**VAPOR PRESSURE THERMOMETRY SYSTEM:
NEAR LN₂ SUBCOOLER**

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ABSTRACT

A nitrogen Vapor Pressure Thermometer (VPT) system is designed to determine the temperature of the liquid nitrogen (LN_2) supply line, after exiting the LN_2 subcooler, inside the D-Zero Assembly Hall. The operating temperature range is designed from 77 to 300 Kelvin with an initial charge pressure of 100 psia. A cylindrical bulb with a 0.1875" diameter and 0.625" length allows for minimum cold and warm $\frac{1}{4}$ " O.D. SS 304L tubing lengths, 12" and 18" respectively, and maintains a liquid level of 50% inside the bulb during cold operation. The amount of nitrogen needed to fill the cylindrical bulb approximately half full is 0.149 grams. In order to conform to the conventional cold volume and warm volume VPT systems, we need to enlarge the existing $\frac{1}{2}$ " x 2" SCH. 10 LN_2 supply line over a one foot section to 1" x 3" SCH. 10 piping.

INTRODUCTION

Fermi National Accelerator Laboratory (Fermilab) is in the process of upgrading its detectors. Among these upgrades is the need for more transfer lines containing both liquid nitrogen and helium gas. These two fluids are used to provide the necessary operating cryogenic temperatures for the various detectors, such as the Visible Light Photon Counter (VLPC) and the solenoid inside the detector's calorimeter. With additional piping, it is important to monitor the temperatures to assure that the detectors can operate correctly. This can be done two ways. The first method is to use a Resistance Temperature Device, called a RTD, which is made using either a carbon resistor or a platinum resistor and measures the temperature based on resistance. The second method is to use a vapor-pressure thermometry system. This design will focus on the second method.

A vapor-pressure thermometer consists of a bulb filled partly with liquid and partly with vapor in equilibrium with the condensed phase, connected by a pressure-transmitting line to a pressure measuring instrument. Vapor-pressure thermometry can provide quite accurate measurements of temperature over extended ranges because the saturation vapor pressure of a pure substance such as nitrogen is a "monotonic and sensitive function of temperature." The vapor-pressure thermometer commonly used (regardless of substance) is comprised of two volumes of gas connected by a capillary tube as seen in Figure 1. The left side of the figure shows the warm volume of the system which includes a pressure gauge and a fill valve. The right side of the figure, separated by the dotted line, shows the cold volume of the system which is usually inside the piping. The vapor bulb makes up the remainder of the cold volume and is the portion of the cold volume that extends into the piping containing the fluid which is to be measured.

Figure 1 VPT Apparatus

As the engineer on this project, my purpose is to design a VPT system under the following conditions: 1) use nitrogen as the substance inside the vapor-pressure system, 2) the measured fluid is a LN_2 supply line, and 3) efficient use of space is a priority.

This paper presents the design by first explaining the components of the system and their effects on the system when altered. Second, design methods are presented. Finally, recommendations and an overview of the design specifications are given for the design of the vapor-pressure thermometry system.

VPT DESIGN CONSIDERATIONS

The objective of the VPT system design is to choose a VPT that will conform to the conventional VPT system designs. Namely, the goal is to have the bulb fifty percent full of liquid, by volume, at normal operating conditions. The procedure to meet this goal involves three main initial guesses chosen arbitrarily; the bulb size, the warm capillary tube length and the cold capillary tube length. Included in these three main assumptions are the adequate pipe and tube sizing, bulb positioning, and the states which define the cold operating condition and the charge condition. Since there are numerous dependent variables, an iterative process is used. The FORTRAN program, Nitro, has been designed to execute the iterative process that will search for a combination of variables which will define an adequate vapor-pressure thermometer according to the designer's preference. The FORTRAN program has been attached in Appendix A and is accompanied by detailed explanations. However, some of the variable names used in this paper are different from the variable names used in the program due to the format used in FORTRAN programming logic.

In order to continue with the design considerations, proper knowledge of the variables used is important. Table 1 is a listing of all the vapor-pressure thermometry system variables. The table presents a reference for each of the variables such as the charge pressure. Charge pressure has the symbol, P_{CH} , and is accompanied by a short explanation of its function; the "Pressure needed to initiate the VPT system."

Table 1. Vapor Pressure Thermometry System Nomenclature

REFERENCE DESIGNATION	DESCRIPTION	FUNCTION/PURPOSE
Charge Pressure	P_{CH}	Pressure needed to initiate the VPT system.
Charge Temperature	T_{CH}	Temperature at which the system is charged.

Table 1. Vapor Pressure Thermometry System Nomenclature (continued)

REFERENCE DESIGNATION	DESCRIPTION	FUNCTION/PURPOSE
Mass at Charge Pressure and Temperature	M_{CH}	Total mass of the system at charged temperature and pressure.
Charge Density	ρ_{CH}	Density of the fluid at the charge condition.
Cold Bulb Temperature	T_c	Temperature of the bulb at cold conditions.
Length of Cold Tubing	L_c	Length of tubing from the vacuum jacketed pipe to the bulb connection.
Length of Warm Tubing	L_w	Total length of tubing exiting the vacuum jacketed pipe.
Total Capillary Tube Length	L_T	Length of warm and cold tubing.
Volume of Capillary Tube	V_{CAP}	Volume of fluid in the cold portion of the capillary tube.
Volume of Bulb	V_B	The bulb volume.
Cold Volume	V_c	The volume of fluid in the cold tubing and in the bulb.
Volume of Warm Tubing	V_w	The volume of the gas in the warm tubing.
Volume of Gauge	V_{GAUGE}	The volume of the pressure gauge.
Total Volume	$V_T = V_c + V_w + V_{GAUGE}$	The total overall volume of the fluid.
Mass of Cold Volume	M_c	The total mass of the fluid in the cold volume.
Mass of Warm Volume	M_w	The total mass of the fluid in the warm volume.

Table 1. Vapor Pressure Thermometry System Nomenclature (continued)

REFERENCE DESIGNATION	DESCRIPTION	FUNCTION/PURPOSE
Density of Liquid in Bulb	ρ	The density of the liquid in the bulb.
Density of Warm Gas in Capillary Tube	ρ_w	The total density of the warm gas in the capillary tubing.
Percent of Liquid in Bulb	X	Percentage of liquid in the bulb.
Length of Bulb	L_b	The length of the bulb.
Diameter of Bulb	D_b	The diameter of the bulb.
Density of Gas in Bulb	ρ_g	The density of the bulb.
Mass of Capillary Tube	M_{CAP}	The mass of the fluid in the capillary tube.

Bulb Sizing

The choice for a vapor-pressure thermometer bulb is divided into two geometries: 1) a spherical bulb, and 2) a cylindrical bulb. The initial guess for this design was to use a spherical bulb, but as I investigated further I found that, due to the amount of nitrogen needed to fill the bulb half full, a cylindrical bulb would be a better choice. The geometry of the bulb is completely arbitrary. A spherical bulb and a cylindrical bulb are only different in shape. The volume is the most important issue when choosing a bulb size. I chose a cylindrical bulb because of the amount of nitrogen needed to fill the bulb half full. This concept of filling the bulb half full and the amount of nitrogen needed to accomplish this will be explained shortly. I also chose a cylindrical bulb because it is easy to machine and build. The choice of a cylindrical bulb is also dictated by the size of the capillary tube which will also be mentioned below.

Bulb Positioning

The bulb position is just as important as the bulb size. Bulb positioning deals with the depth the bulb protrudes into the pipe containing the measured fluid. It is very important to have the bulb fully immersed into the pipe containing the liquid nitrogen in order to receive accurate temperature measurements. When choosing the bulb position I need to define the length of the bulb since I am using a cylindrical bulb. This choice is made partly with the help of previous engineering notes on VPT designs and the requirement for the bulb to be surrounded by the fluid that is being measured. I chose to design the bulb with the dimensions as seen here in Figure 2. I chose to dimension the bulb in increments of a sixteenth for simple machining. The bulb will start out as a $\frac{1}{4}$ " nominal diameter Stainless Steel 304L solid rod, and the inner dimensions should be machined as closely as possible to the tolerances set in the figure. This will insure that the bulb will be sealed properly to its end cap with an eighth inch weld as seen in Fig. 2, and will insure that there will be no mixing of the nitrogen in the bulb and the LN_2 from the supply line.

Figure 2. Enlarged View of the VPT Cylindrical Bulb
SCALE: 10 x 1

Capillary Tube Sizing

The bulb geometry, as defined in Fig. 2, is also dependent on the size of the capillary tube since the capillary tube will be welded to the bulb. The capillary tube sizing is very dependent on the amount of nitrogen needed to fill the bulb half full since part of the capillary tubing makes up the cold volume of the system. This causes some difficulty when trying to determine the proper size needed to complete the VPT system. However, the initial choice for tube sizing is based on the size of tubing available at Fermilab. There is an extensive selection of tubing in the Fermi Stock Room and there may also be tubing in the machine shop here at D-Zero. The sizes of tubing considered for this design are: 1/8", 3/16", and 1/4" SS 304L tubing. From the D-Zero pipe database, I found that the pressure gauge that will be used has already been chosen with a 1/4" male pipe thread. Therefore, I will use 1/4" SS 304L tubing for the capillary tube size to remain consistent with the pressure gauge dimension.

Pipe Sizing

Now that the bulb dimensions have been established, as seen in Fig. 2, and the capillary tubing has been defined as 1/4" SS 304L tubing, the pipe size must be defined. The VPT bulb will be inserted into the existing LN₂ transfer line and the capillary tube, which makes up the rest of the cold volume, and will travel from the cylindrical bulb through the vacuum space between the pipes to the vacuum jacket pipe wall. The capillary tube then continues outside the vacuum jacket pipe as seen in Figure 3.

Figure 3 Piping Configuration With Cylindrical Bulb

The existing pipe is ½" SCH. 10 x 2" SCH. 10 Vacuum Jacket. This means that the inner liquid nitrogen pipe is made of ½" Schedule 10 stainless steel and the vacuum jacket is made of 2" Schedule 10 stainless steel. Since the inner pipe is insulated with approximately ¼" insulation, there is only ¼" of space between the inner pipe and the vacuum jacket. In the design, I decided to increase these dimensions so that the technicians building the VPT system would have more space to work with when installing the capillary tube between the two pipes. Since there is to be no contact between the capillary tubing and the pipe walls, I increased the pipe size using SCH. 10S 304L Reducers to a one foot section of 1" SCH. 10 x 3" SCH. 10 piping. The increase in the inner pipe allows for the bulb to be surrounded by the liquid nitrogen and the increase in the vacuum jacket pipe size allows for easier installment of the capillary tubing.

Charge Condition

Now that the geometry of the VPT system is defined, as seen above, the internal conditions must be specified. The initial state of the VPT system is defined as the charge condition. The charge condition is the condition at which the system is initialized, i.e., at a given set temperature and a set pressure. Initialization involves filling the VPT system with the correct amount of nitrogen and is the upper range for the VPT temperature range. From the research I did on VPT systems, a charge pressure near 100 psia is acceptable. I found one instance in an engineering note by Eric Larson where the charge pressure was 123 psia. For all practical purposes, I chose a charge pressure of 100 psia and had it approved by my head engineer, Russell Rucinski, before I continued. The charge temperature is based on the temperature at which the system is initialized. In the case for the VPT at D-Zero, the charge temperature will be room temperature or 300 Kelvin. In addition to the charge conditions, I must also define the lower operating range of the VPT system, known as the cold condition.

Cold Condition

Up to this point, many of the design considerations have been educated guesses based on previous experience and research about vapor-pressure thermometry. The cold condition of the VPT is specifically defined by the state of the fluid the sensor is measuring. In my design, the lowest operating range is approximately 77 Kelvin at 14.7 psia taken from the nitrogen curve in Figure 4. Figure 4 is a common equilibrium vapor curve used by the engineers and was given to me by Russell Rucinski for reference. Seventy-seven Kelvin will be the lowest working temperature of the LN_2 supply line, and at operating conditions, the LN_2 should be at 14.7 psia. I used these values to define the lower limits of the VPT system.

Argon, Nitrogen Equilibrium Vapor

METHODS OF DESIGN

By defining the variables and their physical properties the VPT system is almost complete. I have chosen to evaluate the system two different ways. In the first analysis of the system, I chose to solve for the overall mass of the fluid, which can be either all gas, all liquid, or a fraction of both, and from there I define the mass of nitrogen needed to fill the bulb half full. The second analysis begins by assuming that the bulb is half full and then solving for the amount of nitrogen needed. Both of these methods are used to check the other.

The goal of these two methods is not just for agreement in the geometry chosen, but also to determine the right amount of nitrogen needed. That is to say, when I solve for the amount of nitrogen needed at the charge condition and the amount of nitrogen needed at the cold condition, I want the amount of nitrogen to satisfy the cold condition first. The cold condition is the limiting factor and the amount of nitrogen needed should be less than or equal to the amount of nitrogen needed for the charge condition given the geometry of the design. This goal will be explained later in the paper once the idea of a charge condition and cold condition is established.

Method 1

Charge Condition

With the charge temperature and pressure already determined above as 300 Kelvin and 100 psia, approximately 7 bars, I must choose an arbitrary total volume, V_T for the system. The total volume of the system is defined as the total volume the measuring fluid can occupy. In this design, the total volume is the space that the nitrogen can occupy and is made up of the cold and warm tubing lengths, the amount of volume inside the pressure gauge and the bulb size.

I have chosen a $\frac{1}{4}$ " O.D. x 0.049 wall thickness SS 304L as the capillary tubing size. I chose the length of the cold capillary tubing is 12", the length of the warm capillary tubing is 18", and the bulb length and diameter of 0.625" and 0.1875"

respectively. The calculations for the volumes below are found in Appendix B. The volume of the pressure gauge is 10 cubic centimeters (cc), chosen from another engineering note done on VPT systems, the volume of the cold portion of the VPT system is 3.851 cc, the volume of the warm portion of the VPT system, excluding the volume of the pressure gauge, is 5.352 cc, and the volume of the bulb is 0.2828 cubic centimeters. The cold volume of the system is the sum of the volume of the bulb and the volume of the capillary tube in the cold portion, or the portion of the capillary tube extending from the bulb to the vacuum jacket. The warm volume is strictly the volume of the capillary tubing outside the vacuum jacket to the pressure gauge and fill valve. The cold volume is defined as:

$$V_C = V_B + V_{CAP} \quad [1]$$

and the cold volume, the warm volume and the volume of the pressure gauge make up the total volume of the system as seen below:

$$V_T = V_C + V_W + V_{GAUGE} \quad [2]$$

The total volume of my design is 19.204 cubic centimeters.

The charge pressure, the charge temperature and the total volume defines the initial system density, otherwise known as the charge density. The charge density is found by using the thermodynamic properties table for nitrogen under 1 bar at 300 Kelvin and is 0.00797555 g/cc. With the total volume calculated above and the charge density, the total mass of the system can be calculated using equation [3] as follows:

$$M_{CH} = \rho_{CH} * V_T \quad [3]$$

The mass at the charge condition is 0.153 grams.

Warm Mass of Fluid at Cold Condition

With the mass of nitrogen at the charge condition known, the next step is to obtain the mass of the nitrogen in the bulb. This is done by solving the system for the portion that is considered the warm volume; the volume of fluid, most likely gas, occupying the portion of the capillary tube extending from the vacuum jacket to the pressure gauge and fill valve. As the bulb cools the measured pressure, P_M , decreases and knowing the measured pressure at ambient conditions, one can determine the warm density, ρ_w . The warm density is found

using the lowest operating pressure of the system being measured and the lowest known operating temperature. In this design, the operating temperature and pressure has been defined earlier as 77 K and 1 bar. Although the temperature at cold conditions is approximately 77 Kelvin, we want the warm volume of at cold conditions. Therefore, I used 300 Kelvin as the temperature for determining the warm volume. Using 1 bar and 300 K, I found the density of the fluid in the warm volume of the tubing to be 0.00113844 g/cc. Knowing the warm volume and the density found above, the equation for the mass of the warm region is as follows:

$$M_w = \rho_w * V_w \quad [4]$$

The mass of the warm region which is calculated as 0.017 grams.

Cold Condition: Capillary Tubing

Now that we have been able to calculate both the mass of the nitrogen at the charge condition and the mass of the fluid in the warm volume, we are ready to determine the final mass to complete the first design method. Finding the mass of the fluid in the cold volume is a much more complicated process than finding the charge and warm masses above. The approach that this method now takes is finding the mass of the fluid that exists in the capillary tube from the bulb to the vacuum jacket. This mass is known as the mass of the capillary tube, M_{CAP} .

In order to determine the mass of the fluid in the capillary tube, the variables $K(T_C)$, λ , and ΔT_i must be defined. A plot of the thermal conductivity of the tubing material and its temperature range is required for further analysis. The plot shown in Figure 5 is a plot of the thermal conductivity of stainless steel 304 at various temperatures ranging from 0 Kelvin to 300 Kelvin. I used the program 'Nitro' to integrate the curve from 77 to 300 Kelvin, thus finding the area under the curve between our operating temperatures. The integration gives the value $K(T_C)$ in milliwatts per centimeter. $K(T_C)$ is the average thermal conductivity over the entire temperature range, and this is one of the terms used to determine the length of the cold tubing.

In order to determine the mass of the capillary tube, we must understand the temperature gradient that the cold portion of the capillary tube (L_C) experiences. The cold

portion of the capillary tube is divided into 'i' segments such that $L_c = \sum_0^i L_i$. The thermal conductivity of the tube material over segment 'i' is λ_i , and the temperature difference is ΔT_i . Assigning arbitrary temperature values, along the cold portion of the capillary tube, from the connection at the bulb to the vacuum jacketed pipe defines the individual segments L_i . Refer to Figure 6 for an example of a possible bulb design and how the capillary tube may be sectioned according to temperature.

Figure 6. Division of Capillary Tube Length L_c Into 'i' Segments

In Figure 6 we see that the first temperature is defined as 78 K at the point where the capillary tube enters the pipe containing the fluid which is to be measured. This temperature is a fairly accurate assumption since I know that the bulb is submerged in the LN_2 line that will be at 77 Kelvin. The final temperature is 300 K at the point where the capillary tube reaches the vacuum jacketed pipe. This temperature is also fairly accurate since the vacuum jacket is at ambient conditions. The temperatures used to fill the range between 78 and 300 Kelvin is arbitrary, but I do know that the temperature increases from the bulb to the vacuum jacket. Therefore I chose the intermediate temperatures in

ascending order along the tube from 78 to 300 Kelvin. Each of the segments defined by a different temperature are then assigned length variables such as $L_1, L_2, \dots, L_n$. For example, I chose the next temperature after 78 K to be 90 K. I then labeled the length of tubing between them as L_7 , since I do not know the true length between those two temperatures.

At this point we have only defined ΔT_i for each of the segments L_i . In order to calculate the lengths of the individual segments, the lengths are defined as follows:

$$L_i = \frac{\lambda_i L_c \Delta T_i}{K(T_c)} \quad [5]$$

Where λ_i is taken from Fig. 5 as an average thermal conductivity for the temperature range of each individual segment. L_c is the known desired cold capillary tube length, which was chosen previously as 12 inches, ΔT_i is defined by the temperature increments chosen by the designer, and $K(T_c)$ has been determined by integrating the curve in Fig. 5. Each segment L_i has an average temperature value ΔT_i and each ΔT_i has a unique density, ρ_i since the measured pressure is constant for the entire tube. The mass of the gas in each segment can then be calculated, assuming the cross-sectional area of the hole in the tube is known and in this design we know the tube size is $\frac{1}{4}$ " O.D. x 0.049 wall thickness. Therefore, the mass of the gas in each segment is:

$$M_i = L_i \cdot Area \cdot \rho_i \quad [6]$$

The mass of the fluid in the capillary tube follows:

$$M_{CAP} = \sum_0^i M_i \quad [7]$$

The equation for the density in the cold bulb, ρ_c is:

$$\rho_c = \frac{M_{CH} - M_w - M_{CAP}}{V_B} \quad [8]$$

The mass of the fluid in the capillary tube, in the cold volume, is found to be 0.007044 grams and the density of the cold bulb is 0.456005 grams per cubic centimeter. Then, by using the pressure readout from the pressure gauge and the calculated cold bulb density along with the thermodynamic property tables for nitrogen, we can define the temperature of the LN_2 supply line.

In our nitrogen VPT design, we chose to create a process in the Fortran program, 'Nitro,' to iterate the possibilities for the length of segments L_i . In the output file 'disp,' I chose a range of temperature values from 78 to 300 Kelvin. I then used Fig. 5 to find the average thermal conductivity values of the SS 304 tubing material. I also entered a column for the densities of each segment, taken from the thermodynamic property table for nitrogen, and had the program compute L_i and eventually M_i and M_{CAP} . Details of this procedure are documented in the program itself in Appendix A.

Method 2

In order to confirm the values we determined from the first method, I tried another approach to find the density of the fluid in the cold bulb. This method, however, focuses on determining the volume fraction of the liquid in the bulb and seeing if it is close to 50% at the normal operating condition. In the second approach I determined the cold volume and warm volume in the same manner in which they were determined in the first method. The mass of the system at the charge condition and the warm condition is found using equations [3] and [4] as mentioned above. The major difference in this second approach is that instead of subtracting the mass of the fluid in the warm tubing from the total mass of the fluid in the system, which should equal the mass of the fluid in the cold tubing, I solved for the mass of the fluid in the cold tubing directly:

$$M_C = \rho_l V_B X + \rho_g [(1 - X)V_B + V_{CAP}] + \rho_w (V_w + V_{gauge}) \quad [9]$$

The first term in equation [9] is the percentage of liquid in the bulb; the density of the liquid multiplied by the total volume of the bulb and then multiplied by a fraction of the volume of liquid in the bulb. The second term concerns the gas that fills the remaining portion of the bulb and the gas in the capillary tube that extends from the bulb to the vacuum jacket. In this term, the density of the gas is multiplied by one minus the fraction used to determine the amount of liquid in the bulb. Since the temperature of the capillary tube is above 77.3 Kelvin, it is safe to assume that the fluid in the capillary tube is a gas. The third and final term in the equation is the mass of the fluid, or in this case the mass of the nitrogen gas that fills the capillary tube extending from the vacuum jacket

to the pressure gauge and the fill valve. The mass of the fluid at cold conditions is found to be 0.149 grams. The density of the fluid in the cold bulb is:

$$\rho_C = \frac{M_C - M_{CAP}}{V_B} \quad [10]$$

The density of the liquid in the cold bulb is found to be 0.441860 grams per cubic centimeter.

If the analysis is done correctly, the cold bulb density from the first method should be close to the cold bulb density found from the second method or equation [8] should be equal to equation [10]. Since there are a number of variables that can be changed in the VPT system, the program 'Nitro' is used to make this comparison. As seen in the display output, the percent difference between the two different cold bulb densities is 3.10 percent. Since the difference between the two cold bulb densities is only 0.0141 grams, we are able to assume that the percentage of liquid in the bulb is approximately 56.15 percent as seen in Appendix A on page A19. The analysis that I conducted is not critical in determining that the percentage of liquid in the bulb is exactly 50 percent, but that the analysis shows that at the operating conditions the bulb is nearly half full of liquid nitrogen.

VPT DESIGN CONCLUSIONS

Throughout the whole design considerations, I work with a cold capillary tube length of 12 inches and a warm capillary tube length of 18 inches. As I mentioned previously, this choice is arbitrary, but I chose this combination for two reasons. The first reason I chose this combination of length is because I found as the total length of the capillary tube increases, the mass of the nitrogen also increases. Figure 7 demonstrates that as the bulb volume increases, the mass of nitrogen increases, and the overall length of the capillary tube also increases. With the bulb dimensions set at 0.625 inches long and a diameter of 0.1875 inches, the bulb volume equal to 0.2828 g/cc, I needed to choose a combination of lengths that were easy to machine. Since I will increase the LN₂ supply line from ½" to 1" pipe over a one foot section, I chose a 12 inch cold capillary tube length.

The second reason for the current design is due to the warm tube length choice. I chose an 18 inch warm tube length because of the amount of nitrogen needed for the bulb to be filled half full. Also, by choosing the cold tube to be 12 inches long and the warm tube to be 18 inches long, I found the corresponding mass of nitrogen to be comparable to previous VPT designs. Therefore, since 0.149 grams of nitrogen is needed to fill the bulb half full, with the tube dimensions above, I found an acceptable bulb capacity for my VPT system.

Now that we have a better understanding of the charge condition and the cold condition, from the explanation of Method 1, we can refer to Figure 8. Figure 8 shows the effect of the capillary tube nominal diameter to the change in the mass of nitrogen for the cold capillary tube length of 12 inches and the warm capillary tube length of 18 inches. This graph is used to represent one of the criterion for choosing the proper VPT capillary tube geometry. The graph shows two sets of data points; 1) the data points for the mass of the fluid at charge conditions, and 2) the mass of the fluid at cold conditions. From this graph I can determine which capillary tube nominal diameter will be acceptable. Notice the shaded region is all of the acceptable capillary tube nominal diameters for the chosen capillary tube lengths. As I mentioned at the beginning of the

Figure 7. Bulb Capacity for VPT System at Cold Conditions: 77 K and 1 Bar

Figure 8. VPT Capillary Tube Geometry for Cold Length = 12 in., Warm Length = 18 in.

VPT DESIGN METHODS, I want the mass of the nitrogen at cold conditions to be less than or equal to the mass of the nitrogen at charge conditions. The actual intersection of the two lines containing both sets of data is a little less than a $\frac{1}{4}$ " capillary tube nominal diameter. Therefore, I chose a $\frac{1}{4}$ " nominal diameter capillary tube since the mass of the nitrogen at cold conditions is less than the mass of nitrogen at charge conditions.

To better understand the criterion for the sizing of the capillary tubing, I will discuss what could happen if the mass of the nitrogen used in the system is the mass of the fluid at charge conditions when that mass is greater than the mass at cold conditions. First of all, by using a $\frac{3}{16}$ " nominal diameter capillary tube with the cold length equal to 12" and the warm length equal to 18", we can see from Fig. 8 that the mass of the nitrogen at the charge condition is greater than the mass of nitrogen at the cold condition. This means that 0.1 grams of nitrogen is needed to assure that the charge pressure of 100 psia and the charge temperature of 300 Kelvin is satisfied for the given tubing lengths. The mass for this same $\frac{3}{16}$ " nominal diameter capillary tube is 0.13 grams of nitrogen at the cold condition. That is to say, 0.13 grams of nitrogen are needed to assure that the bulb will be half full at the operating conditions of 14.7 psia and 77 Kelvin.

Since the goal of the VPT design is to have the bulb initially filled half full with liquid nitrogen, the limiting factor is the mass of the nitrogen at the cold condition. If we chose to use the mass of the nitrogen at the charge condition, we would not be able to fill the bulb half full. The mass of the nitrogen at the charge condition is not as crucial as the mass of the nitrogen at the cold condition. Therefore, once I can satisfy the mass of the nitrogen at the cold condition, where the bulb is half filled with liquid, and the mass of the nitrogen at the cold condition is less than the mass of the nitrogen at the charge condition, I have found a solution. Any capillary tube with its nominal diameter inside the shaded region in Fig. 8 is technically acceptable, but I want to conserve tubing material and space so I chose to use a $\frac{1}{4}$ " nominal diameter capillary tube rather than a $\frac{1}{2}$ " nominal diameter capillary tube.

I also decided to make a plot of the normal operating conditions so that the engineers at D-Zero could have some indication of how much liquid is in the bulb. In Figure 9, the performance curve of the VPT system begins at the initial cool down of the

Figure 9. Performance of VPT System Under the Normal Operating Temperature Range

system at 14.7 psia and 77 Kelvin. The final point of the operating range is 49.7 psia and 89 Kelvin. The last point is used because 49.7 psia is the saturation pressure of nitrogen, the highest pressure where liquid still exists. At 49.7 psia, the temperature at which liquid is still present is 89 Kelvin according to the thermodynamic property table for nitrogen. These two points allow me to plot a curve of the percentage of liquid in the bulb. I assume that the curve is linear and this is based on the linearity of the equilibrium curve for nitrogen as was seen in Fig. 4. The percentage of liquid in the bulb by volume may not be exactly linear, but this curve does give an indication of how the percentage of liquid decreases with increased temperature and how the pressure increases when the temperature increases.

I could not define a curve beyond the 49.7 psia at 89 K data point since I can no longer choose a known pressure or temperature until I reach 100 psia at 300 Kelvin. At this pressure and temperature, I do know that the fluid throughout the whole system is gas, but I do not know the nature of the curve between 49.7 psia and 89 K at 100 psia at 300 Kelvin.

VPT DESIGN RECOMMENDATIONS

The amount of nitrogen needed for the VPT system design will be 0.149 grams. I recommend a 12 inch cold capillary tubing length and an 18 inch warm capillary tubing length made of $\frac{1}{4}$ " stainless steel. I also recommend a charge pressure of 100 psia and for this particular design and an expansion of a one foot section along the LN_2 supply line from $\frac{1}{2}$ " x 2" SCH. 10 piping to 1" x 3" SCH. 10 piping near the LN_2 subcooler. The orientation of the $\frac{1}{4}$ " tubing inside and outside the 3" vacuum jacket is not critical, but the length of tubing must be 12 and 18 inches for the cold and warm portions of the design respectively. The table below provides for an easy overview of the design criteria.

Table 2. VPT Design Summary

General Parameters	
Tubing Type	SS 304L
Piping	1" x 3" SCH. 10
Outer Diameter of Tubing	0.25 in.
Wall Thickness of Tubing	0.049 in.
Inside Area of Tubing	0.0185 in. ² (0.1171 cm ²)
Length of Cold Tubing	12.0 in.
Length of Warm Tubing	18.0 in.
Bulb Length	0.625 in.
Volume of Vapor in Bulb	0.28280 cc
Volume of Pressure Gauge	10.0 cc
Charge Conditions	
Temperature	300 K
Charge Pressure	100 psia
Density of Ambient Gas	0.00797555g/cc
Cold Conditions	
Temperature	77 K
Measure Vapor Pressure	14.7 psia
Density of Liquid	0.80853186 g/cc
Density of Cold Gas	0.00461227 g/cc
Density of Warm Gas	0.00113844 g/cc
Liquid Fraction in Bulb	56.15%

APPENDIX A. Nitrogen VPT Program Summary and Procedures

In order to run the program 'nitro.f' the program must first be compiled. Compiling is recommended with the use of the 77 or 90 FORTRAN compiler. The command to compile the program is as follows:

```
f77 -o nitro nitro.f
```

Upon compilation it is recommended that the user write a short UNIX program to help with file maintenance. File maintenance is required because the files that were created with the first run will interfere with the files created by the second run. The following lines are the format that should be used in the maintenance program. First an editing program, such as 'vi' or 'pico' should be used to write a file called 'nit' (note: 'nit' is only an example for a file name and the user may chose any name.) Next, the maintenance program should be edited in this manner:

```
clear;  
rm disp;  
rm out;  
rm out2;  
nitro;
```

After editing is completed, the file 'nit' should be initialized in the following manner. At the UNIX prompt type:

```
chmod u+rw nit
```

To run the program, the user must type "nit" at the prompt. The program used for the design of the nitrogen VPT, which is written by Mariusz Zaczek and Andrew Kuwazaki (D-Zero Mechanical Division, Fermilab), will design the following outputs as described below. First, the Bulb length and diameter will be displayed. Next the program will run the subroutine 'IMPED' and display onto the screen a message stating whether the flow is impeded. The liquid fraction chosen by the designer is then displayed. Then the program runs the subroutine 'volume,' calculating the cold, warm, and total masses and volumes of the system based on the array of inputs it received from the 'in' file. These inputs produce various combinations of warm and cold capillary tubing lengths.

The next display is a display of the liquid and gas densities for the chosen fluid, in the program, we used nitrogen. Also the bulb volume is calculated and displayed. Next, the user is prompted to choose a line from the display which is the users ideal combination of masses and volumes, trying to get the best agreement between the mass at extreme conditions (MASSEX) and the mass at cold conditions (MASSC). After the choice has been made, the program outputs

the selected MASSC and TOTAL VOLUMES. It then calculates and displays a new charge density. This new charge density is then compared to the original charge density (DENEX) obtained from the input file 'in.'

The following procedure is the calculation of the area under the SS 304 curve. This portion of the program involves reading an array of values and performing a trapezoidal calculation for the area. The integrated value is then displayed. The next display is a table which contains eight ranges of temperature values and the corresponding densities. The program uses these temperature ranges and densities to calculate the lengths and masses of the capillary tubing for each range. A total of the individual lengths and masses are then displayed. Next, the total length of the capillary tube is compared to the length of the cold capillary tube chosen earlier in the program. The program then computes the percent difference of these two lengths.

Finally, the program calculates the density of the liquid in the bulb two different ways. After displaying these densities, the program calculates the percent difference. The last calculation involves a check on the liquid fraction in the bulb. This value is displayed and should match the value of 'X' chosen as the percent of liquid in the bulb in the input file 'in.'

This is just a brief summary of how the program operates in an attempt to explain what each output represents. The purpose of this program is to perform numerous iterative processes quickly in order to accommodate various changes made on the system.

Program Nitro

```

*****
***      Program written by Zaczek, Mariusz and Kuwazaki, Andrew ***
***      of the D-zero Mechanical Division of FERMILAB          ***
***      June-July 1996                                         ***
*****
*****

```

```

C-----C
C      The program "Nitro" is written for assistance in the  C
C      design of a liquid nitrogen Vapor Pressure Thermometer, C
C      also known as a VPT.  Some of the equations used in this C
C      program were obtained from the FERMILAB technical memo C
C      TM-1063 1650.00 "DESIGN CONSIDERATIONS IN VAPOR PRESSURE C
C      THERMOMETRY" by Eric Larson in August, 1981.  The values C
C      for the data array are taken from Figure 1 in the C
C      technical memo. C
C      The main body of this program initializes variables, C
C      and it opens the input file called 'in.'  The 'in' file C
C      contains the input that will be used throughout the C
C      program, and allows the programmer/designer easy access C
C      to manipulate various parameters. C
C      After the inputs have been specified, the program C
C      uses these values in subroutines where numerous C
C      operations occur.  The first subroutine, called 'imped,' C
C      is used to determine if the addition of a bulb will C
C      affect the flow of the fluid through the pipe.  The C
C      next subroutine is 'volume.'  'Volume' calculates the C
C      warm, cold, and total volumes of the capillary tube C
C      and bulb.  In addition to the calculated volumes, this C
C      subroutine also calculates the mass of the system. C
C      These values are then exported to a file called 'out.' C
C      From the 'out' file, the charge density is calculated C
C      along with the mass of the capillary tube. C
C      The next step involves the calculation of the C
C      area under the SS304 curve of Thermal conductivity vs C
C      Temperature as seen in Figure 1.  The subroutine C
C      'area' is where the integration of the curve is C
C      performed in the program.  'Area' also determines C
C      the lengths and masses of the capillary tube sections C
C      for various temperature ranges.  The output is once C
C      again written into the 'disp' file along with the C
C      'out2' file.  The 'out2' file is used later in the C
C      program to calculate the total length and mass.  The C
C      data is then used to help check the percent of liquid, C
C      'X,' in the bulb. C
C      The subroutine 'plot' is used next, and its purpose C
C      is to present graphically the SS 304 graph using C
C      the function f(x) which is in the program itself. C
C

```



```

C      Summary of files used in this program      C
C      nitro.f      main program file      C
C      in      input file (listed below)      C
C      disp      output file of entire display      C
C               includes(out,out2,and graph)      C
C      out      output file of masses and volumes      C
C      out2      output file of lengths and temp.range      C
C-----C

```

```

C*****
C      Input file      'in'      *
C      *      *
C      type      Type of Bulb      (1=sphere 2=cylinder) *
C      dpipeo      diameter of old section of pipe      *
C      dpipe      diameter of new section of pipe      *
C               when different from old section      *
C               of pipe      *
C      dtubeV      diameter of capillary tube      *
C      ltubeb      length of capillary tube protruding      *
C               into pipe containing desired      *
C               measurable fluid      *
C      Dbulb or dtubeB      Bulb diameter or cap. tube diameter      *
C      X      quality (amount of liquid in bulb)      *
C      n      number of LC and LW fields      *
C               (used for input of data)      *
C      TEX, PEX      extreme temperature and pressure      *
C               of the system      *
C      TCOLD, PCOLD      cold condition temperature and      *
C               pressure of the system      *
C      DENEX      extreme density at EXTREME PRES.(PEX)      *
C      DENLIQ      density of liq. at COLD PRES.(PCOLD)      *
C      DENGAS      density of gas at COLD PRES. (PCOLD)      *
C      DENGW      density of gas in warm portion of      *
C               tubing operating at the cold      *
C               pressure (PCOLD)      *
C      VGAUGE      volume of gauge      *
C      thick      thickness of capillary tube wall      *
C      LC, LW      length of COLD tubing, length of      *
C               WARM tubing      *
C      LC, LW      *
C      ..      *
C      ..      *
C      parts      number of interval      *
C      TLOW, THIGH, denseI      low and high temperature of interval      *
C      TLOW, THIGH, denseI      *
C      ..      *
C      ..      *
C*****

```

```

implicit none
real dpipeo,dpipe,dtubeV,LC,LW,Dbulb,ltubeB,LC,LW,X
real DENEX,DENLIQ,DENGAS,DENGW,Vbulb,VGAUGE,thick
real PEX,PCOLD,dtubeB,DENSI
real NUM,one,two,three,four,five,six,seven,eight
real select,foive
real f,xmin,xmax,ymin,ymax
external f
integer i,n,type,TEX,TCOLD

C Open file 'in' --this is the input file that will be read.
  open(unit=3,file='in',status='old')

C Open file 'disp'--this is an output file that will contain
C   everything that is displayed onto the screen.
  open(unit=4,file='disp',status='new')

C Open file 'out'--this is an output file that contains a table
C   of the masses and volumes that is needed in later
C   calculations.
  open(unit=7,file='out',status='new')

C*****
C Test if the bulb and capillary tube protrusion into the pipe *
C take up more area than what the pipe had before the pipe *
C expansion was created for the VPT. If the flow area is *
C smaller, with the addition of the VPT, than the original *
C pipe flow area before the expansion, a bottleneck affect at *
C the bulb section may occur. This test will determine if the *
C pipe sizing is adequate. *
C*****
      write(4,*)'          NOTE: BE CONSISTENT WITH THE UNITS.'
      write(4,*)'          PART #1: TEST if flow is impeded.'

C**** (1)for spherical or (2)for cylindrical
      read(3,*) type

C**** Read Original pipe Diameter.
      read(3,*) dpipeo

C**** Read New pipe Diameter.
      read(3,*) dpipe
      read(3,*) dtubeV

C**** Call IMPED subroutine to check the impedance.
      call imped(type,dpipeo,dpipe,dtubeV,Dbulb,ltubeB,dtubeB)

C**** Estimate of the percentage of liquid in the bulb.
      read(3,*) X
      write(4,'(1X,A,F6.2,A)')'          The desired percentage of
& liquid in the bulb is =',X*100.0,'% '
      write(6,'(1X,A,F6.2,A)')'          The desired percentage of
& liquid in the bulb is =',X*100.0,'% '

```

```

C**** Format the display.
  write(6,*)'*****'
  write(4,*)'*****'
  write(4,*)'#      LC   LW   MASSEX   MASSC   MASSW   VC   VW
&      VT   VCCAP'
  write(4,*)'-----'

  write(4,*)'      (inch)(inch) (grams) (grams) (grams)   (cc)   (cc)
&      (cc)   (cc)   '
  write(4,*)'*****'
  write(6,*)'#      LC   LW   MASSEX   MASSC   MASSW   VC   VW
&      VT   VCCAP'
  write(6,*)'-----'

  write(6,*)'      (inch)(inch) (grams) (grams) (grams)   (cc)   (cc)
&      (cc)   (cc)   '
  write(6,*)'*****'

C**** Read other values from the input file--'in'
  read(3,*) n
  read(3,*) TEX,PEX
  read(3,*) TCOLD,PCOLD
  read(3,*) DENEX
  read(3,*) DENLIQ
  read(3,*) DENGAS
  read(3,*) DENGW
  read(3,*) VGAUGE
  read(3,*) thick
  do i=1,n
  read(3,*) LC,LW
  if ((LC.eq.-1) .and. (LW.eq.-1))then
    write(4,*)'-----'

    write(6,*)'-----'
  end if

C**** Call VOLUME subroutine to check volumes,masses and density of
C**** selected choice.
  call volume(i,type,LC,LW,Dbulb,dtubeV,1tubeB,X,DENEX,DENLIQ,
&DENGAS,DENGW,Vbulb,VGAUGE,thick,dtubeB)
  end do

C**** Display results.
  write(6,*)'*****'
  write(4,*)'*****'
  write(6, '(1X,A,F8.5,A,F8.5,A,F8.5,A)') 'DENEX =',DENEX,
&' g/cc DENLIQ =',DENLIQ,' g/cc DENGAS =',DENGAS,' g/cc'
  write(4, '(1X,A,F8.5,A,F8.5,A,F8.5,A)') 'DENEX =',DENEX,
&' g/cc DENLIQ =',DENLIQ,' g/cc DENGAS =',DENGAS,' g/cc'
  write(4, '(1X,A,F8.5,A,F8.5,A)') 'DENGW =',DENGW,
&' g/cc BULB Volume =',Vbulb,' cc'
  write(6, '(1X,A,F8.5,A,F8.5,A)') 'DENGW =',DENGW,
&' g/cc BULB Volume =',Vbulb,' cc'

```

```

write(6,*)'#####'
write(4,*)'#####'

C**** Prompt user to choose desired data configuration for analysis
C**** output.
write(6,*) 'Select your line of choice for further
&calculations.'
read(5,*) select
do while (select.gt.n)
    write(6,*) 'SELECT a number within the range.'
    read(5,*) select
end do
close(7)

C**** Open file 'out' in order to more efficiently calculate
C**** the density by prompting the user for a line choice
C**** from the given display.
open(unit=8,file='out',status='old')

C**** Read from the file 'old' the values displayed in the output.
read(8,*) NUM,one,two,three,four,foive,five,six,seven,eight
do while (NUM.ne.select)
read(8,*) NUM,one,two,three,four,foive,five,six,seven,eight
end do
if (one.eq.-1) then
    write(6,*) 'The values you chose is incorrect..try again'
    pause
end if

C**** Calculate the charge density.
write(6, '(1X,A,F8.3,A,F8.3,A)') ' MASS =',three,
&' g VOLUME =',seven,' cc'
write(4, '(1X,A,F8.3,A,F8.3,A)') ' MASS =',three,
&' g VOLUME =',seven,' cc'
DENSI=three/seven
write(6, '(1X,A,F8.6,A)') ' THE NEW CHARGE DENSITY IS = '
&,DENSI,' g/cc'
write(4, '(1X,A,F8.6,A)') ' THE NEW CHARGE DENSITY IS = '
&,DENSI,' g/cc'

C**** Call AREA subroutine in order to determine the area under
C**** the Stainless Steel 304 curve (Fig. 1), to be used in the thermal
C**** conductivity calculations.
open(unit=9,file='out2',status='new')
call area(TCOLD,TEX,one,dtubeV,thick,three,four,foive,
*five,Vbulb,DENLIQ,DENGAS)

C**** The min and max values of the graph for SS 304.
C**** (these values are the extremes of the graph)
xmin=0.0
ymin=0.0
xmax=300.0
ymax=0.165

```

```

C**** Call subroutine plot to graph the SS 304 points.
      call plot(f,xmin,xmax,ymin,ymax)

C**** Close the "open" statements and end the file.
      close(3)
      close(4)
      close(8)
      close(9)
      end

C*****
C      Subroutine IMPED ==> TO TEST IF FLOW IS IMPEDED      *
C*****
      subroutine imped(type,dpipeo,dpipe,dtubeV,Dbulb,ltubeB,dtubeB)
      real Dbulb,dtubeV,ltubeB,dpipeo,dpipe,Abt,Aold,Anew,Area
      real PI,dtubeB
      integer type
      parameter (PI=3.141592654)

C**** Length of capillary tube protruding into the pipe.
      read(3,*) ltubeB
      write(4,*) '      BULB length =',ltubeB,' in'
      write(6,*) '      BULB length =',ltubeB,' in'

C**** Total Area taken up by bulb and tube protrusion.
C**** Determine area of bulb and tube based on choice of bulb
C**** configuration (i.e. either spherical(1) or cylindrical(2)).
      if (type.eq.1) then

C**** Program reads bulb diameter from the input file for spherical
C**** bulb.
          read(3,*) Dbulb
          Abt=(PI*((Dbulb/2.0)**2.0))+((dtubeV)*(ltubeB))
          write(4,*) ' BULB DIAMETER =',Dbulb,' in'
          write(6,*) ' BULB DIAMETER =',Dbulb,' in'
      else if (type.eq.2) then

C**** Program reads tube diameter from the input file cylindrical
C**** bulb.
          read(3,*) dtubeB
          Abt=dtubeB*ltubeB
          write(4,*) ' BULB Diameter =',dtubeB,' in'
          write(6,*) ' BULB Diameter =',dtubeB,' in'
      else
          pause
      end if

C**** Area of original pipe.
      Aold=(PI*((dpipeo/2.0)**2.0))

C**** Area of new section of pipe.
      Anew=(PI*((dpipe/2.0)**2.0))

```

```

C**** Area remaining to flow when bulb is present.
      Area=Anew-Abt

C**** Determine if impedance occurs.
      if (Area.ge.Aold) then
        write(4,*) ' There is no impedance of flow.'
        write(6,*) '       There is no impedance of flow.'
      else
        write(4,*) '*****WARNING: THE FLOW IS IMPEDED.*****'
        write(6,*) '*****WARNING: THE FLOW IS IMPEDED.*****'
        pause
      end if
    end

C*****
C      Subroutine VOLUME ==> determine volumes and masses      *
C*****
      subroutine volume(i,type,LC,LW,Dbulb,dtubeV,ltubeB,X,DENEX,
&DENLIQ,DENGAS,DENGW,Vbulb,VGAUGE,thick,dtubeB)
      real LC,LW,Dbulb,dtubeV,ltubeB,Vbulb,VCCAP,VC,VW,VT,Vball
      real MASSEX,DENEX,DENLIQ,DENGAS,DENGW,MASSC,VGAUGE,PI,thick
      real dtubeB,MASW
      integer type,i
      parameter (PI=3.141592654)

C**** Volume of cold portion inside pipe.
C**** Determine volumes based on choice of bulb configuration.
C**** (1)spherical or (2)cylindrical
      if (type.eq.1) then
        Vball=(4.0/3.0)*PI*((Dbulb/2.0)**3.0)*(2.54**3.0)
        Vbulb=Vball+((PI*((dtubeV/2.0)**2.0)*ltubeB)*
&(2.54**3.0))
      else if (type.eq.2) then
        Vbulb=(PI*((dtubeB/2.0)**2.0)*ltubeB)*(2.54**3.0)
      else
        pause
      end if

C**** Volume of the cold portion of the capillary tube.
      VCCAP=PI*((dtubeV/2.0)-thick)**2.0*LC*(2.54**3.0)

C**** Total cold volume.
      VC=Vbulb+VCCAP

C**** Total warm volume.
      VW=(PI*((dtubeV/2.0)-thick)**2.0)*LW*(2.54**3.0)

C**** TOTAL OVERALL VOLUME.
      VT=VC+VW+VGAUGE

C**** Evaluate mass at extreme conditions.
      MASSEX=DENEX*VT

```

```

C**** WARM MASS
      MASSW=(VW+VGAUGE)*DENGW

C**** MASS AT COLD CONDITIONS.
      MASSC=(DENLIQ*Vbulb*X)+((DENGAS)*(((1-X)*(Vbulb))+VCCAP))+
      & (DENGW*(VW+VGAUGE))

C**** Display in column form the masses and volumes for the
C**** corresponding warm and cold lengths.
      write(4,15) i,LC,LW,MASSEX,MASSC,MASSW,VC,VW,VT,VCCAP
      write(6,15) i,LC,LW,MASSEX,MASSC,MASSW,VC,VW,VT,VCCAP
      write(7,16) i,LC,LW,MASSEX,MASSC,MASSW,VC,VW,VT,VCCAP
15 format(1X,I2,' ',2F6.1,3F8.3,4F8.3,)
16 format(1X,I2,2F6.1,3F9.3,4F8.3,)
      end

C*****
C      subroutine AREA
C*****
      subroutine area(TCOLD,TEX,one,dtubeV,thick,MASSEX,
&MASSC,MASSW,VC,Vbulb,DENLIQ,DENGAS)
      real Carea,Careao,base,baseor,y,inter,one,lambda
      real diff,Li,LWtot,denseI,dtubeV,thick,CAPar,PI
      real Licm,Mi,Mcap,LcmTOT,dcold,dcold1,MASSW,VC
      real MASSC,MASSEX,X1,X2,X3,X4
      real F,VGAS,VLIQ,X5,DENL
      integer TLaa,THaa
      integer TCOLD,TEX,TCINT,TEINT,TLOW,THIGH
      parameter (PI=3.141592654)
      dimension array(2,202)

C**** Data array for the SS 304 curve. Points are interpolated
C**** from the curve in Figure 1.
      data array/0.0,0,.001,1,.001875,2,.00375,3,.005,4,.00625,5,.00875,
&6,.01,7,.0125,8,.01375,9,.0165,10,.018,11,.0195,12,.021,13,.0225,
&14,.0255,15,.027,16,.0285,17,.03,18,.0315,19,.033,20,.0345,21,
&.036,22,.0375,23,.039,24,.0405,25,.042,26,.0435,27,.045,28,
&.0465,29,.048,30,.0495,31,.051,32,.0525,33,.054,34,.0555,35,
&.057,36,.0585,37,.06,38,.0615,39,.063,40,.0645,41,.066,42,
&.0675,43,.069,44,.0705,45,.072,46,.0735,47,.075,48,.0765,49,
&.078,50,.07875,51,.08025,52,.081,53,.0825,54,.08325,55,.084,56,
&.0855,57,.08625,58,.08775,59,.0885,60,.08925,61,.089625,62,.09,63,
&.09075,64,.09225,65,.09375,66,.0945,67,.09525,68,.096,69,
&.09675,70,.0975,71,.09825,72,.099,73,.09975,74,.1005,75,.10125,
&.102,76,.10275,77,.1035,78,.10425,79,.104625,80,.1048,81,.1048,82,
&.105,83,.10575,84,.10625,85,.106875,86,.10725,87,.108,88,.10875,
&.109125,89,.109875,91,.110625,92,.11175,93,.11215,94,.1123,
&.1125,95,.113,97,.1135,98,.114,99,.11475,100,.1155,101,.1157,
&.1159,103,.1160,104,.1165,105,.117,106,.1175,107,.1180,108,
&.1185,109,.1190,110,.1195,111,.12,112,.1204,113,.1204,114,.1208,
&.1215,.1213,116,.1218,117,.1222,118,.1226,119,.1231,120,.1235,121,
&.1240,122,.1244,123,.1249,124,.1253,125,.1257,126,.1262,127,.1266,
&.128,.1271,129,.1275,130,.1279,131,.1283,132,.1287,133,.1291,134,

```

```

*.1295,135,.1298,136,.1303,137,.1307,138,.1311,139,.1314,140,.1318,
*.141,.1322,142,.1326,143,.133,144,.1334,145,.1338,146,.1342,147,
*.1346,148,.135,149,.1353,150,.1357,151,.1360,152,.1364,153,.1367,
*.154,.1370,155,.1375,156,.1377,157,.1381,158,.1384,159,.1387,160,
*.1391,161,.1394,162,.1398,163,.140,163,.1405,165,.1408,166,.1411,
*.167,.1415,168,.1418,169,.1422,170,.1425,171,.1428,172,.1431,173,
*.1434,174,.1437,175,.1440,176,.1443,177,.1446,178,.1449,179,.1452,
*.180,.1455,181,.1458,182,.1461,183,.1464,184,.1467,185,.147,186,
*.1473,187,.1476,188,.1479,189,.1482,190,.1485,191,.1488,192,.1491,
*.193,.1494,194,.1497,195,.150,196,.1503,197,.1506,198,.1509,199,
*.1513,200,.1516,201/

C**** Initialize area under the curve.
      Careao=0.0

C**** "inter" is the spacing chosen as the height in calculating the
C**** area of a trapezoid.
      inter=1.5
      TCINT=(TCOLD/inter)+2
      TEINT=(TEX/inter)+2

C**** One base of the trapezoidal segments.
      baseor=array(1,TCINT)

C**** Begin DO loop to determine the area under the SS 304 curve.
      do y=TCINT+1,TEINT

C**** The second base of the trapezoidal segments.
          base=array(1,y)

C**** "Carea" is the trapezoidal area of individual segments which
C**** make up the total area under the curve in Figure 1.
          Carea=(inter/2.0)*(baseor+base)
          Careao=Careao+Carea
          baseor=base
        end do

        write(6,*)'.....',
        write(4,*)'.....'

C**** Display area under the curve for the given boundary values of
C**** TCINT(minimum) and TEINT(maximum).
        write(6,'(1X,A,I2,A,I3,A)')' AREA under the SS 304 curve
&between ',TCOLD,' and ',TEX,' Kelvin'
        write(6,*)' is equal to =',Careao,' mW/cm'
        write(4,'(1X,A,I2,A,I3,A)')' AREA under the SS 304 curve
&between ',TCOLD,' and ',TEX,' Kelvin'
        write(4,*)' is equal to =',Careao,' mW/cm'

C**** Read from input file the number of intervals to be used.
      read(3,*) parts

```



```

C**** Begin looping to calculate lambda-i's.
  LWtot=0.0
  write(6,*)'-----'
  write(4,*)'-----'
  write(6,*)'TEMP range(K)      Density(g/cc)      Li (inch & cm)
&      Mi(g)      '
  write(4,*)'TEMP range(K)      Density(g/cc)      Li (inch & cm)
&      Mi(g)      '
  write(6,*)'-----'
  write(4,*)'-----'

C**** The cross-sectional area of the capillary tube.
  CAPar=((PI*((dtubeV/2.0)-thick)**2.0))*(2.54**2.0)
  LcmTOT=0.0
  Mcap=0.0

C**** Beginning of the loop used to determine the mass of the
C**** capillary tube.
  do j=1,parts
    TLOW=0
    THIGH=0
    TLaa=0
    THaa=0
    lambda=0.0
    diff=0.0

C**** TLOW and THIGH should be multiples of 1.5 because
C**** the array spacing is 1.5 K units.
    read(3,*) TLOW,THIGH,denseI
    TLaa=(TLOW/inter)+2
    THaa=(THIGH/inter)+2

C**** The thermal conductivity of SS 304 over segment 'i'
    lambda=(array(1,TLaa)+array(1,THaa))/2.0
    diff=THIGH-TLOW

C**** 'Li' is the length of segments that make up the total
C**** length of the cold capillary tube.
    Li=(lambda*one*diff)/Careao
    Licm=Li*2.54
    Mi=Licm*CAPar*denseI

C**** Mass of capillary tube.
    Mcap=Mcap+Mi
    LWtot=LWtot+Li
    LcmTOT=LcmTOT+Licm

C**** Display temperature range, density and length calculations
C**** in tabular form.
    write(6,100)TLOW,THIGH,denseI,Li,Licm,Mi
    write(4,100)TLOW,THIGH,denseI,Li,Licm,Mi
    write(9,*)TLOW,THIGH,denseI,Li,Licm,Mi
100    format(1X,I4,' - ',I4,F18.5,F12.3,F11.3,F13.6)
    end do

```

```

        write(6,*)'-----'
        write(6, '(1X,A,F12.3,F11.3,F13.6)')
&'TOTALS                                ',LWtot,LcmTOT,Mcap
        write(4,*)'-----'
        write(4, '(1X,A,F12.3,F11.3,F13.6)')
&'TOTALS                                ',LWtot,LcmTOT,Mcap
        write(6,*)'-----'
        write(4,*)'-----'

C**** The total length of the capillary tube.
        write(6,*)'The total length of the capillary tube from the
* vacuum jacket to'
        write(6, '(1X,A,F5.2,A,F5.2,A)')'the gauge should be ',one,
*' inches but it is actually ',LWtot,' inches'
        write(6, '(1X,A,F8.5,A)')'Percent difference =',
*(abs(one-LWtot)/one)*100,' %'
        write(4,*)'The total length of the capillary tube from the
* vacuum jacket to'
        write(4, '(1X,A,F5.2,A,F5.2,A)')'the gauge should be ',one,
*' inches but it is actually ',LWtot,' inches'
        write(4, '(1X,A,F8.5,A)')'Percent difference =',
*(abs(one-LWtot)/one)*100,' %'

C**** Check of Percent difference. If difference if greater than
C**** about 2% than the user must check his/her values for
C**** for any possible errors.
        if (((abs(one-LWtot)/one)*100) .le. 2) then
            write(6,*)'Since the percent difference is below
* the 2% limit we are able to'
            write(6,*)' assume the analysis is correct.'
            write(4,*)'Since the percent difference is below
* the 2% limit we are able to'
            write(4,*)' assume the analysis is correct.'
        else
            write(6,*)'ERROR--CHECK your values and inputs for
* possible errors.'
            write(4,*)'ERROR--CHECK your values and inputs for
* possible errors.'
        end if

C*****
C This section of the program is used to check the methods for *
C determining the density in the cold bulb. The densities are *
C found two different ways and this check provides reassurance *
C for an accurate design. The first density equation *
C  $dcold = (MASSEX - MASSW - Mcap) / Vbulb$  is calculated based on the *
C maximum allowable mass, subtracted from the warm mass which in *
C turn is the cold mass and when divided by its volume yields *
C the density. The second equation  $dcold1 = (MASSC - Mcap) / Vbulb$  is *
C an alternate approach involving strictly the cold mass and its *
C volume yielding yet another density. These two densities are *
C expected to be nearly equal and thus confirming the mass of *
C the liquid needed in the VPT. *
C*****

```

```

C**** Check the percentage of liquid in the bulb.
C**** X1
      X1=((MASSEX-(MASSW+Mcap))-(Vbulb*DENGAS))/
      &(Vbulb*(DENLIQ-DENGAS))

C**** X2
      X2=((MASSEX-MASSW-Mcap)/DENLIQ)/Vbulb

C**** Density in the cold bulb.
      dcold1=(MASSC-MASSW-Mcap)/(Vbulb)
      dcold=(MASSEX-MASSW-Mcap)/(Vbulb)

C**** X4
      X4=(dcold1-DENGAS)/(DENLIQ-DENGAS)

C**** X3
      X3=(dcold-DENGAS)/(DENLIQ-DENGAS)

C**** X5
      F=MASSEX-MASSW-Mcap
      VGAS=((F/DENLIQ)-Vbulb)/((DENGAS/DENLIQ)-1)
      VLIQ=Vbulb-VGAS

      WRITE(6,*)'Volume of Liquid   =',VLIQ
      Write(6,*)'Volume of Gas      =',VGAS
      write(6,*)'Total Volume       =',VLIQ+VGAS

      X5=(VLIQ)/(VLIQ+VGAS)
      DENL=(F-(DENGAS*VGAS))/VLIQ
      write(6, '(1X,A,F8.6,A)') 'The density of the liquid is = ',
      &DENL, ' g/cc'

C**** Display the various percent liquids.
      write(6,*)'The Percent of liquid in the bulb is=====>'
      write(6,*)'          X1          X2          X3
      &X4          X5'
      write(6, '(1X,5F13.2)') X1*100.0,X2*100.0,X3*100.0,
      &X4*100.0,X5*100.0
      write(4,*)'The Percent of liquid in the bulb is=====>'
      write(4,*)'          X1          X2          X3
      &X4          X5'
      write(4, '(1X,5F13.2)') X1*100.0,X2*100.0,X3*100.0,
      &X4*100.0,X5*100.0

C**** DISPLAY results.
      write(6, '(1X,A,F8.6,A)') '      Method #1: DENSITY
      &in the bulb is =',dcold, ' g/cc'
      write(6, '(1X,A,F8.6,A)') '      Method #2: DENSITY
      &in the bulb is =',dcold1, ' g/cc'
      write(6, '(1X,A,F6.2,A)') 'The percent difference is =',
      &(abs(dcold1-dcold)/dcold)*100, ' for the two densities.'
      write(4, '(1X,A,F8.6,A)') '      Method #1: DENSITY in the
      &bulb is =',dcold, ' g/cc'

```

```

        write(4, '(1X,A,F8.6,A)') '    Method #2: DENSITY in the
& bulb is =',dcold1,' g/cc'
        write(4, '(1X,A,F6.2,A)') 'The percent difference is =',
&(abs(dcold1-dcold)/dcold)*100,' for the two densities.'
        end
C*****
C          FUNCTION      F(x)                                *
C*****
C**** Function whose graph is to be plotted
        function f(x)
        real x,f

C**** The equation was obtained with the use of a spread-sheet
C    utility called 'Cricket Graph'
        f=(-4.5461E-3)+(x*1.4648E-3)-((x**2.0)*6.0447E-6)+
&((x**3.0)*1.1644E-8)-((x**4.0)*6.5387E-12)
        end

C*****
C          SUBROUTINE PLOT                                    *
C*****
C    This program was taken from 'FORTRAN 77 for Engineers    *
C    and Scientists' by Larry Nyhoff and Sanford Leestma.    *
C    Chapter 10.4 p. 478-480 "Program Graph"                  *
C*****

        subroutine plot(f,xmin,xmax,ymin,ymax)
        real f,xmin,xmax,ymin,ymax,delx,dely,x,y
        integer hlimit,vlimit,xloc,yloc,count
        parameter (hlimit=70, vlimit=20)
        character*1 window(0: hlimit, 0:vlimit), symbol
        parameter (symbol='*')

C**** Display graph in 'disp' file
        write(4,*)
        write(4,*)'-----'
        write(4,*) '          FIGURE 1 : Graph of Thermal Conductivity
&of SS 304 vs. Temperature(K)'
        write(4,*)'-----'
        delx=(xmax-xmin)/real(hlimit)
        dely=(ymax-ymin)/real(vlimit)
        do 20 yloc=0,vlimit
        do 10 xloc=0,hlimit
            window(xloc,yloc)= ' '
10      continue
20      continue

C**** Turn on points in window corresponding to points on graph.
        x=xmin
        do 30 xloc=0,hlimit
            y=f(x)
            if(y.ge.ymin .and. y.le.ymax) then
                yloc=nint((y-ymin)/dely)
                window(xloc,yloc)=symbol
            end if
        end do
    
```

```
        end if
        x=x+delx
30      continue

C**** Draw the Window in the file together with labeled y-axis.
        y=ymax
        count=5*(vlimit/5)
        do 40 yloc=vlimit,0,-1
          if (mod(count,5).eq.0) then
            write(4,100) y,(window(xloc,yloc),xloc=0,hlimit)
100         format(1X,F8.2,':',200A)
          else
            write(4,101) (window(xloc,yloc), xloc=0,hlimit)
101         format(9X,':',200A)
          end if
          count=count-1
          y=y-dely
40      continue

C**** Draw a labeled x-axis in the file.
        write(4,102) ,(' ',xloc=0,hlimit)
102     format(9X,200A)
        write(4,103) (xmin+xloc*delx,xloc=0,hlimit,10)
103     format(3X,50F10.3)
        end
```

'in'

2	type [--]	Type of bulb (1=sphere 2=cylinder)
0.5	dpipeo [in]	Diameter of old section of pipe
1.0	dpipe [in]	Diameter of new section of pipe
0.25	dtubeV [in]	Diameter of capillary tube
0.625	ltubeB [in]	Length of capillary protruding in pipe
0.1875	Dbulb or dtubeB[in]	Bulb diameter or cap.tube diameter
0.5	X [--]	Liquid fraction(% of liquid in bulb)
23	n [--]	# of LC and LW fields below
300 7	TEX, PEX [K] [atm]	Extreme temperature and pressure
77 1	TCOLD, PCOLD[K] [atm]	Cold temperature and pressure
0.00797555	DENEX [g/cc]	Extreme density at extreme pressure
0.80853186	DENLIQ [g/cc]	Density of liquid at cold pressure
0.00461227	DENGAS [g/cc]	Density of gas at cold pressure
0.00113844	DENGW [g/cc]	Density of gas in war portion of cap.
10.0	VGAUGE [cc]	Volume of gauge
0.049	thick [in]	Thickness of capillary tube wall
2.0 60.0	LC, LW [in] [in]	lengths of cold and warm portions of
3.0 60.0		capillary tubing
4.0 60.0		(# of fields is dependent on 'n' above)
5.0 45.0		(note: -1 -1 -1 fields are read by the
5.0 30.0		program as dividers)
5.0 15.0		
6.0 6.0		
6.0 12.0		
6.0 18.0		
6.0 24.0		
6.0 30.0		
6.0 36.0		
-1 -1 -1		
12.0 6.0		
12.0 12.0		
12.0 18.0		
12.0 24.0		
12.0 30.0		
12.0 36.0		
-1 -1 -1		
24.0 6.0		
24.0 12.0		
24.0 18.0		
8	parts [--]	Number of Intervals
78 90 0.004234805	TLOW, THIGH, denseI	low and high temperatures of interval
90 102 0.00365586	[K] [K] [g/cc]	and density at these temps.
102 111 0.00326689		
111 120 0.003000515		
120 150 0.002584385		
150 201 0.001996273		
201 249 0.001537626		
249 300 0.001255508		

(NOTE: THE COMMENTS LISTED ON THE RIGHT HAND SIDE OF THIS PAGE ALONG WITH THE TITLE ARE TOO BE OMITTED IN THE ACTUAL INPUT FILE)

'disp'

NOTE: BE CONSISTENT WITH THE UNITS.

PART #1: TEST if flow is impeded.

BULB length = 0.625000 in

BULB Diameter = 0.187500 in

There is no impedance of flow.

The desired percentage of liquid in the bulb is = 50.00%

#	LC	LW	MASSEX	MASSC	MASSW	VC	VW	VT	VCCAP
	(inch)	(inch)	(grams)	(grams)	(grams)	(cc)	(cc)	(cc)	(cc)
1)	2.0	60.0	0.229	0.149	0.032	0.878	17.841	28.719	0.595
2)	3.0	60.0	0.231	0.151	0.032	1.175	17.841	29.016	0.892
3)	4.0	60.0	0.234	0.152	0.032	1.472	17.841	29.314	1.189
4)	5.0	45.0	0.201	0.148	0.027	1.770	13.381	25.151	1.487
5)	5.0	30.0	0.165	0.143	0.022	1.770	8.921	20.690	1.487
6)	5.0	15.0	0.129	0.138	0.016	1.770	4.460	16.230	1.487
7)	6.0	6.0	0.110	0.137	0.013	2.067	1.784	13.851	1.784
8)	6.0	12.0	0.125	0.139	0.015	2.067	3.568	15.635	1.784
9)	6.0	18.0	0.139	0.141	0.017	2.067	5.352	17.419	1.784
10)	6.0	24.0	0.153	0.143	0.020	2.067	7.137	19.204	1.784
11)	6.0	30.0	0.167	0.145	0.022	2.067	8.921	20.988	1.784
12)	6.0	36.0	0.182	0.147	0.024	2.067	10.705	22.772	1.784
13)	-1.0	-1.0	0.077	0.125	0.011	-0.015	-0.297	9.688	-0.297
14)	12.0	6.0	0.125	0.145	0.013	3.851	1.784	15.635	3.568
15)	12.0	12.0	0.139	0.147	0.015	3.851	3.568	17.419	3.568
16)	12.0	18.0	0.153	0.149	0.017	3.851	5.352	19.204	3.568
17)	12.0	24.0	0.167	0.151	0.020	3.851	7.137	20.988	3.568
18)	12.0	30.0	0.182	0.153	0.022	3.851	8.921	22.772	3.568
19)	12.0	36.0	0.196	0.155	0.024	3.851	10.705	24.556	3.568
20)	-1.0	-1.0	0.077	0.125	0.011	-0.015	-0.297	9.688	-0.297
21)	24.0	6.0	0.153	0.161	0.013	7.419	1.784	19.204	7.137
22)	24.0	12.0	0.167	0.163	0.015	7.419	3.568	20.988	7.137
23)	24.0	18.0	0.182	0.165	0.017	7.419	5.352	22.772	7.137

*****
DENEX = 0.00798 g/cc DENLIQ = 0.80853 g/cc DENGAS = 0.00461 g/cc
DENGW = 0.00114 g/cc BULB Volume = 0.28280 cc
*****
MASS = 0.153 g VOLUME = 19.204 cc
THE NEW CHARGE DENSITY IS = 0.007967 g/cc

AREA under the SS 304 curve between 77 and 300 Kelvin
is equal to = 27.5640 mW/cm

TEMP range(K)	Density(g/cc)	Li (inch & cm)		Mi (g)
78 - 90	0.00423	0.445	1.130	0.000560
90 - 102	0.00366	0.484	1.229	0.000526
102 - 111	0.00327	0.385	0.978	0.000374
111 - 120	0.00300	0.402	1.021	0.000359
120 - 150	0.00258	1.437	3.651	0.001105
150 - 201	0.00200	2.720	6.908	0.001615
201 - 249	0.00154	2.827	7.181	0.001293
249 - 300	0.00126	3.249	8.253	0.001213
TOTALS		11.949	30.352	0.007044

The total length of the capillary tube from the vacuum jacket to the gauge should be 12.00 inches but it is actually 11.95 inches
Percent difference = 0.42119 %

Since the percent difference is below the 2% limit we are able to assume the analysis is correct.

The Percent of liquid in the bulb is=====>

X1	X2	X3	X4	X5
56.15	56.40	56.15	54.39	56.15

Method #1: DENSITY in the bulb is =0.456005 g/cc

Method #2: DENSITY in the bulb is =0.441860 g/cc

The percent difference is = 3.10 for the two densities.

FIGURE 1 : Graph of Thermal Conductivity of SS 304 vs. Temperature(K)

'out'									
#	LC	LW	MASSEX	MASSC	MASSW	VC	VW	VT	VCCAP
	(inch)	(inch)	(grams)	(grams)	(grams)	(cc)	(cc)	(cc)	(cc)
1	2.0	60.0	0.229	0.149	0.032	0.878	17.841	28.719	0.595
2	3.0	60.0	0.231	0.151	0.032	1.175	17.841	29.016	0.892
3	4.0	60.0	0.234	0.152	0.032	1.472	17.841	29.314	1.189
4	5.0	45.0	0.201	0.148	0.027	1.770	13.381	25.151	1.487
5	5.0	30.0	0.165	0.143	0.022	1.770	8.921	20.690	1.487
6	5.0	15.0	0.129	0.138	0.016	1.770	4.460	16.230	1.487
7	6.0	6.0	0.110	0.137	0.013	2.067	1.784	13.851	1.784
8	6.0	12.0	0.125	0.139	0.015	2.067	3.568	15.635	1.784
9	6.0	18.0	0.139	0.141	0.017	2.067	5.352	17.419	1.784
10	6.0	24.0	0.153	0.143	0.020	2.067	7.137	19.204	1.784
11	6.0	30.0	0.167	0.145	0.022	2.067	8.921	20.988	1.784
12	6.0	36.0	0.182	0.147	0.024	2.067	10.705	22.772	1.784
13	-1.0	-1.0	0.077	0.125	0.011	-0.015	-0.297	9.688	-0.297
14	12.0	6.0	0.125	0.145	0.013	3.851	1.784	15.635	3.568
15	12.0	12.0	0.139	0.147	0.015	3.851	3.568	17.419	3.568
16	12.0	18.0	0.153	0.149	0.017	3.851	5.352	19.204	3.568
17	12.0	24.0	0.167	0.151	0.020	3.851	7.137	20.988	3.568
18	12.0	30.0	0.182	0.153	0.022	3.851	8.921	22.772	3.568
19	12.0	36.0	0.196	0.155	0.024	3.851	10.705	24.556	3.568
20	-1.0	-1.0	0.077	0.125	0.011	-0.015	-0.297	9.688	-0.297
21	24.0	6.0	0.153	0.161	0.013	7.419	1.784	19.204	7.137
22	24.0	12.0	0.167	0.163	0.015	7.419	3.568	20.988	7.137
23	24.0	18.0	0.182	0.165	0.017	7.419	5.352	22.772	7.137

'out2'

TEMP	RANGE(K)	DENSITY(g/cc)	Li(inches & cm)	Mi(g)	
78	90	4.23480E-03	0.444710	1.12956	5.60000E-04
90	102	3.65586E-03	0.483891	1.22908	5.26036E-04
102	111	3.26689E-03	0.384958	0.977794	3.73961E-04
111	120	3.00052E-03	0.401855	1.02071	3.58545E-04
120	150	2.58438E-03	1.43747	3.65118	1.10468E-03
150	201	1.99627E-03	2.71985	6.90842	1.61452E-03
201	249	1.53763E-03	2.82734	7.18143	1.29273E-03
249	300	1.25551E-03	3.24939	8.25344	1.21311E-03

APPENDIX B: Volume Calculations

Volume of Bulb

Bulb Diameter: 0.1875 in.

Length of Bulb: 0.625 in.

$$V_B = \pi \left(\frac{D_B}{2} \right)^2 L_B = \pi \left(\frac{0.1875}{2} \right)^2 0.625 = 1.72573 \text{ E} - 2 \text{ in}^3$$

Conversion from inches to centimeters:

$$V_B = 1.72573 \text{ E} - 2 \text{ in}^3 \left(\frac{2.54 \text{ in}}{1 \text{ cm}} \right)^3 = 0.28280 \text{ cm}^3 (\text{cc})$$

Volume of Capillary Tube

Tube Diameter (D_T): $\frac{1}{4}$ "

Tube Wall Thickness (t): 0.049 in.

L_C : 12 in.

$$V_{CAP} = \pi \left(\frac{D_T}{2} - t \right)^2 L_C = \pi \left(\frac{0.25}{2} - 0.049 \right)^2 12 = 0.21775 \text{ in}^3$$

Conversion from inches to centimeters:

$$V_{CAP} = 0.21775 \text{ in}^3 \left(\frac{2.54 \text{ in}}{1 \text{ cm}} \right)^3 = 3.5683 \text{ cm}^3 (\text{cc})$$

Volume of Cold Portion of VPT System

$$V_C = V_B + V_{CAP} = 0.28280 \text{ cc} + 3.5683 \text{ cc} = 3.851 \text{ cc}$$

Volume of Warm Portion of VPT System

Tube Diameter (D_T): $\frac{1}{4}$ "

Tube Wall Thickness (t):   0.049 in.

L_w :   18 in.

$$V_w = \pi \left(\frac{D_T}{2} - t \right)^2 L_w = \pi \left(\frac{0.25}{2} - 0.049 \right)^2 18 = 0.326625 \text{ in}^3$$

Conversion from inches to centimeters:

$$V_w = 0.326625 \text{ in}^3 \left(\frac{2.54 \text{ in}}{1 \text{ cm}} \right)^3 = 5.352 \text{ cm}^3 (\text{cc})$$

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