ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Technical Report

TEMPERATURE GRADIENT NEAR LIQUID-VAPOR INTERFACE IN A DEWAR FLASK CONTAINING LIQUID NITROGEN

R. B. Bernstein

Project 2254

THE ARO EQUIPMENT CORPORATION
BRYAN, OHIO

April 1956

A series of experiments was carried out in order to determine the temperature gradient in the vicinity of the liquid-vapor interface in a Dewar flask containing boiling liquid nitrogen at atmospheric pressure.

Figure 1 shows a sketch of the apparatus. A commercial 5.3-liter narrow-neck, storage-type Dewar flask was mounted on a Cenco Lab-jack which permitted smooth vertical motion over a distance of some 20 cm. A thermocouple probe was maintained in a fixed position. A glass sleeve in the cork of the Dewar served to align the probe axially with respect to the movable Dewar. Fiduciary marks allowed measurement of the depth of immersion of the thermocouple in the Dewar. The depth of the liquid-vapor interface was determined by immersion of a meter stick; the frost line was reproducible to ± 1 mm. The liquid level was recorded before and after each series of measurements; it usually dropped 1-2 mm during the course of a run. The Dewar was normally used half-filled, corresponding to a level 10-12 cm above the bottom of the flask.

The normal heat leak into the Dewar was measured by collection of the nitrogen gas evolved in a known time. The average loss of 2.1 cc atm/sec corresponds to a heat leak of 0.12 cal/sec into the Dewar. The rate of weight loss is thus of the order of 5%/24 hr.

The major problem was to evaluate and minimize the heat leak by conduction through the thermocouple leads, in order that the temperature readings in the gas phase would be meaningful. In the early experiments straight thermocouples of bare Chromel-Alumel wire (B. and S. No. 25) were used; here conduction would tend to give high apparent gas temperatures. Next, a similar thermocouple was used with the modification that the lower end (the test junction) was turned up in the form of a J, as shown in Fig. 1. In this case conduction toward the cooled bottom of the loop would tend to lower the apparent gas temperature.

The final thermocouple probe design consisted of an enameled copper-Advance couple (B. and S. No. 40); the wires were cemented in a fixed position inside a 3-mm-OD Pyrex reference tube which extended down to within a few centimeters of the interface. Thin fibers of Duco cement were used as bridges across the loop of the J to keep the junction position fixed relative to the reference tube. The upper portion of the tube passed through the glass sleeve in the Dewar cork and was clamped in the usual way.

The usual procedure was to measure the thermocouple output (emf) at varying settings of the height of the platform under the Dewar flask, corresponding to known values of h, the height of the probe junction above the inside bottom of the flask. Ascending and descending sets of readings were taken, usually allowing an equilibration time of 3-5 min for each new setting of the height. This was particularly important when the junction had been recently immersed in the liquid.

Five runs were carried out using varying probe designs. Shown in Fig. 2 is a graph of thermocouple output (millivolts) vs h for the straight Chromel-Alumel probe. Figure 3 shows a similar graph for the J-type copper-Advance probe. It is believed that the results with the latter probe are more reliable. Absolute temperature values are not obtainable from the emf data since low-temperature calibrations were not carried out.

From these results it appears that a temperature gradient exists in the gas phase near the interface, of magnitude approximately 2°C/cm, which is maintained in the steady state.

It is of interest to make a theoretical estimate of the upper limit of such a temperature gradient, assuming no turbulence or mixing in the gas phase (which will, of course, lower the gradient). Consider the very much oversimplified case of a very long cylindrical Dewar of radius r with a hemispherical bottom. Let the liquid-gas interface be at a height ℓ above the bottom of the Dewar and consider a cylindrical volume element at a height h ($h > \ell$) of altitude dh. Assume a constant heat leak through the walls of the Dewar of magnitude q cal/sec/cm^2; let C_p and L_v be the molal heat capacity of the gas and the molal heat of vaporization of the liquid, respectively, assumed constant. Neglecting longitudinal back-conduction of heat through the gas, for the steady state one obtains: $q2\pi r dh = C_p \frac{qA}{L_v}\left(\frac{\overline{dT}}{dh}\right) dh$, where A = total wall area for heat leak into liquid ($A = 2\pi r\,(\ell - r) + 2\pi r^2 = 2\pi r\ell$) and $\left(\frac{\overline{dT}}{dh}\right)$ = temperature gradient averaged over the cross section of the cylinder.

Thus,
$$\frac{\overline{dT}}{dh} = \frac{L_v}{\ell C_p} \quad .$$

Note that in the present approximation the gradient is found to be independent of the magnitude of the heat leak; a larger value of the heat leak would increase the heat flow into the gas by heat transfer through the walls but would also increase the rate of evolution of cold gas from the liquid; thus the heat balance in the volume element is the same and the gradient is unchanged.

Applying this result to the present experiments, it is found that $\left(\frac{\overline{dT}}{dh}\right)_{max}$ = 16°C/cm. This represents the estimated upper limit on the mean gradient near the interface. The actual gradient as measured on the cylinder axis would be much lower than the mean gradient, and the effect of turbulent mixing would lower the value; it thus appears that the observed gradients of 2-3°C/cm are of a reasonable magnitude.

The actual situation which obtains in a closed spherical Dewar containing liquid oxygen boiling under pressure with intermittent release of gas through a pressure-relief valve is, of course, far more complex. It is clear, however, that a temperature gradient will exist in the gas phase due to heat transfer through the walls to the gas phase. The average gas temperature may well depend on the relative free-gas-to-liquid volume and thus the liquid level.

It would appear to be of some interest to make temperature measurements with a suitable probe in an actual liquid-oxygen converter at several values of the pressure. The influence of continuous or intermittent vibration (and/or agitation) upon the pressure and the local gas temperature could then be evaluated in conjunction with direct measurements of the rate of gas evolution. Since a theoretical treatment of the practical problem would be prohibitively complex, it would seem that probe studies should be part of the experimental research program to be carried out at the Aro Laboratories.

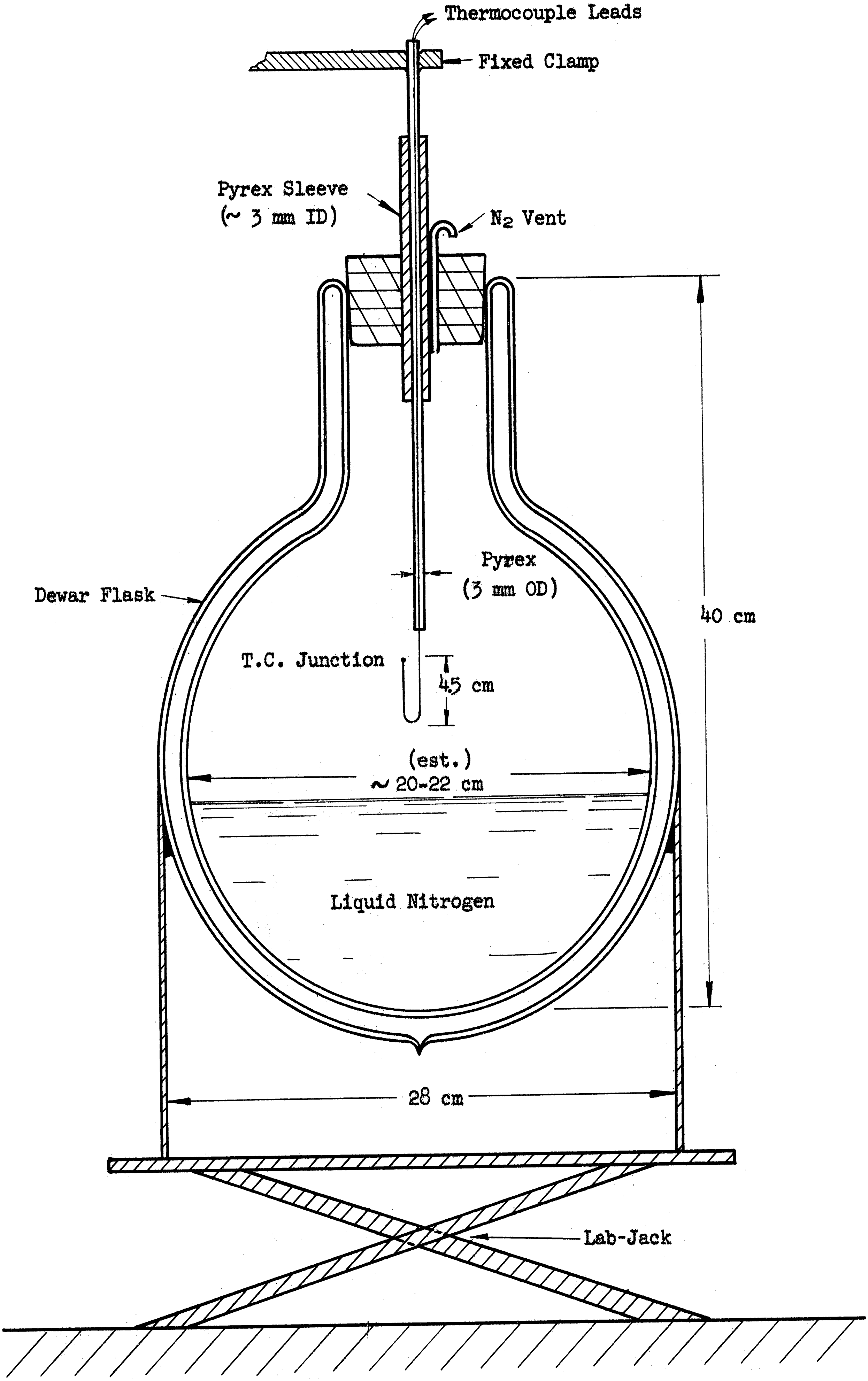
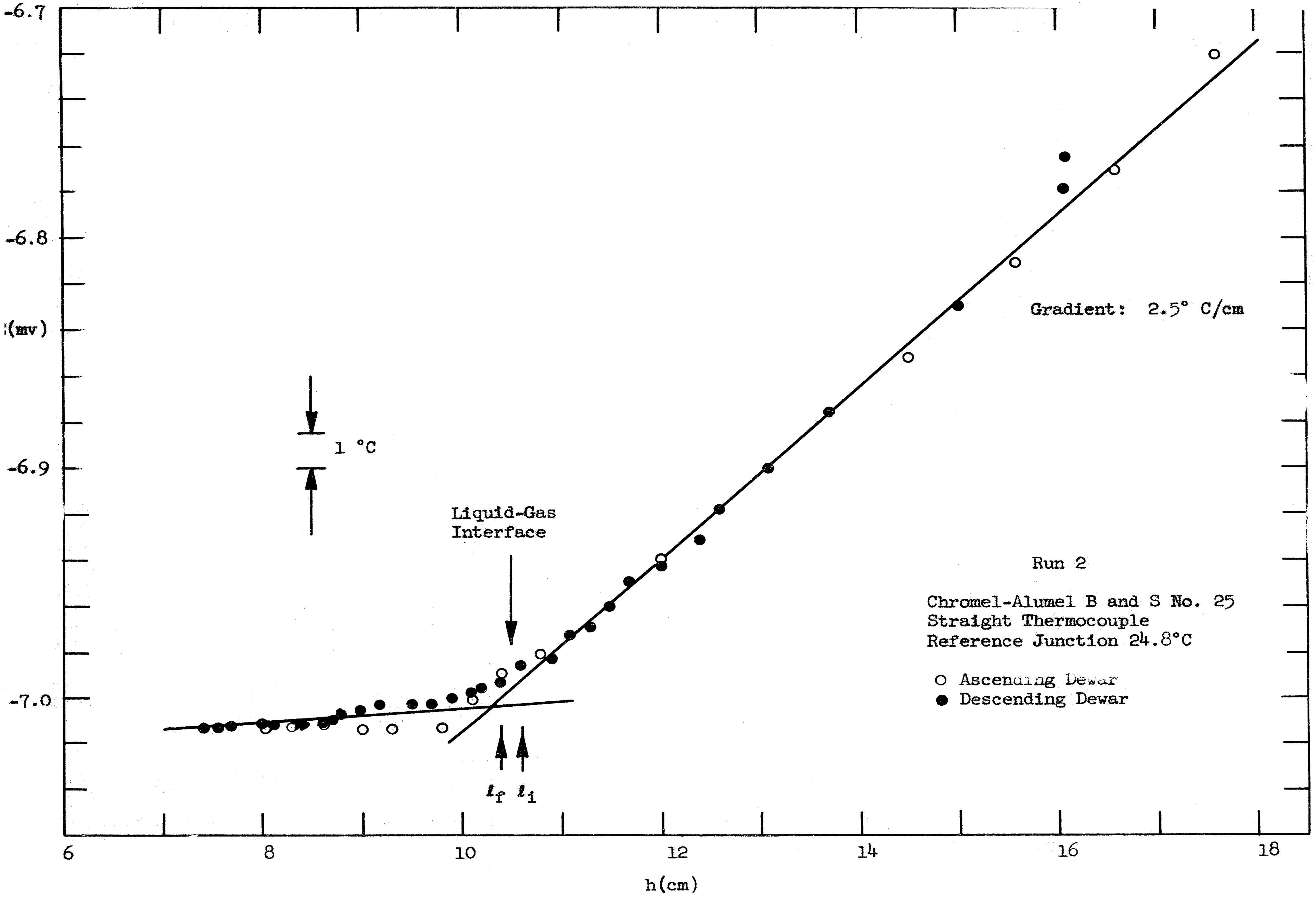


Fig. 1. Dewar flask mount and probe assembly.


-6.7
-6.8
(mv)
-6.9
-7.0
6
8
10
12
14
16
18
h(cm)
Gradient: 2.5° C/cm
1 °C
Liquid-Gas Interface
ℓ_f ℓ_i
Run 2
Chromel-Alumel B and S No. 25
Straight Thermocouple
Reference Junction 24.8°C
○ Ascending Dewar
● Descending Dewar

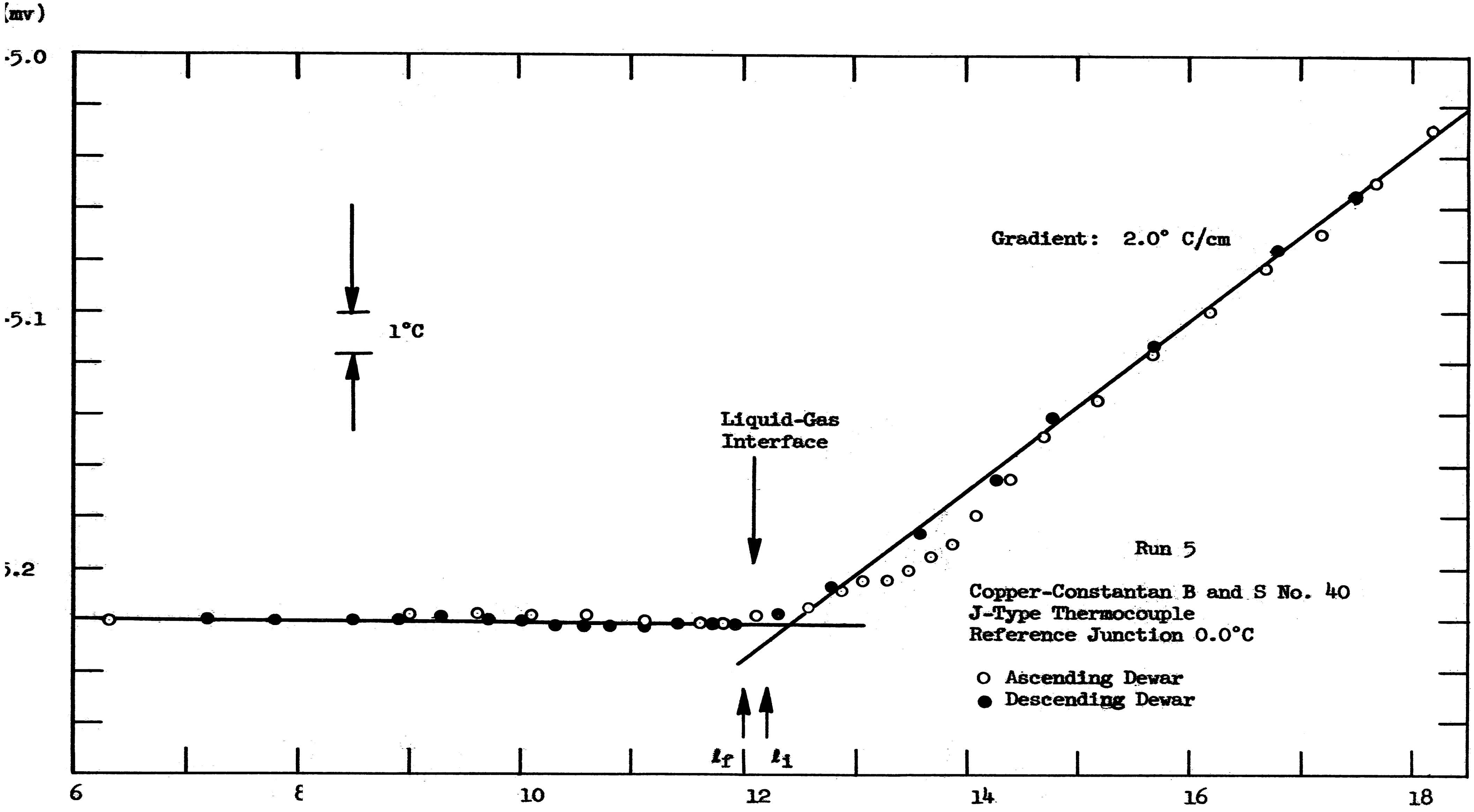


Fig. 3. Vertical temperature profile along axis of Dewar flask containing liquid nitrogen at atmospheric pressure.