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WATER/MONEL HEAT PIPES FOR COOLING OF LIQUID METAL TARGETS FOR SINQ AND ESS

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ABSTRACT

A heat pipe based heat exchanger has been designed for extracting waste thermal energy from the lead-bismuth eutectic (LBE) beam target for the SINQ project at Paul Scherrer Institut (PSI). An array of eight heat pipes is designed to carry a thermal load of 400 kW. The heat pipes feature a double wall evaporator which can reduce the risk of injecting water directly into the liquid metal pool in the case of primary wall failure. The heat pipes can be used without redesign in a larger array in a secondary heat exchanger for mercury target cooling for the European Spallation Source (ESS).

1. Introduction

Both the SINQ project at Paul Scherrer Institut (PSI) and the European Spallation Source (ESS) being developed by the European Union (EU) involve bombarding heavy nuclei by a proton beam to create neutrons. In the SINQ target, the liquid metal (LM) bath is composed of lead-bismuth eutectic (LBE); the ESS target LM bath will be pure mercury. Because of the high heat loading created by the proton beam, cooling of the LM bath is required. Natural convection circulation and cooling of the LM bath will not be adequate at the power levels (~1MW/liter) anticipated for these projects; consequently, some form of active cooling will be required.

Pumped water will be the ultimate sink for the energy dissipated in the LM bath. The high temperature level during operation and the need to avoid cooling of the bath below a certain level during shutdown, however, make direct cooling via a standard design heat exchanger difficult. Preventing the LM temperature from falling below a certain level seems desirable for two reasons: In the case of Pb-Bi-eutectic solidification must be avoided to protect the vessel from stresses resulting from expansion of the material. Secondly, irradiation of the container material causes the ductile-to-brittle transition temperature to rise and therefore the system should be kept above this temperature, in particular in view of sudden load changes due to the variation of the proton beam intensity.

Keywords: Heat Pipe, Liquid Metal, Spallation Target, Cooling

Heat pipe thermosyphons offer a solution to cooling the LM bath without the difficulties associated with circulating water directly in the bath. Heat pipes operate by the evaporation and condensation of a small quantity of working fluid inside a vacuum tight pressure vessel. A diagram showing the operating principles of a heat pipe is shown in Figure 1. The working fluid evaporates and removes heat at one end of the heat pipe, and condenses at the other end of the heat pipe, rejecting heat to the ultimate heat sink, usually at a lower heat flux. Upon condensation, the working fluid is returned to the evaporator by either capillary action, i.e. with a wick, or with the aid of gravity, as in a thermosyphon, or both.

The conductance of a heat pipe can be made variable by introducing a small quantity of noncondensible gas (NCG). Because the NCG does not condense, it does not circulate with the working fluid. Instead the gas collects in the condenser. As the operating temperature of the heat pipe varies, the pressure inside the heat pipe varies; this variation is dictated by the vapor pressure curve of the working fluid. The volume of the NCG will change in response to this change in pressure. When the heat pipe temperature is low the NCG will occupy a large portion of the condenser, reducing the area for the working fluid to condense and lowering the conductance of the heat pipe. At high heat pipe temperatures the volume of the NCG is very small, the condenser area available for condensing working fluid is near its maximum, and the conductance of the heat pipe is high. This feature provides also a convenient way for decay heat removal at a temperature level compatible with the needs mentioned above.

The evaporator can be made double-walled with a gas gap between the walls. This provides two layers of containment between the water working fluid and the liquid metal. If one of the heat pipes does fail, the remaining heat pipes will provide sufficient cooling to allow a safe and controlled shutdown of the target. In the unlikely event that both walls of a single heat pipe fail simultaneously, only a fraction of the roughly 1 kg of water present in the heat pipe would escape into the LM bath instead of several tens of kilograms. Finally, with variable conductance heat pipes, the heat pipe heat exchanger will self regulate how much heat it transfers; this will keep the minimum temperature of the LM bath at a predetermined level, independent of the actual power input.

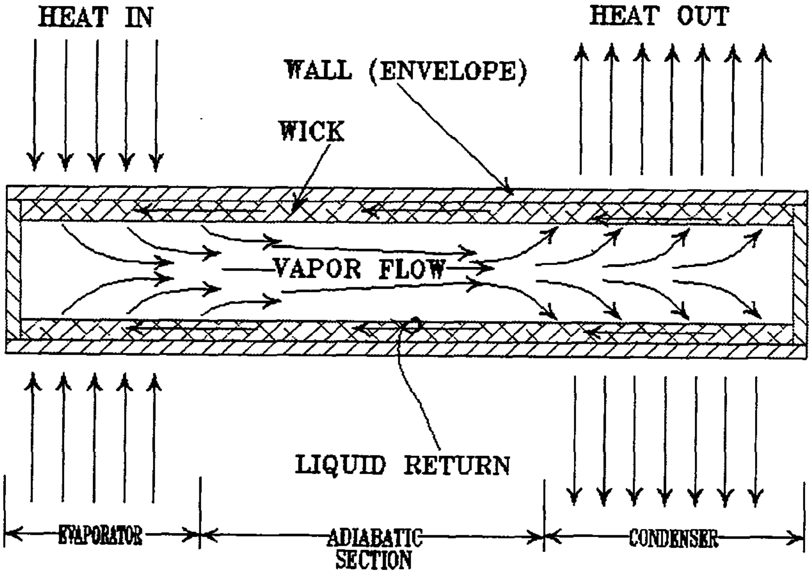
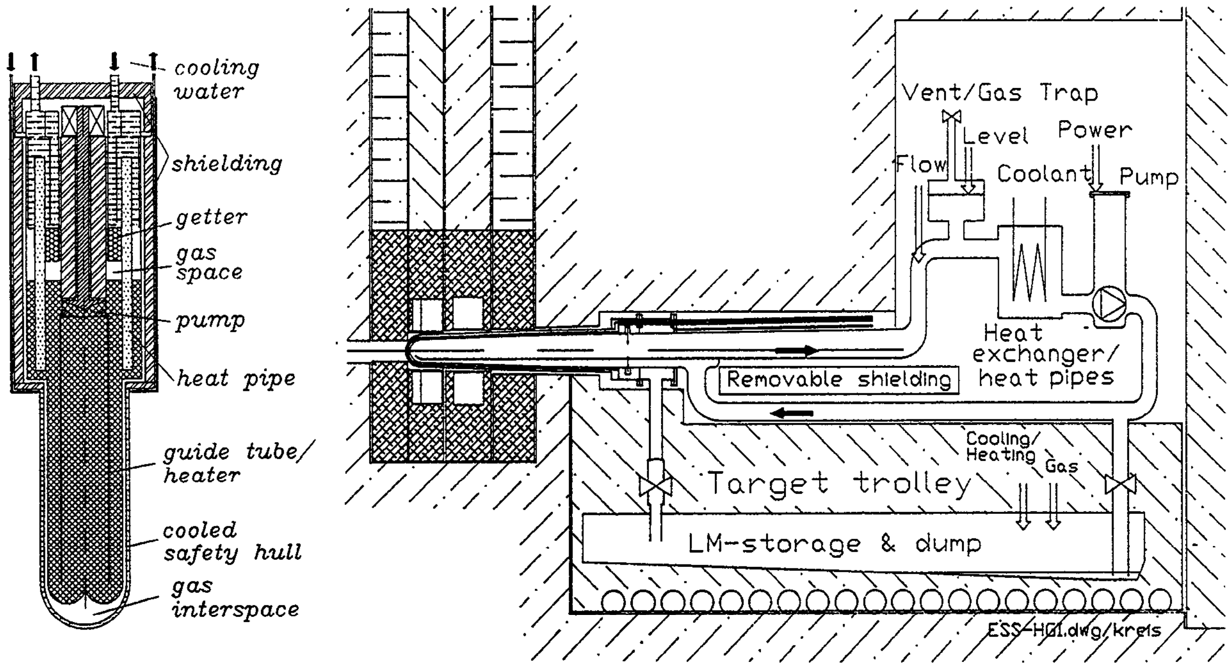


Figure 1: Working Fluid and Heat Flow in the Three Sections of a Generic Heat Pipe

Cross sectional diagrams of the SINQ and ESS targets are shown in Figure 2a and b. In the SINQ LBE bath, an array of vertical water heat pipes would extract heat from the LBE bath and reject it to the cooling water. The heat pipes for this application are constrained to fit in an annular space with an inner diameter of 15 cm and an outer diameter of 40 cm. Additional design parameters for the SINQ target and the ESS target are shown in Table 1 below.



(a) (b)

Figure 2: Schematics of the SINQ and ESS LM-target arrangment

TABLE 1: SINQ AND ESS TARGET COOLER REQUIREMENTS

Requirement	SINQ	ESS
Power Removal (MW)	0.4	3.2
Orientation	Vertical Ring of Heat Pipes	Vertical Array of Heat Pipes
Target Coolant	Lead/Bismuth Eutectic	Mercury
Heat Sink Fluid	Water	Water
Heat Sink Temperature	20-100°C	20-100 °C
Min. LM Target Temperature	170 °C	170 °C
Max. LM Target Temperature	450 °C	450 °C
Evaporator Length	Up to 1.8 m	Same as SINQ
Condenser Length	Up to 1.0 m	Same as SINQ
Operating Life	Minimum of 20,000 hrs	Maximize
Ring Outer Diameter	40 cm	N/A
Ring Inner Diameter	15 cm	N/A

The same heat pipe design can be used for the ESS LM bath; the ESS project will require more heat pipes because of its larger heat load, but there will be no particular geometry constraints because the secondary heat pipe heat exchanger will be separated from the beam target area. Even an inclined mounting position is possible, which would improve the heat transport capability of the individual heat pipes. Using the same heat pipe design, however, will eliminate the cost of redesigning a heat pipe for the heat exchange system of the ESS project. This paper describes the design of the heat pipes for cooling of the LM bath for the SINQ and ESS projects.

2. Heat Pipe Design

A cross sectional drawing of the heat pipe is shown below in Figure 3. The heat pipe features a double-walled gas gap evaporator as well as a concentric tube annular flow condenser. The outer evaporator wall is to be made of HT-9 martensitic steel, and the inner wall is to be made of Monel K-500.

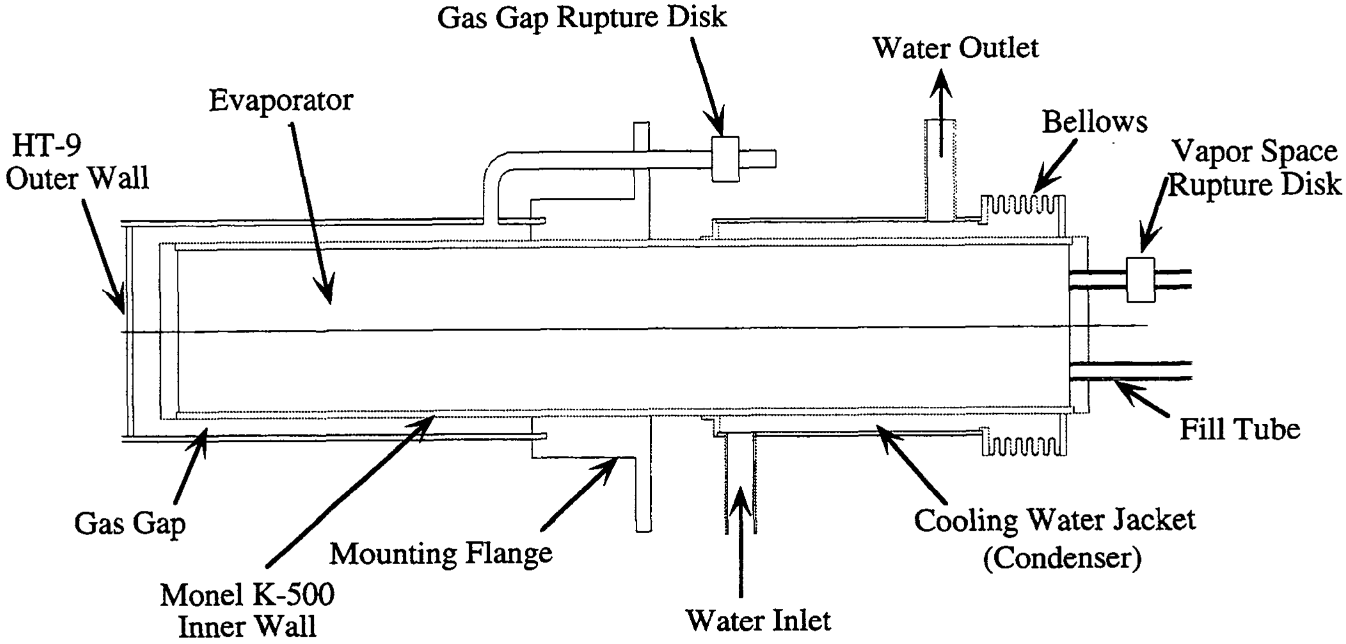


Figure 3: Cross Sectional Drawing of the SINQ-ESS Target Cooler Heat Pipe

A number of analyses were performed during the design of the SINQ-ESS target heat pipe cooler. These included consideration of aspects of the heat pipe design both internal and external to the heat pipe. A description of each of these is given below.

2.1 Heat Pipe External Design

The heat pipe external design included consideration of the heat pipe size and spacing, a bellows for accommodation of differential thermal expansion of the inner and outer condenser walls, and the interface between the heat pipe mounting flange and the wall above the LM bath. Each of these are described in this section.

2.1.1 Heat Pipe Size and Spacing

The heat pipe array in the SINQ target is constrained to fit in an annular space which has an inner diameter of 15 cm and an outer diameter of 40 cm. Heat pipes may be arranged in a number of different ways in this space. The heat pipes must have sufficient space between them to allow the LM to flow between them without excessive pressure drop. Three possible configurations are shown below in Figure 4. The possible configurations span a range between a small number of large diameter heat pipes and a large number of small diameter heat pipes. Each of these was further investigated to determine the optimum for performance and ease and cost of fabrication. Final selection of the heat pipe size and spacing was determined from internal design analyses described below.

2.1.2 Condenser Bellows

To accommodate the differential thermal expansion between the inside and outside walls of the condenser water jacket, a bellows will be placed in the outer wall of the condenser. This will allow the inner wall to expand as the working fluid heats the inner wall while the outer wall stays cool due to the circulating cooling water.

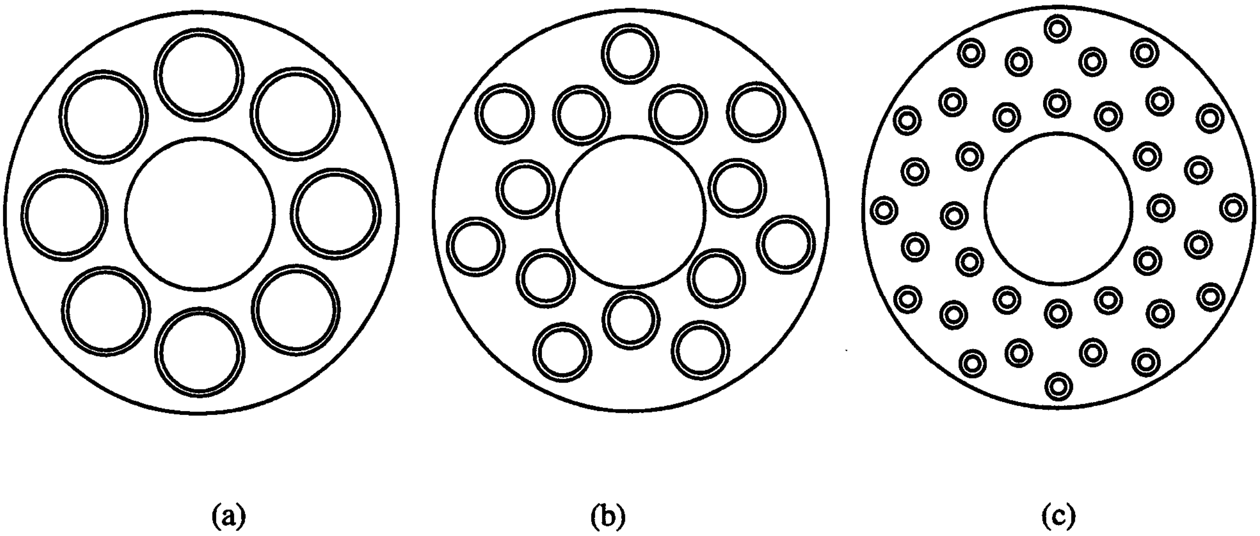


Figure 4: Alternative heat pipe arrays for the SINQ target in 15cm ID/40cm OD annulus. (a) Eight 8.9cm diameter heat pipes, (b) Fourteen 5.7cm diameter heat pipes, (c) Thirty-six 2.54cm diameter heat pipes.

2.1.3 Interface Design

Each heat pipe will have a flange brazed onto the heat pipe wall between the evaporator and condenser. This plate will in turn be mounted into an interface plate above the LM bath. The gas gap rupture disk will penetrate the flange and be integral with it. This will allow the whole heat pipe and rupture disk assembly to be installed and removed/replaced as a single unit. The interface plate will form the wall between the LM bath and the outside environment. All rupture disks and cooling line connections will be made on the outside side of this plate.

2.2 Heat Pipe Internal Design

The heat pipe internal design included consideration of the appropriate operating limits, the size of the gas gap, the wick design, the appropriate gas charge to achieve the required variable conductance, the sizing of the rupture disks, and materials selection. Each of these are described below.

2.2.1 Flooding Limit

In the SINQ and ESS applications, the heat pipes will operate as thermosyphons, using gravity to return the condensed working fluid to the evaporator. In a thermosyphon, the applicable operating limit is the flooding limit. The flooding limit is reached when the counterflowing vapor entrains liquid flowing down toward the evaporator, returning the liquid to the condenser and preventing the evaporator from being resupplied with working fluid. This limit was correlated by Kutateladze [1] and later improved by Tien and Chung [2], and is given by the following:

$$q_{\max} = \frac{C^2 A_{vapor} h_{fg} [\sigma g(\rho_l - \rho_v)]^{0.25}}{\left(\frac{1}{\rho_l^{0.25}} + \frac{1}{\rho_{vl}^{0.25}} \right)^2} \tag{1}$$

where C2 = 3.2 for water, nomenclature see ch. 5.

Equation (1) was used to determine the flooding limit for each of the geometries shown in Figure 4. The outer evaporator wall was assumed to be 0.10cm thick and the gas gap between the walls was assumed to be 0.018cm. The thickness of the inner wall was computed to contain the pressure of the supercritical water at 450 °C (40MPa). The results of these calculations is shown in Figure 5 below. In each case, the flooding limit is shown with the required heat transport rate corresponding to the number of heat pipes. These plots show that the design margin (difference between the peak in the flooding limit and the requirement) decreases as the number of heat pipes is increased. In addition, the peak in the flooding limit occurs at the same temperature, suggesting that the optimal operating temperature for the heat pipes is 250 °C. The design margin is the greatest for the array of eight heat pipes. Using the smallest number of heat pipes has the additional benefit of being the lowest in cost to fabricate. However,for the time being, it was felt that this array might not provide sufficient shielding for the SINQ-arrangement, where the source of energetic neutrons is located vertically under the heat pipes. For this reason, the array of fourteen heat pipes was selected as the reference design.

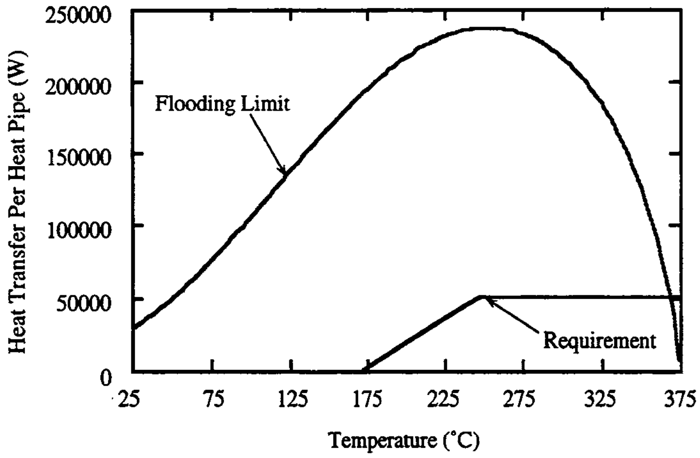


Figure 5a:Flooding Limit for 8 Heat Pipe Array. Max. heat transfer/Requirement = 4.75

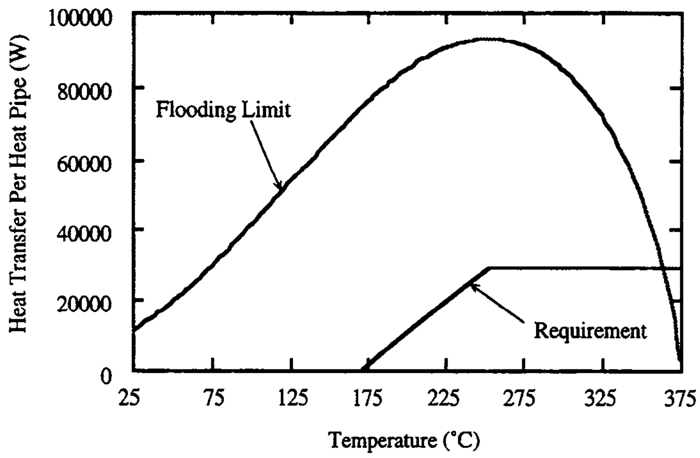


Figure 5b: Flooding Limit for 14 Heat Pipe Array. Max. heat transfer/Requirement = 3.25

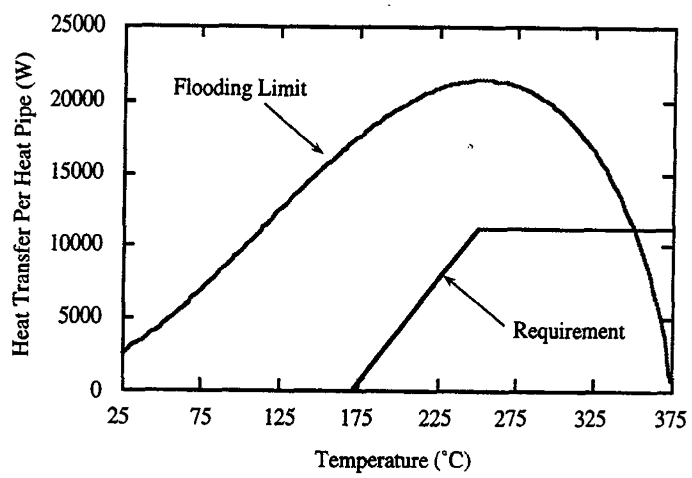


Figure 5c:Flooding Limit for 36 Heat Pipe Array. Max. heat transfer/Requirement = 1.93

2.2.2 Gas Gap

The evaporator of the heat pipe will feature a double wall containment with a gas gap between the two walls. The purpose of the gas gap is fourfold. Primarily, the gas gap provides a material barrier to prevent crack propagation through both the inner and outer walls. If the inner wall fails, high pressure water vapor from the heat pipe will be vented in to the gas gap. This will, in turn, cause the rupture disk to burst, allowing the water vapor to exhaust to a location outside the LM bath. The second purpose of the gas gap is to provide a high thermal resistance heat transfer path between the LM bath and the water heat pipe. The high thermal resistance results in a high temperature difference between the LM bath and the water heat pipe. This makes it possible to cool the 450 °C liquid metal bath with heat pipes which are operating at approximately 250 °C; having the heat pipes well coupled to the hot liquid metal is undesirable because the heat pipe is unable to transport any heat above the critical temperature of the working fluid, which is 374 °C for water. The third purpose of the gap is to reduce thermal stresses in the walls due to a small temperature drop across the walls and a large one across the gap. Finally, the design with a gap enables us to use two different materials for the inner and the outer wall, each selected for optimum compatibility with the medium it is in contact with.

2.2.3 Wick Design

The heat pipe will have two different wicks in the evaporator and condenser. The evaporator will have a felt metal wick. This is the same type of wick previously demonstrated on a water/monel Faraday shield heat pipe [3]. This wick has demonstrated capabilities to operate at high temperature at heat fluxes up to 50W/cm^2 with low ΔT. Having a capillary wick in the evaporator will allow the water inventory inside the heat pipe to be reduced because it will not be necessary to fill the entire evaporator with a pool of working fluid to assure wetting and evaporation from the entire evaporator surface.

Heat transfer in the condenser will be enhanced with a knurled surface. The tops of the knurled surface features will extend through the liquid film, reducing the ΔT between the condenser surface and the saturated vapor and improving condensation heat transfer. The grooves in the knurled surface will help channel the condensate away from the condensation surface and return the liquid to the evaporator wick. In addition to its effectiveness in reducing the effective film thickness in the condenser, the knurled surface is a low cost option for providing wicking to the condenser surface.

2.2.4 Variable Conductance Heat Pipe Design

In the SINQ application, it is desired to prevent freezing of the LBE on the outside of the evaporator wall. Therefore it is necessary to use a variable conductance heat pipe which will not transport heat when the bath temperature falls below the minimum LM bath temperature (170 °C). Similar considerations also hold for the ESS case, where the temperature of the beam window should not be allowed to be below 180 °C when the beam starts, as mentioned above. The variable conductance feature is achieved by charging the heat pipe, in addition to the appropriate quantity of working fluid, with 0.028g of argon. The argon will not condense or circulate inside the heat pipe. Instead, it will collect in the condenser end of the heat pipe where it will displace working fluid vapor. As the temperature of the LBE bath falls, the vapor pressure of the working fluid will decrease and the volume which the fixed mass of argon occupies will increase. The mass of argon is chosen so that it will completely fill the condenser when the bath temperature falls to 170 °C; this prevents additional heat from escaping from the LBE bath through the heat pipe heat exchanger and the liquid metal bath, as a result of decay heat (~ 5 kW after 1 day), will remain at approximately constant temperature.

2.2.5 Rupture Disk

Each heat pipe will be equipped with two rupture disks for safety reasons. The first rupture disk will be installed in the evaporator gas gap. In the event of a failure of the evaporator inner wall, this rupture disk will allow the water vapor to escape into the space outside of the LM bath. This allows the target to continue operating without contaminating the liquid metal bath with water. A second rupture disk will be attached to the heat pipe vapor space. This will allow the heat pipe working fluid to be vented outside of the liquid metal bath in the event that the heat pipe temperature exceeds the critical temperature of water. This reduces the required thickness of the inner evaporator wall because the internal pressure of the heat pipe will not reach supercritical pressures if loss of coolant causes the heat pipe temperature to exceed the critical temperature of the working fluid. In addition, the heat pipe may then be reused by simply replacing the rupture disk and reprocessing the heat pipe rather than replacing the whole heat pipe due to a wall failure.

2.2.6 Materials Selection

The outer wall of the heat pipe evaporator will be made of HT-9 martensitic steel. This is a low nickel alloy which has been shown in the past to demonstrate resistance to corrosion by the LBE and which retains ductility after exposure to high neutron fluence at elevated temperature [4]. Compatibility with mercury is also known to be good. The inner wall will be made of Monel K-500. This material is chosen for its high strength and compatibility with water in a heat pipe. The outer wall of the condenser water jacket will be made of stainless steel 304. The primary requirements for this material is low cost and easy weldability.

3. Future Work

Two pieces of work are planned before full scale heat pipe heat exchangers are produced. These are material life tests and quarter scale prototype fabrication. Each of these are described below.

3.1 Life Tests

A sub scale life test heat pipe will be fabricated using identical materials and fabrication techniques to determine the compatibility of water and Monel K-500 in the temperature range of interest for the target cooling applications. The test will be run for at least several thousand hours at temperatures between 250 and 300 °C. Although water and Monel K-500 have successfully been demonstrated in a heat pipe in the past [3], the higher temperature range of interest for the present target cooling application indicates that a life test be performed in this temperature range.

3.2 Quarter Scale Prototype

Before a full scale heat exchanger is fabricated, the reference design will be reconsidered in detail. A quarter scale heat exchanger of the final design will be fabricated and tested. This prototype will consist of one quarter of the number of heat pipes required to remove the heat from the SINQ target as described above, each built to full scale and designed to transfer the required amount of heat at operating temperature. The purpose of this is to demonstrate fabrication processes and show that the heat pipes will operate as expected under design power and design temperature conditions.

4. Conclusions

A heat pipe has been designed to remove heat from both the SINQ LBE liquid metal target and the ESS mercury target. The heat pipe is designed to transport up to 50 kW per heat pipe of waste heat energy out of the LM bath. The heat pipe design minimizes fabrication costs and can also be used in both target systems without change.

5. Nomenclature

A	cross sectional area, [m^2]
C	coefficient in equation (1), [-]
g	gravitational acceleration, [m/s^2]
h_{fg}	heat of vaporization, [J/kg·K]
q	heat flow, [W]
ρ_l	liquid density, [kg/m^3]
ρ_v	vapor density, [kg/m^3]
σ	surface tension, [N/m]

6. References

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