Fermilab

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FORCED FLOW HEAT LOAD MEASUREMENTS

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Technique

To measure the heat load of a long system of lines and magnets, one cannot measure the boil-off in a nonflow condition. Local hot spots would develop, causing a change in the heat leak distribution between the shield and 4.5°K loops. Also, operating the shield at low flow rates can cause a 5°K increase in the shield temperature due to decreases in film coefficients, since they are proportional to velocity to the .8 power. One could pump helium around the loop and subtract the pump work and the dewar heat leak from the boil-off; this is not a practical approach for us, due to limited refrigeration.

We chose the approach of measuring flow and changes in enthalpy. To measure the flow in the 4.5°K loop we installed a venturi calibrated to .5%,while in the shield we have a 10% orifice. In both the venturi and the orifice the flow is proportional to the square root of the product of density and pressure change. The temperature is measured with vapor pressure thermometers (VPT) which consist of a partially full bulb of liquid which is connected to an absolute pressure gauge. Helium is used to read below 5.2°K while H_2 can cover the 12 to 33°K range. The accuracy of a VPT is very sensitive to how it is installed as well as the accuracy of the gauge. The accuracy of the helium VPT's is better than .01°K, but it can easily be off by .1°K if there is a very small heat leak near the VPT.

Since it is very difficult to measure the quality of a 2Ø fluid, one does not know its enthalpy. Therefore, we have 3 modes of measuring which are listed below with their operating limits:

Mode	Tin °K	Pin atm	Hin J/g	Tout °K	Pout atm	Hout J/g	ΔH J/g
Subcooled Liquid	4.5	2.1	11.22	5.0	2.0	15.16	3.94
Liquid to Gas	4.764	1.6	13.10	4.602	1.4	29.57	16.47
Cold Gas	5.1	2.0	28.36	5.1	1.4	34.52	6.16

It is clear that the liquid to gas mode gives the greatest joules per gram; in fact one can gain another 4.95 J/g by letting the output temperature climb to 5.1°K. Its major drawback, however, is that it does not permit the measurement of the individual components in a loop. For this measurement mode one does not need very accurate VPT's since the energy change is due to liquid gas transformation. The inaccuracy in this mode is solely due to the ability to read the differential pressure of the venturi, since the reading is equal to the mass flow rate squared, divided by the density. If one uses the same venturi for a variety of measurements the reading varies over 2½ orders of magnitude, from 1. psi down to .003 psi. To cover this we have two parallel differential readouts of 2.0 and .1 psi full scale, but we could not get low enough to get good data on C2.5-2 in this mode (see TM-625). A second problem is the stored liquid inventory of the system. If the system holds 50 liters, as it does at B-12, and you want to measure to 5 watts, it takes 7 hours to change the liquid inventory, since 50 liters is approximately equal to 35 watt-hours.

The subcooled liquid and cold gas modes have the great advantage that one can measure all the components of the system independently as well as the heat exchanger effects. Their major drawback, however, is that one requires very accurate VPT's. We use absolute pressure gauges with an accuracy of .1% which corresponds to .01°K. One can then calibrate the gauges to .002°K with 2Ø fluid. The accuracy of the bulbs, which is covered in the next section, can be better than .001°K.

The cold gas mode, because of its smaller enthalpy change, requires a 40% surplus compressor capacity to push enough gas through the loop. This mode was used to measure C2.5-2 at B-12. Since in the Accelerator system, electrical heating is one half of the heat load, this technique would be the major heat leak troubleshooting tool. In addition one would calibrate the VPT's as a gas pressure thermometer for the 5.2 to 15°K range; below 10°K one could have an accuracy of .2°K which drops off to 1.°K as you approach 15°K. This mode has the advantage that during a slow cooldown one can collect heat leak data.

The subcooled liquid mode is the most accurate way to make measurements. One has the ability to take data over a period of days with a stable operation. In the cold gas mode without a complex automatic control system one is always drifting through the temperature range where one can collect data. Out of a 100 hour data run one is lucky if one has 3-one hour periods where the entire loop is in the measuring range. What one does is take the data on the different sections as they individually drift into the range. In the subcooled mode the refrigerator simply makes liquid into a pump dewar and is not affected by changes such as flow rates in the loop, therefore one can run a set of data curves to cross check the system. The major drawback is that it requires substantial additional heat exchangers and dewars as well as refrigeration. Measurements of this type are made in the Proto Main.

Each mode has its proper function in cryogenics. They are:

Liquid to Gas	- Total System Heat Leak
Cold Gas	- Component Heat Leak in an Operating System
Subcooled Liquid	- Fundamental Experimental Data

<u>VPT Accuracy</u>

Let us now calculate the temperature rise of a VPT reading due to heat leak. A typical VPT has a heat leak of .025 watts down the capilary tube, which can be reduced to .005 with a liquid nitrogen intercept. Standard operating conditions at B-12 are:

$W = 5$ g/sec
$T = 4.764°K$
$P = 1.6$ atm

NBS Note #631 gives us the following:

	GAS	LIQUID	
Cp =	17.21	9.763	J/g °K
P_r =	1.84	1.36	
$\mu \cdot 10^6$ =	15.2	28.4	g/cm sec

For Schedule 5 pipe we get the following film coefficients:

Nominal Diameter	Mass Flow Density	Film Coefficients	
d inch	G g/sec cm^2	H_{gas} w/cm^2 °K	H_{liq} w/cm^2 °K
½	1.958	.0436	.0343
1	.714	.0176	.0138
1½	.315	.0084	.0066

The VPT bulbs have a circumference of 1.995 cm and a conduction area of .317 cm^2. The conductivity of stainless steel at this temperature is

$$\sigma = .003 \text{ w/cm°K.}$$

From the appendage we get the following equations for the temperature and heat flux:

$t = t_o\, e^{-x/\ell}$	temperature elevation
$P = P_o\, e^{-x/\ell}$	heat flux
P_o	heat flux into bulb
$t_o = P_o/\sqrt{hc \cdot \sigma A}$	temperature at top of bulb
$\ell = \sqrt{\sigma A/hc}$	decay length

Let us now make the following assumptions, which are a function of the construction:

a) ½ of the heat leak conducted away by the pipe.

b) 1 cm is the distance from the pipe to the liquid-gas interface.

We then obtain the following results for liquid flow:

Nominal Diameter	ℓ	$1/\sqrt{hc \cdot \sigma A}$	P_o = .0125 watt		P_o = .0025 watt	
d inch	cm	°K/watt	t_o °K	$t_{x=1}$ °K	t_o °K	$t_{x=1}$ °K
½	.118	124.0	1.550	.0003	.310	.00006
1	.186	195.5	2.444	.0112	.489	.0022
1½	.269	282.7	3.534	.0854	.707	.0171

As one can see, without the intercept we can have an error from .0003 to .0854°K. The liquid nitrogen intercept reduces the error by a factor of 5. One of our VPT's is located in a dead spot in a 1.5 inch square box. Even with an intercept it still reads high by .07°K in low flow conditions.

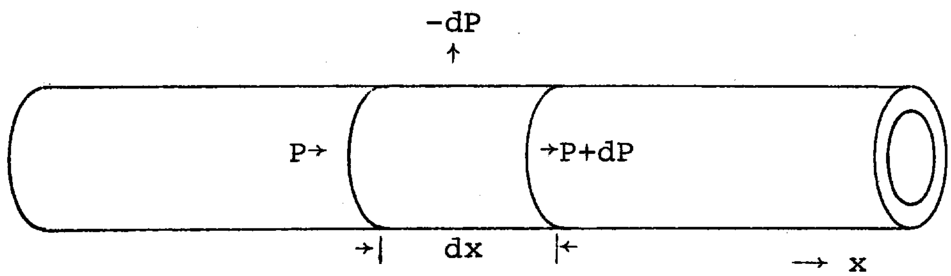
Summary

Although VPT's are accepted field standards for liquid measurements, extreme caution should be used when placing these instruments in long transfer line systems where they are expected to read accurately the amount of subcooling or superheat.

APPENDAGE

Heat Transfer in a Tube

h	film coefficient
c	circumference
σ	conductivity
A	conduction area
P	heat flux
t	temperature elevation



$-dP = htc\,dx$ heat transfer to gas

$P = \sigma A \left(\frac{-dt}{dx}\right)$ heat conduction

Rewriting the equations:

$$\frac{dP}{dx} = -(hc)\,t$$

$$\frac{dt}{dx} = -\left(\frac{1}{\sigma A}\right) P$$

The boundary conditions are:

$$P|_{\circ} = P_{\circ} \qquad P|_{\infty} = 0$$

$$t|_{\circ} = t_{\circ} \qquad t|_{\infty} = 0$$

Let us try a solution of the form:

$$P = P_{\circ}\, e^{-x/\ell} \qquad t = t_{\circ}\, e^{-x/\ell}$$

Therefore:

$$\ell = \sqrt{\sigma A/hc} \qquad t_{\circ} = P_{\circ}/\sqrt{(hc)\cdot(\sigma A)}$$