Title
DESIGN OF A LEAD GAS WARMER

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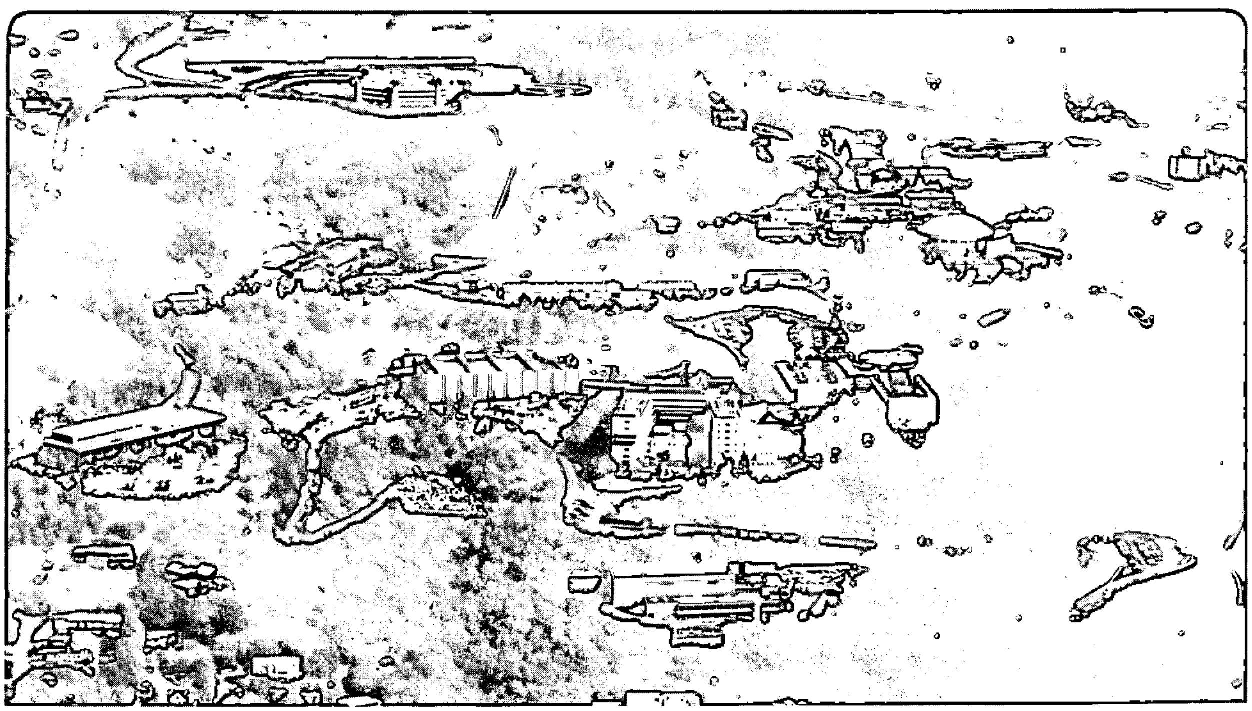

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ENGINEERING NOTE

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LARGE SUPERCONDUCTING SOLENOID

TITLE

DESIGN OF A LEAD GAS WARMER

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The TPC magnet leads are inside the vacuum of the magnet cryostat. Gas leaving the upper end of the leads is often at a temperature of 273K or below. As a result, an ice ball can form on the helium-return line. This ice ball can melt causing shorts in the TPC electronics. The pipe carrying the lead gas can be insulated thermally but such insulation systems are often unreliable when used for long periods of time. This engineering note describes a lead gas heater which is less than 6 inches long which can be mounted directly on the TPC magnet cryostat so that the lead gas leaving the magnet cryostat is always at a temperature above the dew point.

The proposed magnet for Sandia National Laboratory will also be troubled with ice balls on the leads. These leads will be mounted within the vacuum space. In this case, the lead gas and current are brought out through the same bus bar arrangement. The lead bus bar and lead gas port can be warmed by a lead gas heater system similar to that proposed for the TPC magnet. The lead tamer lead gas heater is presented in this report. Like the TPC magnet lead gas heater, the whole assembly proposed for the Sandia magnet is less than 6 inches long and it can be mounted directly on the Sandia magnet cryostat.

The basic theory for the lead gas heater is presented in this report. Sample calculations show that at the mass flows at which the leads operate, the lead gas can be warmed up to 300K without excessively heating the heater itself. A schematic of the proposed lead gas heater for the TPC magnet is presented. In addition, a combined lead gas heater and lead tamer for the proposed Sandia magnet is presented.

1. Basic Theory

The theory for heat transfer in a lead gas heater is similar to that used to design enhanced heat transfer "Tampax" leads.[1,2] The helium flow in a lead gas heater is laminar just as it is in the leads themselves. The heat transfer coefficient $\mho$ is inversely proportional to the boundary layer thickness. For well developed laminar flow, the boundary layer thickness is approximately half of the basic dimension of the tube.[3]

(In an annular tube, this basic dimension is the annulus thickness. In a round tube, the basic dimension is its diameter.)

When one designs a heat transfer system of this sort one wants to make the product of the heat transfer coefficient U and the heat transfer area A as high as possible. The use of an annular tube can permit one to maximize both.

The expression of Reynolds Number in an annular space can be expressed in the following form:

$$Re = \frac{VD^*\rho}{\mu} \qquad -1-$$

Where Re is Reynolds Number, V is gas flow velocity, ρ is density, μ is viscosity, and D^* is the critical dimension of the tube (the hydraulic diameter). For an annulus with an outside diameter of D_1 and an inside diameter of D_2, we find that the hydraulic diameter takes the following form:

$$D^* = \frac{4A}{P} \qquad -1a-$$

$$= \frac{4[\frac{\pi}{4}(D_1^2 - D_2^2)]}{\pi D_1 + D_2)}$$

$$= D_1 - D_2 \qquad -1b-$$

$$= 2t \qquad -1c-$$

Where A is the tube annulus cross-sectional area, P is the wetted perimeter and t is the annular distance between the inside and outside walls.

The Reynolds Number given in Equation 1 can be transformed to one involving fluid mass flow $\dot{m}$ in using the continuity expression.

$$\dot{m} = A\rho V \qquad -2-$$

Using the continuity expression one finds that the Reynolds Number takes the following form:

$$Re = \frac{4\dot{m}}{\pi(D_1 + D_2)\mu} \qquad \text{-3-}$$

If one takes the limit for a round tube where $D_2 \longrightarrow 0$ we find:

$$Re = \frac{4\dot{m}}{\pi D_1 \mu} \qquad \text{-3a-}$$

If one takes the other limit for a round annulus where the annular dimension t is very thin (in other words, $D_2 \longrightarrow D_1$) we find:

$$Re = \frac{2\dot{m}}{\pi D_1 \mu} \qquad \text{-3b-}$$

The conclusion drawn by the exercise is that Reynolds Number goes down as the annular dimension decreases. If flow in a round tube of diameter D_1 is laminar the flow in an annulus with outside dimension D_1 is even more laminar. An investigation of the lead flow problems shows that the leads always have a Reynolds Number below 2000 except possibly at the lowest temperature end.

There are all kinds of papers in the literature on how to calculate the heat transfer coefficient in laminar flow channels. Are they long channels? Are they short channels? We find that electrical leads are usually long compared to their hydraulic diameter. By the time the gas has traveled up the lead more than one-quarter of the way, well developed Pouselle flow has been established (this is another way of saying that the tube is long). For long tubes the Nussels number Nu reaches a minimum value of around 4.[4] In simple terms, when Nu=4 the heat transfer coefficient $\mho$ takes on the following value:

$$\mho = \frac{N_u K}{D^*} \qquad \text{-4a-}$$

$$= \frac{4k}{D^*} \qquad \text{-4b-}$$

$$= \frac{2k}{t} \qquad \text{-4c-}$$

Where k is the thermal conductivity of the gas, $\mathcal{U}$ is the heat transfer coefficient and t is the thickness of the annulus. Equation 4c simply says the boundary layer thickness is half the annulus thickness. The heat transfer coefficient at the entrance to the lead is always higher than the value given by Equation 4c. At tube entrances, the Nussets number can be over ten, so Equation 4c gives sort of an average minimum value for heat transfer coefficient. It should be noted that this simplified method of calculating the heat transfer coefficient is probably good to within twenty per cent.

From Equation 4c it is clear that the annulus should be as thin as possible. The dimension t is a compromise between pressure drop and heat transfer rate for a given size tube. In general an annular dimension of $t = 0.5$ mm is adequate to insure good heat transfer. When the tube diameter D is much larger than t, the $\mathcal{U}A$ product is directly proportional to the diameter of the tube for a given value of t. Oddly enough, the $\mathcal{U}A$ product in a long round tube is nearly constant with diameter ($\mathcal{U}$ is inversely proportional to D while A is directly proportional to D.)

Table I shows the density ρ, viscosity μ, and the thermal conductivity k of helium gas at 1 atm for various temperatures T from 200K to 350K.[5] The calculated heat transfer coefficient $\mathcal{U}$ is given for a tube with a 0.5 mm annulus. From TABLE I, it is clear that high rates of heat transfer can be obtained in an annular tube which is in the laminar flow regime. The value of $\mathcal{U}$ for a particular tube can be calculated using the $\mathcal{U}$ value given in the Table. All one has to do is multiply the Table value of $\mathcal{U}$ by 0.5 divided by t where t is given in millimeters. From Equation 4a, it is clear that the heat transfer can be improved a factor of 50 by using an annular tube in place of a round tube. Even when one considers the boundary layer and the increased Nusselts number near the tube entrance, the use of an annular flow passage improves heat transfer at least an order of magnitude depending on the diameter of the annular tube.

TABLE I. The transport properties of Helium gas at 1 atm for various temperatures and the estimated U factor for heat transfer in an annulus 0.5mm thick containing the Helium gas.

T (K)	ρ (kgm^{-3})	μ (Nsm^{-2})	k ($Wm^{-1}K^{-1}$)	$\mathcal{U}$ ($Wm^{-2}K^{-1}$)
200	0.244	1.51×10^{-5}	0.118	472
225	0.217	1.64×10^{-5}	0.128	512
250	0.195	1.76×10^{-5}	0.137	548
275	0.177	1.88×10^{-5}	0.146	584
300	0.163	1.99×10^{-5}	0.155	620
325	0.151	2.11×10^{-5}	0.164	656
350	0.139	2.22×10^{-5}	0.172	688

Once the heat transfer coefficient has been determined, one can look at the heat transfer process. The heat which must be transferred to the gas in order to warm it up at temperature ΔT_g is as follows:

$$Q = \dot{m} C_p \Delta T_g \qquad -5-$$

where Q is the rate of heat transfer needed to warm up gas which has a mass flow of $\dot{m}$, a specific heat at constant pressure per unit mass C_p, and a temperature rise of ΔT_g.

For helium, the specific heat $C_p = 5.2 J g^{-1} K^{-1}$. The mass flow through each electrical lead is about 0.06 $g\,s^{-1}$ per 1000A of design lead current. If one assumes that one must warm the helium gas up at $\Delta T = 75K$, the rate of heat transfer to the helium gas in the lead gas heater must be about 23.4 W per 1000A of lead current.

The heat transfer from the annular tube walls which are treated by the lead gas heater can be estimated using the following expression:[4]

$$Q = \mathcal{U} A \overline{\Delta T} \qquad -6-$$

where $\overline{\Delta T}$ the log mean temperature difference is calculated as follows:

$$\overline{\Delta T} = \frac{\Delta T_A - \Delta T_B}{\ell n \left(\frac{\Delta T_A}{\Delta T_B} \right)} \qquad -6a-$$

where ΔT_A is the temperature difference between the wall and the gas at the A end (the cold end) of the lead gas heater and ΔT_B is the temperature difference between the wall and the gas at the B end (the warm end) of the lead gas heater. $\mathcal{U}$ is the heat transfer coefficient at the wall calculated using Equation 4c and A is the heat transfer area.

The maximum temperature of the heated surface can be estimated for a lead gas heater which has the B end as the warm end.

$$T_{max} \simeq T_{BG} + \Delta T_B \qquad -7-$$

where T_{max} is the maximum temperature on the surface heated by the lead gas heater. T_{BG} is the desired gas temperature at the warm end of the lead gas heat. ΔT_B is the temperature difference between the gas temperature T_{BG} and the wall.

The temperature difference ΔT_B is a function of the properties of the lead gas heater itself. Is heat transfer easily along the heater? Let's look at two extremes. The first is the assumption that there is perfect heat transfer along the solid part of the heater (both ends of the heater are the same temperature). The second assumption is that there is no heat transfer along the heater and there is uniform heating along the heater. (The heater temperature follows the gas temperature.)

For the first assumption, to apply the relationship between ΔT_A and ΔT_B is as follows:

$$\Delta T_A - \Delta T_B \simeq \Delta T_g \qquad -8a-$$

therefore

$$\ln\left(\frac{\Delta T_A}{\Delta T_B}\right) = \frac{\Delta T_g}{\overline{\Delta T}} \qquad -8b-$$

and

$$\Delta T_B \simeq \frac{\Delta T_g}{\exp\left(\frac{\Delta T_g}{\overline{\Delta T}}\right) - 1} \qquad -8c-$$

where ΔT_g is the temperature rise of the gas in the lead gas heater, and $\overline{\Delta T}$ is the log mean temperature difference calculated from Equation 6. ΔT_A and ΔT_B are the temperature differences between the gas and the lead gas heater at the A and B ends respectively.

For the second assumption to apply, the following relationship between ΔT_A and ΔT_B applies when constant heat transfer to the gas occurs along the heater:

$$\Delta T_A = \Delta T_B = \overline{\Delta T} \qquad \text{-8d-}$$

Equation 8d will lead to a larger value of ΔT_B than will Equation 8c. For our case, the lead gas heater will not overheat as long as $\overline{\Delta T}$ is less than 40K. The product of $\mho$ and A for each lead gas heater must be greater than 0.6 WK^{-1} per 1000A of lead current when the gas temperature is to be raised by 75K. (The $\mho A$ product required is proportional to current.)

2. Two Designs for Lead Gas Heaters

The heat transfer area required in order to warm up the lead gas must be about 10 cm^2 per 1000A of lead current. For the TPC magnet which has a maximum current of 3000A, one must have at least 30 cm^2 of area inside the tube. If the annular space is 1 inch in diameter, the minimum length is about 4 centimeters. Figure 1 shows a design for the proposed lead gas heater for the TPC magnet leads. The design $\mho$ factor is about 500 $Wm^{-2}K^{-1}$ and the design area is about 60 cm^2 ($6 \times 10^{-3} m^{-2}$). This will insure that the lead gas will leave the heater at at least 300K. The maximum temperature of the lead gas heater is expected to be less than 330K when the heater in the well is generating about 70 watts and the lead gas flow is 0.18 g s^{-1} per lead.

Figure 2 shows a design for a lead gas heater which is part of the electrical bus bar system for the Sandia magnet. This lead gas heater combines the function of heating lead gas with heating the lead cable connector in order to prevent an ice ball from forming on the lead assembly. We are proposing to use this assembly on the Sandia magnet.

ACKNOWLEDGEMENTS

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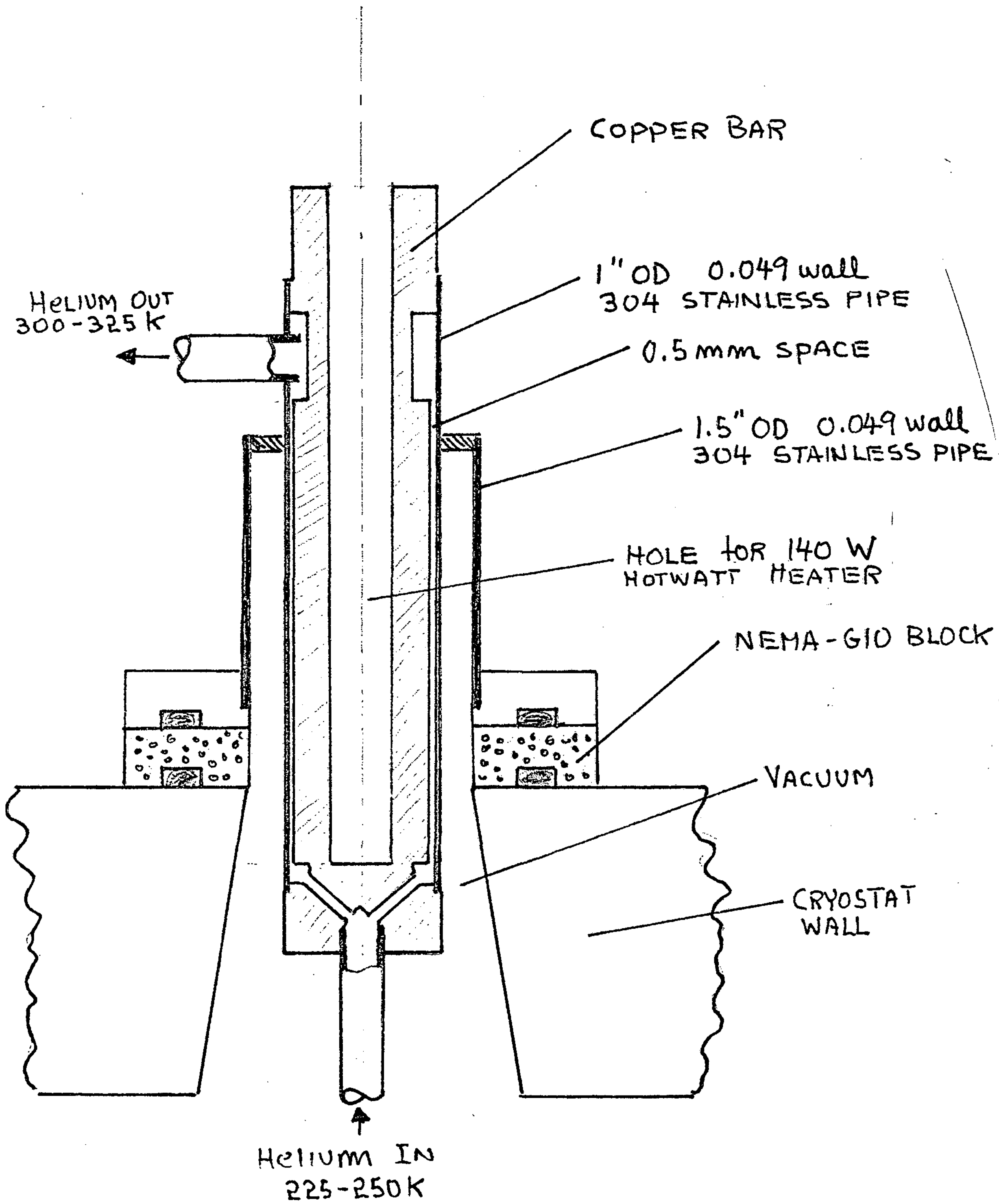

Figure 1. A Proposed Lead Gas Heater for the
TPC Superconducting Magnet

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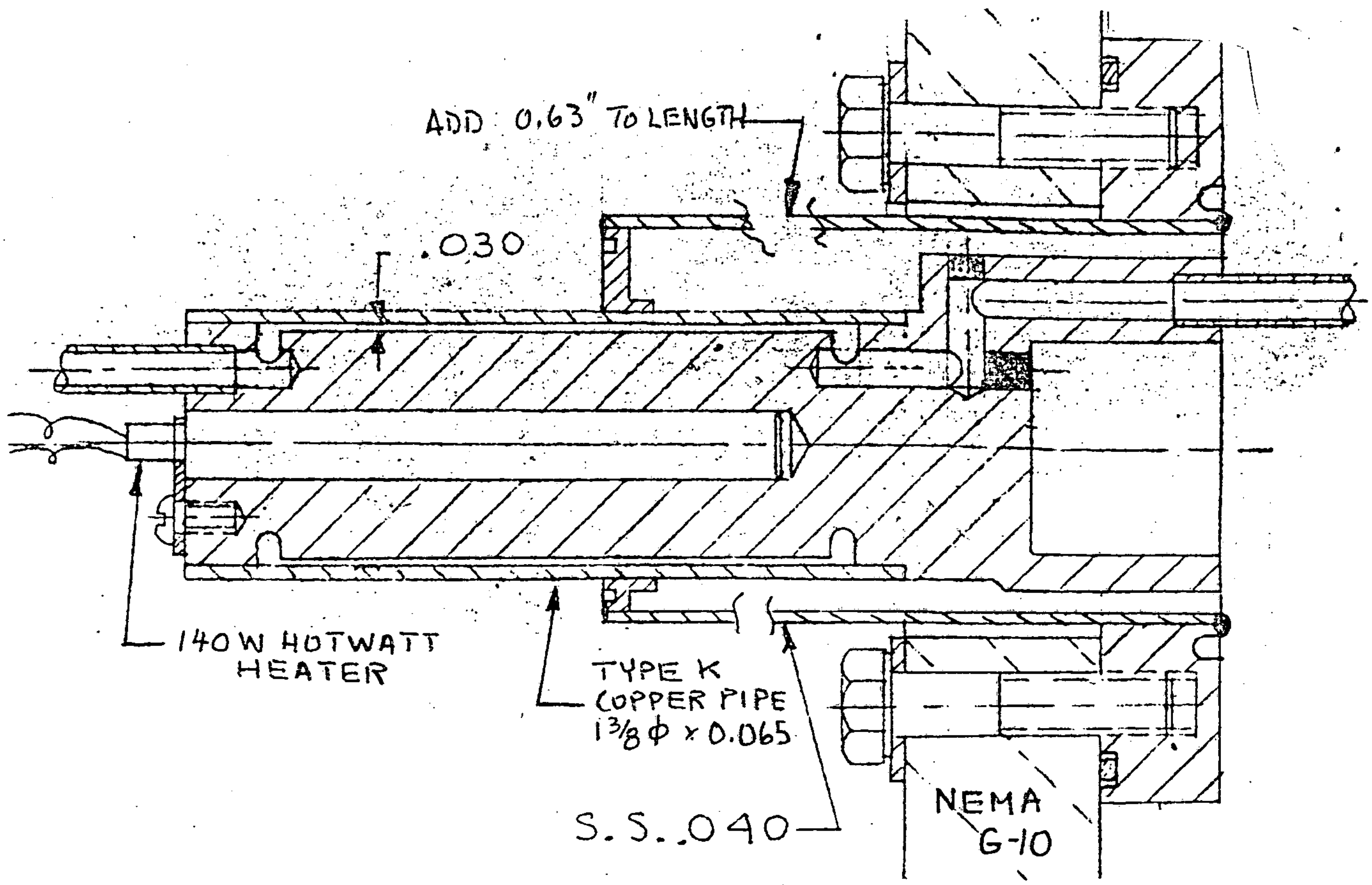

Figure 2. A Combined Lead Gas Heater and Lead Ice Ball Eliminator for the Sandia Superconducting Magnet

See LBL Drawings 20H5664 and 20H6233

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