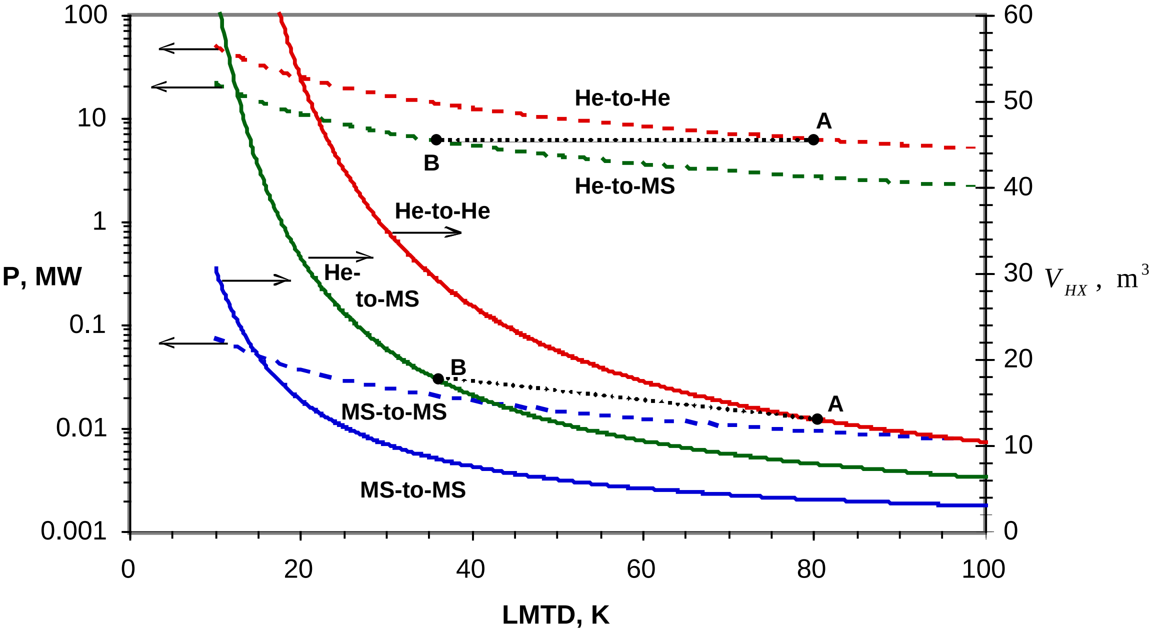


Fig. 3 Total pumping power P (dashed) and the total volume V_{HX} (solid) for a 600 MW(t) compact IHX as a function of LMTD for three combinations of helium (7.0MPa) and/or molten salt.

A second, less obvious difference between helium and molten salts relates to the log-mean temperature difference (LMTD). Smaller values of LMTD are desirable to increase the temperature at which heat is delivered to the hydrogen production process, and/or to decrease the peak temperature of the reactor while maintaining the same hydrogen production efficiency. Heat transfer coefficients for molten salts are typically an order of magnitude greater than those for helium. In compact helium heat exchangers, a strong competition exists between adding surface area to decrease the LMTD, and reducing surface area to reduce the helium pressure drop. Pressure drop and pumping power considerations usually drive helium heat exchangers to higher LMTD values than would be selected for molten salt heat exchangers.

The effect on LMTD can be seen in Fig. 3, which presents the total pumping power (both sides) and the total volume of a 600 MW(t) IHX as a function of LMTD, for three combinations of fluids. In the figure, the comparison between point A and point B shows that the He-to-MS HX has a LMTD less than half of the LMTD for He-to-He HX, for the same pumping power and a similar HX volume (and, approximately, capital cost).

Table 2 compares typical compact heat exchanger parameters for several possible primary and intermediate fluid options, for the case where the pumping power for the helium is kept constant (note that MS-to-MS IHX is just for the purpose of comparison.). The largest surface area occurs with the case of the 1.0 MPa intermediate helium loop, designed to be in pressure balance with process equipment.

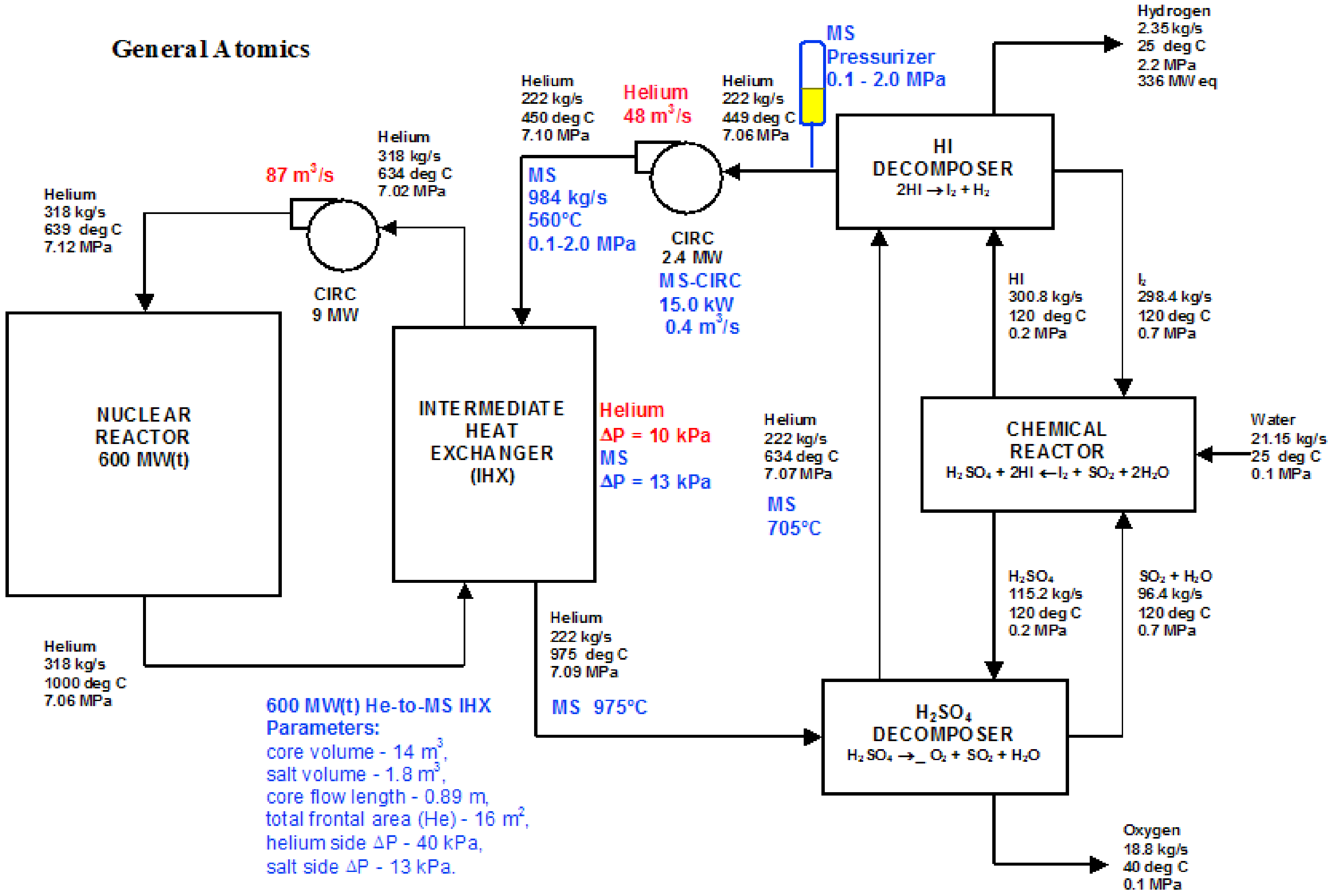
Figure 4 compares typical parameters for a 600 MW(t) intermediate loop with either helium or molten-salt heat as the heat transfer fluid. The molten salt pumping power is a factor of 100 lower, due to the very high volumetric flow rates required for helium (pumping power is proportional to the product of pressure loss times volumetric flow rate). If the helium pressure must be decreased to match the pressure of process fluids (typically around 1 MPa), then the pumping and pipe size differences become yet larger.

Table 2. Comparison of 600 MW(t) compact intermediate heat exchanger designs (the molten salt is $0.42LiF-0.29NaF-0.29ZrF_4$).

Primary/Intermediate Fluids	**He/He**	**He/He**	**He/MS**	**MS/MS**
Primary/Inter. Pressures (MPa)	7.0/7.0	7.0/1.0	7.0/ *	* / *
Primary Inlet/Outlet Temp. (°C)	1000/634	1000/634	1000/634	1000/634
Intermediate Outlet/Inlet Temperatures (°C)	975/450	975/450	975/560	975/595
LMTD (°C)	**80**	**80**	**45**	**31**
Primary/Inter. Pressure Loss (kPa)	40/19	2.7/9.0	40/13	24/25
Primary/Inter. Pump Power (MW)†	**4.8/1.5**	**0.3/4.8**	**4.8/0.005**	**0.012/0.012**
Primary/Inter. Fin Heights (mm)	2.0/2.0	2.0/2.0	2.0/1.0	1.0/1.0
IHX flow length (m)	0.76	0.40	0.89	1.1
IHX plate area (m^2)	3200	5600	4100	3500
IHX volume (m^3)	13	23	14	9.7

† Power required to pump primary and intermediate fluids through IHX.

* Molten salt is incompressible, so pressure and pumping power are independent, and pressure can be set to any desired value.



600 MW(t) He-to-MS IHX Parameters:
core volume - 14 m^3,
salt volume - 1.8 m^3,
core flow length - 0.89 m,
total frontal area (He) - 16 m^2,
helium side ΔP - 40 kPa,
salt side ΔP - 13 kPa.

Fig. 4 Flow sheet for the reference 600 MW(t) sulfur-iodine thermochemical hydrogen process. Black font notes are original GA design. Blue and red notes are added by authors. The blue notes are for molten salt and the red notes for helium.

Materials

Two primary issues must be considered in selecting the high-temperature materials and coolant used for the NGNP intermediate loop: corrosion and high-temperature mechanical properties (strength, creep, and fabricability).

Clean helium clearly does not have the potential to corrode intermediate loop materials. Likewise, molten salts exhibit very low corrosion rates if their fluorine potential is controlled to be low, and if the container material is either carbon, or a high nickel alloy. Figure 5 shows an Ellingham diagram for several container and molten salt materials. Higher free energy (smaller value with a negative sign) means easier corrosion. In general, carbon-based container materials will show very low corrosion rates with high-temperature molten salts. For nickel alloys, chromium is typically the most soluble constituent, and corrosion can proceed by dissolution of chromium in hot parts of the loop, with saturation-induced deposition in cold parts of the loop.

Recent molten-salt corrosion experiments at ORNL [2], testing Hastelloy-N, concluded that:

> This potential for greatly reduced corrosion suggests that the higher temperature nickel super-alloys, such as Hastelloy-X, be tested in molten fluoride systems. Previous analysis had largely excluded these alloys because their chromium content was as large as that of the Inconel alloys or stainless steels. Alloys with this amount of chromium were found to be unsuitable choices for use with fuel salts. However, it is very possible that these alloys will be suitable for use with coolant salts at very high temperatures, provided that a reducing environment is maintained.

The potential thermal performance advantages of molten salts suggest that this high-temperature corrosion testing with molten salts should be a priority for the NGNP project.

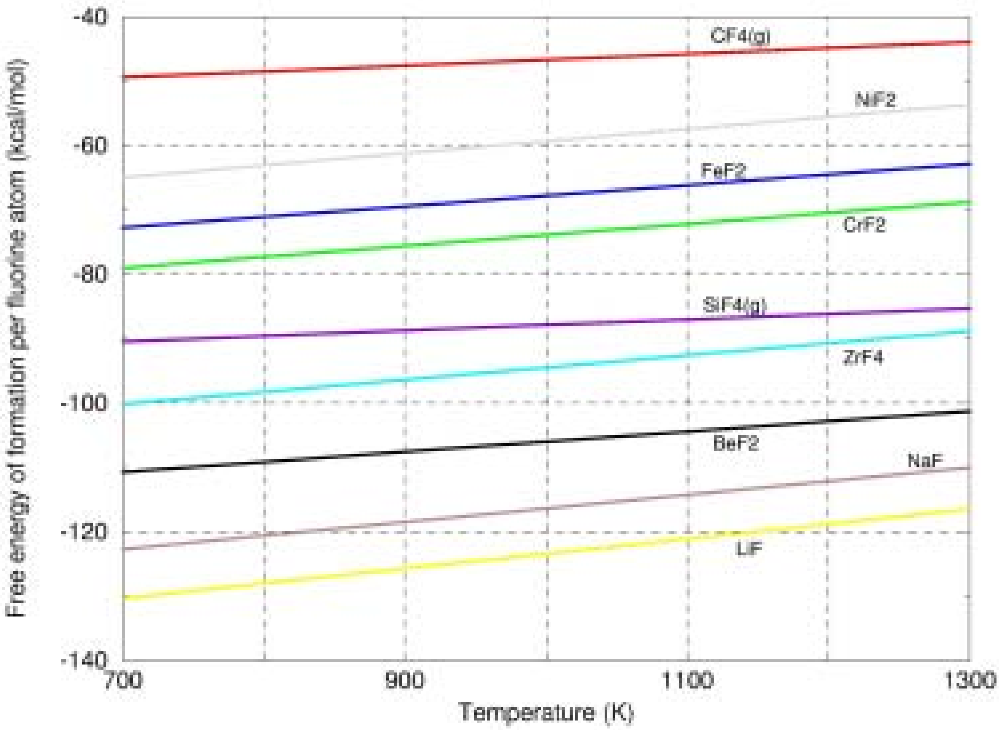


Fig. 5 Ellingham diagram for some container (e.g., carbon, nickel, iron, chromium, silicon) and solvent (e.g., lithium, sodium, beryllium, zirconium) fluorides (per fluorine atom).

Mechanical creep will be an important problem for metallic intermediate loop heat exchangers for the NGNP, particularly in the temperature range from 900°C to 1000°C. Mechanical creep is a lesser issue for direct gas-cycle electricity production with high-temperature gas reactors, because the hot gas only needs to contact the hot-duct and turbine inlet shrouds, which can be designed to minimize mechanical stresses, and the turbine rotor and first few rows of blades, which can be actively cooled, as is the GT-MHR rotor with a 850°C inlet temperature, to permit for a full 6-year lifetime.

For thermochemical hydrogen production with gas cooled high temperature reactors, larger mechanical stresses can not be avoided. At least one of the high-temperature heat exchangers in the intermediate loop will need to sustain the relatively large pressure differential between the 7-MPa primary coolant, and the approximately 1-MPa pressure of sulfur-iodine process fluids. One of the best metallic heat exchanger designs for resisting large pressure differentials at high temperatures is the Heatric design, but as shown in Fig. 6 creep becomes an important design issue for high-temperature metals at temperatures above 900°C.

The IHX can be immersed in the primary helium environment, so that the intermediate fluid channels are placed in compression. If the ~6-MPa pressure differential between primary helium and process fluids is accommodated by the IHX, these stresses will tend to cause creep closure of the intermediate fluid flow channels. Because the molten-salt flow channels can have much smaller cross-sectional area than helium channels, for the same heat removal capability, for compact heat exchanger geometries like the Heatric design [3] these compressive stresses can be reduced, as illustrated schematically in Fig. 7.

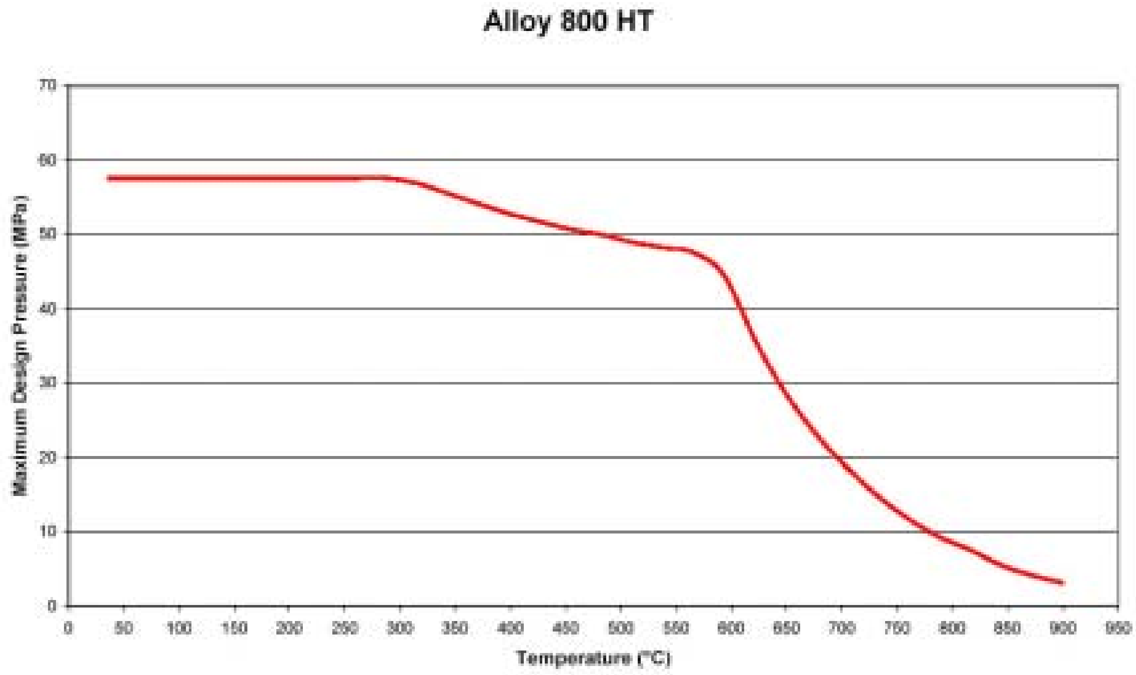
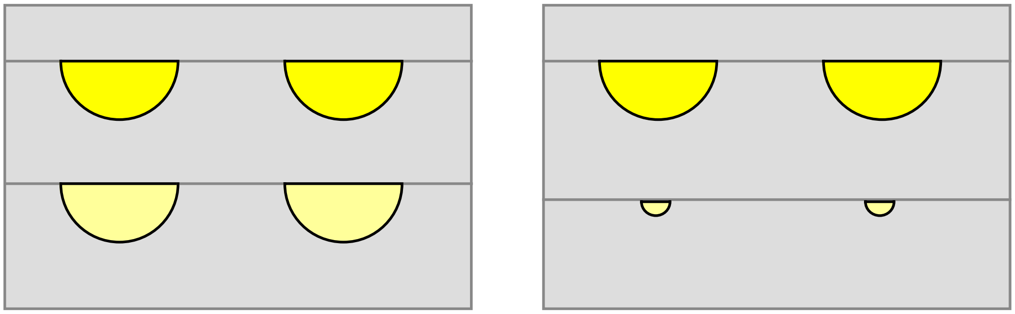


Fig. 6 Maximum fluid pressure differential for a high-temperature helium-to-helium Heatric heat exchanger fabricated from Incoloy 800 HT, based on a creep limited life of 10^5 hours [3].



He-to-He

He-to-MS

Fig. 7 Schematic of He-to-He and He-to-MS Heatric IHX flow channels.

Melt-infiltrated carbon-carbon composites are also now under investigation for use in fabricating compact heat exchangers for the NGNP intermediate loop [3]. These heat exchangers will use CVI carbon coating on the interior heat transfer surfaces, using a method developed at ORNL for coating carbon-carbon composite fuel cell plates. Thus it is anticipated that molten-salt corrosion will not be a significant design issue for these heat exchangers. Likewise, these composite materials maintain full mechanical strength and are not subject to creep in the temperature range of interest for thermochemical hydrogen production. Significant progress has been made in mechanical and thermal design (Fig. 8) for these heat exchangers. However, resistance to helium permeation, materials compatibility with molten salts, and ASME code certification must be demonstrated before these materials could be qualified for commercial use [3].

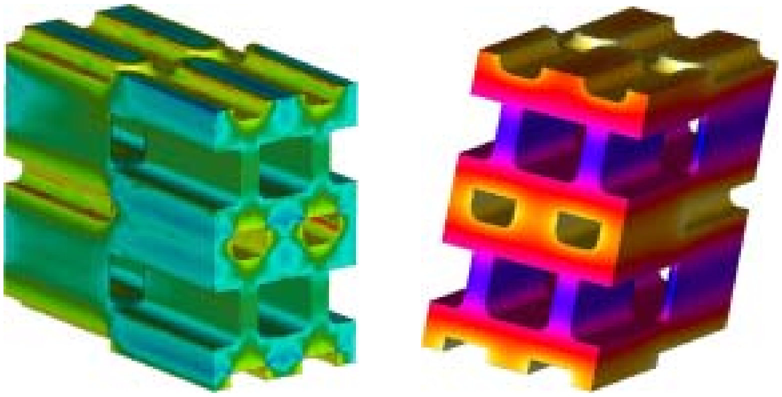


Fig. 8 Stress and temperature distributions in a typical high-temperature composite plate heat exchanger [3].

Safety

The sulfur-iodine process uses chemicals (sulfuric acid, HI) which are hazardous. The intermediate heat transfer fluid provides a stored energy source that can potentially be released rapidly, generating mechanical damage and potentially dispersing flammable or toxic chemicals. For helium intermediate fluid, the stored energy comes from the high pressure of the gas, and the large volume of gas due to the large duct sizes required to transfer helium with reasonable pressure losses. For molten salts, the stored energy comes from the high temperature and high heat capacity of the liquid. This energy can be released if the molten salt mixes with a volatile liquid (e.g. water), through a well-studied phenomena typically referred to as a “steam explosion.” Additionally, fluoride salts can react with sulfuric acid to form HF, a quite toxic chemical.

Molten salts, due to their much lower pumping power and piping size, permit greater physical separation between the nuclear reactor and the hydrogen production plant. This reduces or eliminates the need for berms or other structures to provide isolation between the reactor and hydrogen plant.

To reduce the potential for over-pressurization of process piping and dispersal of chemicals, the use of a tertiary heat transfer fluid may be required to isolate process heat exchangers from the intermediate fluid. Figure 9 provides a schematic diagram of a compact tertiary helium loop using forced circulation, while Fig. 10 shows a schematic of a double-walled plate heat exchanger with a helium tertiary fluid in the gap. The use of a tertiary heat transfer fluid clearly creates penalties for thermodynamic performance of the S-I process, and for the cost of heat exchangers. However, due to the superior heat transfer properties of molten salts, the penalties for using a tertiary heat transfer fluid are smaller for molten salts than for helium intermediate fluid.

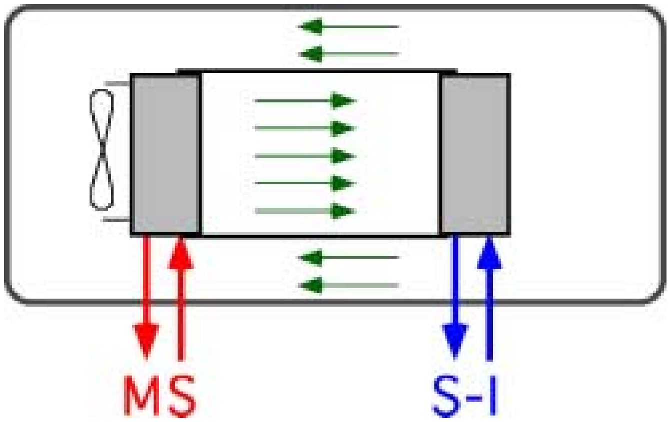


Fig. 9 Schematic diagram of a compact tertiary forced-convection helium loop for transferring heat from intermediate molten salt to process fluids.

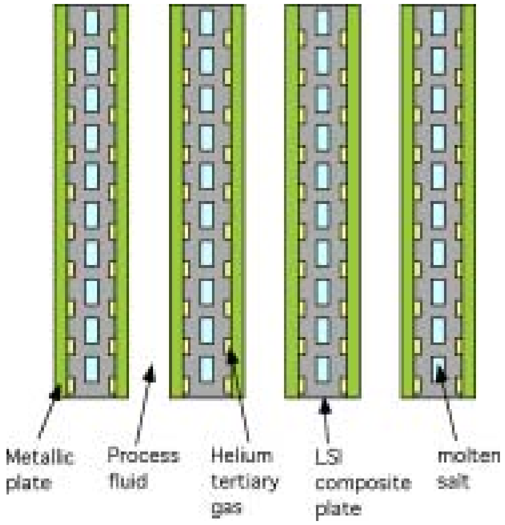


Fig. 10 Schematic diagram of a double-wall plate heat exchanger for transferring heat from intermediate molten salt to process fluids.

REFERENCES

1. “Next Generation Nuclear Plant – High-Level Functions and Requirements,” Idaho National Engineering Laboratory, INEEL/EXT-03-01163 (2003).
2. D. F. Williams, D. F. Wilson, J. E. Keiser, L . M. Toth, J. Caja , “Research on Molten Fluorides as High Temperature Heat Transfer Agents,” Global 2003, New Orleans, LA, pp. 2136-2140, Nov. 16-20, 2003.
3. S. Dewson and B. Thonon , “The Development of High Efficiency Heat Exchangers for Helium Gas Cooled Reactors,” 2003 International Congress on Advances in Nuclear Power Plants, May 4-7, Congress Palais, Córdoba, Spain.

4. P.F. Peterson, “Development of liquid-silicon-impregnated C/C-SiC composites for high-temperature heat transport,” U.C. Berkeley Department of Nuclear Engineering Report UCBTH-03-001, Oct. 1, 2003.