ERRATA

Page 21 Line 21 For "Table 2.2" read "Table 2.3"

Page 34 Line 14 For "$\left(-K \frac{n^2 \pi^2}{L^2}\right)$" read "$\left(-K \frac{n^2 \pi^2}{L^2} \lambda\right)$"

Page 40 For "$T_{(x=\delta x)}$" read "$\frac{T_{(x=\delta x)}}{\delta x}$" throughout

Line 1 Should read $\left(\frac{\partial T}{\partial x}\right)_{x=0} \simeq \frac{T_{(x=\delta x)} - T_{(x=0)}}{\delta x}$

$= \frac{T_{(x=\delta x)}}{\delta x}$

Line 3 For "$\sin \frac{n \pi}{} \delta x$" read "$\sin \frac{n \pi}{L} \delta x$"

Line 4 For "$\sin \frac{n \pi}{L} x$" read "$\sin \frac{n \pi}{L} \delta x$"

Page 98 Line 4 For "Prandth" read "Prandtl"

Page 115 Line 20 For "SH" read "CF"

Page 120 Line 13 For "nine" read "eleven"

Page 132 Line 18 For "once" read "one"

Page 165 Line 22 For "100^{o}k" read "100^{o}K"

Page 180 Line 26 For "agrees well" read "may be compared"

Page 181 Line 2 For ".0145" read ".0117"

Page 214 Line 14 For "1934" read "1944"

Heat and Energy Transfer in the ~~large-scale~~ Piping and Storage ~~and Piping~~ of Liquefied Gases

A Thesis submitted for the Degree of

DOCTOR OF PHILOSOPHY

in the Faculty of Engineering

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by

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ABSTRACT

The purpose of this research was to study problems associated with the large-scale storage of liquefied gases, particularly those problems involving the transfer of heat and energy. The work was carried out with the co-operation of the North Thames Gas Board who consented to field work being carried out at their liquid methane storage depot at Canvey Island.

A study was made of the pressure drops accompanying the flow of liquid methane through a ten-inch diameter insulated pipeline during delivery of methane to the storage tanks and the experimentally determined values have been compared with those calculated theoretically by the methods normally employed for liquids at atmospheric temperature.

The problem of allowing for the effect of transient atmospheric conditions when analysing the insulation performance of liquefied gas storage tanks has been studied theoretically and in the field. A method of calculation, involving the use of a digital computer, has been developed to calculate the effect of changing conditions of outside temperature on the evaporation rate. Measured rates of evaporation for a storage tank at Canvey Island were found to be greater than those calculated. It is considered that the discrepancy may be due to the effect of gas convection within the porous insulation.

Gas convection within porous insulants has been studied theoretically and a means of calculation of the effect (again involving the use of an electronic computer) has been developed. A laboratory-scale apparatus has been constructed and used to measure the amount of heat transfer by convection and the measured values agree reasonably well with those calculated.

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CHAPTER I

Introduction

In recent years, the development of processes involving the handling and storage of large quantities of liquefied gases at temperatures well below atmospheric has presented a number of interesting challenges. The first developments in this field stemmed from the growing demand for large quantities of oxygen in industry particularly for steel-making. "Tonnage oxygen" plants were developed which employed low-temperature distillation techniques for the separation of oxygen from air on a large scale. Low load factor of the steel making processes and the necessity for maintaining large reserve supplies of oxygen led to the development of equipment for the handling and storage of gas in the liquid form.

The large contraction in volume accompanying liquefaction makes the storage and transport of liquefied gases an attractive proposition provided that the problems of liquefaction and subsequent handling can be overcome.

Liquid oxygen has, for this reason, been used extensively as an oxidant in rocket propulsion and the expansion of missile technology has opened up further new fields for the use of liquefied gases.

In 1937 Egerton (Refs. 1,2) suggested that the separation and storage of liquid methane could be used to help meet peak-load problems of the gas industry. Some theoretical work was carried out in support of these ideas (Refs. 3,4) but no practical use was made of them in this country. Similar ideas in the United States led to the building

of a liquefaction and storage plant for natural gas at Cleveland, Ohio (Ref. 5,6) in 1941. Surplus gas available during the summer months was liquefied and stored until required at peak-load times during the winter. This plant closed down after three years following a serious fire (Ref. 7,8) and there was little further development in America until 1954. In this year a scheme was developed for the transportation of liquefied natural gas, by barge, from the Gulf Coast, up the Mississippi and its canal system to Chicago (Ref. 9). A large scale storage plant for liquid natural gas has also been built, and is in commission, in the U.S.S.R. (Ref. 10).

Developments along similar lines in this country led, in 1957, to a large-scale experiment carried out by the Constock International Methane Limited of America and the British Gas Council to investigate the possibility of conveying liquefied natural gas, by ocean-going tanker, from its source in America to Great Britain. A storage and evaporation plant was constructed on Canvey Island in the Thames estuary and a tanker (converted from a dry-cargo boat) was used to transport a few shipments of liquid methane from Louisiana, U.S.A. to this country, so that experience could be gained in the ocean-transport and handling of the liquid.

The Canvey Island installation consists of two storage tanks each of about 1,000 tons capacity designed for the storage of liquid methane at atmospheric pressure. A ten-inch diameter insulated pipeline connects the tanks with the deep-water jetty of a neighbouring oil storage depot which was used for the tanker. Boil-off gas from the tanks was fed to

a "Wiggins" type gas holder and was subsequently compressed into a 16 in. pipeline. Liquid methane from the tanks could be forced by pumps into either a steam heated evaporator or an evaporator using the sensible heat of river water which converted the liquid into high pressure gas. This gas was added to the compressed boil-off gas in the 16 in. pipeline which conveyed it away from the plant to a reforming station at Romford, Essex.

The experiment was a success (Ref. 11) and it seems probable that, if the scheme were to be developed further, many more larger tanks would be constructed. In order to effect economies in future designs, the experience gained with this existing plant must be exploited to the full and this research work was carried out to investigate various problems associated with the storage of liquefied gases on such a scale.

The work was carried out with the co-operation of the North Thames Gas Board and the Gas Council who consented to field work being undertaken at the Canvey Island storage depot during deliveries of liquid methane. The work is, however, intended to be general in nature since the problems investigated are common to any plant where liquefied gases are stored at temperatures below atmospheric.

CHAPTER II

Pressure Drops Accompanying the Pumping of Liquid Methane through a ten-inch diameter Pipeline

2.1 Introduction

During the discharge of liquid methane from the ship to the storage depot the liquid is pumped through a ten-inch diameter insulated pipeline some 2,000 feet long which terminates in a manifold from which liquid is fed to the tanks.

The pipeline is pre-cooled before the unloading operation by passing through it, firstly cold gas and, finally, liquid from the storage tanks. The boil-off gas is returned to the plant through a second, four-inch diameter, aluminium line.

Liquid methane is discharged at a rate of about 80,000 gallons per hour during the main period of the unloading. The pumping power required, which is a function of the pressure drop in the pipeline will depend on the state of the methane in the line. Flow may be either single-phase with the methane flowing as liquid at or below its saturation temperature, or two-phase with the methane being partially vaporised by the heat leaking into the pipeline. In this case the pressure drop will be much increased.

Little or no published information exists for the large scale flow of liquefied gases through pipelines. The object of this part of the research was, therefore, to measure the pressure drops during a delivery of liquid methane to establish the type of flow and to compare the measured pressure drops with those calculated using normal pipe friction

chart methods.

2.2 Pipeline Details

The general arrangement of the pipeline leading from the unloading jetty to the storage tanks is shown in Fig. 2.1 Fig. 2.2 is a diagrammatic representation of the pipeline showing the position of the various pressure tapping points and the absolute levels of the pipe centre line at those points. The pipeline is of extruded aluminium tubing with butt-welded joints.

The pressure tappings were of $\frac{7}{8}$ inch O.D. tube welded into the upper surface of the pipeline and terminating in a flange. The cover plate for each flange was drilled and tapped to take a stop cock which was connected via a length of rubber pressure tubing to a mercury manometer. A manometer was similarly connected to the liquid drain cock at F the lowest point in the pipeline.

The pipeline is insulated by a six inch thick layer of "Onazote" (a type of expanded ebonite) insulation suitably vapour sealed and protected by a layer of bitumastic sheeting. Dimensions of the pipeline are as follows:-

Outside diameter of Aluminium pipe	10 ins.
Nominal wall thickness	5/16 ins.
Thickness of insulation	6 ins.
Thermal conductivity of insulation (at approx. - 100°F)	0.20 Btu/ft^{2}hr°F/in
Approximate total length	2,000 ft.

2.3 Experimental Procedure

Pressures at the various tappings were measured at half-hourly intervals during the unloading of liquid methane Liquid levels in the

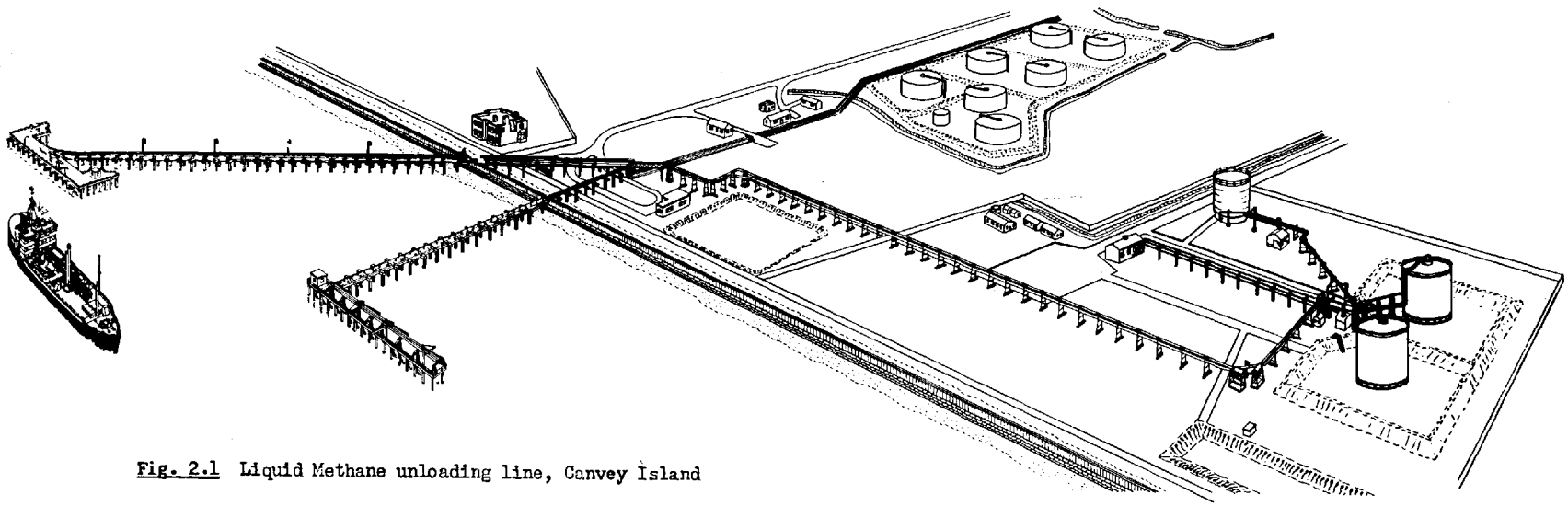


Fig. 2.1 Liquid Methane unloading line, Canvey Island

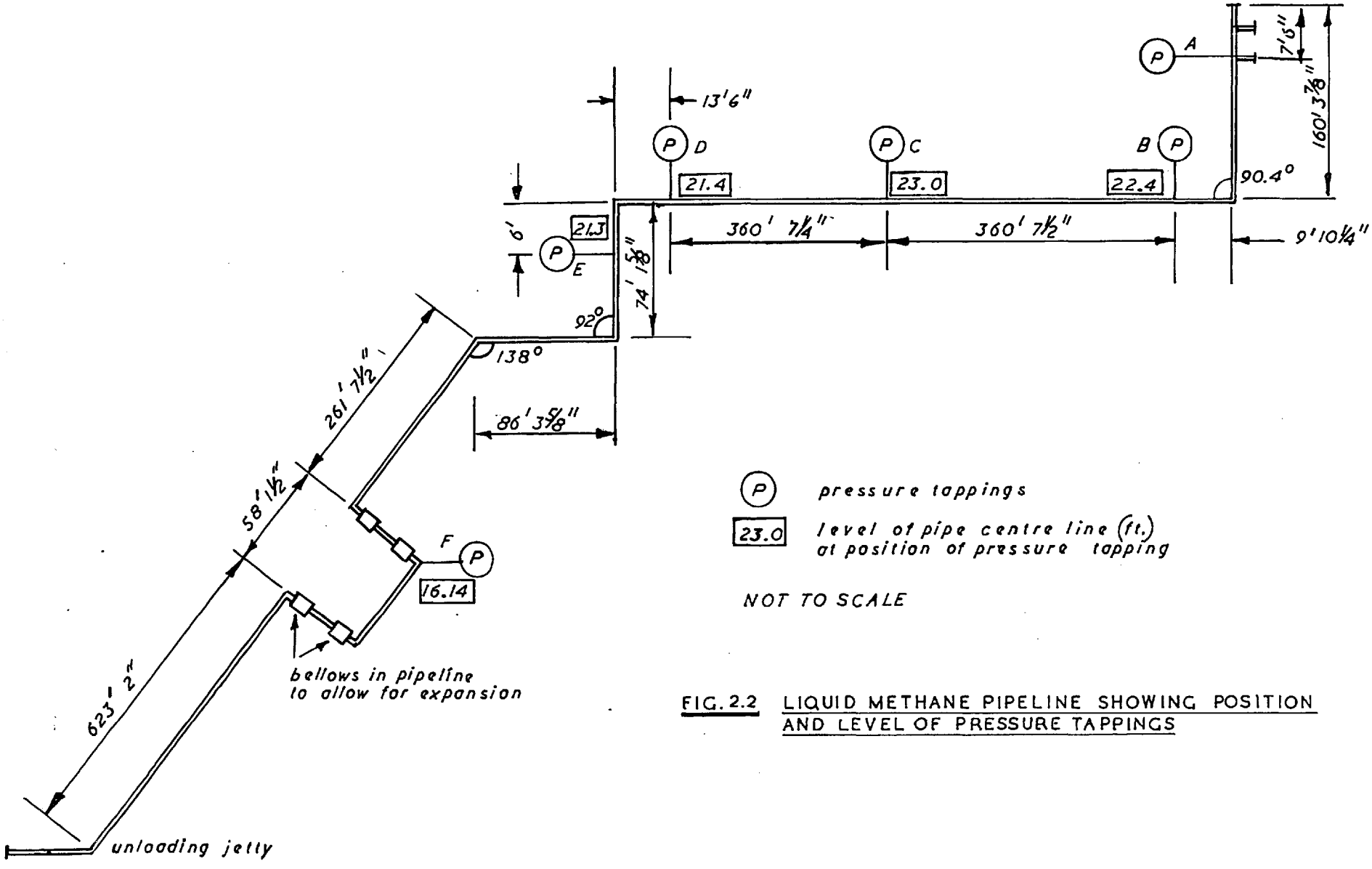


FIG. 2.2 LIQUID METHANE PIPELINE SHOWING POSITION AND LEVEL OF PRESSURE TAPPINGS

storage tanks were also measured at similar intervals. Periodically measurements were also made to determine the total boil-off rate. This was done by directing the total vapour discharge from both tanks into the gas holder for a measured period. The time taken for a gain of 5,000 cu. ft. of gas was determined.

2.4 Results

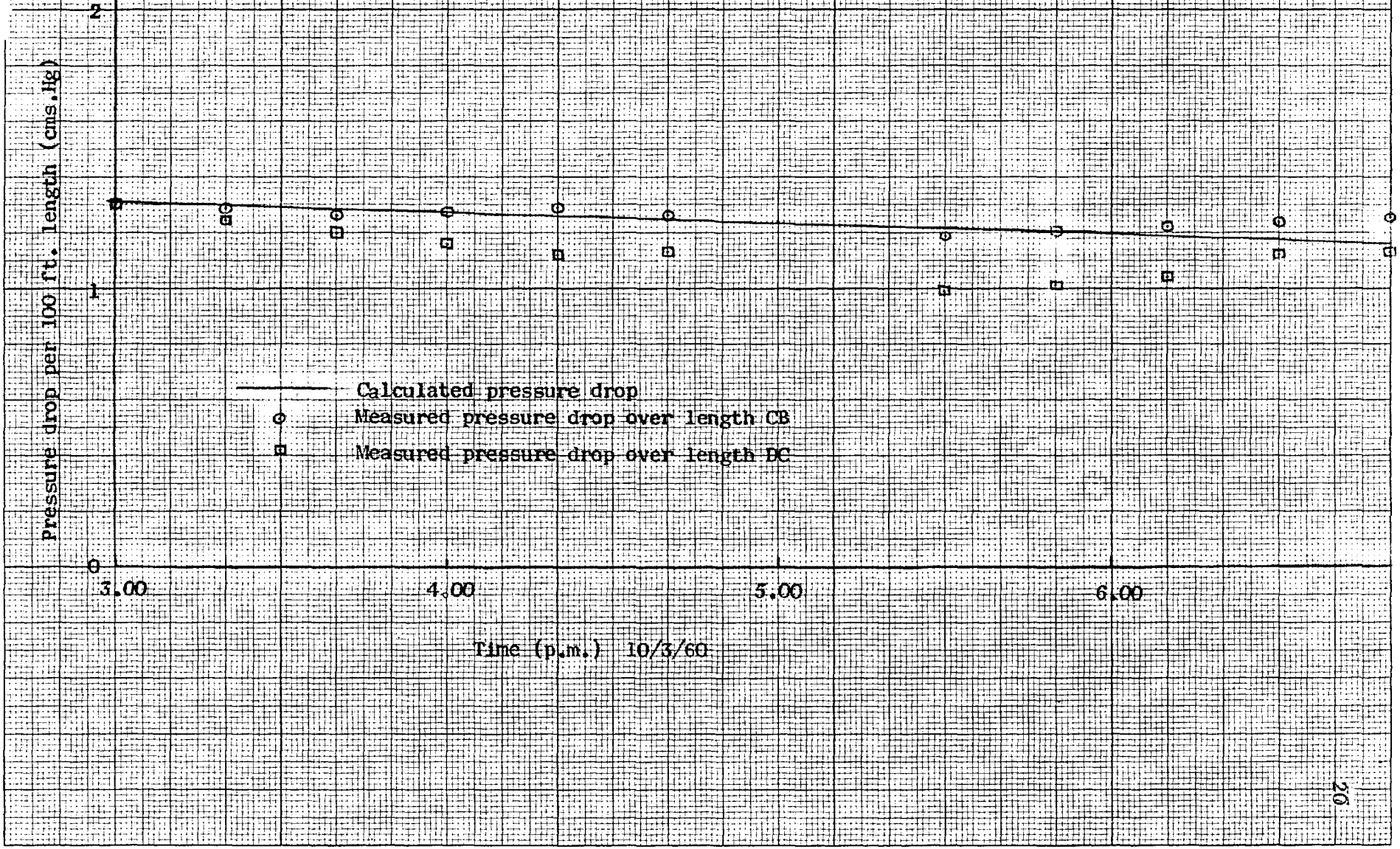
Table 2.1 gives the measured pressures over the course of the unloading and table 2.2 gives the corresponding liquid flow rates. The flow rates were calculated from the half-hourly tank level readings and have been corrected for boil-off loss and also for losses during evaporator tests which were carried out from time to time during the unloading. Since the flow rates showed considerable scatter when plotted against time the best straight line was calculated by statistical methods, the flow rate in subsequent calculations being assumed equal to the value given by this straight line.

Pressures at points B, C and D (Fig. 2.2) were plotted against time and smooth curves were drawn through the points. The pressure drops at various times along the straight sections BC and CD were measured from the graphs and corrected for change of level of the pipeline. The resultant frictional pressure drop expressed per 100 foot length of pipe is shown as a function of time in Fig. 2.3

Pressure drops along the sections AB, EF have not been included because of the uncertainty of the effects of the manifold at A and two stainless steel bellows in the section EF.

Assuming that the methane is completely in the liquid phase and that normal pipe friction chart methods may be applied, the pressure

Fig. 2.3 Frictional pressure drop per 100 ft. for the flow of liquid methane in a 10 inch diameter pipeline.



drop at any time may be calculated from the flow rate as follows:-

3.15 p.m. Flow Rate = 325,000 lbs./hr.

Using the properties of methane at its normal boiling point.

Viscosity (μ) = 0.119 cp

= 0.000080 lb/ft sec

Density (ρ) = 26.4 lb/ft^3

Area of cross section of pipeline

= 0.479 ft^2

$\therefore$ Velocity of flow (u) = $\frac{325,000}{26.4} \times \frac{1}{3600} \times \frac{1}{0.479}$

= 7.15 ft/sec

Reynolds Number (Re) = $\frac{ud\rho}{\mu}$ = 1.84×10^6

Assuming that the roughness of pipe (e) = 0.00015 ft

$$\frac{e}{d} = 0.00019$$

and from pipe friction chart

Friction Factor $\left(\frac{R}{\rho u^2}\right)$ = 0.00170

Pressure drop (ΔP) is given by

$$P = 4\left(\frac{R}{\rho u^2}\right) \cdot \frac{1}{d} \cdot \rho u^2$$ where l = length of pipe

hence ΔP = 36.5 psi per 100 ft. length

ΔP = 1.31 cms Hg per 100 ft. length

By this method the pressure drop was calculated at various times, the result being given in table 2.2. Fig. 2.3 gives a comparison of these values with the measured values.

2.5 Discussion

Estimated state of Methane at pump outlet

Suppose that the liquid is pumped from rest in the ships tanks (at atmospheric pressure and saturation temperature) into a 10 inch pipeline at a pressure of 21 psig (this was the maximum pressure encountered at the pump outlet during the unloading)

Flow of liquid = 325,000 lb/hr

∴ Assuming that the methane is entirely in the liquid phase

Velocity = 7.15 ft/sec

Work done in changing state from 15 psia at rest to 36 psia at a velocity of 7.15 ft/sec (neglecting frictional effects)

$$= \frac{\Delta u^2}{2} + g\Delta Z + v\Delta P$$

where ΔZ = change in head

and v = specific volume

$$\frac{\Delta u^2}{2} = \frac{7.15^2}{2} \quad \text{ft pdls/lb}$$

$$= \frac{7.15^2}{64} \quad \text{ft lb/lb}$$

$$= \underline{0.8 \text{ ft lb/lb}}$$

$$v\Delta P = 0.038\ (36 - 15) \times 144 \text{ ft lb/lb}$$

$$= \underline{115 \text{ ft lb/lb}}$$

∴ Total energy required to pump methane (neglecting change of head)

= 116 ft lb/lb

= <u>0.149 Btu/lb</u>

Suppose the pump is 50% efficient

then, actual work done = 0.298 Btu/lb

and work appearing as heat = 0.149 Btu/lb

Specific heat of liquid methane = 0.84 Btu/lb°F

∴ Rise in temperature during pumping = <u>0.18°F</u>

Saturation temperature at 14.7 psia = -258°F

Saturation temperature at 36 psia = -237°F

It appears, therefore, that the methane remains considerably below its saturation temperature at the higher pressure and exists as liquid at the pipeline inlet.

<u>Estimated heat leakage into pipeline and rise of methane temperature along pipeline</u>

Log. mean radius of insulation = $\frac{6}{\ln 11/5}$ ins.

= <u>7.63</u> ins.

∴ Log. mean area for heat flow = 4.00 ft^2 per ft length

Approximate length of pipeline = 2,000 ft.

∴ Assuming that the inside temperature = -258°F and

outside temperature = 60°F

$$\text{Heat inleak} = \frac{0.20 \times 318 \times 4.00 \times 2,000}{6}$$

= <u>84,700 Btu/hr</u>.

∴ Rise in temperature of methane over whole length, due to heat leakage through insulation

$$= \frac{84,700}{325,000} \times \frac{1}{0.84}$$

= <u>0.31°F</u>

Pressure drop along pipeline = 36 - 25

= 11 psi

∴ Frictional work done = $\upsilon \Delta P$

= 0.038 x 11 x 144 ft lb/lb

= 60.1 ft lb/lb

= 0.077 Btu/lb

and rise in temperature due to friction

= 0.09°F

∴ Total temperature rise in 2000 ft of pipe = 0.40°F

Saturation temperature at 25 psia (the manifold pressure)

= -246°F

Thus, the liquid will be considerably below its boiling point at the downstream end of the pipeline and flow will, therefore, be completely in the liquid phase.

Total increase in temperature for 2000 ft of pipeline

= 0.40 + 0.18

= 0.58°F

Rise in temperature permissible before two phase flow occurs in pipeline = -246°F - (-258°F)

= 12°F

∴ Length of pipeline which could be used before two phase flow occurs

$$= \frac{12}{0.58} \times 2000$$

= 41,000 ft.

2.6 Conclusion

Fig. 2.3. shows that the measured pressure drops approached closely those calculated by applying pipe friction chart methods. It would appear that, in the design of this type of installation, pipeline pressure drops may be predicted reasonably accurately by conventional methods, provided that the liquid flow rates are such that flow is entirely single phase.

Under the conditions of flow rate and manifold pressure used in the test it would have been possible to use a pipeline approximately 41,000 ft. long before any two phase flow would have occurred.

Table 2.1 Pressures in unloading line during methane unloading 10th March, 1960.

t = Time (P.M.) P_A, P_B, P_C, etc. = Pressures at A, B, C, etc. in cms. of mercury.

t	P_A	t	P_B	t	P_C	t	P_D	t	P_E	t	P_F
2.25	50.1	2.26	52.2	2.24	57.6	2.22	62.9	2.21	63.7	2.19	77.5
2.55	50.5	2.53	52.5	2.52	56.6	2.49	62.8	2.48	63.4	2.45	76.7
3.21	52.2	3.20	54.0	3.18	58.1	3.17	64.2	3.16	64.9	3.15	77.9
3.52	53.5	3.51	55.1	3.50	59.1	3.48	64.8	3.47	65.6	3.45	78.4
4.23	54.2	4.22	55.7	4.20	59.8	4.19	65.5	4.18	66.1	4.16	78.9
4.55	54.3	4.53	55.5	4.51	59.8	4.50	65.5	4.49	66.1	4.47	79.7
5.21	55.6	5.20	57.0	5.19	60.8	5.17	65.9	5.17	66.7	5.15	79.4
5.52	56.4	5.50	57.8	5.49	61.6	5.48	66.8	5.47	67.2	5.45	79.7
6.24	57.7	6.23	58.9	6.21	62.8	6.20	68.3	6.19	68.6	6.17	81.1
6.49	59.5	6.48	60.8	6.48	64.6	6.44	70.0	6.44	70.5	6.42	82.6
7.49	56.2	7.48	58.1	7.46	63.3	7.45	71.2	7.44	71.7	7.42	84.0

Table 2.2 Liquid methane flow rates during unloading

10th March, 1960.

Time	Flow rate from liquid level indicator readings (lb./hr.)	Correction for boil-off loss (lb./hr.)	Correction for evaporator test losses (lb./hr.)	Total flow in pipeline (lb./hr.)
12.45	357,500	-	2,100	360,000
1.15	336,500	-	2,100	339,000
1.45	331,000	-	2,200	333,000
2.15	313,000	-	2,200	315,000
2.45	303,500	7,300	2,200	313,000
3.15	352,000	-	2,300	354,000
3.45	281,000	-	2,300	283,000
4.15	308,000	-	2,300	310,000
4.45	315,000	5,900	2,300	323,000
5.15	327,000	2,900	2,300	332,000
5.45	338,000	-	2,300	340,000
6.15	259,000	8,200	2,300	270,000
6.45	318,000	1,700	2,300	322,000

Table 2.3 Summary of calculation of pressure drop from smoothed liquid flow rates.

Time (P.M.)	Liquid flow rate (lb./hr.)	Reynolds Number (Re)	Friction factor $\frac{R}{\rho u^2}$	Pressure drop (cms. Hg per 100 ft.)
3.00	326,000	1.84×10^6	.00170	1.31
4.00	321,000	1.81×10^6	.00170	1.27
5.00	316,000	1.79×10^6	.00171	1.24
6.00	311,000	1.76×10^6	.00171	1.20
7.00	306,000	1.73×10^6	.00171	1.16

CHAPTER III

The effect of Transients on the Analysis of Heat Leakage into Liquefied Gas Storage Tanks

3.1 Introduction

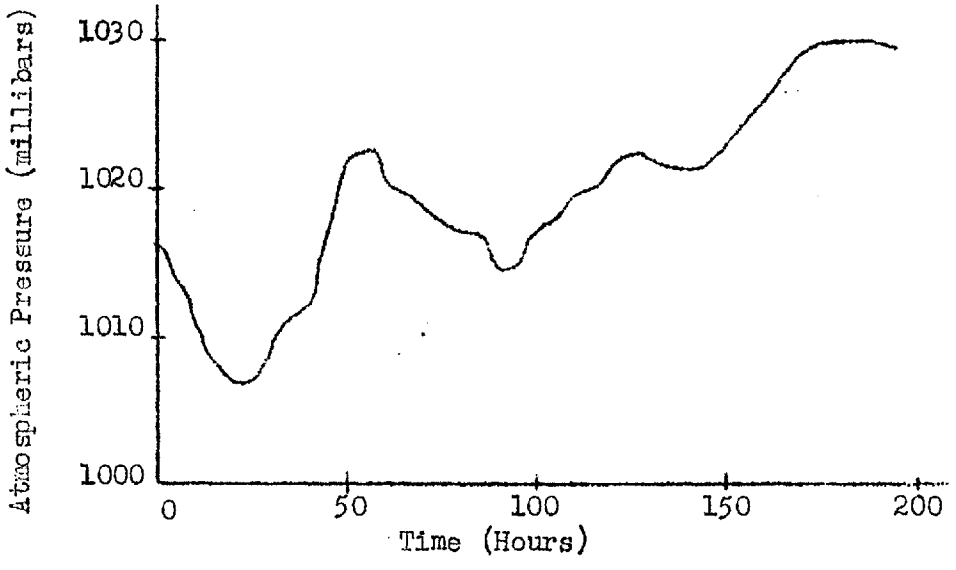
The currently favoured design for large-scale liquefied gas storage tanks consists of an inner vessel (normally cylindrical) made of aluminium or a high nickel steel, separated by a layer of fibrous or powdered insulation from an outer vessel of mild steel. The cost of the insulating material represents a significant fraction of the total cost and in addition the size (and hence, cost) of the outer mild steel vessel is dependent on the insulation thickness. It is necessary, therefore, to reduce the insulation thickness to the minimum required to keep evaporation losses down to an acceptable level. To design new tanks with confidence an accurate study of the performance of existing ones is essential.

Such a study is complicated, however, by two factors. Firstly, if the heat inleak is estimated by measuring liquid boil-off, atmospheric pressure changes may be expected to have a profound influence on the results. Secondly, a large process lag occurs between the occurrence of a temperature change at the outside surface of the insulation and the resulting change of heat flux into the liquid. Since the outside temperature, in the case of outdoor storage tanks, will show large irregular variations a steady-state approach to the problem is not justifiable.

3.2 The Effect of Atmospheric Pressure Changes

Fig. 3.1 shows typical variations in atmospheric pressure over a period of seven days. The maximum rate of change of pressure is approximately 0.6 millibars per hour. The effect of increasing atmospheric pressure is to raise the boiling point so that some of the heat being transferred into the liquid is used as sensible heat in maintaining the liquid temperature at the boiling point.

Fig. 3.1 Typical variations in Atmospheric Pressure



Considering the effect of this thermal capacity in the case one of the liquid methane storage tanks containing 1000 tons of liquid; a rise in pressure of 0.6 millibars per hour is equivalent (for methane) to a rise in boiling point of .013°F per hour.

Specific heat of liquid methane = 0.84 Btu/16°F

∴ Heat required to raise 1000 tons of liquid by 0.013°F

= 2240 x 1000 x .013 x 0.84

= 24,000 Btu.

Thus, to maintain the liquid at its boiling point 24,000 Btu/hr. would be required.

The total boil-off for the tank is approximately .04 ins. of liquid per hour which is equivalent to 170 lb/hr.

Heat of vaporisation = 219 Btu/lb.

∴ This boil-off is equivalent to a heat inleak of 37,000 Btu/hr.

It is therefore to be expected that the change of pressure will exert a very large influence on the rate of evaporation.

This effect would be easily calculable if there were no time lag involved in the transfer of heat from the walls of the tank to the bulk of the liquid. Such a time lag would, however, be expected but its effects are not easily predicted.

A considerable amount of work has recently been reported (Refs. 12,13,14) on the effect of pressurising liquefied gas storage tanks of sizes up to a few thousand gallons. The pressure rise causes an immediate temperature increase at the free liquid surface, due to condensation, but the bulk of the liquid heats up only slowly as heat is received through the walls of the vessel. With larger tanks the delay will be even greater. Convection currents will be set up within the liquid mass due to temperature inequality and even due to the presence of bubbles near the wall. Uncertainty as to the influence of these convection currents makes the prediction of pressure response virtually impossible.

Similarly a decrease of atmospheric pressure will lead to an enhanced evaporation effect. The resulting bubble generation within the liquid will probably lead to increased liquid circulation and

hence to a shorter transfer lag but, again, the effects cannot be quantitatively predicted.

It is therefore vital when analysing the behaviour of large storage tanks to choose a test period during which the change of atmospheric pressure is small unless provision can be made to hold the pressure at a constant absolute value. Alternatively, though less satisfactorily, a period must be chosen over which the atmospheric pressure has gone through, as near as possible, a complete cycle from a period of increasing pressure, through a period of decreasing pressure and back to a period of increasing pressure (or vice versa).

3.3 The effect of Atmospheric Temperature Changes

Fig. 3.2 shows the variations in temperature of the outside surface of a liquid methane storage tank over a period of about seven days during a temperate part of the year. The temperatures are the mean of three values recorded at points spaced around the circumference of the tank. The measurements were made as described in 4.2. With strong sunshine, the variations would have been more extreme.

If the inner tank is assumed to be at liquid methane boiling point ($-258^{\circ}F$), it may be seen that over the above period the temperature difference across the insulation fluctuates between 352 and $293^{\circ}F$.

If the boil-off has been measured over a period of, say, forty hours and it is required to calculate the apparent thermal conductivity of the insulation an exact solution may only be obtained by solving the unsteady state equation for heat transfer across the insulation. Alternatively, a mean temperature difference over 40 hours could be used, introducing a time lag to allow for the capacity and transfer

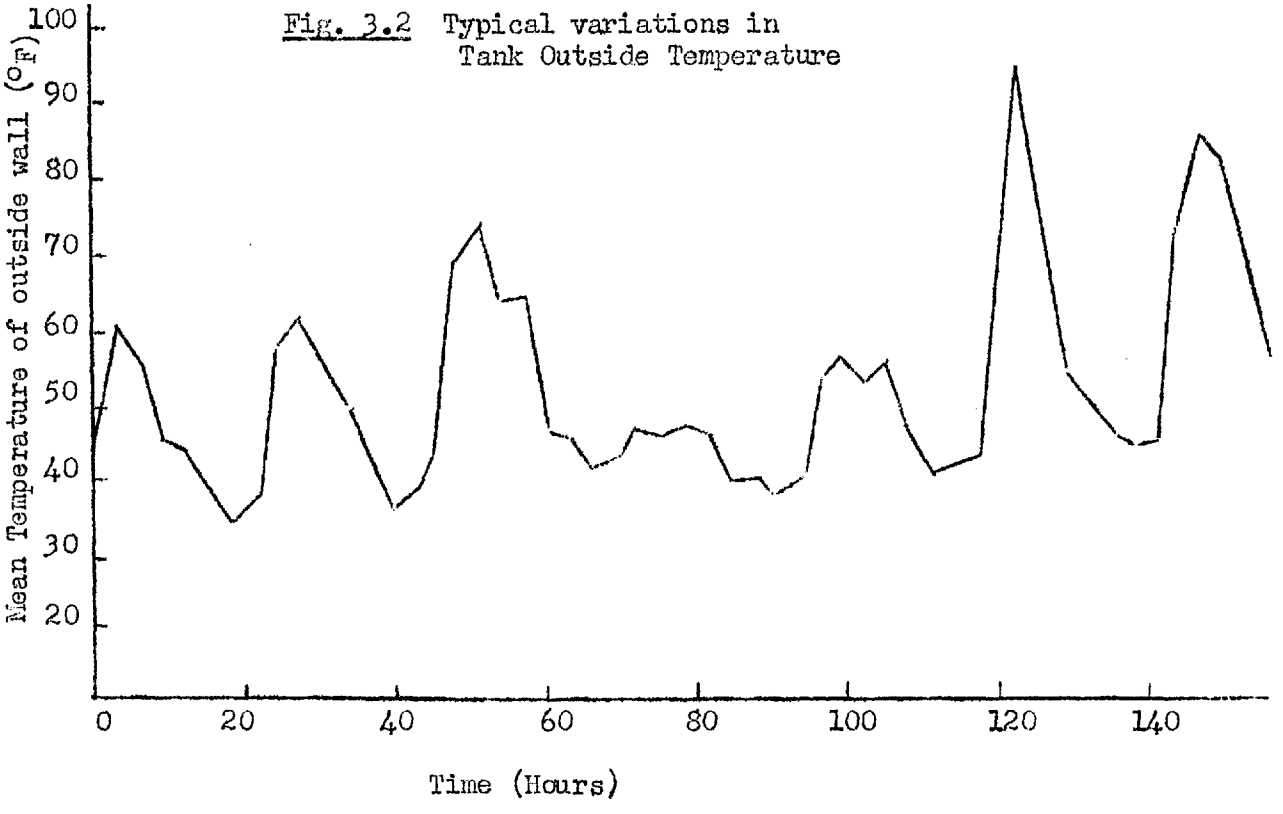


Fig. 3.2 Typical variations in Tank Outside Temperature

lags of the system. This would be less accurate but would, in general, give a better approximation than that given by using the mean temperature difference over the same forty hours.

3.4 The Magnitude of Time Lags involved

The problem may be simplified to one of two plates at uniform temperatures T_1 and T_0 separated by insulation of thickness L with the flow of heat being considered only in a direction at right angles to the plates.

The classical mathematical equation for uni-dimensional heat conduction in the unsteady state is

$$\frac{\partial T}{\partial t} = K \cdot \frac{\partial^2 T}{\partial x^2} \qquad \ldots\ldots\ldots\ldots (1)$$

where T = temperature

x = distance in direction of heat transfer

t = time

K = thermal diffusivity

$$K = \frac{k}{Cp\rho}$$

where k = thermal conductivity

Cp = heat capacity

ρ = density

If $T = f_1(t)$ when $x = 0$

$T = f_2(t)$ when $x = L$

and $T = f(x)$ when $t = 0$

then the solution of equation (1) can be shown (Ref. 15) to be

$$T = \frac{2}{L} \sum_{n=1}^{\infty}{}' \exp\left(-K \frac{n^2\pi^2}{L^2} t\right) \cdot \sin \frac{n\pi}{L} x \left[\int_0^L f(x') \sin \frac{n\pi}{L} x' \, dx' - \frac{nK\pi}{L} \int_0^t \exp\left(-K \frac{n^2\pi^2}{L^2}\right) \cdot \left\{f_1(\lambda) - (-1)^n f_2(\lambda)\right\} d\lambda\right] \quad \ldots\ldots\ldots\ldots (2)$$

This may be solved if $f_1(t)$, $f_2(t)$ and $f(x)$ are known.

In the case of storage tanks containing liquefied gases, if

x = distance measured from the inner tank

L = thickness of insulation

$T = f_1(T) = T_0$ (= boiling point of liquid) when $x = L$

At any instant the heat transferred (Q) per unit area through the inner tank is given by

$$Q = k \left(\frac{\partial T}{\partial x}\right) x = 0$$

Step Change in Outside Temperature

If at time zero the outside wall temperature undergoes a step change from a constant value T_1 to a second constant value T_2 then

$$T = f(x) = T_0 + \frac{T_1 - T_0}{L}x \qquad \text{at } t = 0$$

$$T = T_2 \text{ at } x = L \qquad t > 0$$

$$T = T_0 \text{ at } x = 0 \qquad \text{for all values of } t$$

The solution of equation (1) can then be shown to be

$$T = T_0 + \left(T_2 - T_0\right)\frac{x}{L} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\left(T_2\cos n\pi - T_0\right)\exp\left(-K\frac{n^2\pi^2}{L^2}t\right)\sin\frac{n\pi}{L}x + \frac{2}{L}\sum_{n=1}^{\infty}\sin\frac{n\pi}{L}x\cdot\exp\left(-K\frac{n^2\pi^2}{L^2}t\right)\int_0^L f(x')\sin\frac{n\pi}{L}x'\,dx' \qquad \ldots\ldots\ldots\ldots(3)$$

$$\int_0^L f(x')\sin\frac{n\pi}{L}x'dx' = T_0\int_0^L \sin\frac{n\pi}{L}x'dx' + \frac{T_1 - T_0}{L}\int_0^L x\sin\frac{n\pi}{L}x'dx'$$

$$= -T_0\frac{L}{n\pi}\left(\cos n\pi - 1\right) - \frac{T_1 - T_0}{L}\cdot\frac{L^2}{n\pi}\cos n\pi$$

$$= -\frac{L}{n\pi}\cdot\left(T_1\cos n\pi - T_0\right)$$

Substituting in (3) and simplifying

$$T = T_0 + \left(T_2 - T_0\right)\frac{x}{L} + \frac{2}{\pi}\left(T_2 - T_1\right)\sum_{n=1}^{\infty}\frac{\cos n\pi}{n}\sin\frac{n\pi}{L}x\cdot\exp\left(-K\frac{n^2\pi^2}{L^2}t\right)$$

$$\frac{\partial T}{\partial x} = \frac{T_2 - T_0}{L} + \frac{2}{L}\left(T_2 - T_1\right)\sum_{n=1}^{\infty}(-1)^n\exp\left(-K\frac{n^2\pi^2}{L^2}t\right)\cdot\cos\frac{n\pi x}{L}$$

$$\left(\frac{\partial T}{\partial x}\right)_{x=0} = \frac{T_2 - T_0}{L} + \frac{2\left(T_2 - T_1\right)}{L}\sum_{n=1}^{\infty}(-1)^n\exp\left(-K\frac{n^2\pi^2}{L^2}t\right) \qquad \ldots\ldots(4)$$

In a particular case if

$$L = 3 \text{ feet}$$

$$k = .0133 \text{ Btu/ft. hr. } ^{o}F$$

$$\rho = 3 \text{ lb/ft}^3$$

$$Cp = 0.1 \text{ Btu/lb}^{o}F$$

$$K = \frac{k}{Cp\rho} = 0.0444$$

and if

$$T_0 = -260^{o}F$$

$$T_1 = 30^{o}F$$

$$T_2 = 100^{o}F$$

$$\left(\frac{\partial T}{\partial x}\right)_{x=0} = 120 + 46.6\sum_{n=1}^{\infty}(-1)^n e^{-.0487\, n^2 t}$$

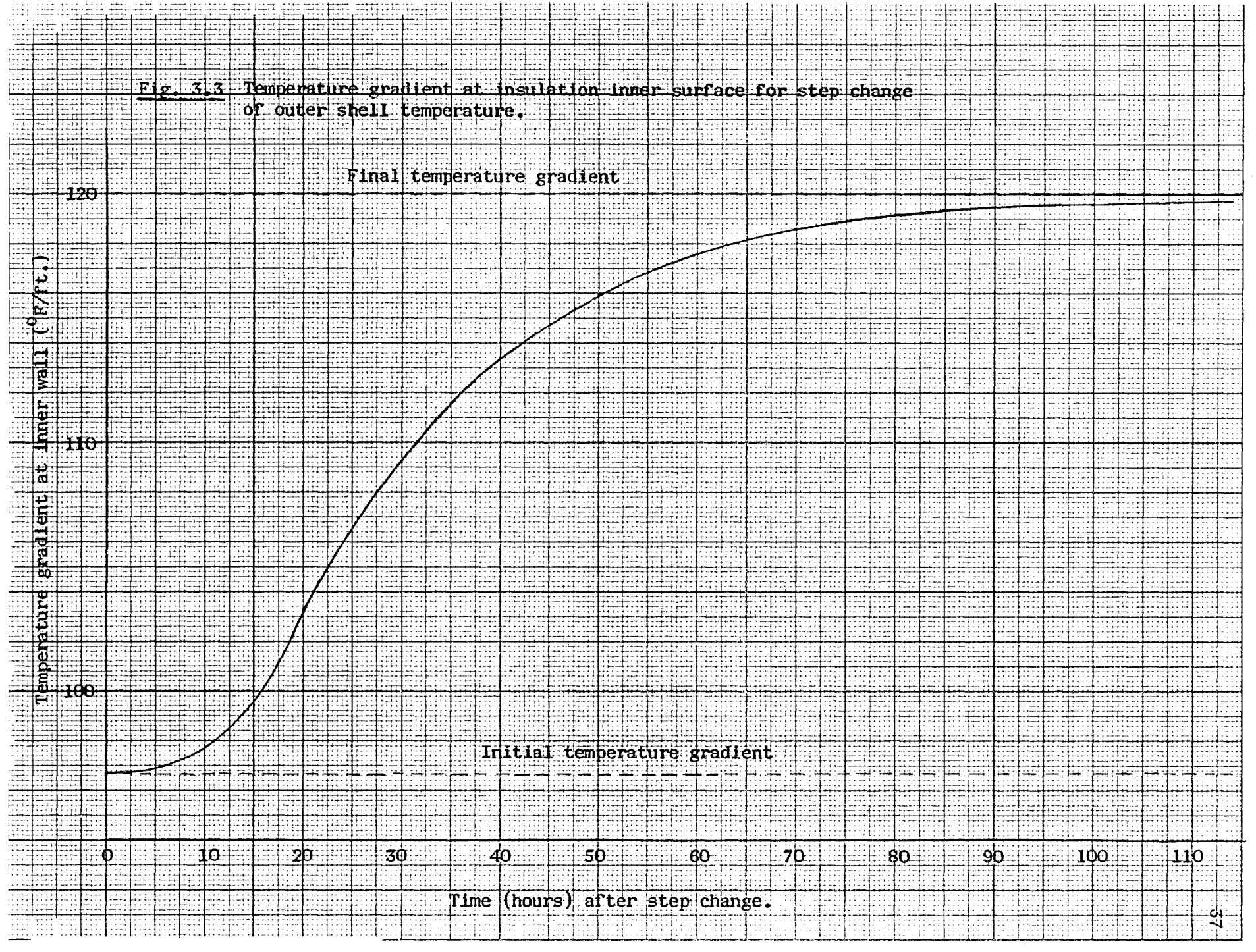
The temperature gradient at the inner tank, so calculated, is shown plotted in Fig. 3.3. This shows that the time taken for the heat transfer to have completed 90% of its change is approximately 64 hours and for 80% of its total change 45 hours.

Another case which may be studied theoretically is that of a linear change in outside temperature.

Linear Change in outside temperature

Suppose the tank starts with a linear temperature distribution through the insulation (constant outside surface temperature) giving a constant rate of heat transfer. If the outside temperature then begins to rise at a steady rate, the rate of heat transfer at the inner surface will begin to rise and, after a sufficiently long time for the initial change to cease to have effect, will be rising linearly with

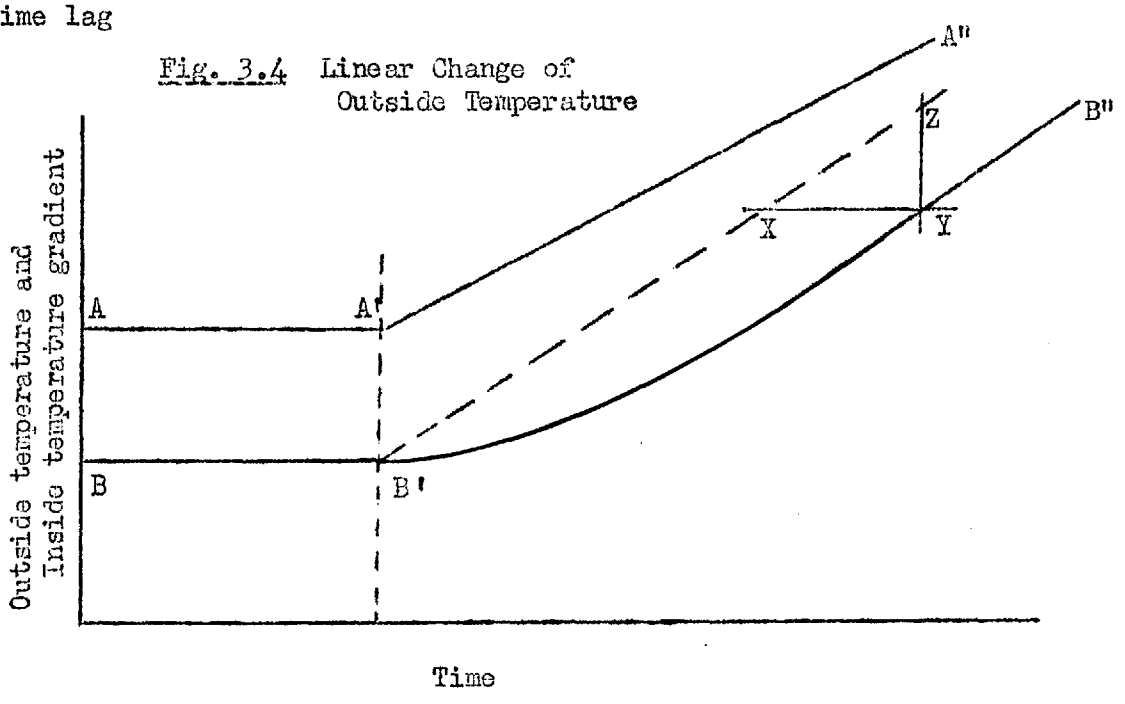
Fig. 3.3 Temperature gradient at insulation inner surface for step change of outer shell temperature.



time but will be lagging behind that value which it would have had if there had been no capacity effects.

This is illustrated graphically in Fig. 3.4 XY represents the time lag

Fig. 3.4 Linear Change of Outside Temperature



AA'A" Outside temperature vs time

BB'B" Inside temperature gradient vs time

Choosing a temperature scale such that the inside temperature at $x = 0$ is 0° we have

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2}$$

with $T = Cx$ at $t = 0$

$T = 0$ at $x = 0$ for all values of t

$T = A + Bt$ at $x = L$

The solution in this case can be shown to be

$$T = \sum_{n=1}^{\infty} \left[\frac{2}{L} \exp\left(-K \frac{n^2 \pi^2}{L^2} t\right) \sin \frac{n\pi}{L} x \left\{ \int_0^L Cx' \sin \frac{n\pi}{L} x' dx' - \frac{n\pi}{L} K \int_0^t \exp\left(-K \frac{n^2\pi^2}{L^2} \lambda\right) \cdot \left(A + B\lambda\right) d\lambda \right\} \right] \quad \ldots\ldots\ldots (5)$$

$$\int_0^L x' \sin \frac{n\pi}{L} x' dx' = - \frac{L^2}{n\pi} (-1)^n$$

and $$\int_0^t \exp\left(-K \frac{n^2 \pi^2}{L^2} \lambda\right) \cdot \left(A + B\lambda\right) d\lambda$$

$$= \frac{L^2}{n^2 \pi^2 K} \left[\left(A - \frac{BL^2}{n^2 \pi^2 K}\right) \left\{ \exp\left(\frac{n^2 \pi^2}{L^2} Kt\right) - 1 \right\} + Bt \exp\left(\frac{n^2 \pi^2 K}{L^2} t\right) \right]$$

Hence by substituting and simplifying

$$T = \sum_{n=1}^{\infty} 2 \sin \frac{n\pi}{L} x (-1)^{n+1} \cdot \frac{1}{n\pi} \left[CL \exp\left(-K \frac{n^2 \pi^2}{L^2} t\right) + \left(A - \frac{BL^2}{n^2 \pi^2 K}\right) \left\{ 1 - \exp\left(- K \frac{n^2}{L^2} t\right) \right\} + Bt \right] \ldots\ldots\ldots (6)$$

If t is sufficiently large, terms containing $\exp\left(-K \frac{n^2 \pi^2}{L^2} t\right)$ may be neglected and equation (6) becomes

$$T = \sum_{n=1}^{\infty} 2 \sin \frac{n\pi}{L} x \ (-1)^{n+1} \cdot \frac{1}{n\pi} \left\{ A + Bt - \frac{BL^2}{n^2 \pi^2 K} \right\} \quad \ldots\ldots\ldots (7)$$

The rate of boil-off is proportional to $\left(\frac{\partial T}{\partial x}\right)_{x = 0}$ but if equation (7) is differentiated with respect to x a divergent series is obtained which does not, therefore represent $\frac{\partial T}{\partial x}$.

We can, however, obtain an approximation to the gradient at x = 0 by putting $x = \delta x$ in equation (7)

Then $\left(\frac{\partial T}{\partial x}\right)_{x=0} \quad \frac{T(x=\delta x) - T(x=0)}{x} = \frac{T(x=\delta x)}{x}$

$$\frac{T(x=\delta x)}{x} = \frac{1}{\delta x}\sum_{n=1}^{\infty} 2\sin\frac{n\pi}{L}\delta x(-1)^{n+1}\cdot\frac{1}{n\pi}\left\{A + Bt - \frac{BL^2}{n^2\pi^2 K}\right\}$$

$$= \frac{2(A+Bt)}{\delta x}\sum_{n=1}^{\infty}(-1)^{n+1}\cdot\frac{1}{n\pi}\sin\frac{n\pi}{L}\delta x$$

$$- \frac{2BL^2}{K\delta x}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{1}{n^3\pi^3}\sin\frac{n\pi}{L}x.$$

It can be shown, using Fourrier series methods that

$$2\sum_{n=1}^{\infty}(-1)^{n+1}\frac{1}{n}\sin\frac{n\pi}{L}\delta x = \pi\frac{\delta x}{L}$$

and $$12\sum_{n=1}^{\infty}(-1)^{n+1}\frac{1}{n^3}\sin\frac{n\pi}{L}\delta x = \pi^3\frac{\delta x}{L} - \pi^3\left(\frac{\delta x}{L}\right)^3$$

$$\therefore \quad \frac{T(x=\delta x)}{x} = \frac{1}{L}(A+Bt) - \frac{BL}{6K}\left\{1 - \left(\frac{\delta x}{L}\right)^2\right\}$$

Therefore, in the limit as $\delta x \longrightarrow 0$

$$\frac{T(x=\delta x)}{x} = \left(\frac{\partial T}{\partial x}\right)_{x=0}$$

i.e. Temperature gradient (G) at the inside surface is given by

$$G = \frac{1}{L}(A+Bt) - \frac{BL}{6K}$$

If there were no delay involved then

$$G = \frac{T_{(x=L)}}{L}$$

$$= \frac{A+Bt}{L}$$

So that in Fig. 3.4 the magnitude of YZ is given by

$$\frac{BL}{6K}$$

Slope of A'A" = B

& Slope of B'Z $= \frac{B}{L}$

$$XY = \frac{BL}{6K} \times \frac{L}{B}$$

$$= \frac{L^2}{6K}$$

This is independent of B so that for any linear change of outside temperature the inside temperature gradient will experience a time lag equal to $\frac{L^2}{6K}$

As in the previous example if L = 3 feet

and K = .0444

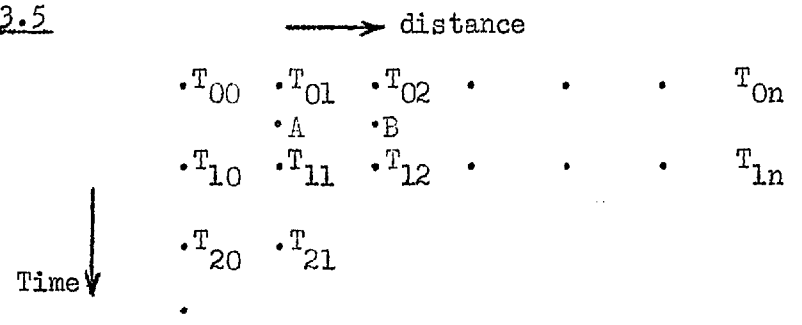
Time Lag = 34 hours

3.5 A finite difference method for the solution of the general case

In general, if the outside temperature is not a simple function of time, an exact mathematical solution to equation (1) is impossible. A finite difference method of solution has been developed to solve the equation given empirical temperatures at x = 0 and x = L and an initial temperature distribution in the insulation.

If the insulation is considered to be split into n equal steps in the thickness and T_{00}, T_{01}, T_{02} ..... T_{0n} are the temperatures at t = 0, T_{10}, T_{11}, T_{12}, ... T_{1n}, are the temperatures at t = one time step from the beginning, then the system may be represented diagramatically as shown in Fig. 3.5.

Fig. 3.5



T_{00}, T_{01}, T_{02}, etc. are given as the original temperature distribution at $t = 0$

T_{10}, T_{20}, T_{30} etc. are given as the outside temperature at given time intervals

T_{1n}, T_{2n}, T_{3n} etc. are given as the inside temperature at the same intervals.

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2}$$

At A (x = 1 distance step, $t = \frac{1}{2}$ time step)

$$\frac{\partial T}{\partial t} \simeq \frac{T_{11} - T_{01}}{Y}$$

and $$\frac{\partial^2 T}{\partial x^2} \simeq \frac{\frac{1}{2}\left\{(T_{02} - T_{01}) - (T_{01} - T_{00})\right\} + \frac{1}{2}\left\{(T_{12} - T_{11}) - (T_{11} - T_{10})\right\}}{X^2}$$

where Y = length of 1 time step

X = length of 1 distance step

Thus $$(T_{11} - T_{01})\frac{2X^2}{YK} \simeq (T_{02} - 2T_{01} + T_{00}) + (T_{12} - 2T_{11} + T_{10})$$

T_{00} T_{01} T_{02} T_{10} are all known

$\therefore$ T_{12} may be calculated in terms of T_{11}

Similarly by considering the point B

T_{13} may be calculated in terms of T_{11} and T_{12} and hence in terms of T_{12} alone.

In General

$$T_{tr} = K_1 T_{t(r-1)} - T_{t(r-2)} + \gamma_r$$

where $\gamma_r = -T_{(t-1)r} + K_2 T_{(t-1)(r-1)} - T_{(t-1)(r-2)}$

$$K_1 = 2\left(1 + \frac{YK}{K^2}\right)$$

$$K_2 = 2\left(1 - \frac{YK}{K^2}\right)$$

It can be shown that, expressing T_{tr} in terms of $T_{t(r-1)}$ if

$$T_{tr} = M_r T_{t(r-1)} + C_r$$

then $$M_r = K_1 - \frac{1}{M_{(r-1)}}$$

$$C_r = \frac{C_{(r-1)}}{M_{(r-1)}} + \gamma_r$$

with $M_2 = K_1$ and $C_2 = \gamma_2 - T_{t,0}$

Thus beginning with M_2, C_2 at t = 1 successive values of M and C may be calculated from the preceeding values and from the γ_r terms which are functions of $T_{(t=0)}$ (known)

Finally we have $T_{1n} = M_n T_{1(n-1)} + C_n$

But T_{1n} is known (inside temperature at t = 1)

$\therefore$ $T_{1(n-1)}$ may be calculated.

Working back across the thickness of the insulation each value of $T_{(t=1)}$ may now be calculated.

Moving on to the next step in time the process is repeated until the temperature distribution throughout the insulation at all times has been calculated.

The temperature gradient (G) at the inside wall may then be calculated at each time by

$$G = \frac{T_{(n-1)} - T_n}{X}$$

Determination of total heat transfer

The heat transfer per unit area (Q) across the inside face at any time is then given by

$$Q = \frac{T_{(n-1)} - T_n}{X} \cdot k$$

and the total heat transfer over any time interval may be calculated by numerical integration of the values thus calculated.

If G_0, G_1, G_2, G_3 ..... G_N are the temperature gradients at intervals of one time step over the period for which total heat transfer is required then the total heat transfer (Q_T) may be assumed to be

$$Q_T = k\left\{\frac{Y}{2}(G_0 + G_1) + \frac{Y}{2}(G_1 + G_2) + \frac{Y}{2}(G_2 + G_3)..... + \right\}$$

$$= kY\left\{\tfrac{1}{2}G_0 + G_1 + G_2 + ... + G_{(n-1)} + \tfrac{1}{2}G_n\right\}$$

Determination of the Best Time Lag in the General Case

In the case of a linear change in outside temperature the total heat transfer over any period of time could be calculated by using the mean temperature of the outside shell over a period of the same length but with the introduction of the requisite time-lag. In the general case, it is obvious that an accurate estimation of the heat inleak cannot be obtained simply by using mean outside temperatures even with the introduction of a time-lag. It is of interest, however, to determine the magnitude of the time lag which would give the best correlation of temperature gradient with outside shell temperature.

This may best be achieved by a method of regression, introducing various time lags and then correlating temperature gradients with outside shell temperatures to determine which time lag gives the most significant correlation.

If a series of n temperature gradients G_0, G_1, G_2 ..... $G_{(n-1)}$ are correlated with n outside temperatures T_0, T_1, T_2 ..... $T_{(n-1)}$ then the best straight line through the points is given by

$$G = MT + C$$

$$\text{where } M = \frac{n \sum GT - \sum G . \sum T}{n \sum G^2 - \left(\sum G\right)^2}$$

$$\text{and } C = \frac{\sum T}{n} - M \frac{\sum G}{n}$$

$\sum G$, $\sum T$ etc. are written for $\sum_{r=0}^{r=n} G_r$, $\sum_{r=0}^{r=n} T_r$ etc

The significance of the correlation or "closeness of fit" of the points to this line has been expressed in a number of ways. One such expression Student's t is given by

$$t' = r . \sqrt{\frac{n-2}{1-r^2}}$$

$$\text{where } r = \frac{n \sum GT - \sum G . \sum T}{\left\{n \sum G^2 - \left(\sum G\right)^2\right\}^{1/2} \left\{n \sum T^2 - \left(\sum T\right)^2\right\}^{\frac{1}{2}}}$$

The number of degrees of freedom is equal to n - 2. Graphs of Student's t against the number of degrees of freedom for various degrees of significance are given in standard mathematical text books (e.g. Ref. 32). If n - 2 is greater than 10 it may be assumed that t' is independent of n and the significance of fit is expressed only by t'.

CHAPTER IV

Experimental Determination of Heat Leakage into a Liquid Methane Storage Tank

4.1 Details of Storage Tank

The storage tank shown in Fig. 4.1 consists of an inner aluminium tank 50ft. in diameter and 50ft. high surrounded by a mild steel shell. The annualar space between the two is filled with perlite, an expanded mineral powder insulation. A six inch thick blanket of "Fibroceta" is attached to the aluminium tank wall and separates it from the powder. The purpose of this blanket, which is resilient, is to allow for movement of the aluminium tank (due to thermal expansion) without causing excessive packing of the powder insulant. The inner tank rests on an insulating brickwork structure and the whole assembly stands on a concrete platform supported some three feet above ground level on 97 concrete pillars 21 inches in diameter.

The construction of the tank is shown in Fig. 4.2 and detailed dimensions are as follows:

Aluminium Tank

Height to centre of domed roof = 52 ft. $8\frac{7}{8}$ ins.

Radius of curvature of domed roof = 50 ft. $0\frac{3}{8}$ ins.

Thickness of roof = $\frac{3}{8}$ ins.

Sides consist of 8 courses 5 ft. 9 ins. high with butt-welded joints.

Bottom course thickness = $9/16$ in.

2nd course thickness = $1/2$ in.

3rd course thickness = $7/16$ in.



Fig. 4.1 Liquid Methane storage tanks, Canvey Island

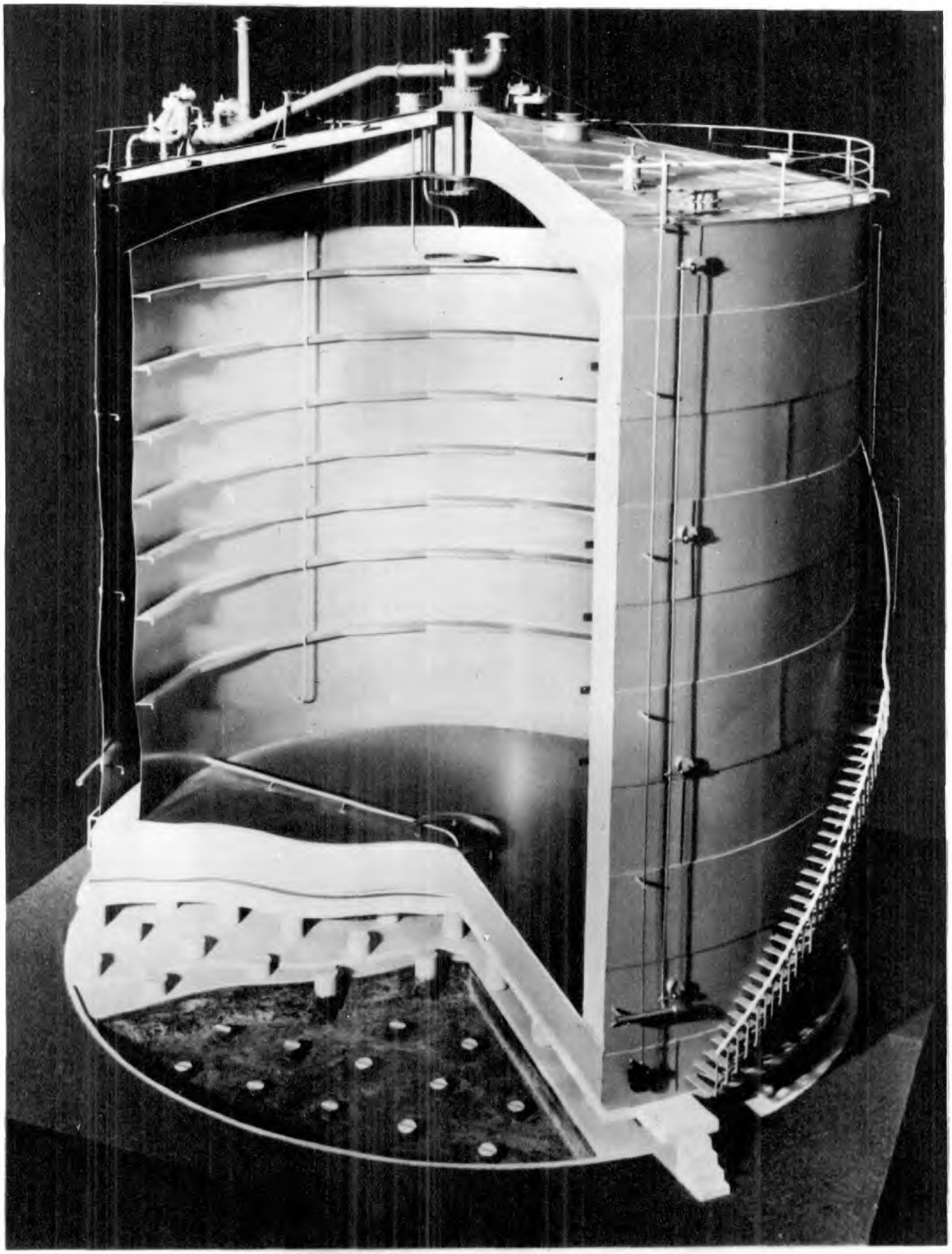


Fig. 4.2 Section of Liquid Methane Storage Tank, Canvey Island

4th and subsequent courses, thickness = $\frac{3}{8}$ in.

Outside diameter = 50 ft. $0\frac{3}{8}$ in.

Mild Steel outer tank

Height to centre of conical roof = 61 ft. 7 ins.

Height of straight sides = 56 ft. 0 ins.

Thickness of sides and base = $\frac{1}{4}$ in.

Thickness of roof = $\frac{3}{16}$ in.

Diameter (inside) = 55 ft. $9\frac{3}{8}$ ins.

The outer surface of the mild steel tank is painted dark green up to level of 15 ft. above the concrete plinth. The upper part of the sides and the roof are light green.

Liquid level in the tank is measured by a float and tape level indicator calibrated in feet and inches to $\frac{1}{10}$ inch. A diagrammatic representation of this device is given in Fig. 4.3. The float and tape are stainless steel.

Twelve thermocouples were used to determine the temperature at various positions on the tank outer shell and on the concrete base. The thermocouples were of 22 swg. copper-constantan wire with silver-soldered junctions. One junction of each was fixed to the tank at the point of temperature measurement while the second, acting as a reference junction, was surrounded by a glass sheath and immersed in water contained in a 4 in. diameter dewar vessel. The dewar was in turn surrounded by slag wool insulation. The e.m.f. developed was fed to a 12 point recording potentiometer with a $\pm$ 5 mV full-scale deflection.

The junctions attached to the mild steel tank were clamped within mild steel blocks approximately 2 ins. diameter and $\frac{3}{4}$ in. thick, welded

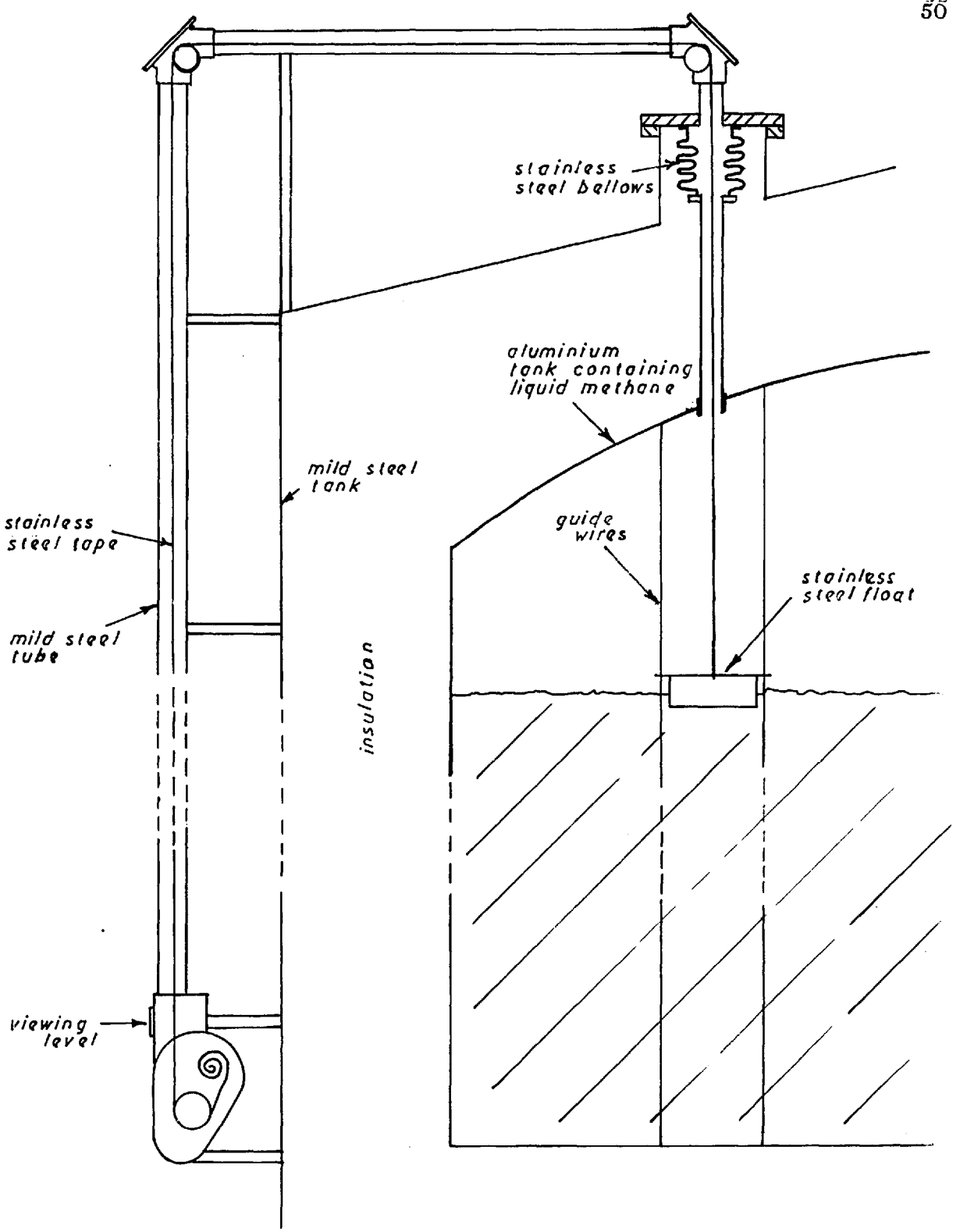


FIG. 4.3 FLOAT AND TAPE LIQUID LEVEL INDICATOR

to the tank outer surface. The thermocouple junction inside a short length of soft copper tubing was inserted into a hole drilled into the block parallel to the tank side and clamped in position by means of a $\frac{1}{4}$ in. diameter bolt protruding through the hole wall. The soft copper deformed and gave good thermal contact between thermocouple and tank wall, at the same time preventing damage to the thermocouple junction by the clamping screw.

The temperature of the underside of the concrete platform was measured by a length of thermocouple wire coiled in the form of a flat spiral 1 in. in diameter, with the junction at the centre. The spiral was pressed firmly to the underside of the concrete base by means of a copper disc and a wooden strut wedged between it and the ground.

One thermocouple only was used for the base since a preliminary investigation showed very small temperature differences on different parts of the base. The thermocouple was situated at a distance of approximately one third of the radius from the outer edge.

Two thermocouples were inserted into $1\frac{3}{4}$ in. deep holes at different heights in one of the concrete pillars to determine whether any appreciable temperature gradient could be detected. These thermocouples were held in place by packing the holes with asbestos fibre.

The positions of the various thermocouples were as follows:

Thermocouple Number	Position
1	Approximately 15 ft. above concrete platform on tank West side
2	Approximately 15 ft. above concrete platform on tank South side

Thermocouple Number (contd.)	Postition (contd.)
3	Approximately 15 ft. above concrete platform on tank East side.
4	In concrete pillar, approximately 1 in. from top
5	Approximately 18 ft. from top of straight side on tank West side.
6	Approximately 18 ft. from top of straight side on tank South side.
7	In concrete pillar approximately 1 in. above ground level.
8	Approximately 18 ft. from top of straight side on tank North side.
9	On concrete base
10	On top of tank. South side, 12 ft. 3 ins. from outer edge.
11	On top of tank. East side, 12 ft. 3 ins. from outer edge.
12	Ambient temperature (a few yards under tank).

4.2 Experimental Procedure

Liquid methane levels, tank gauge pressure, gauge pressure in the annulus, and reference junction temperature were measured every hour and e.m.f.s of the thermocouples were recorded continuously over a period of six weeks while the tank was in use for the storage of liquid methane.

Liquid levels were held constant for periods as long as possible bearing in mind that methane was being evaporated and used almost

continuously. This was achieved by isolating the tank for a period and using methane from the second tank until its level was low. Methane was then allowed to flow from the first tank into the second and the procedure was repeated.

In this way measurements for levels of 42, 30, 15 and 5 ft. were obtained.

4.3 Readings

Tank level indicator readings, tank pressures and annulus pressures at 1 hour intervals over the period of the tests were obtained from the operating records of the Liquid Methane terminal held by the North Thames Gas Board. Thermocouple e.m.f.s, measured from the recorder charts, are given at 3 hour intervals in the computer data input (see chapter 4.9). In some cases the readings of ambient temperature and the temperatures inside the concrete pillars have been omitted. In these cases the digit 1 has been included to keep the total number of readings correct. (e.g. Run 4).

4.4 Corrections to Level Indicator Readings

Differences in liquid methane levels as measured by the level indicator will be in error due to the change in temperature of the tape as it comes into contact with the cold gas in the tank. This error will, however, be very small. A change in level of 1 foot would cause a change in temperature, in the worst case, of approximately 350°F in 1 foot of the tape. This would cause a contraction of $350 \times 7 \times 10^{-6}$ ft. $= 2.4 \times 10^{-3}$ ft., an error of less than $\frac{1}{4}$ per cent. More significant errors will be introduced by movement of the outer steel tank due to variations in temperature and pressure.

A simple increase in temperature of the steel outer tank causing an increase in linear dimensions will be balanced by a similar increase in the length of the tape outside the tank since the coefficients of expansion of mild steel and stainless steel are very similar. Under conditions of strong sunshine, however, the tank will deform considerably due to the uneven temperature distribution and error will be introduced into the level indicator reading.

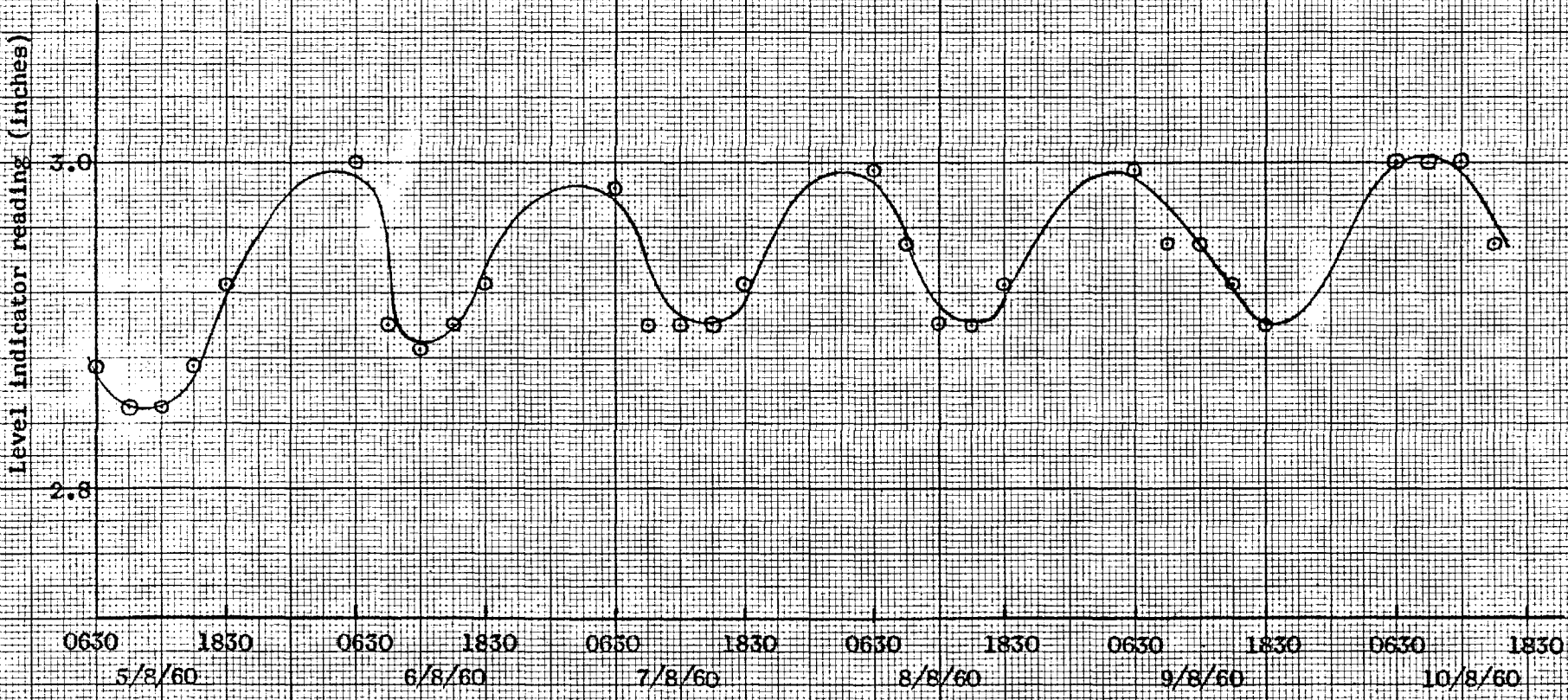
For example, the difference in temperature between opposite sides of the tank has been observed (in strong sunshine) to be as great as $70^{\circ}F$. Over a 50 ft. length of tank side this represents a difference in height of approximately 0.3 inches. Considerable distortion of the tank is, therefore, likely and the effect of this on the level indicator reading cannot easily be calculated.

A typical variation of the reading is shown in Fig. 4.4 which represents the tank level indicator readings over a period of several days, the tank being empty and tank and annulus being at atmospheric pressure. The lower end of the tape, normally attached to the float was clamped to the tank floor. The graph shows a regular daily variation of approximately 0.1 inch.

Error due to this cause may be minimised by drawing smooth curves through the plot of level indicator reading vs time.

Changes in the gauge pressure of the annular space between the tanks will cause movement of the outer shell which will affect the level indicator reading. Tests were carried out to determine the extent of the error introduced in this way.

Fig. 4.4 *Variations in liquid level indicator reading due to temperature cycling in tank outer shell.*



In these tests the level indicator reading was taken at five minute intervals while liquid was being pumped into the tank. Annulus pressures were also measured at five minute intervals and sudden changes were made in the annulus pressure by venting it to atmosphere. Graphs of liquid level indicator against time gave discontinuities where the pressure had changed and, from these graphs, the change of reading for a given pressure increase was determined.

Table 4.1 gives liquid level indicator readings and annulus pressures during the course of the test.

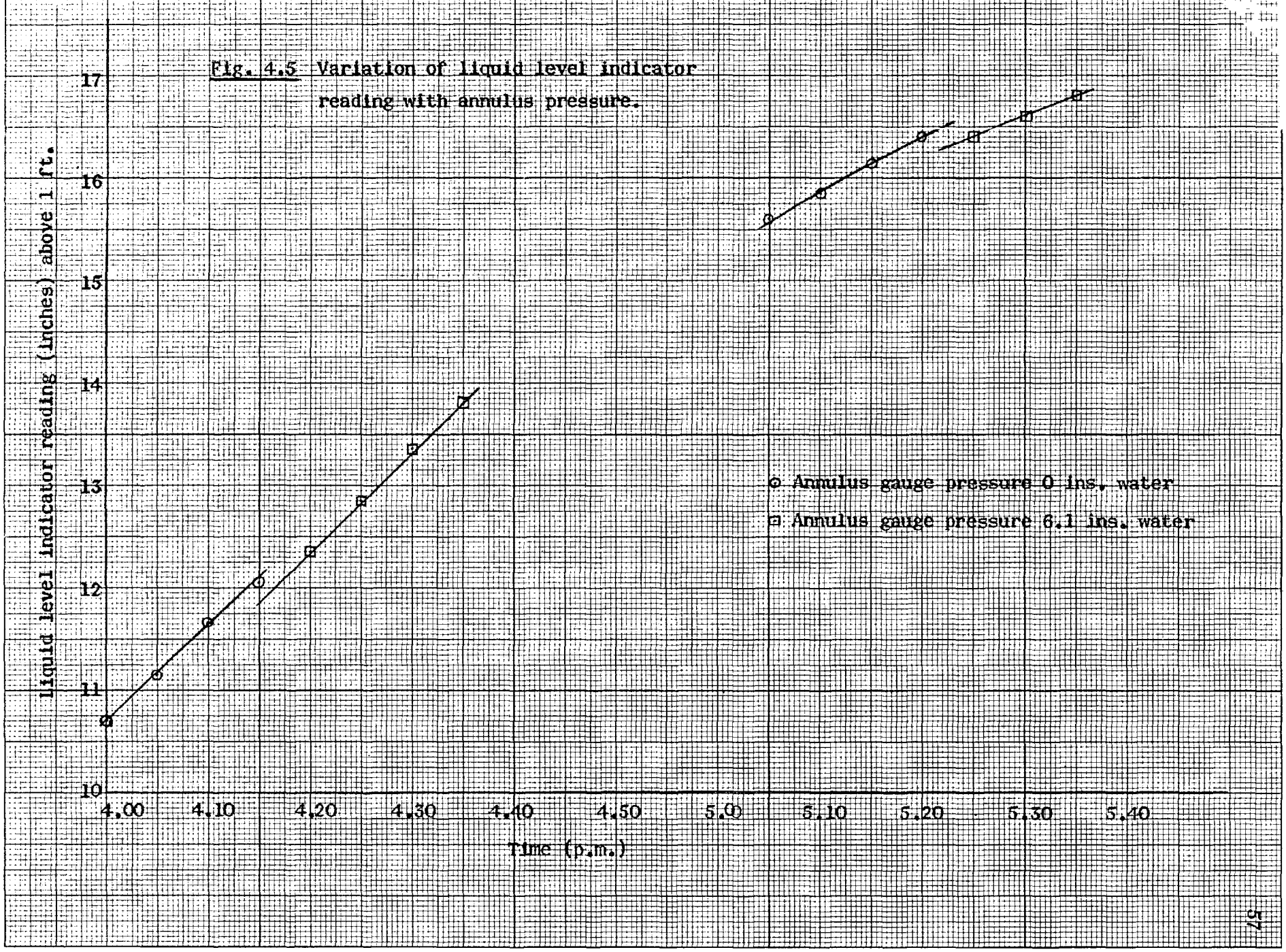
Fig. 4.5 shows that for an increase in annulus pressure of 6.1 in. of water the level indicator reading changes by 0.22 in. Thus, the correction to be applied for annulus pressure is 0.036 in. per in. of water annulus pressure.

4.5 Choice of Test Periods

It was shown in 3.2 that atmospheric pressure changes are likely to have a profound effect on the rate of boil-off from a liquefied gas storage tank. A record of atmospheric pressure for the location of the tests was, therefore obtained from the Meteorological Office. Figs. 4.6 to 4.11 show the variation of methane pressure (atmospheric pressure plus tank gauge pressure) over the periods of constant level. The best test periods were chosen as those over which the pressure had gone, as nearly as possible, through a complete cycle. In all cases a period of at least 48 hours was allowed after a change of level before a test period was begun.

In the case of run 2 (30 ft. level) it was not possible to choose

Fig. 4.5 Variation of liquid level indicator reading with annulus pressure.



a period over which the pressure had gone through a complete cycle so the results for this level must be regarded as less reliable than those for other tests.

4.6 Determination of Evaporation Rate Over Selected Periods

The tank level readings (corrected to zero annulus pressure) are plotted as a function of time in Figs. 4.12 to 4.17. Smooth curves were drawn and the total evaporation (expressed as inches of liquid) was determined for the selected periods and corrected for any net change of pressure.

4.7 Results

The results of the evaporation rate measurements are summarised in Table 4.2. The method of treatment in each case was the same as for run 1 given below.

Speciment Calculation for Run 1

Approximate level = 42.7 ft.

Selected period of test = 0001 hrs. 3/4/60

to 0300 hrs. 7/4/60

Time interval = 99 hrs.

Net increase of pressure = 1026.3 - 1020.7 millibars (Fig. 4.12)

= 5.6 millibars

This is equivalent to a rise in boiling point of 0.121°F

Mass of methane in tank $= 42.7 \times \frac{\pi}{4} \times 50^2 \times 26.4$

$= 2.21 \times 10^6$ lbs.

∴ Heat required to raise temperature 0.121°F

$= 0.121 \times 0.84 \times 2.21 \times 10^6$

$= 2.24 \times 10^5$ Btu.

Fig. 4.6 Corrected Methane Pressure, Run 1.

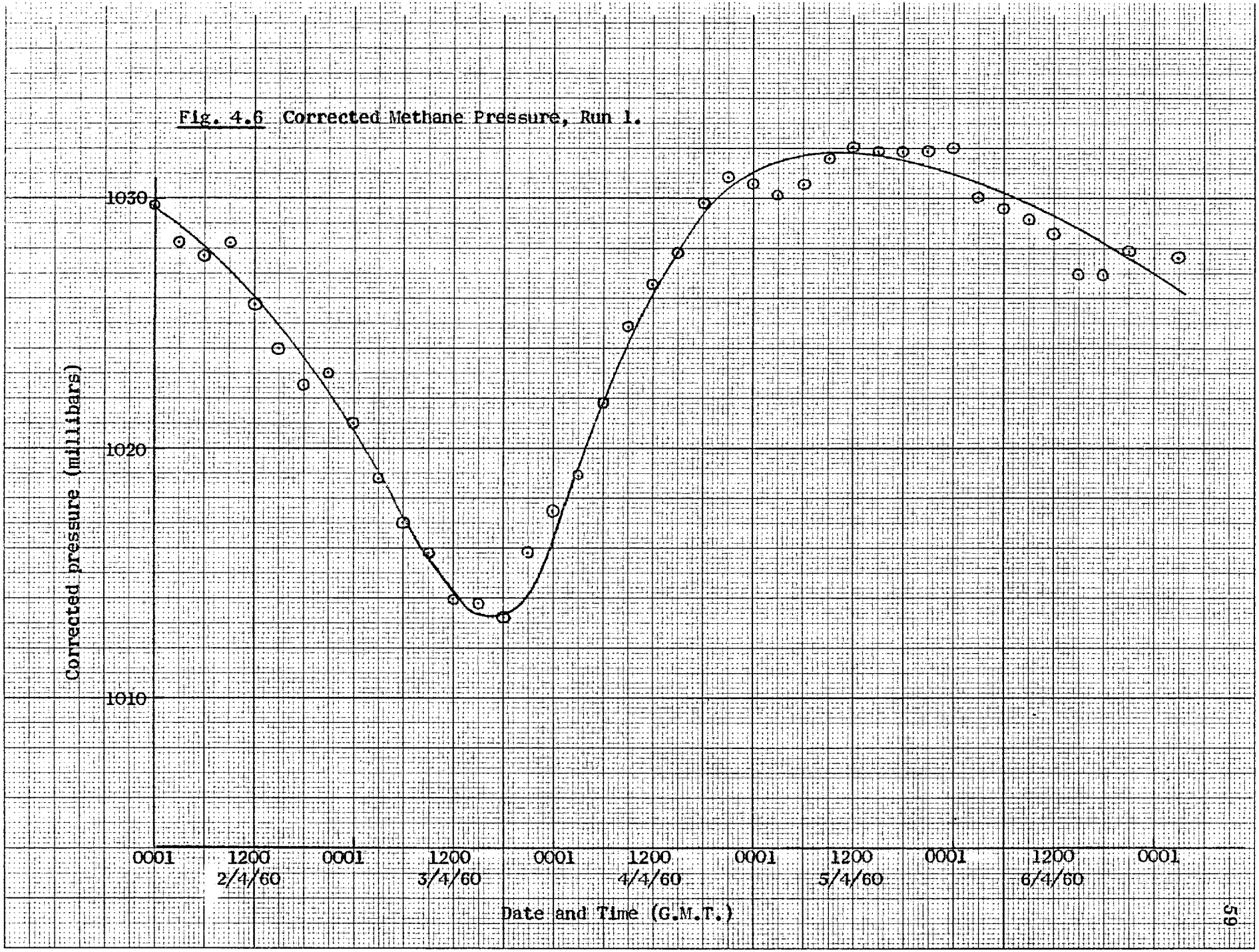


Fig. 4.7 Corrected Methane Pressure, Run 2.

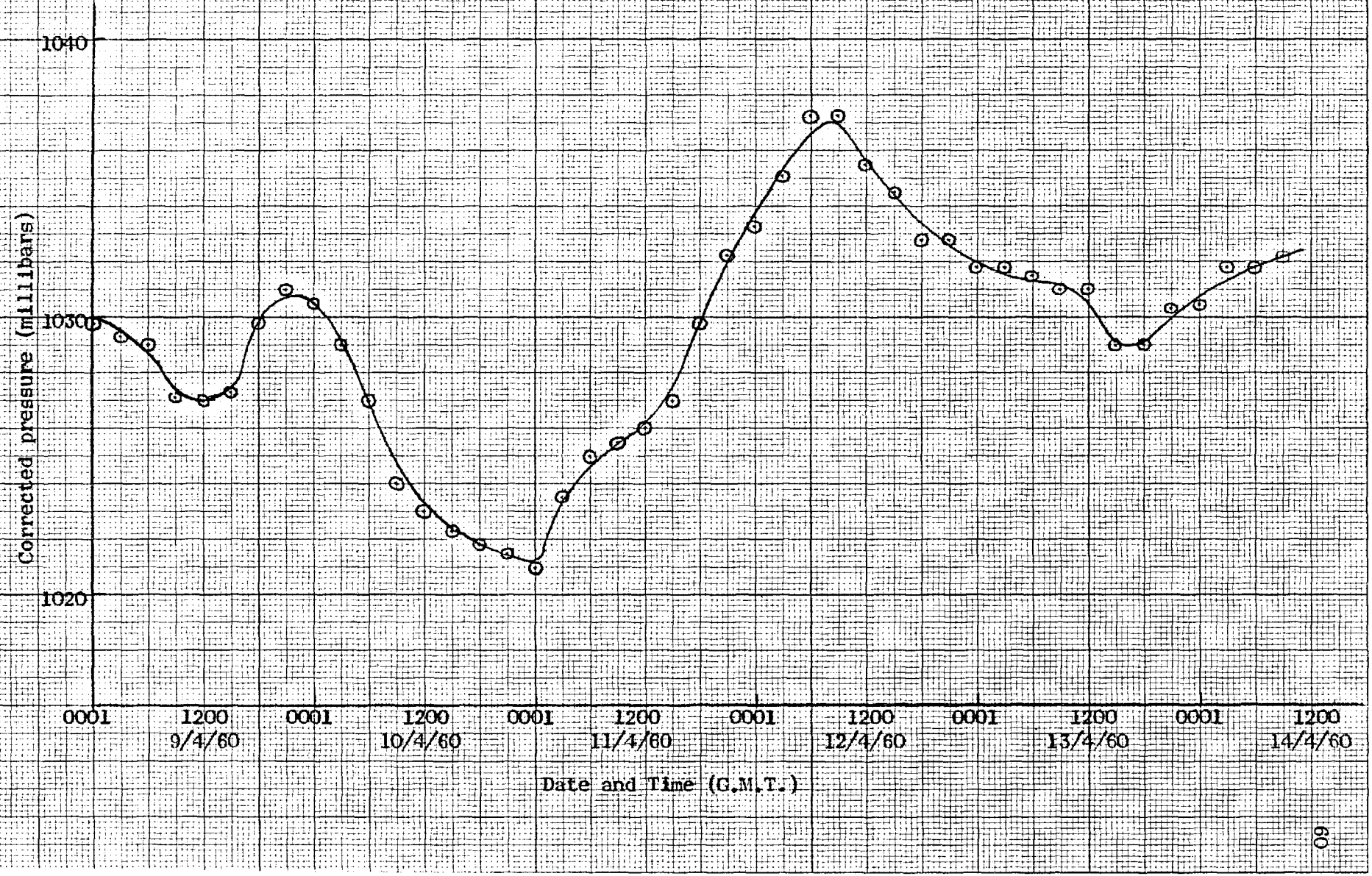


Fig. 4.8 Corrected Methane Pressure, Run 3.

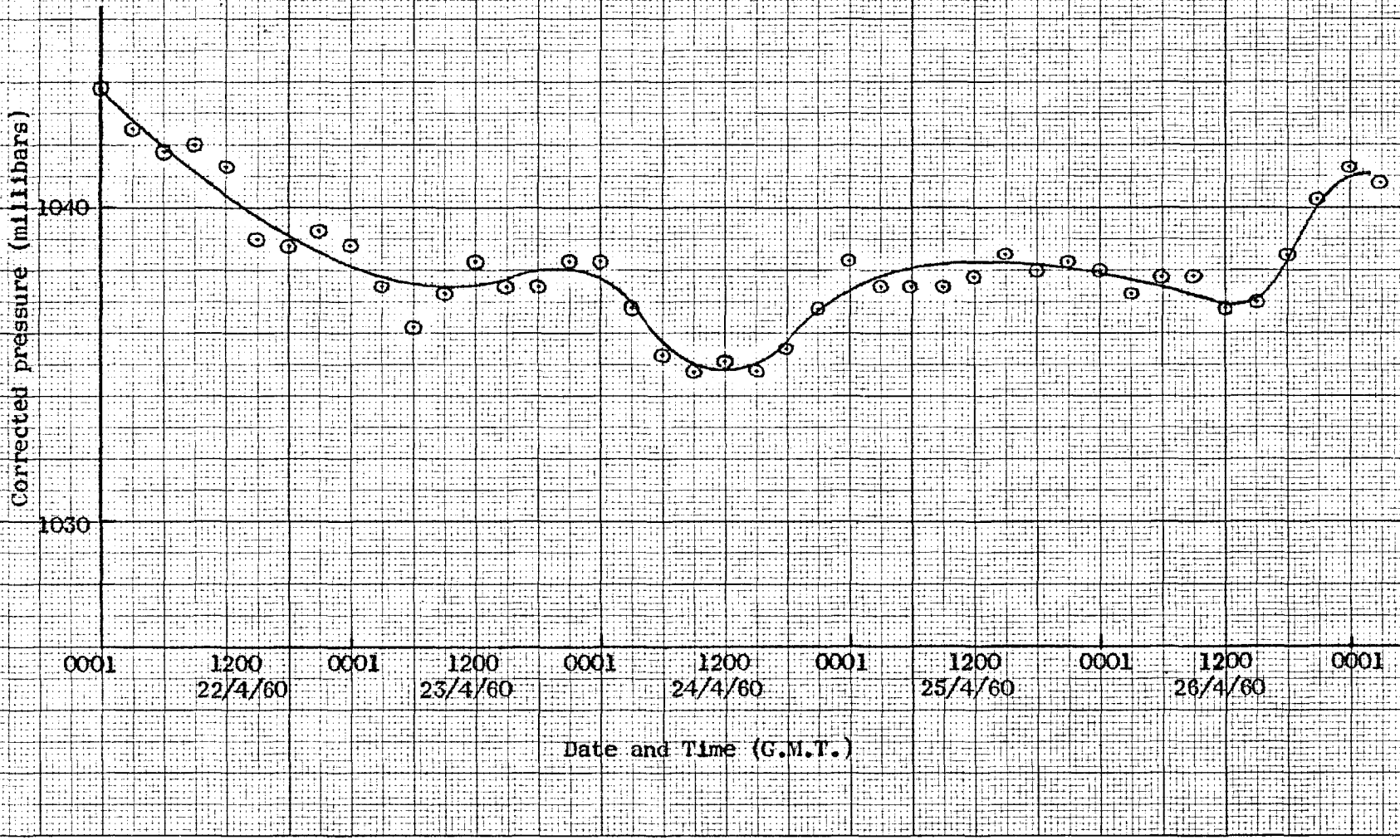


Fig. 4.9 Corrected Methane Pressure, Run 4.

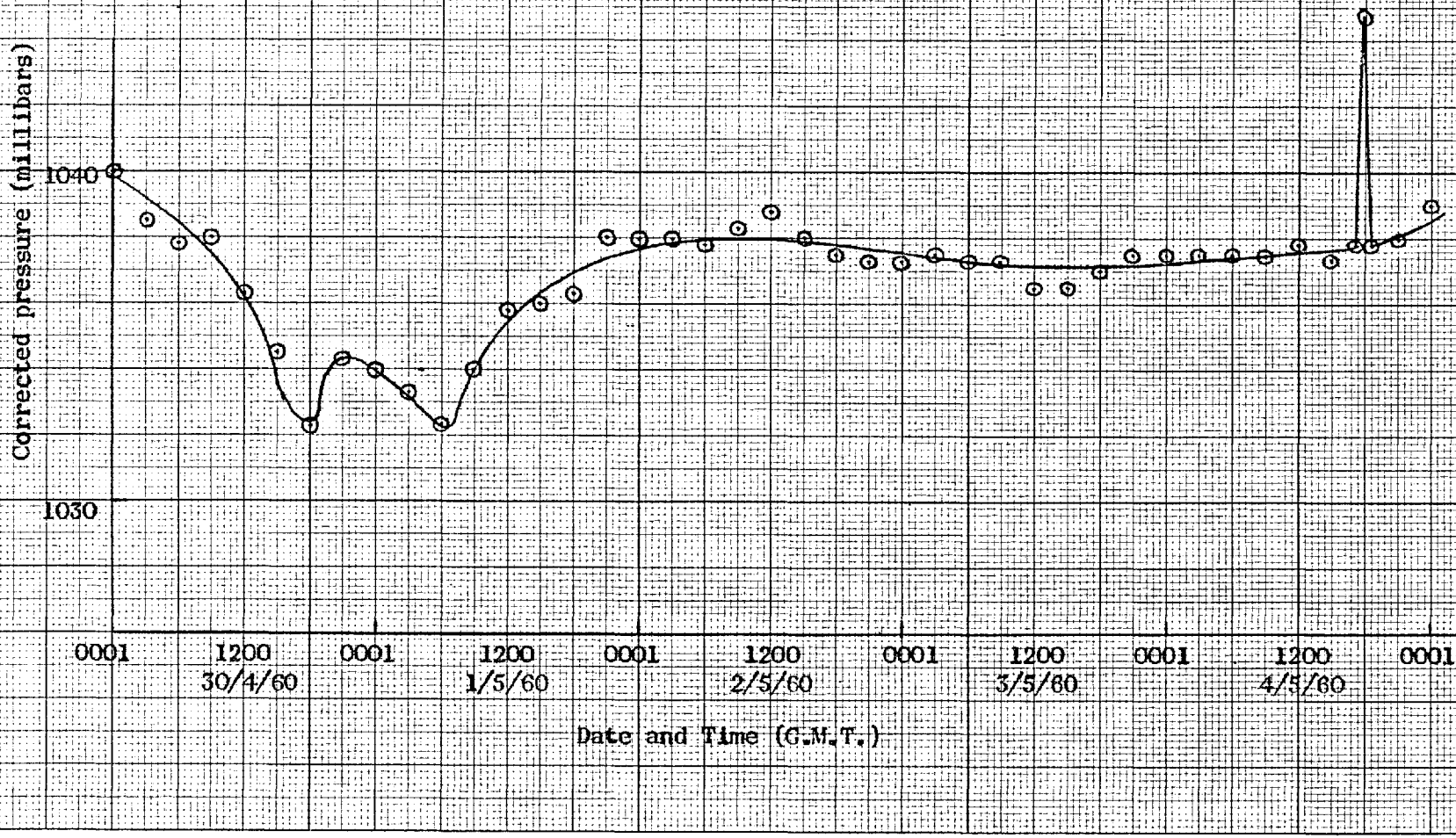


Fig. 4.10 Corrected Methane Pressure, Run 5.

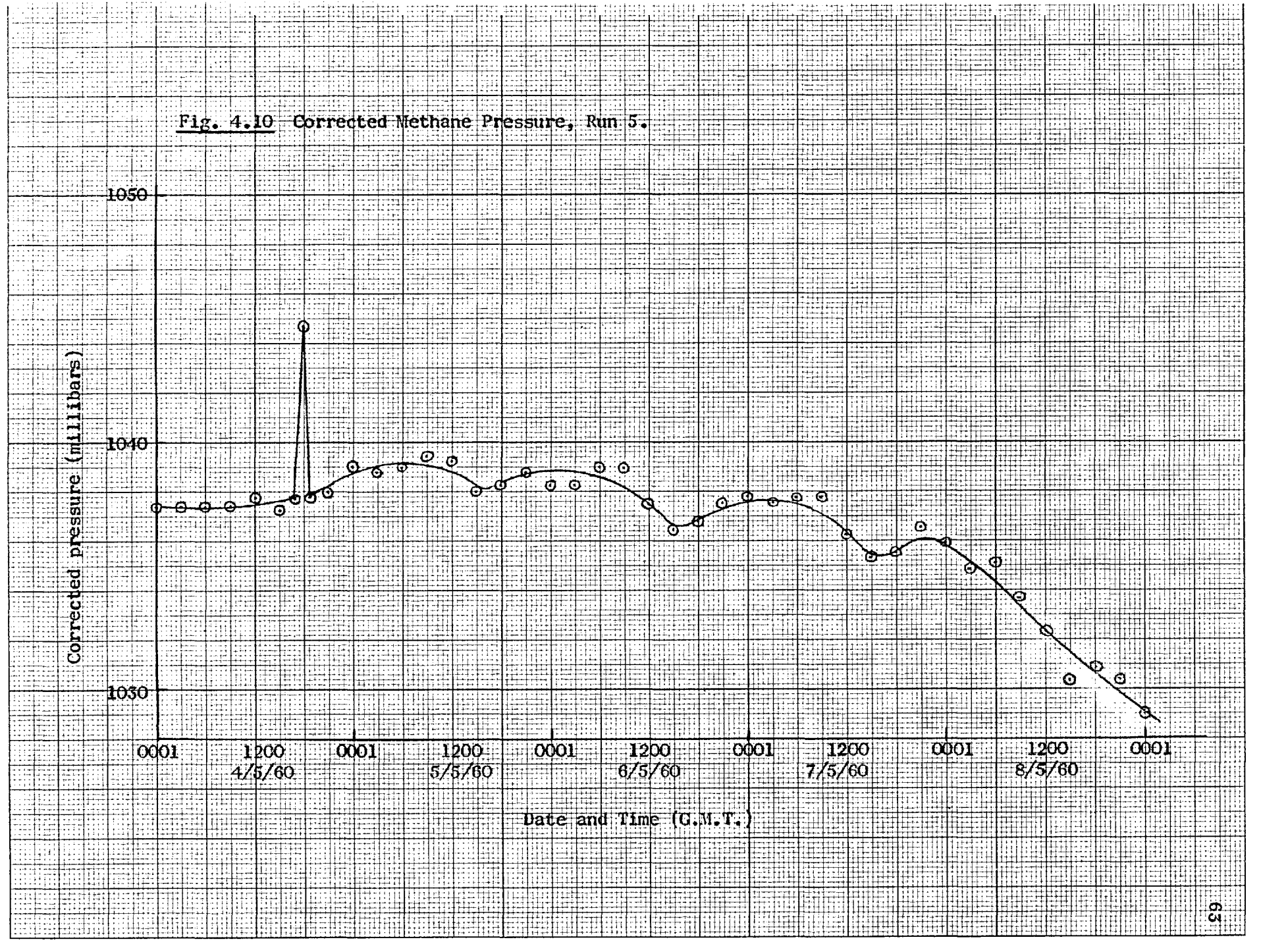


Fig 4.11 Corrected Methane Pressure, Run 6.

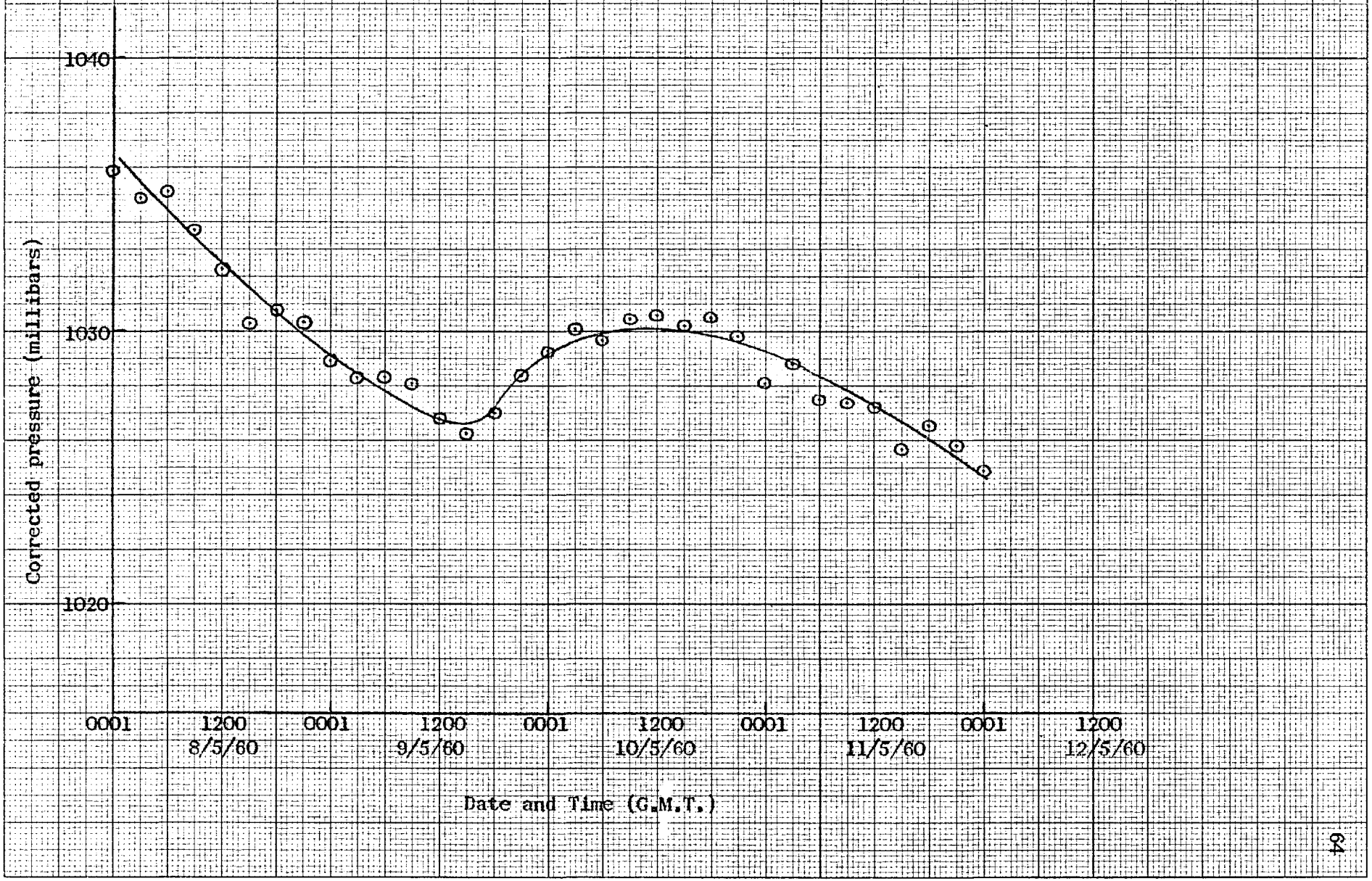
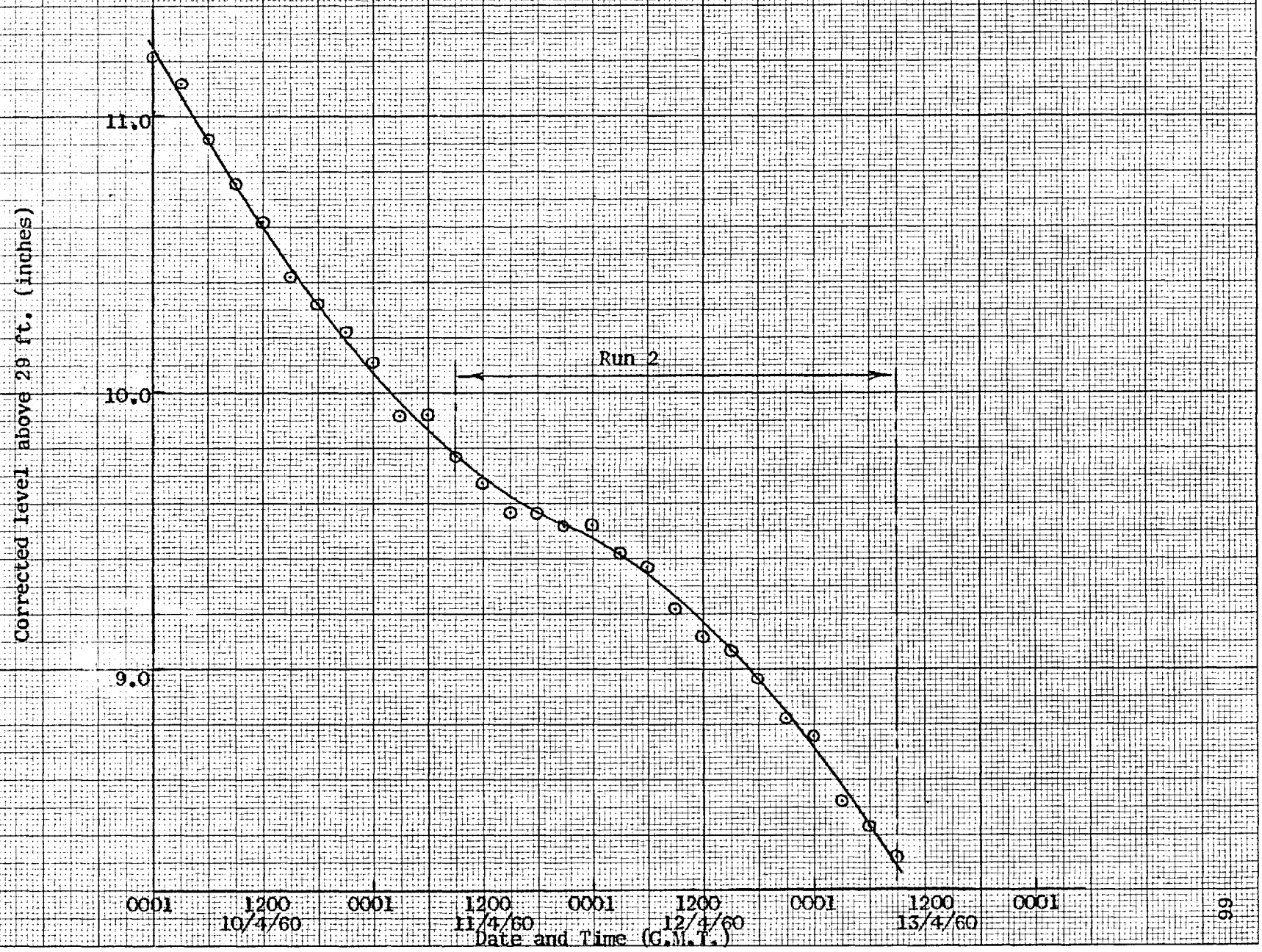


Fig. 4.12 Corrected Liquid Methane Level, Run 1



Fig 4.13 Corrected Liquid Methane Level, Run 2.



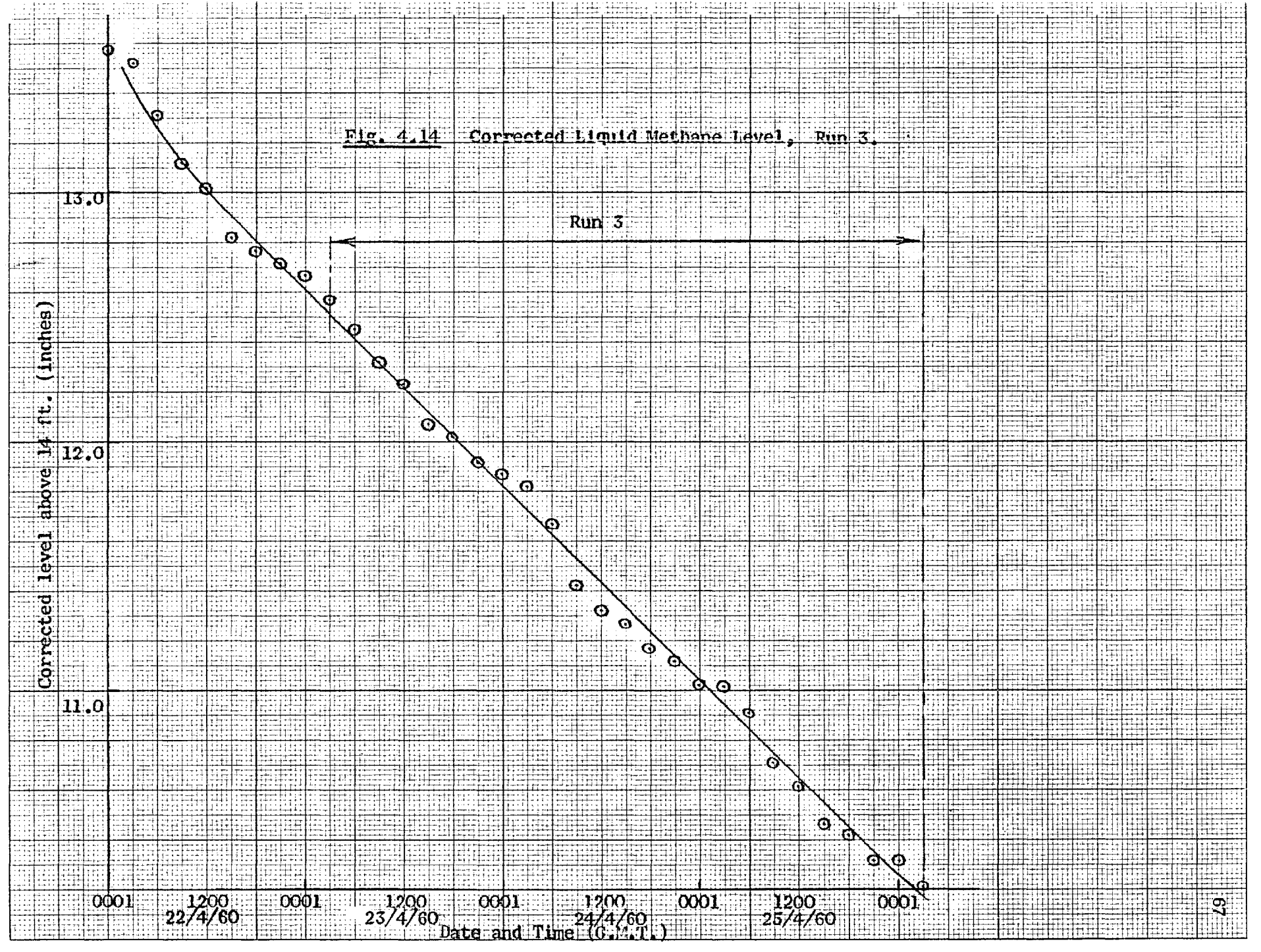
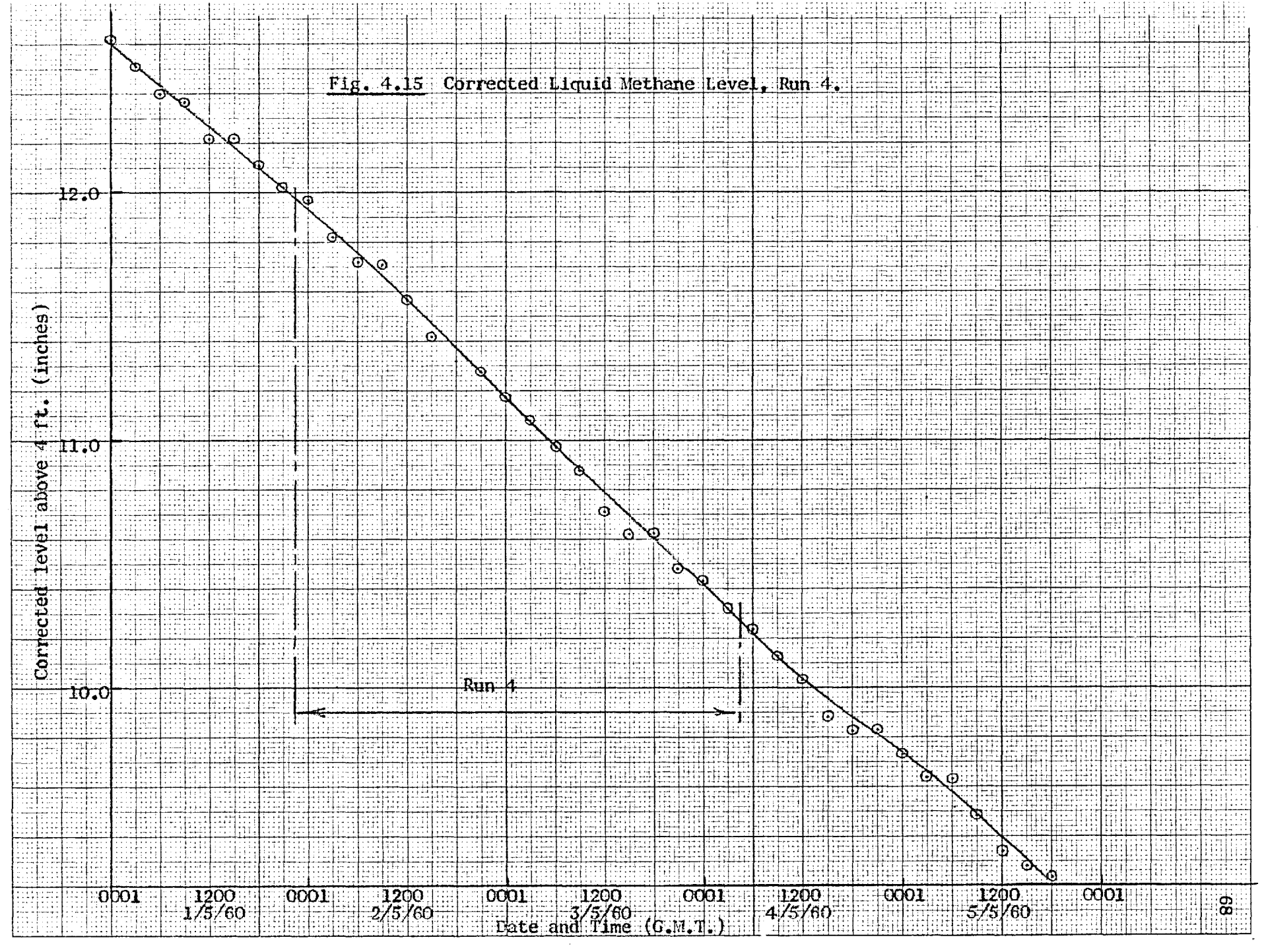


Fig. 4.14 Corrected Liquid Methane Level, Run 3.


Fig. 4.15 Corrected Liquid Methane Level, Run 4.
12.0
11.0
10.0
Corrected level above 4 ft. (inches)
Run 4
0001
1200
1/5/60
0001
1200
2/5/60
0001
1200
3/5/60
0001
1200
4/5/60
0001
1200
5/5/60
0001
Date and Time (G.M.T.)

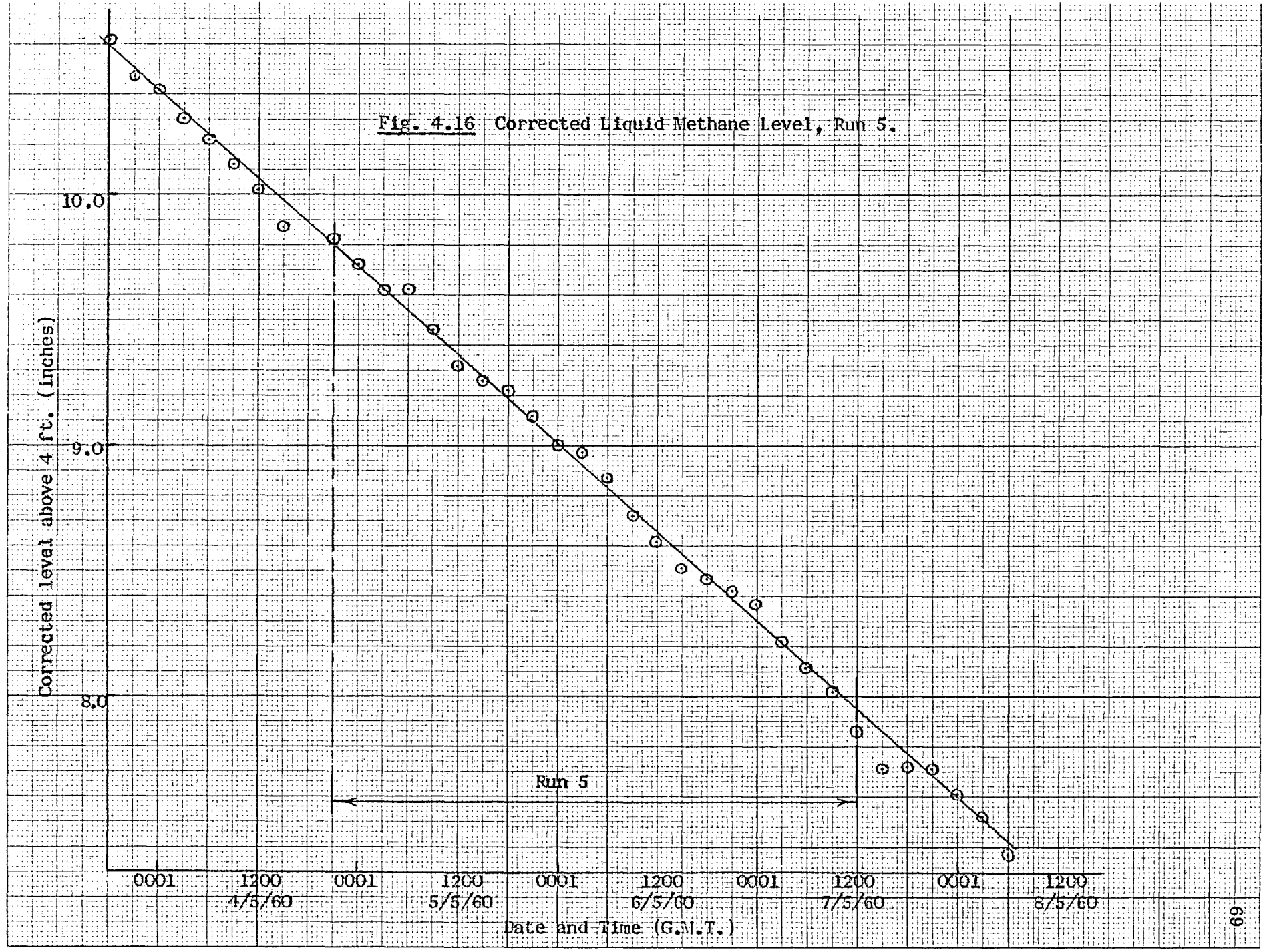


Fig. 4.16 Corrected Liquid Methane Level, Run 5.

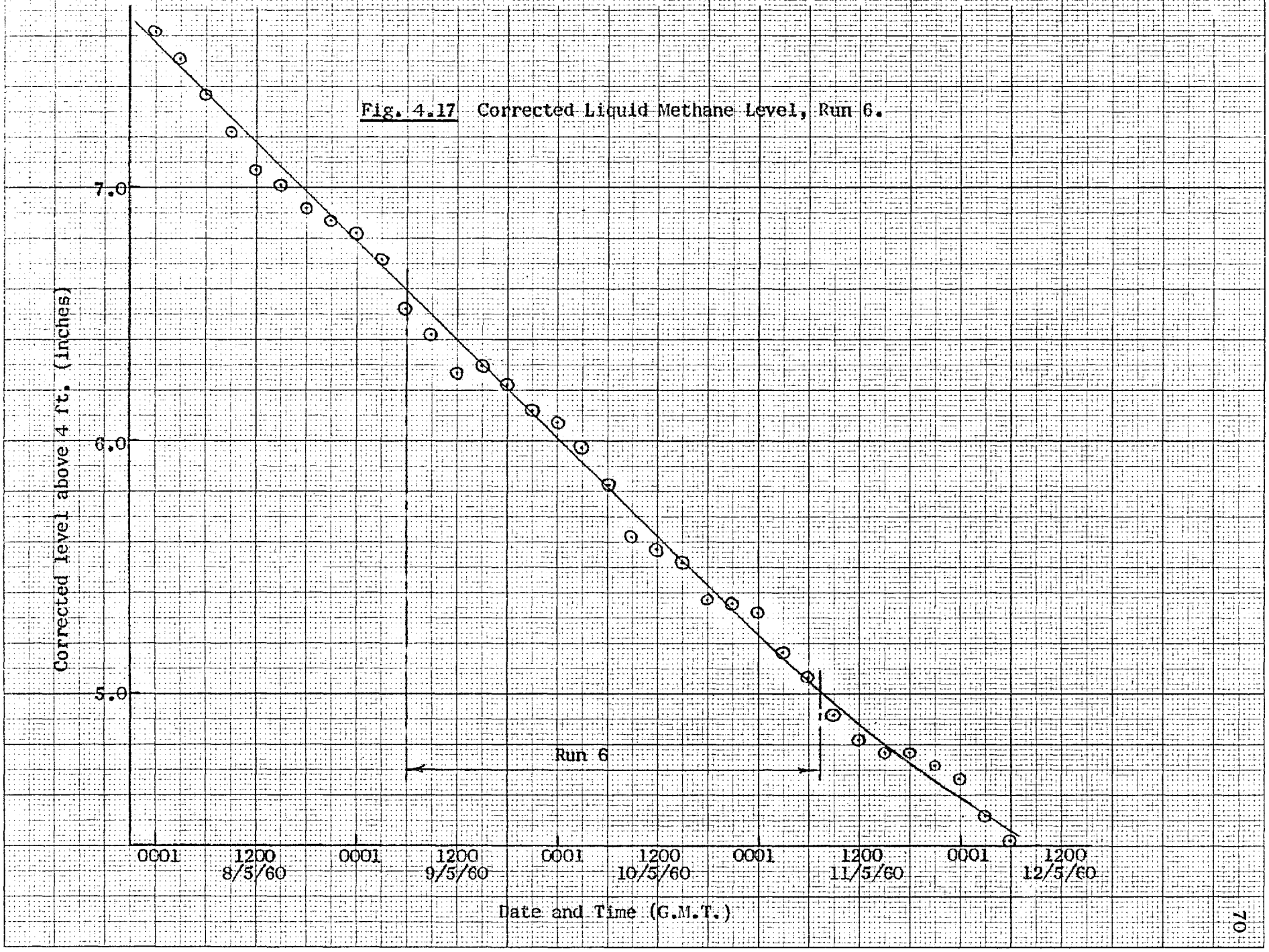


Fig. 4.17 Corrected Liquid Methane Level, Run 6.

Boil-off equivalent = 0.23 ins. of methane liquid

Change in level over period of test = 42 ft. 10.85 ins.

- 42 ft. 7.07 ins.

= 3.78 ins.

∴ Boil-off equivalent of total heat inleak = 4.01 ins.

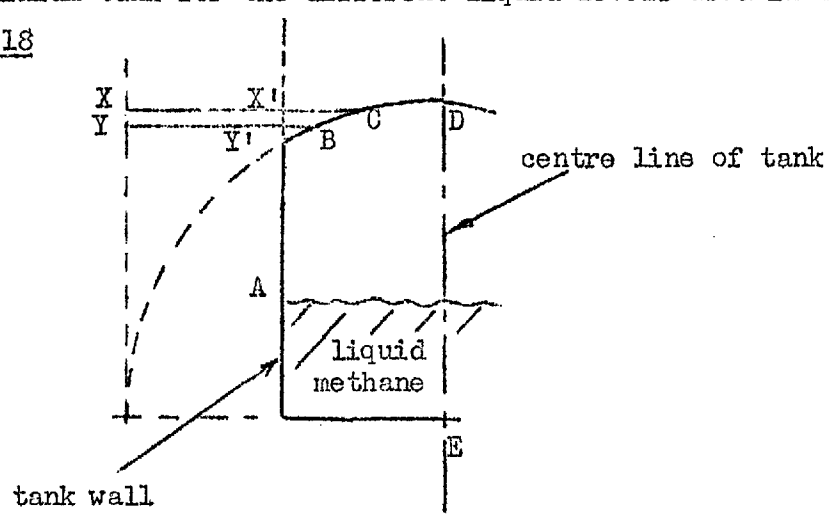
= 0.0405 ins./hr.

In the case of Run 1 a correction to the level change was applied because of a sudden increase in level at 0600 hrs. on 6th April which was probably due to the accidental introduction of liquid into the tank (Fig. 4.12).

4.8 Estimation of Aluminium Tank Temperatures for Different Levels of Liquid Methane

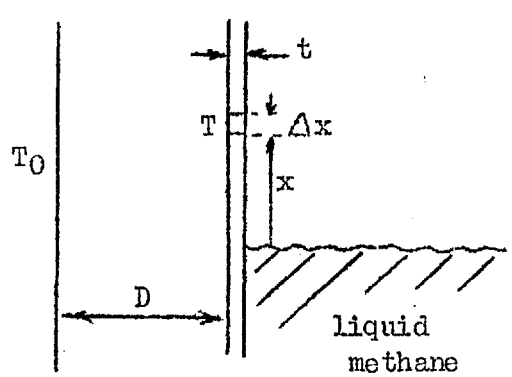
When the level of liquid methane in the tank is low, the roof and upper parts of the aluminium tank sides may warm up considerably due to heat leakage through the insulation. The following calculations were carried out to determine the approximate temperatures of all parts of the aluminium tank for the different liquid levels used in the tests.

Fig. 4.18



Referring to Fig. 4.18 on previous page, the area of the surface of revolutionof BC about DE is equal to the area of the surface of revolution of XY about DE. The radius of curvature of the dome is twice the radius of the aluminium tank so that the area of the surface of revolution of BC is twice the area of the surface of revolution of X'Y'. The insulation on the roof, however, is thicker than that in the annulus by a factor of about 1.6 so that for a similar temperature difference the heat leakage through BC could be assumed equal to the heat leakage through a length X'Y' of the vertical wall without the introduction of a large error. The problem may thus be simplified, with very little loss of accuracy, to one of an aluminium plate of uniform thickness ($\frac{3}{8}$") and height equal to the height of the tank DE, losing heat through insulation of thickness 2.875 ft. with an outside temperature equal to the mean outer wall temperature during each run. If it is assumed that there is no heat lost or gained from the exposed inner surface of the inner shell this is equivalent to assuming that there is no heat transfer from the aluminium shell to the gas above the liquid. The temperature of the tank wall immediately adjacent to the liquid surface is assumed to be - 258°F, and at a height equal to that of the dome it is assumed that the rate of change of temperature with height is zero.

Fig. 4.19



Referring to Fig. 4.19,

D = thickness of the insulation (ft.)

t = " " aluminium wall (ft.)

k_I = thermal conductivity of the insulation (Btu./ft.^{2}hr.(^{o}F/ft.))

k_A = " " " " aluminium "

T_0 = temperature of outer face of insulation (^{o}F)

T = temperature of the aluminium wall at a height x feet above the liquid surface.

Considering an element of the aluminium wall of height Δx and of unit length in a horizontal direction along the plane of the wall.

Rate of flow of heat into element from below = $- k_A \frac{dT}{dx} \cdot t$

Rate of flow of heat into element from above = $k_A t \cdot \frac{d}{dx}\left(T + \frac{dT}{dx}\Delta x\right)$

Rate of flow of heat into element through the insulation

$$= - k_I \cdot \Delta x \cdot \frac{(T - T_0)}{D}$$

In the steady state the net rate of flow of heat into the element is zero so that

$$k_A t \frac{d^2T}{dx^2} \Delta x - k_I \Delta x \frac{(T - T_0)}{D} = 0$$

or $$\frac{d^2T}{dx^2} = \frac{k_I}{k_A} \cdot \frac{1}{D \cdot t} (T - T_0)$$

from which

$$T - T_0 = Ae^{cx} + Be^{-cx}$$

where $$c^2 = \frac{k_I}{k_A} \cdot \frac{1}{D \cdot t} (T - T_0)$$

At the mean temperature it may be assured that

$$k_I = 0.015 \text{ Btu/ft}^2\text{hr}(^\circ\text{F/ft})$$

$$k_A = 130 \quad "$$

$$D = 2.875 \text{ ft.}$$

$$t = 3/96 \text{ ft.}$$

$$\therefore C = \sqrt{\frac{.015}{130} \cdot \frac{96}{3} \cdot \frac{1}{2.875}}$$

$$= \sqrt{12.8 \times 10^{-4}}$$

$$= .0358$$

$$T - T_0 = Ae^{.0358x} + Be^{-.0358x} \quad \ldots\ldots\ldots\ldots\ldots 1$$

Equation (1) gives the temperature T of the aluminium wall at any height x. The constants A and B will differ for each run and may be calculated from the boundary conditions

at $x = 0$ $\quad T = -258^\circ F$

at $x = H$ $\quad \frac{dT}{dx} = 0$

where H = height of the aluminium tank roof above the liquid surface.

The mean temperature T_M of the tank surface between any two levels x_1 and x_2 is given by

$$T_M = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} T dx \quad \ldots\ldots\ldots (2)$$

The temperatures of parts of the aluminium tank in contact with methane liquid were assumed to be equal to the boiling point of methane at that point taking into account the increase in boiling point with depth of methane.

Using equations (1) and (2), the mean temperatures of the various parts of the tank were calculated for runs 1 to 6.

Specimen Calculation for Run 3

Density of methane liquid = 26.4 lb/ft^3

$\therefore$ Increase of pressure with depth = $\frac{26.4}{144}$ psi per ft.

= 0.183 psi per ft.

Increase of Boiling point with pressure

= 1.49°F per psi

$\therefore$ Increase of Boiling point with depth

= 0.273°F per ft.

Mean depth of liquid = 14.9 ft.

$\therefore$ Mean temperature of base = -258 + 14.9 x 0.273

= -254°F

Mean temperature of outside surface = 49°F

Height of tank roof (at centre) above liquid surface

= 52.74 - 14.93

= 37.81 ft.

$\therefore$ In equation (1)

when $x = 37.8$ $\quad \frac{dT}{dx} = 0$

i.e. $.0358\ Ae^{.0358 \times 37.8} + .0358\ Be^{-.0358 \times 37.8} = 0$

hence $3.86A = \frac{B}{3.86}$

$B = 14.9A$

when $x = 0 \quad T = -258$

$\therefore$ $(-258 - 49) = A + B$

$-307 = 15.9A$

$$A = -19.3$$

$$B = -287.7$$

$$\therefore \quad \underline{T = 49 - 19.3\, e^{.0358x} - 287.7\, e^{-.0358x}}$$

Aluminium Tank Roof

$$\text{Mean Temperature} = \frac{1}{6.74} \int_{31.07}^{37.81} \left(49 - 19.3\, e^{.0358x} - 287.7\, e^{-.0358x}\right) dx$$

$$= \frac{1}{6.74}\left[49 \times 6.74 - \frac{19.3}{.0358}(3.86 - 3.04) + \frac{287.7}{.0358}\left(\frac{1}{3.86} - \frac{1}{3.04}\right)\right]$$

$$= 49 - 149$$

$$= \underline{-100^{\circ}F}$$

Aluminium Tank Wall Inside Light Green Part of Tank

Mean temperature of aluminium tank wall above methane

$$= \frac{1}{31.07} \int_{0}^{31.07} \left(49 - 19.3\, e^{.0358x} - 287.7\, e^{-.0358x}\right) dx$$

$$= \underline{-161^{\circ}F}$$

Height of light green - dark green boundary above base of steel tank = 15 ft.

Thickness of insulation in base = 3.75 ft.

$\therefore$ Height of boundary above base of aluminium tank

$$= 11.25 \text{ ft.}$$

and height above methane surface = 3.68 ft.

$\therefore$ Mean temperature of wall in contact with liquid

$$= -258 + \frac{3.68}{2} \times 0.273$$

$$= \underline{-257^{\circ}F}$$

∴ Mean temperature of Aluminium tank for whole of the light green section

$$= \frac{3.68 \times -257 + 31.07 \times -161}{34.75}$$

$$= \underline{-172^{\circ}F}$$

Aluminium tank wall inside dark green part of tank

The aluminium tank wall inside the dark green part of the tank is completely in contact with liquid.

$$\text{Mean Temperature} = -258 + \frac{3.68 \times 0.273 + 14.9 \times 0.273}{2}$$

$$= -258 + 3$$

$$= \underline{-255^{\circ}F}$$

The results of this calculations for each run are summarised in Table 4.3.

4.9 A Solution of the Unsteady State Equation for Heat Leakage into a Liquid Methane Storage Tank using an Electronic Digital Computer

The calculation of evaporation rate using the finite-difference method described in 3.5 was programmed for solution by Ferranti Pegasus computer. The programme was written to calculate the temperature gradients at the inside wall directly from thermocouple e.m.f.s. and reference junction temperatures.

The programme was written mainly in Pegasus autocode and uses the sixcode input routine (Ref. 16) for data input. It is flexible in that it can use any number of steps in length across the insulation and any magnitude of time step. E.m.f. data may be given at any convenient time interval and the programme assumes a linear change of temperature between times at which data have been given.

Because of the differences in the nature and thickness of the insulation in different parts of the tank and because of the considerable differences in temperature between the upper, light green, and the lower, dark green, parts of the tank sides, the programme was written to carry out the calculation in four separate parts or "phases", namely, the roof, the light green section of the sides, the dark green section of the sides, and the base. These will hereafter be referred to as phases 0, 1, 2, 3.

Data

The following is a list of data which must be supplied, together with the warning sequences (Ref. 16) used in the data input routine.

DTS Data time step. The interval in hours at which e.m.f. data is supplied.

TSD Number of integration time steps per data time step. This sets the fundamental time step used in the calculation and from which all other time is reckoned.

DST Number of distance steps in the thickness.

TSB Number of time steps from the start of the calculation to the beginning of the period of numerical integration.

TSE Number of time steps from the start of the calculation to the end of the period of numerical integration.

TSP Number of time steps per punching step for the punching of temperature gradients.

CE A conversion factor for converting thermocouple e.m.f. to a temperature difference ($^{o}F/mV \times \frac{1}{100}$)

CL A conversion factor for converting rate of evaporation to rate of change of tank level (ins./lb. of liquid methane).

H Latent heat of evaporisation (Btu./lb.).

All the above warning sequences must be followed by one number which represents the data in the units quoted.

A Area for heat flow for each phase ($ft.^2$).

X Thickness of insulation (ft.).

K Thermal conductivity of insulation ($Btu./ft.^2hr.^oF/in$).

CP Heat capacity of the insulation (Btu/lb^oF).

BD Bulk density of the insulation (lb/ft^3).

BP Aluminium tank temperature.

These warning sequences must be followed by four numbers which represent the data for each of the four phases.

E Thermocouple e.m.f.s. must be given as a series of integers in groups of 12. Each group represents the thermocouple e.m.f., in hundredths of a millivolt, of each of the 12 thermocouples. Successive groups represent the e.m.f.s at successive time intervals given by DTS.

R Reference junction temperatures must be given as integers (^oF) at the same time interval as e.m.f.s.

Print-outs of data tapes for the six runs are given with the programme in Appendix 4.

The Programme

A print-out of the programme is included in Appendix 1 together with a list of the variables and indices with the items which they are used to represent.

Fig. 4.20 is a block diagram of the calculation showing the main steps. The programme (LG) must be read into the computer after Sixcode MK8 or MK9 and must be followed by a data tape which sets all the necessary data and also contains the directives ?, Q, and BO necessary to enter the calculation.

On reading each warning sequence on the data tape the numbers following are stored in the appropriate place in the computer. On reading the directive E the numbers following are stored in v600 onwards. As soon as L is read the programme checks that a multiple of 12 numbers has been stored. If not, the text 'EMF's not multiple of 12, remainder = ' is printed together with the remainder after dividing the total by 12. If the e.m.f.s. have been read correctly data input continues and the directive R causes the reference junction temperatures to be stored in v500 onwards - again a check is made (on reading L) to ensure that the number of reference junction temperatures is equal to the number of dozens of e.m.f. readings. The mean outer shell temperatures for the four phases are then calculated from the appropriate e.m.f. readings and stored in v200 to v500.

On reading ? the main part of the programme is entered and temperature gradients at the inside wall are calculated by the method described in 3.5. After completing the calculation of temperature gradients for the whole duration of the run the programme returns to Sixways input and reads more tape.

The directive Q causes the punching of a table of the calculated temperature gradients for each phase at time intervals given by TSP. Again, on completion, more tape is read.

FIG. 4.20 BLOCK DIAGRAM OF COMPUTER PROGRAMME LG

POSITION OF INSTRUCTIONS IN PROGRAMME PAGE	LINE	TAPE CHARACTERS READ FROM DATA TAPE	INSTRUCTIONS OBEYED
		n	Print name of programme → Return to data tape input
		Any warning sequence given in chapter 4.9	Read and store data → Return to data tape input
221	15	E	Read and store e.m.f.s → Return to data tape input
221	16	L after E	Check number of e.m.f.s
221	21		number incorrect; number correct → Return to data tape input
221	28		STOP
221	30	R	Read and store reference junction temperatures → Return to data tape input
221	32	L after R	Check number of reference junction temperatures
221	33		number incorrect; number correct
221	28		STOP; Calculate average outside temperatures → Return to data tape input
222	22	?	Set phase no.=0
222	35		Calculate K_1, K_f, K_2
223	8		Set t=1
223	9		Set up initial temperature distribution
232	23		Calculate $\gamma_2, m_2, c_2, \gamma_3$
233	4		Set r=3
233	5		Calculate m_r, c_r, γ_{r+1}
	12		Increase r by 1
233	13		if $r \neq n+1$; if $r=n+1$
233	14		Calculate $T_{t(n-1)} = \frac{T_{tn} - c_n}{m_n}$
233	16		Decrease r by 1
233	17		Calculate $T_{t(r-1)} = \frac{T_{t(r-1)} - c_{(r-1)}}{m_{(r-1)}}$
233	19		Decrease r by 1
233	20		if r=2; if $r \neq 2$
233	21		Calculate gradient $G_t = \frac{T_{t(n-1)} - T_{tn}}{x}$
233	26		increase t by 1
233	27		if t not equal to total no. of time steps+1; If t equal to total no. of time steps+1
224	25		increase phase no. by 1
224	26		if phase no.≠4; if phase no.=4 → Return to data tape input
224	31	Q	Print table of temperature gradients → Return to data tape input
226	24	BO	Carry out numerical integration of temperature gradients from TSB to TSE Calculate total heat leakage Convert to boil-off in inches of liquid Print result → Return to data tape input
228	11	CST	Introduce time lag given by TL and calculate Student's t Print time lag, no. of degrees of freedom and Student's t → Return to data tape input
		Y	STOP (optional)
		Z	STOP

On reading BO numerical integration is carried out to calculate the total heat inleak over the period of the run (TSB to TSE). The heat inleak is printed out for each phase as the equivalent boil-off in inches of liquid methane.

A regression programme was written into the main programme to calculate the best time lag to impose on the temperature data for a direct correlation. The time lag must be set by the warning sequence TL followed by a number representing the time lag in hours. (This must be a multiple of DTS). The directive CST then causes a correlation of temperature gradients with outside shell temperature after introducing the given time lag. Student's t is then calculated and the value of time lag, t', and the number of degrees of freedom are printed out. This may be repeated for several values of TL.

Any of the above stages in the calculation may be suppressed for one or more phases by the setting of handswitches 1,2,3,4. These suppress respectively the calculations for phases 0,1,2,3.

Testing of the Computer Programme

The programme was tested by carrying out various stages of the calculation on a desk calculating machine and comparing the results with those calculated by the computer. Use was made of the optional printing facility to enable this to be done.

The validity of the method of calculation was checked by calculating inside wall temperature gradients for step and linear changes in outside temperature and comparing the results with those calculated theoretically by the methods given in section 3.4.

a) Step Change in Outside Temperature

A print-out of the data tape is given in Appendix 1.2 and represents approximately a step change from 30°F to 100°F at t = 13½ hours. The computation was done for various time and distance steps and it was found that no significant increase in accuracy was obtained by using more than 10 distance steps in the thickness or using a time step of less than 3 hours. For the data given and with TSD = 1, DTS = 3 hours, DST = 10 Table 4.4 gives a comparison of inside temperature gradients calculated by the computer method with those calculated from Theory (chapter 3.4).

b) Linear Change in Outside Temperature

Appendix 1.3 gives a print-out of the data tape for the linear change test case. An increase of temperature of 0.75°F per hour is assumed. Again sufficient accuracy was achieved using DTS = 3 hours TSD = 1 and DST = 10. Table 4.5 gives a comparison of the results with those calculated as in chapter 3.4.

Good agreement was shown between values calculated theoretically and by the computer method for both the above test cases.

Results

Print-outs of the data tapes for runs 1 to 6 are given in Appendix 1.4. The values of insulation properties were based on figures given by the manufacturers or measured by the North Thames Gas Board. The area for heat transfer for each phase was assumed to be the mean of the area of aluminium tank surface and mild steel tank surface. Mean insulation thickness (at right angles to the aluminium tank) was determined graphically in the case of the roof.

Zero time for each run was as follows:-

Run No.	Zero time
1	1500 hrs. 1/4/60
2	1800 hrs. 8/4/60
3	1500 hrs. 20/4/60
4	0900 hrs. 28/4/60
5	1500 hrs. 30/4/60
6	0900 hrs. 4/5/60

All tables of results are given with time measured in hours from these initial times.

Appendix 1.5 gives tables of the outside temperatures at 3 hour intervals calculated from the e.m.f.s. and reference junction temperatures. The calculated inside temperature gradients at corresponding times are given in Appendix 1.6 which also gives the calculated boil-off over the periods given by TSB to TSE for each run. These periods corresponded as near as possible to the periods over which boil-off was measured in practice (4.5).

In the case of run 4 phase 2 (dark green part of tank sides) the outer shell temperature and inside temperature gradient are shown plotted against time in Fig. 4.21.

The regression calculation was used in this case to determine the best time lag as described in 3.5. Fig. 4.22 shows the calculated values of Student's 't' plotted against time lag.

The output shows that for phase 3 (the base of the tank) the calculated temperature gradient does not change by more than 1% from its initial value throughout the calculation. The transfer lag

Fig 4.21 Outside wall temperature and calculated inside temperature gradient vs time (Run 4)

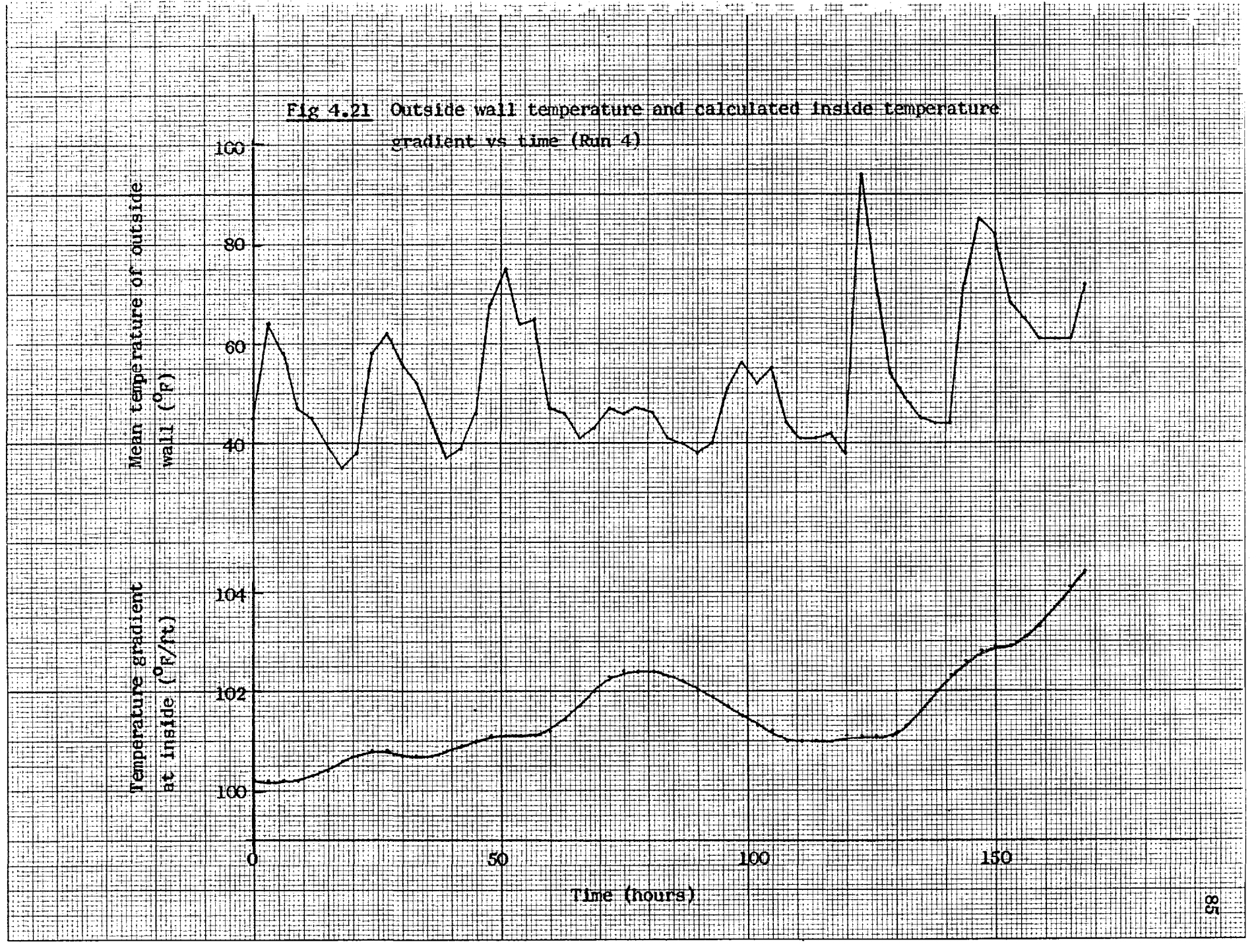
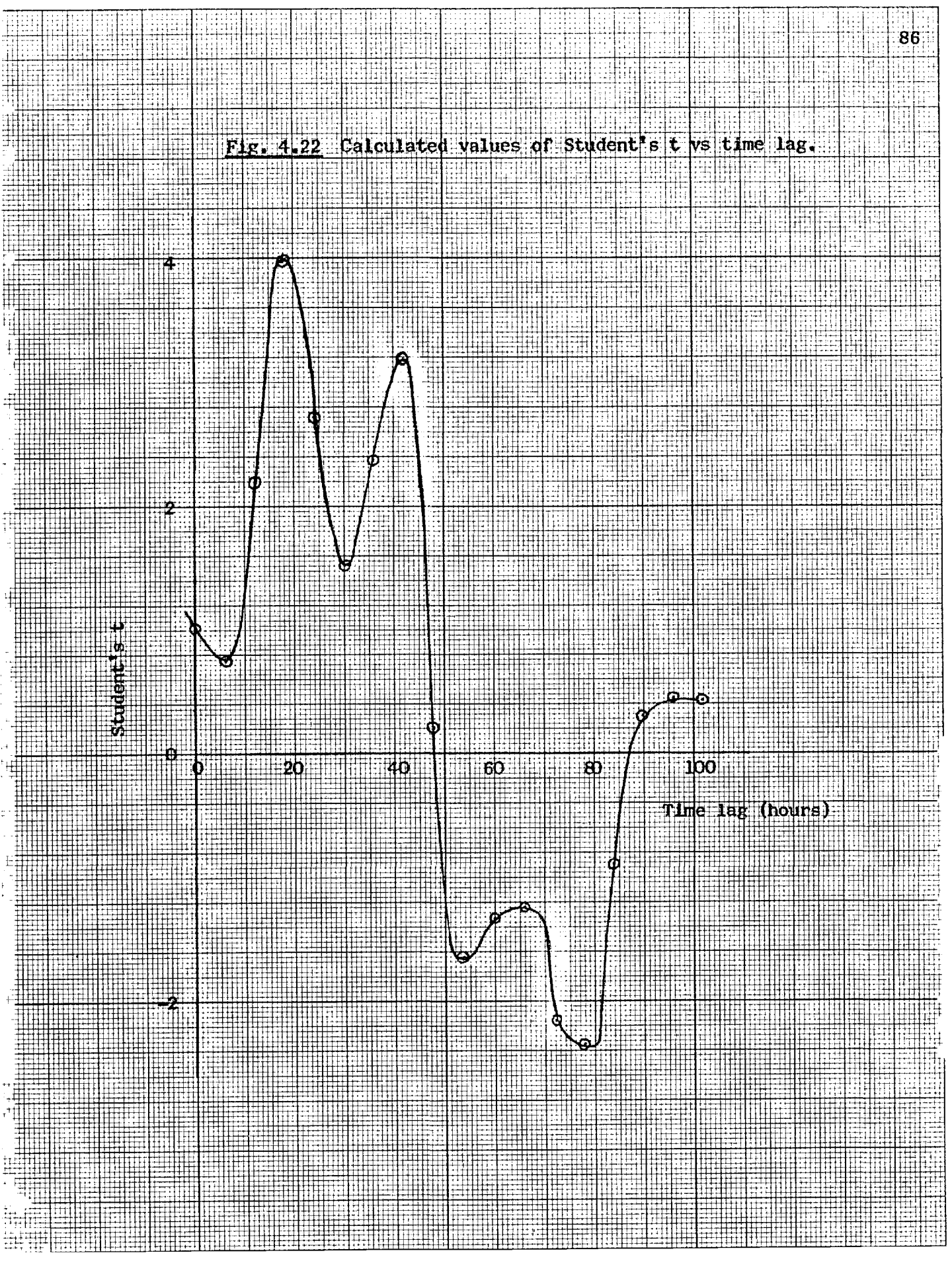


Fig. 4.22 Calculated values of Student's t vs time lag.



associated with the base is very much larger than that associated with the other three phases. For example if the factor $\frac{L^2}{6K}$ (see section 3.4) is assumed to be a measure of the time lag then the base would have a lag of 660 compared with 48 for the sides. It is therefore believed that a sufficiently long period of time was not allowed for the calculation in the case of the base insulation. An examination of the base temperatures over the period of the six runs and for some considerable time before the commencement of runs shows that the mean temperature was fluctuating between about 40°F and 50°F except for the last seven days when it showed a slight increase. Daily variations were small (about 10°F) compared with those on other parts of the tank.

The heat inleak through the base was therefore recalculated assuming a constant temperature of 45°F on the underside.

Table 4.6 summarises the calculated heat leakage and compares this with the measured values corrected as described in 4.6.

4.10 Conclusions

In all cases the actual boil-off exceeded the calculated value by about 25%. The discrepancy could be due to two main factors.

Some heat leakage would be expected through various pipes and fittings leading from the aluminium tank through the outer shell. An accurate determination of heat inleak by this means is impossible but it has been estimated at about 10%.

The effect of gas convection has been ignored in the calculations, heat transfer being assumed due to conduction alone. Gas convection could, however, be a contributory factor in the case of the roof and sides where the insulation is sufficiently porous to allow considerable gas flow.

Any error introduced by an incorrect estimation of aluminium tank temperatures (section 4.8) would have been indicated by the results showing a greater discrepancy for runs at low liquid level than for those at higher levels. No such difference is apparent.

The results indicate, therefore, a possibility that gas convection made some contribution to the heat leakage into the tanks although no quantitative estimate can be made.

Table 4.1 The Effect of Annulus pressure on Liquid Level Indicator Reading.

Time (P.M.)	Pressure in annulus (ins. H_2O gauge)	Pressure in tank (ins. H_2O gauge)	Liquid Level indicator reading (ins.)
4.00	0.0	6.2	10.70
4.05	0.0	6.2	11.15
4.10	0.0	6.2	11.65
4.15	0.0	6.2	12.10
4.20	5.7	6.2	12.35
4.25	6.2	6.2	12.85
4.30	6.2	6.2	13.35
4.35	6.2	6.2	13.80
5.05	-0.1	6.2	15.60
5.10	-0.1	6.2	15.85
5.15	-0.1	6.2	16.15
5.20	0.0	6.2	16.40
5.25	6.0	6.2	16.40
5.30	6.1	6.2	16.6
5.35	6.15	6.2	16.8

Table 4.2 Summary of boil-off measurements corrected for pressure changes.

Run Number	Approximate level (ft.)	Date and Time		Length of run (hrs.)	Measured boil-off (ins.)	Increase in pressure (millibars)	Correction for pressure change (ins.)	Boil-off equivalent of mean heat inleak (ins./hr.)
		Initial (G.M.T.)	Final (G.M.T.)					
1	43	0001 hrs. 3/4/60	0300 hrs. 7/4/60	99	3.78	5.6	0.23	0.0405
2	30	0900 hrs. 11/4/60	0900 hrs. 13/4/60	48	1.49	5.8	0.17	0.0346
3	15	0300 hrs. 23/4/60	0300 hrs. 26/4/60	72	2.34	0.1	-	0.0325
4	5	2230 hrs. 1/5/60	0430 hrs. 4/5/60	54	1.70	0.2	-	0.0315
5	5	2100 hrs. 4/5/60	1200 hrs. 7/5/60	63	1.85	-2.0	-0.01	0.0292
6	5	0600 hrs. 9 /5/60	0730 hrs. 11/5/60	49.5	1.59	0.3	-	0.0321

Table 4.3 Summary of Calculated Mean Temperatures of Aluminium tank

Run Number	Mean Aluminium tank temperature (°F)			
	Roof	L.G.	D.G.	Base
1	-242	-254	-248	-247
2	-178	-236	-251	-250
3	-100	172	-255	-254
4	-62	-113	-243	-257
5	-58	-109	-238	-257
6	-54	-109	-241	-257

L.G. Section of aluminium tank inside light green (upper) part of mild steel shell.

D.G. Section of aluminium tank inside dark green (lower) part of mild steel shell.

Table 4.4 Step change in outside temperature

Time (hrs.) after step change	Gradient A	Gradient B
0	96.7	96.7
10	97.7	97.8
20	103.3	103.5
35	111.6	111.6
50	115.9	115.9
70	118.5	118.5
100	119.6	-

Table 4.5 Linear change of outside temperature

Time (hrs.) from start of linear change	Gradient A	Gradient B
0	100.8	100.8
20	-	101.2
40	-	103.2
60	105.6	107.0
80	110.9	111.7
100	116.2	116.6
120	121.5	121.8
140	126.8	127.0
160	132.1	132.3
180	137.4	137.6

A Temperature gradient at inside wall ($^{\circ}$F/ft.) calculated theoretically

B Temperature gradient at inside wall ($^{\circ}$F/ft.) calculated using computer programme LG

Table 4.6 Summary of theoretical calculation of boil-off and comparison with measured values.

Run No.	Duration (hrs.)	Calculated boil-off (ins.methane liquid).					Mean boil-off (ins./hr.)	Measured boil-off (ins./hr.)	Calculated as %ge of measured %
		Phase 0 (roof)	Phase 1 (light green)	Phase 2 (dark green)	Phase 3 (base)	Total			
1	99	0.232	1.055	0.356	1.160	2.80	.0284	.0405	70
2	48	0.089	0.483	0.176	0.569	1.32	.0274	.0346	79
3	72	0.094	0.570	0.271	0.865	1.80	.0250	.0325	77
4	54	0.047	0.303	0.189	0.655	1.19	.0221	.0315	70
5	63	0.058	0.364	0.225	0.765	1.41	.0224	.0292	77
6	48	0.045	0.283	0.175	0.601	1.10	.0223	.0321	70

Roof and sides calculated using computer programme LG.

Base calculated as steady state heat transfer with outside temperature = 45°F.

CHAPTER V

Heat Transfer by Natural Convection in Porous Insulants

5.1 Introduction

Several workers have reported the observation of an increase in the apparent conductivity of powder or fibrous insulants due to the existence of convection currents within the material. Methods of investigation used to indicate the extent of this effect have been

a) The testing of materials in both horizontal and vertical positions (Ref. 17).

b) The dividing of specimens horizontally by thin partitions (Ref. 18).

c) The testing of different densities of compressible materials (Ref. 19).

d) The variation of the temperature difference between the hot and cold plates of the test cell (Ref. 18).

e) The testing of different thicknesses of material (Ref. 18).

Most of this work, however, has been of a qualitative nature, no attempt having been made to correlate the data or to find parameters which could be used to predict the magnitude of convection effects in different systems. The work was carried out on small sections of the order of 1 square foot in area and less than four inches in thickness. Under these conditions the effect of convection would be expected to be less than in industrial scale insulation systems where heights up to 40 or 50 ft. and thicknesses of 2 or 3 ft. may be used.

Measurements of the heat flux through sections of a cold room wall approximately $3\frac{1}{2}$ ft. wide, 8 ft. high and $8\frac{1}{4}$ inches thick were

carried out by Lorentzen and Brendeng (Ref. 20). They concluded that free convection may add considerably to the heat leakage through an insulated wall, especially in the case of loose-fill fibre insulation. Again, no attempt was made to calculate the effects theoretically.

The difficulty of experimental investigation in this field revolves largely around the practical difficulty of the construction and operation of the large test sections which are necessary to simulate industrial conditions. Small test sections are of limited value because of the mutual interference of gas flows in different directions. It was, therefore, decided that a conductivity cell of the greatest practicable dimensions would be constructed and, in addition, some method of amplifying the convection effect would be desirable.

Since the initiation and subsequent continuation of convection is dependent on gas density differences in regions of different temperatures, the effect of convection may be increased by raising the pressure of the gas in the body of the insulation. Allcut (Ref. 17) used this variation of convection effect with pressure to demonstrate the effect of convection in glass wool of various densities. His experiments were mainly confined to pressures below atmospheric although a few values are given at pressures up to 80 inches of mercury absolute. In his test cell, eight inches square and one inch in thickness, the percentage of the heat transfer attributed to convection is given as 11% at atmospheric pressure and 7% at a pressure of 25 inches of mercury absolute for glass wool at a bulk density of 1.25 lb/ft^3.

Elevated gas pressures may thus be used to amplify the effects

of convection and use was made of this fact in the experimental study which will be described.

All the above mentioned work was carried out at temperatures near to or above atmospheric. The effects of convection would be expected to be much greater at low temperatures where gas density is increased and viscosity is reduced.

5.2 Theoretical Aspects

The theoretical calculation of the contribution to heat transfer made by gas convection requires, in addition to the usual parameters used in heat transfer calculations, some parameter expressing the resistance of the material to gas flow. A suitable parameter which has been used throughout in this work is the permeability (α) defined by

$$\frac{\Delta P}{l} = \frac{\mu u}{\alpha}$$

where $\frac{\Delta P}{l}$ is the pressure drop per unit length causing the flow of fluid of viscosity μ.

u is the mean velocity of flow based on the total cross sectional area of the sample and is defined by

$$u = \frac{V}{A}$$

where V is the volumetric flow rate of gas through a cross sectional area A of the insulant.

In the case of streamline flow it has been shown that for a fairly wide range of temperatures and pressures

$\frac{\Delta P}{l}$ is proportional to the product μu and α is constant.

For beds of regularly shaped particles α may be calculated from the porosity and specific surface (Ref. 23) but in the case of most insulants this cannot be done. The permeability may, however, be easily measured by a determination of pressure drops in a column packed with the insulant through which gas is flowing.

Dimensional Analysis

Considering, as a simple case, the heat transfer between vertical, parallel plates separated by a porous insulant, the factors which will affect the total heat transfer by convection and conduction will be as follows:-

H	The height of the insulation	(ft.)
L	The thickness of the insulation	(ft.)
ΔT	The temperature differnce between plates	(^oF)
α	The permeability of the insulation	($ft.^3 hr.^{-2}$)
k_i	The thermal conductivity of the insulation free from convection effects	($Btu.ft.^{-1} hr.^{-1} {}^oF^{-1}$)
k_g	The thermal conductivity of the gas	($Btu.ft.^{-1} hr.^{-1} {}^oF^{-1}$)
μ	The gas viscosity	($lb.ft.^{-1} hr.^{-1}$)
Cp	The heat capacity of the gas	($Btu.lb.^{-1} {}^oF^{-1}$)
βg	The gas coefficient of expansion	($ft.hr.^{-2} {}^oF^{-1}$)
ρ	The gas density	($lb.ft.^{-3}$)

All the properties must be given at the mean temperature of the insulation.

If q is the heat transferred across the insulation per unit area per unit time ($Btu.hr.^{-1} ft.^{-2}$) it can be shown using the methods of dimensional analysis on the above variables that

$$\frac{qL}{k_g \Delta T} = f\left(\frac{H}{L}, \frac{k_i}{k_g}, \frac{\alpha}{L^2}, \frac{C_p \mu}{k_g}, \frac{L^3 \rho^2 \beta g \Delta T}{\mu^2}\right)$$

$$\text{or } Nu = f\left(Pr, Gr, \frac{k_i}{k_g}, \frac{\alpha}{L^2}, \frac{H}{L}\right)$$

where Nu = Nusselt group

Pr = Prandth group for the gas

and Gr = Grashof group for the gas

At present there is insufficient data available to enable the form of the above relationship to be determined.

The Mechanism of Convective Heat Transfer

The existence of convection currents within porous media may effect the heat transfer in two ways.

a) Heat will be transported as sensible heat in the flowing gas, the gas giving up heat in the cooler regions which it acquired in the warmer parts of the system.

b) The passage of gas through the insulant may increase the effective conductivity due, for instance, to micro turbulence in the pores. If no convection is present, heat transfer takes place by, solid conduction, gas conduction and radiation between adjacent particles or fibres. The resistance to heat transfer at the gas-solid interfaces may be considerably reduced by the flow of gas and, if this resistance is a significant part of the total, the flow of gas may cause a significant increase of conductivity.

The existence of this last effect can be tested experimentally and a few experiments were carried out on slag wool and Brelite, powder insulation, to determine the influence of flowing air on heat transfer.

An Experimental Investigation of the Effect of Gas Flow on the Effective Conductivity of Porous Insulation

A diagrammatic representation of the apparatus is given in Fig. 5.1. It consisted essentially of three cylindrical brass tubes $2\frac{1}{2}$ inches in diameter heated electrically by nichrome wires wound on the surface, electrically insulated from the brass by silicone varnish. The heaters were placed along the axis of a cylindrical container filled with the insulant to be tested. Dry air was passed into a distributor in the space above the insulation and allowed to flow slowly through the insulation. From the bottom of the insulation the air was passed through a cooling coil to a gas meter. The three heaters consisted of a central test section 3 inches in length with a guard plate section above (6 inches long) and below (3 inches long). The extra length of the upper guard section was to allow the gas to reach the insulation temperature before entering the test zone. Temperatures of the central test section and the inner ends of the guard sections were measured by copper-constantan thermocouples silver soldered to the surface of the brass. The temperature of the outside wall was also measured by a copper-constantan thermocouple.

With no air flowing to the apparatus the power supplied to the heaters was adjusted until the three thermocouples on the central heaters showed steady, equal temperatures about 90°C above room temperature. The heat input to the test section and the temperatures were then noted. The experiment was repeated with higher power inputs giving different temperature differences, and a graph of power input against temperature difference was drawn. The procedure was repeated with air flowing

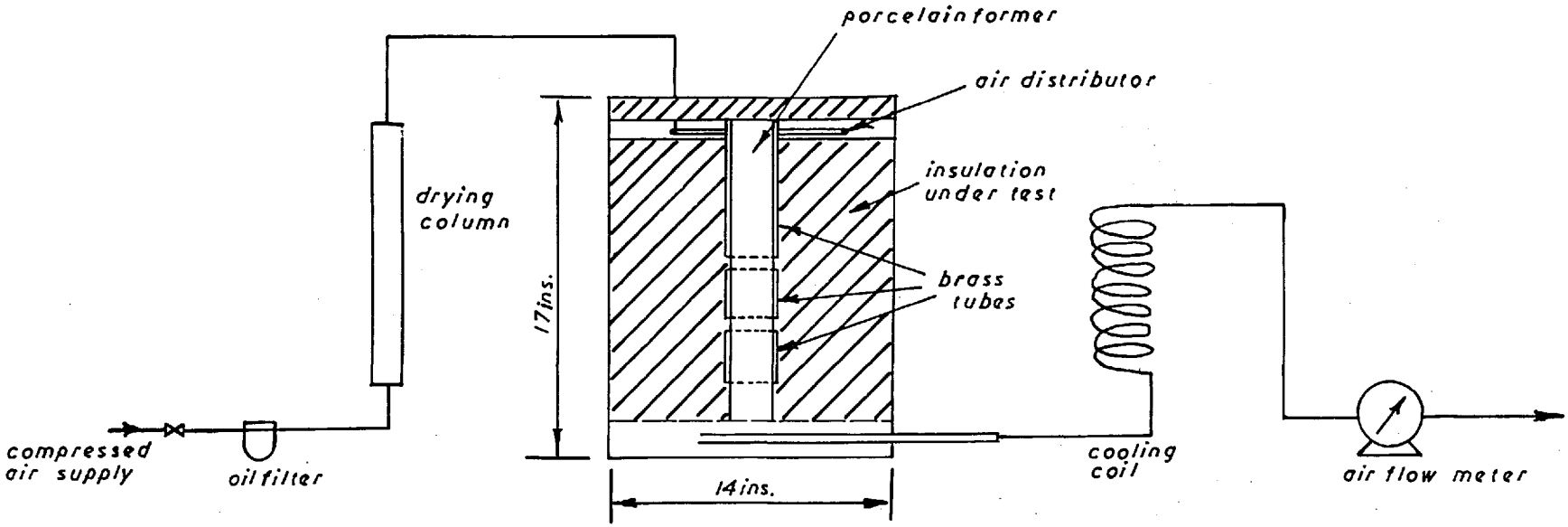


FIG. 5.1 APPARATUS FOR THE INVESTIGATION OF THE EFFECT OF GAS FLOW ON CONDUCTION

through the insulation.

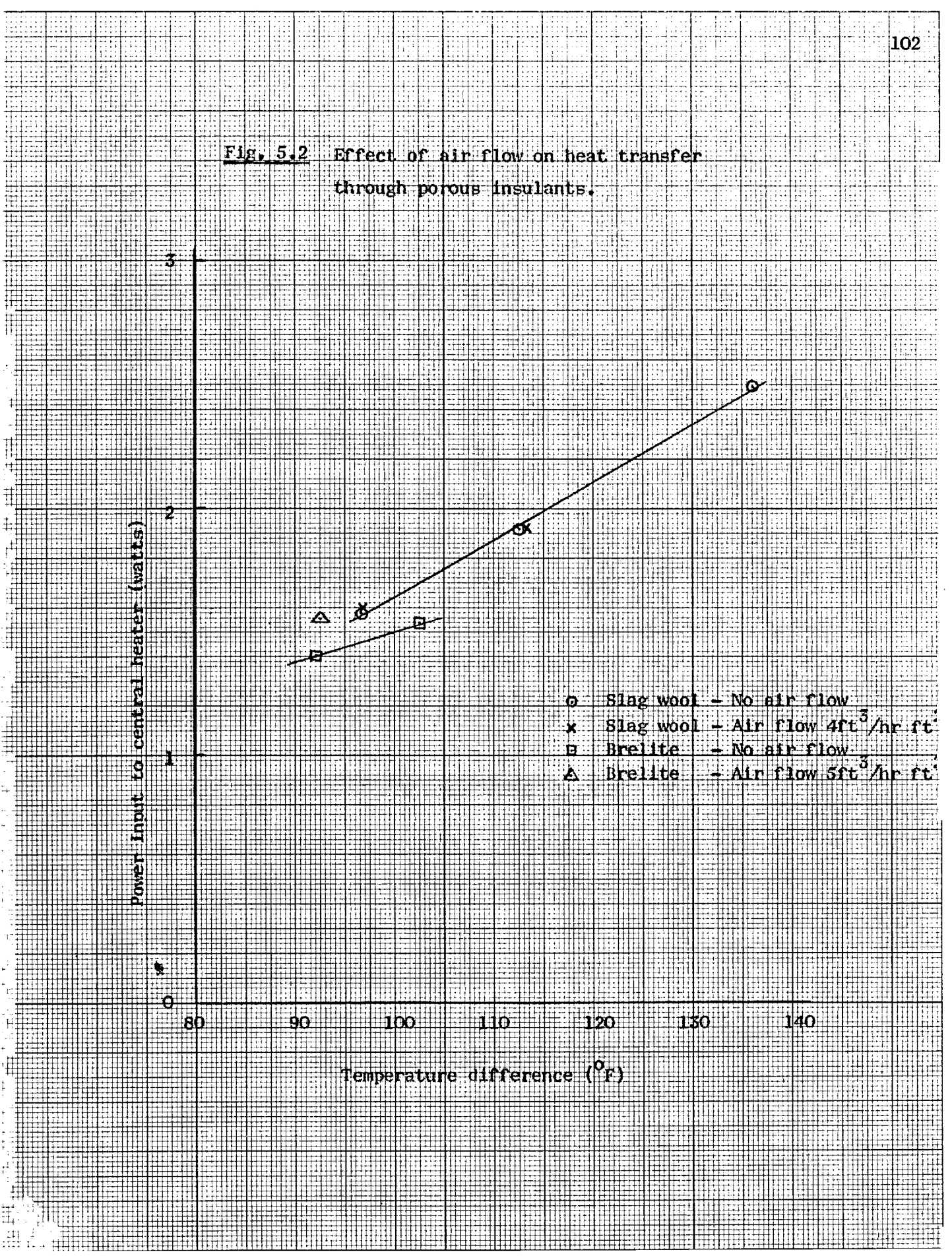
Fig. 5.2 shows the power input to the central heater (equal to the heat flowing radially through the insulation) plotted as a function of temperature difference for slag wool and Brelite with and without air flow.

The results show that for slag wool with an air flow of approximately 4 ft.^{3}/hr. per square foot no appreciable increase in conductivity occurs. Brelite showed an increase of about 10% with an air flow of 5 ft.^{3}/hr./ft.^{2} This may have been due to the downward flow of air causing packing down of the bed of Brelite. These air flows are much greater than those which would be expected due to convection effectsand it may be concluded that the effect of gas flow on the conductivity is small compared with the heat carried as sensible heat by the gas.

Theoretical Calculation of Heat Transfer by Natural Convection

A complete mathematical solution of the problem is difficult because of the large number of variables to be considered. At any particular point in the insulation the variables can be reduced to gas and solid temperatures, gas pressure, velocity and direction of flow. If it is considered that the gas and solid at any point are at essentially the same temperature. (This may be justified, since the rate of flow of gas will be small) the problem is very similar to that of the free convection of fluid between parallel plates at different temperatures, except that a resistance to gas flow is introduced due to the presence of the insulant. Attempts have been made to solve the problem of the free convection of fluids mathematically (Refs. 21, 22) but gross approximations have been necessary in order to

Fig. 5.2 Effect of air flow on heat transfer through porous insulants.



arrive at a solution. For example, in the work of Batchelor (Ref. 21) the assumption was made that the temperature differences were small compared with the absolute temperature. This may be justified in the case of small temperature differences near room temperature but is not justifiable in the case of temperature differences between, say, liquid methane and atmospheric temperature.

A study of the mechanism of convective heat transfer shows, however, how an approximate finite difference method could be used to find a solution.

Considering again the case of heat transfer between vertical parallel plates at different temperatures separated by insulation and supposing that initially there is no convection occurring, heat transfer will take place entirely by conduction (the insulation is assumed opaque to radiation). The temperature distribution will then be as shown in Fig. 5.3 with the isotherms being vertical and parallel (Equally spaced if conductivity is assumed constant with temperature). Assuming (to maintain symmetry) that the pressure across AB (mid-way down the insulation) is constant, the pressure at other points may be calculated from the gas density and distance above or below AB. Fig. 5.4 shows the distribution of the isobars so calculated. It may be seen that there are now pressure gradients in the horizontal direction which will cause the gas to flow, carrying heat and distorting the isotherms to the form shown in Fig. 5.5.

If the insulation is considered to be divided into a number of small elements, the pressure and temperature in each element may be calculated, as a first approximation, to be as in Figs. 5.3 and 5.4

FIG. 5.3 DISTRIBUTION OF ISOTHERMS-CONDUCTION

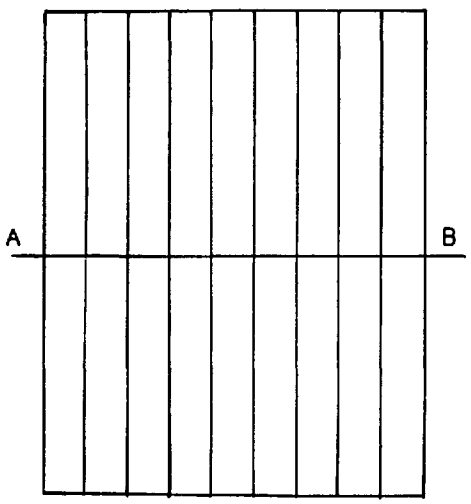


FIG. 5.4 DISTRIBUTION OF ISOBARS

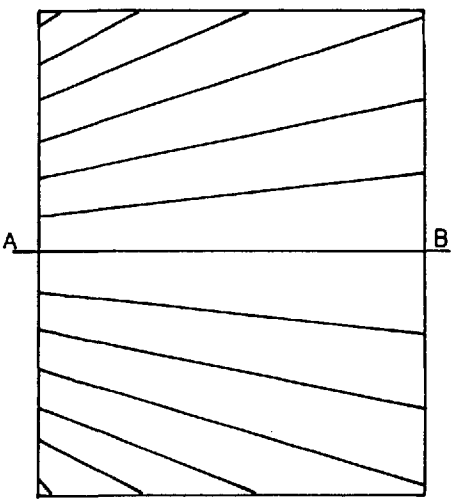
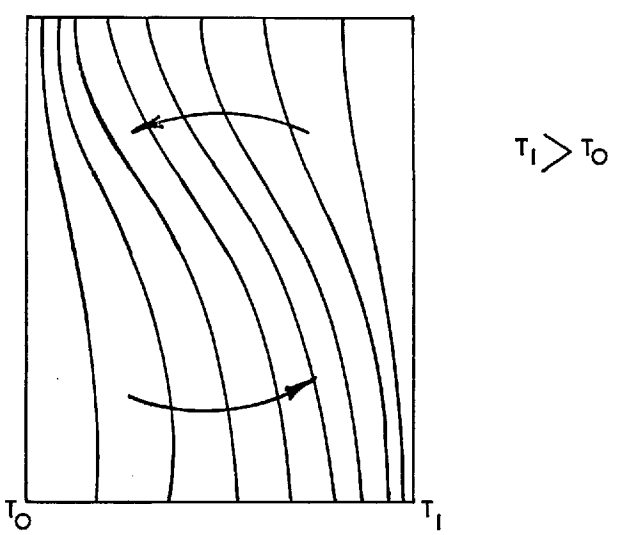


FIG. 5.5 DISTORTION OF ISOTHERMS DUE TO CONVECTION



The mass flow into each element from the surrounding elements may then be calculated from the pressure gradients, and by carrying out a mass balance on the element a new approximation to its pressure may be found. Similarly a heat balance, including the heat flow by conduction and the heat carried as sensible heat by the gas, enables a new approximation to the temperature to be found.

Repeating the calculation several times will produce a reasonably accurate approximation to the final temperature and pressure distribution.

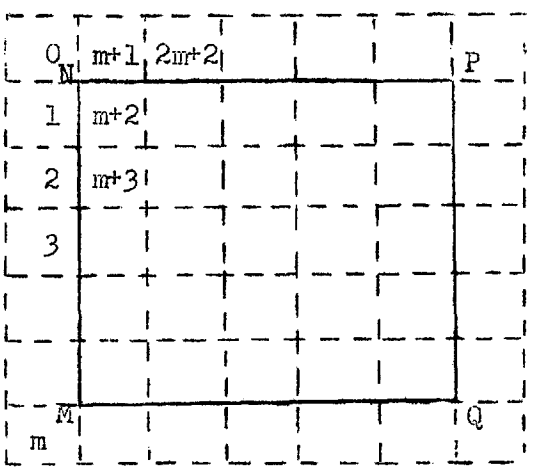
The rate of heat transfer may then be calculated by summing the amounts of heat transferred both by conduction and by gas flow for all elements along any vertical plane through the lagging.

This approach has been followed and has led to a method of calculation which will be described.

5.3 An Iterative Method for the Calculation of Heat Transfer by Natural Convection in Porous Insulants

MNPQ (Fig. 5.6) is a section through a block of insulation having the vertical faces MN and PQ at uniform constant temperatures T_0 and T_1. Unit depth in the third dimension is assumed. The insulation is divided into a number of small elements as shown.

Fig. 5.6



The significance of the elements immediately outside the boundary MNPQ will be discussed later. T_0, T_1 ..... T_m ..... etc. and P_0, P_1 ..... P_m ..... etc. are the temperatures and pressures at the centre of each element. The flowing variables will be used in the calculation :-

H the height of the insulation MN (ft.)

L the insulation thickness MQ (ft.)

P the absolute gas pressure at any point (lb./ft.^{2})

T the temperature at any point. The temperature difference between gas and solid is assumed small compared with the temperature gradients involved. T therefore represents the solid and gas temperature ($^\circ$R)

k the thermal conductivity of the insulation in the absence of convection. This is assumed constant with gas flow rate (see 5.2) and is a function of temperature only (Btu./ft.^{2}hr. ($^\circ$F/ft.))

Cp the heat capacity of the gas, assumed constant (Btu./lb. $^\circ$F)

ρ the gas density. It is assumed that this can be expressed as $\rho = \frac{\rho_0}{T}$ where ρ_0 is constant (lb./ft.^{3})

(The effect of pressure on the density may be ignored since pressure variations in the insulation, due to convection, will be small compared with the absolute pressure.)

μ the gas viscosity assumed to be a function of temperature only (lb./ft. hr.)

α the permeability defined in chapter 5.2 ($ft.^3/hr.^2$)

Over the range of temperatures used it will be assumed that the gas viscosity and thermal conductivity may be expressed as linear functions of temperature

i.e. $\mu = \mu_0 + \mu_1 T$

and $k = k_0 + k_1 T$

where μ_0, μ_1, k_0, k_1 are constants.

Let m + 1 be the total number of elements in the mesh in the vertical direction (m - 1 inside the system boundary) and n + 1 be the total number of elements in the horizontal direction (n - 1 inside the system boundary).

First approximations

a) Temperature

The first approximation to the temperature will be calculated on the assumption that heat transfer takes place entirely by conduction.

Suppose the upper and lower boundaries of the system are perfect insulators so that no heat is transferred in the vertical direction. In the steady state the heat transfer through any vertical boundary is constant. If **x** is the distance from the left hand boundary (T_0).

$$k\frac{dT}{dx} = C \quad \text{where C is a constant} \qquad \ldots\ldots\ldots\ldots (1)$$

or $$\frac{dT}{dx}(k_0 + k_1 T) = C \qquad \ldots\ldots\ldots\ldots (2)$$

Integrating, we have

$$k_0T + \tfrac{1}{2}k_1T^2 = Cx + D \quad \ldots\ldots\ (3) \text{ where D is constant.}$$

at x = 0 $\quad k_0T_0 + \tfrac{1}{2}k_1T_0^2 = D$

at x = L $\quad k_0T_1 + \tfrac{1}{2}k_1T_1^2 = CL + D$

$$= CL + k_0T_0 + \tfrac{1}{2}k_1T_0^2$$

whence $C = \frac{k_0}{L}(T_1 - T_0) + \frac{k_1}{2L}(T_1^2 - T_0^2)$

Rewriting (3) $\tfrac{1}{2}T^2 + \frac{k_0}{k_1}T - \frac{1}{k_1}(Cx + D) = 0$

and $T = -\frac{k_0}{k_1} \pm \sqrt{\left(\frac{k_0}{k_1}\right)^2 + \frac{2(Cx + D)}{k_1}}$

Since T is in °R the real solution must be

$$T = -\frac{k_0}{k_1} + \sqrt{\left(\frac{k_0}{k_1}\right)^2 + \frac{2(Cx + D)}{k_1}} \quad \ldots\ldots\ (4)$$

where $C = \frac{k_0}{L}(T_1 - T_0) + \frac{k_1}{2L}(T_1^2 - T_0^2)$ $\quad \ldots\ldots\ (5)$

and $D = k_0T_0 + \tfrac{1}{2}k_1T_0^2$ $\quad \ldots\ldots\ (6)$

Referring to Fig. 5.6

$$T_{(m+2)} = T_{(m+3)} = \ldots\ldots \text{ etc.} = -\frac{k_0}{k_1} + \sqrt{\left(\frac{k_0}{k_1}\right)^2 + \frac{2}{k_1}\left[\frac{CL}{2(n-1)} + D\right]}$$

$$T_{(2m+3)} = T_{(2m+4)} = \ldots\ldots \text{etc.} = -\frac{k_0}{k_1} + \sqrt{\left(\frac{k_0}{k_1}\right)^2 + \frac{2}{k_1}\left[\frac{3CL}{2(n-1)} + D\right]}$$

In this way the temperature of each element may be calculated.

b) Pressure

If m is assumed to be even, then the condition that the pressure mid-way down the insulation is constant is given by

$$P\left(\frac{m}{2}\right) = P\left(\frac{3m}{2} + 1\right) = P\left(\frac{5m}{2} + 2\right) = \ldots\ldots \text{ etc.} = P_C = \text{constant.}$$

The other pressures may now be calculated from the difference in height of each point from the centre line.

e.g. $P_{\left(\frac{3m}{2}+2\right)} = P_C + \frac{\rho' H}{m-1}$

$P_{\left(\frac{3m}{2}\right)} = P_C - \frac{\rho' H}{m-1}$

and $P_{\left(\frac{3m}{2}-1\right)} = P_{\left(\frac{3m}{2}\right)} - \frac{\rho' H}{m-1}$

where $\rho' = \frac{\rho_o}{T_{(m+2)}}$

Boundary Conditions

The necessary boundary conditions may be set before each series of approximations is calculated by setting the temperature and pressures of each of the hypothetical elements outside the system boundary at appropriate values, as shown below.

The vertical boundaries MN and PQ may be assumed to be at uniform temperatures T_0 and T_1.

$$\frac{T_1 + T_{(m+2)}}{2} = T_0$$

$$\therefore \quad T_1 = 2T_0 - T_{(m+2)}$$

in general $T_r = 2T_0 - T_{(m+1+r)}$ where $0<r<m$

and $T_r = 2T_0 - T_{(r-m-1)}$ where $n(m+1)<r<n(m+1)+m$

There can be no flow of gas through the boundaries MN and PQ. This condition may be achieved by setting:-

$P_1 = P_{(m+2)}$ etc.

in general $P_r = P_{(m+1+r)}$ where $0 \ll r \ll m$

and $P_r = P_{(r-m-1)}$ where $n(m+1) \ll r \ll n(m+1) + m$

The upper and lower boundary conditions will vary according to the system under investigation. In this work it will be assumed that these boundaries are perfect insulators and are impervious to gas flow. There will be no flow of heat or of gas across these boundaries. This may be achieved by setting

$$T_{[r(m+1)]} = T_{[r(m+1)+1]} \quad \text{for } 0 \ll r \ll n$$

$$T_{[r(m+1)+m]} = T_{[r(m+1)+m-1]} \quad \text{for } 0 \ll r \ll n$$

$$P_{[r(m+1)]} = P_{[r(m+1)+1]} - \frac{\rho'_r H}{m-1} \qquad 0 \ll r \ll n$$

where $\rho'_r = \dfrac{2\rho_o}{T_{[r(m+1)]} + T_{[r(m+1)+1]}}$

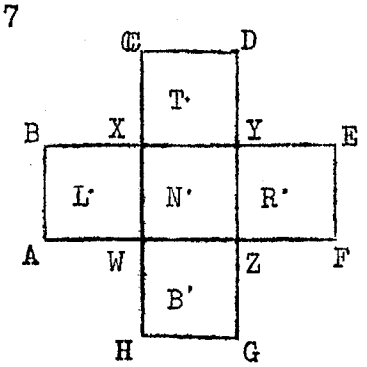
$$P_{[r(m+1)+m]} = P_{[r(m+1)+m-1]} + \frac{\rho''_r H}{m-1} \qquad 0 \ll r \ll n$$

where $\rho''_r = \dfrac{2\rho_o}{T_{[r(m+1)+m]} + T_{[r(m+1)+m-1]}}$

The Calculation of Successive Approximations

Consider any element WXYZ surrounded by the four elements WABX, XCDY, YEFZ and ZGHW (Fig. 5.7)

Fig. 5.7



Let the subscripts N, T, L, R and B denote properties at the centre of each element as shown in Fig. 5.7. The subscripts TN, RN, BN and LN will be used to denote mean properties at the faces XY, YZ, ZW and WX.

P_T, P_L, P_B, P_R, T_T, T_L, T_B, T_R are the existing approximations to the pressure and temperature in each element.

$$T_{TN} = \frac{T_T + T_N}{2} \quad \text{and} \quad T_{LN} = \frac{T_L + T_N}{2} \quad \text{etc.}$$

The other properties may be calculated from

$$\rho_{TN} = \frac{\rho_o}{T_{TN}}$$

$$k_{TN} = k_0 + k_1 . T_{TN} \quad \text{etc.}$$

Carrying out a mass balance on gas flowing into the element WXYZ a better approximation to the pressure ($P_{N'}$) may now be calculated.

If ℓ = width of each element

and d = height of each element

The mass of gas flowing into the element through YZ is given by

$$\text{Mass flow} = \frac{P_R - P_{N'}}{\ell} \times d \times \rho_{RN} \frac{\alpha}{\mu_{RN}}$$

and the mass of gas flowing into the element through XY is equal to

$$\left(P_T - P_N + d\rho_{TN}\right) \times \frac{1}{d} \times \ell \times \rho_{TN} \frac{\alpha}{\mu_{TN}}$$

$$= \left(\frac{P_T - P_N}{d} + \rho_{TN}\right) \frac{\ell \rho_{TN} \alpha}{\mu_{TN}}$$

Similar expressions give the mass flow through WX and WZ. Equating the net flow of gas into the element to zero (steady state) we have

$$0 = \left(\frac{P_T - P_{N'}}{d} + \rho_{TN}\right)\frac{\ell}{\mu_{TN}} + \left(\frac{P_B - P_{N'}}{d} - \rho_{BN}\right)\frac{\ell}{\mu_{BN}}$$

$$+ \frac{P_L - P_{N'}}{\ell}\,\frac{d\rho_{LN}}{\mu_{RN}} + \frac{P_R - P_{N'}}{\ell}\,\frac{d\rho_{RN}}{\mu_{RN}}$$

From which

$$P_{N'} = \frac{\left(\frac{P_T\rho_{TN}}{\mu_{TN}} + \frac{P_B\rho_{BN}}{\mu_{BN}}\right)\frac{\ell}{d} + \left(\frac{P_L\rho_{LN}}{\mu_{LN}} + \frac{P_R\rho_{RN}}{\mu_{RN}}\right)\frac{d}{\ell} + \left(\frac{\rho^2_{TN}}{\mu_{TN}} - \frac{\rho^2_{BN}}{\mu_{BN}}\right)\ell}{\left(\frac{\rho_{TN}}{\mu_{TN}} + \frac{\rho_{BN}}{\mu_{BN}}\right)\frac{\ell}{d} + \left(\frac{\rho_{LN}}{\mu_{LN}} + \frac{\rho_{RN}}{\mu_{RN}}\right)\frac{d}{\ell}}$$

The amount of heat being carried into the element by gas flowing across any boundary is given by

Mass flow x specific heat x absolute temperature

so that the net flow of heat into the element by convection (H_C) is given by

$$H_C = \left[\left(\frac{P_T - P_{N'}}{d} + \rho_{TN}\right)\frac{\ell}{\mu_{TN}}\rho_{TN}T_{TN} + \left(\frac{P_B - P_N}{d} - \rho_{BN}\right)\frac{\ell}{\mu_{BN}}\rho_{BN}T_{BN}\right.$$

$$\left. + \left(\frac{P_L - P_N}{\ell}\right)\frac{d}{\mu_{LN}}\rho_{LN}T_{LN} + \left(\frac{P_R - P_N}{\ell}\right)\frac{d\rho_{RN}T_{RN}}{\mu_{RN}}\right] \propto Cp.$$

and if $T_{N'}$ is the next approximation to the temperature of the element WXYZ. The net flow of heat into the element by conduction (H_k) is given by

$$H_k = k_{TN}\,\ell\left(\frac{T_T - T_{N'}}{d}\right) + k_{BN}\,\ell\left(\frac{T_B - T_{N'}}{d}\right) + k_{LN}\,d\left(\frac{T_L - T_{N'}}{\ell}\right) + k_{RN}\,d\left(\frac{T_R - T_{N'}}{\ell}\right)$$

In the steady state the total flow of heat into the element by conduction and convection must be zero

$$H_C + H_k = 0$$

from which

$$T_{N'} = \frac{H_C + \frac{\ell}{d}\left(k_{TN}T_T + k_{BN}T_B\right) + \frac{d}{\ell}\left(k_{LN}T_L + k_{RN}T_R\right)}{\frac{\ell}{d}\left(k_{TN} + k_{BN}\right) + \frac{d}{\ell}\left(k_{LN} + k_{RN}\right)}$$

In this way a better approximation to the temperature and pressure in each element inside the system boundary may be calculated. At the conclusion of the calculation of each new set of temperatures and pressures the boundary conditions are reset by suitable adjustment of the temperatures and pressures of the elements outside the system boundary.

Intermediate calculated values of P_N and T_N are meaningless since the heat and mass balances use $P_{N'}$ and $T_{N'}$ with the properties calculated assuming the temperature to be T_N. When, however, the calculated temperatures converge and $T_{N'} = T_N$ for each element these must represent the true temperatures at each point. This treatment assumes that the mesh used is fine enough to justify the assumption of a linear change of temperature and pressure between elements.

The total heat transfer may be calculated by summing the heat transfer by conduction across the right hand boundary for all elements in the vertical height

$$\text{Heat transfer} = \sum_{r = n(m+1)+1}^{r = n(m+1)+m-1} k'\left[T_r - T_{r-m-1}\right]\frac{d}{l}$$

$$\text{where } k' = k_0 + k_1\left(\frac{T_r + T_{r-m-1}}{2}\right)$$

5.4 A Computer Programme for the Calculation of Heat Transfer by Convection

The programme (LN) was written to calculate the heat transfer by natural convection by the method given in 5.3 using a Ferranti "Pegasus 2" computer.

A straighforward calculation of a succession of approximations as described was found to be unsuitable for most systems. The initial approximations were so much in error that an oscillation was set up, successive values being further and further in error. The initial values of temperature, however, approximate closely to the true values for $\alpha = 0$ (i.e. an impermeable insulation). It was found, therefore, that convergence could be achieved for all the systems investigated by starting with $\alpha = 0$ and increasing its value in steps, with one or more series of approximations at each value until the final desired value of α was reached. The programme was therefore written so that, after each series of approximations, the value of α could be easily reset.

For calculations with low values of α, the initial values of pressure show much greater error than the initial values of temperature. The programme was, therefore, written so that the calculation of each new temperature could be inhibited by the setting of hand-switch 2. In this way a few approximations of the pressures alone could be calculated to achieve a more exact value before the heat balances were commenced.

The programme is written partly in Pegasus autocode and partly in Pegasus machine-orders and uses "Sixcode" for data input. A print-out of the programme is given in Appendix 2 with a list of the variables and indices used. The programme may be used on any size of mesh up to 20 elements in the vertical direction and 35 elements in the horizontal direction (19 x 34 elements inside the system boundary). The programme, as written, must be used in conjunction with MAGLIB (the magnetic library tape of the Leeds University Computing Laboratory). It may, however, be read into the computer directly after Sixcode MK9 if the instructions

Q7901 and Q7850 are omitted. The programme must be followed by a data tape which sets the necessary data and enters the calculation, this tape is also used to reset the value of α during the calculation. The following is a list of the data which must be supplied and the warning sequences used for data input.

VISC must be followed by two constants μ_0 and μ_1 in the equation

$$\mu = \mu_0 + \mu_1 T \qquad \text{where } \mu = \text{lb.ft.}^{-1}\text{hr.}^{-1}$$

$$T = {}^{\circ}R$$

The constants may be given as either fixed or floating-point numbers in the punching convention required by Sixcode (Ref. 16).

COND must be followed by the two constant k_0 and k_1 in

$$k = k_0 + k_1 T \qquad \text{where } k = \text{Btu.ft.}^{-1}\text{hr.}^{-1}{}^{\circ}\text{F}^{-1}$$

TEMPS must be followed by T_0 and T_1 the boundary temperatures in $^{\circ}R$. Each of the following warning sequences must be followed by one constant only (again given as a fixed-point or floating-point number).

XH The thickness of the element **L** (ft.)

XV The vertical height of the element H (ft.)

SH The number of steps in the horizontal direction (n)

SV The number of steps in the vertical direction (m)

SH The specific heat of the gas (Btu./lb.$^{\circ}$F)

DENS The constant ρ_0 in the equation

$$\rho = \frac{\rho_0}{T} \qquad \text{where } \rho \text{ is gas density (lb.ft.}^{-3}\text{)}$$

ALPHA The permeability α

PRES The reference pressure P_0 (lb./ft.^{2} gauge)

A specimen data tape is given in Appendix 2.2.

The directive CD causes the data to be printed out so that a check may be made to ensure that this has been read correctly.

The calculation proper is entered on reading ? whereupon the initial temperature and pressure distribution are set up. Hand-switch 13 is then consulted. If this is set the programme returns to data input and reads more tape. If R is read from tape or if hand-switch 13 is not set the boundary conditions are set up and a new approximation to the pressure in the first element inside the system boundary is calculated. If hand-switch 2 is not set a new approximation to the temperature is also calculated. The calculation of T and P is then repeated for the next element and the process is continued until the elements immediately inside the right hand vertical boundary are reached. After each approximation for these elements the heat transfer across the right hand boundary is summed into U25.

Finally after the calculation for all elements in the mesh the values of the temperatures of each of the elements immediately inside the right hand boundary are printed out followed by U25 the total heat transfer across the right hand boundary.

The directive →6 followed by any number causes α to be reset to this value, the new value of α to be printed out, and the calculation to be re-entered as if R had been read.

The directive PLOT causes the punching of the temperatures and pressures of each of the elements in the mesh. The temperatures are given to the nearest ^{o}R and pressures are given in lb./ft.^{2} x 100.

Fig. 5.8 is a block diagram of the computer programme showing the main steps in the calculation.

The printing out of the last vertical row of temperatures enables the course of the calculation to be followed. Any divergence or oscillation of the values is immediately obvious and the calculation may be stopped without further loss of time.

The rate at which α may be increased can be found only by experience and depends upon the particular conditions for each run. The calculation was assumed to have converged sufficiently when none of the temperatures of the last column of elements showed a difference of more than $.01^{\circ}R$ between successive approximations. A specimen output tape is given in Appendix 2.3.

FIG. 5.8 BLOCK DIAGRAM OF COMPUTER PROGRAMME LN

POSITION OF INSTRUCTIONS IN PROGRAMME		TAPE CHARACTERS READ FROM DATA TAPE	INSTRUCTIONS OBEYED	
PAGE	LINE			
284	20	n	Print name of programme	Return to data tape input
		Any warning sequence given in chapter 5.4	Read and store data	Return to data tape input
302	39	C D	Print out all data	Return to data tape input
284	23	?	Set up initial temperature and pressure distribution	
302	19		Consult handswitch 13	
			If H/S 13 not set	If H/S 13 set → Return to data tape input
285	35		Set boundary conditions	
286	30		$q = 1$	
286	35		$p = 1$	
287	1		$v_{25} = 0$	
287	8		Calculate $P'_{[q(m+1)+p]}$	
			Consult H/S 2 → H/S 2 set	
			H/S 2 not set	
296	1		Calculate $T'_{[q(m+1)+p]}$	
300	40		Check whether $q=(n-1)$	
			$q \neq (n-1)$	$q=(n-1)$
			increase p by 1	Calculate heat transfer over right hand boundary of element and add to v_{25}
301	28		$p \neq m$	$p=m$
				Increase q by 1
302	40		$q \neq n$	$q=n$
302	29			Print last column of temperatures Print v_{25}
284	14	→6r	Set $\alpha = r$ Print α	
304	5	PLOT	Print all temperatures and pressures	Return to data tape input
		Y	STOP (optional)	
		Z	STOP	

CHAPTER VI

An Experimental Investigation of Heat Transfer by Natural Convection in Slag Wool

The object of this part of the research was to make experimental measurements of the heat transfer through slag wool insulation in a test cell 1 ft. in thickness and 4 ft. in height at pressures up to 150 psig. The effect of convection was to be demonstrated by the variation of the apparent conductivity with pressure. Slag wool was chosen as the test material since, at all reasonable bulk densities, the pore sizes are large compared with the mean free path of air and the true thermal conductivity is essentially constant with pressure over this rango. In powdered insulating materials of the silica aerogel type the size of the pore space between particles is of the same order but the particles themselves contain pores of sizes which may compare with the gas mean free path. An increase in effective conductivity with pressure could, for these materials, be attributed to the effect of pressure on the gas mean free path.

The apparatus was designed to measure the heat transfer between vertical plates at constant temperatures. One plate was cooled with liquid oxygen whilst the other was maintained near room temperature by electrical heating. The test cell itself was placed inside a pressure vessel to enable the necessary changes of air pressure to be made. A few experiments were carried out with the cold plate water cooled and the warm plate heated to a maximum of 300°F.

6.1 Apparatus

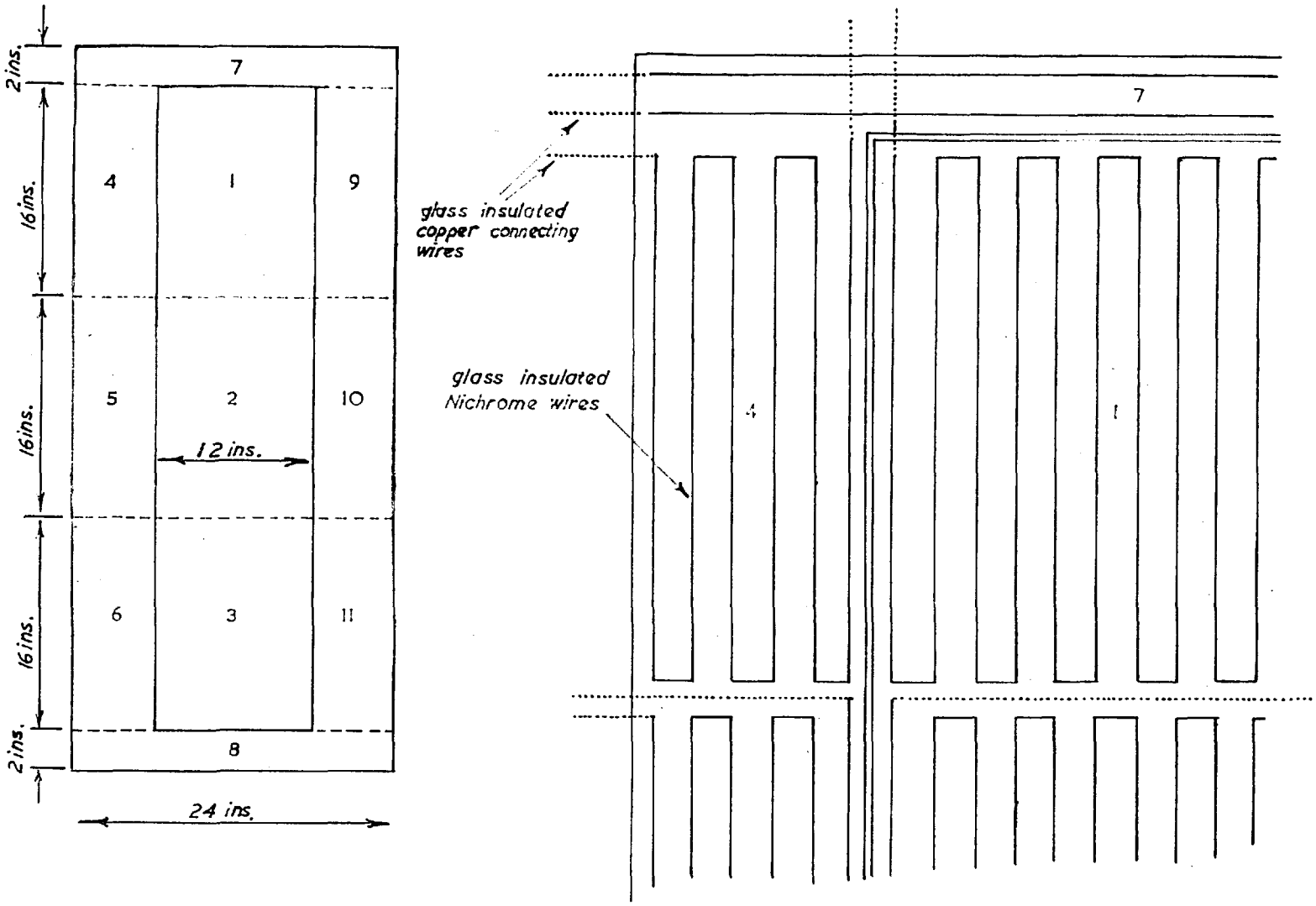
The Hot Plate

The hot plate, of 18 s.w.g. aluminium, was heated by glass insulated Nichrome wires bonded to the surface by "Araldite 105" adhesive. The plate consisted of a central test section 48 ins. x 12 ins. surrounded by a guard ring with outside dimensions 52 ins. x 24 ins. The test section was completely separated from the guard ring by a $\frac{1}{8}$ in. gap and was held in position by glass fibre tape stretched across the gap and bonded to the surfaces of test section and guard plate with "Araldite" adhesive.

Any convection in the cell would cause preferential cooling of the lower part of the hot plate so that, to maintain the temperature as uniform as possible, nine separate heaters were attached to the test section and guard plate covering the areas shown in Fig. 6.1. Pairs of heaters 4 and 9, 5 and 10, and 6 and 11, were connected in series. The heating wires were positioned to give, as nearly as possible, uniform coverage of the area (Fig. 6.1) and the spacing was chosen to give a variation of temperature less than $0.1^{\circ}F$ over the plate surface.

Assuming a thermal conductivity of 0.015 Btu./hr.ft.^{2}($^{\circ}$F/ft.) at the mean temperature of the insulation under test the heat flow per square foot for a thickness of 1 foot and at temperature difference of $350^{\circ}F$, will be 5.25 Btu./hr. To allow for the effects of convection and for the possibility of testing materials of higher conductivity the necessary heater wire spacing was calculated for a heat flow of 15 Btu./hr.

FIG. 6.1 HEATING ELEMENTS ON HOT PLATE



Q = heat flow per square foot (Btu./hr.)

ℓ = distance between adjacent heating wires (ft.)

k = thermal conductivity of aluminium (Btu./ft.^{2}hr.($^\circ$F/ft.)

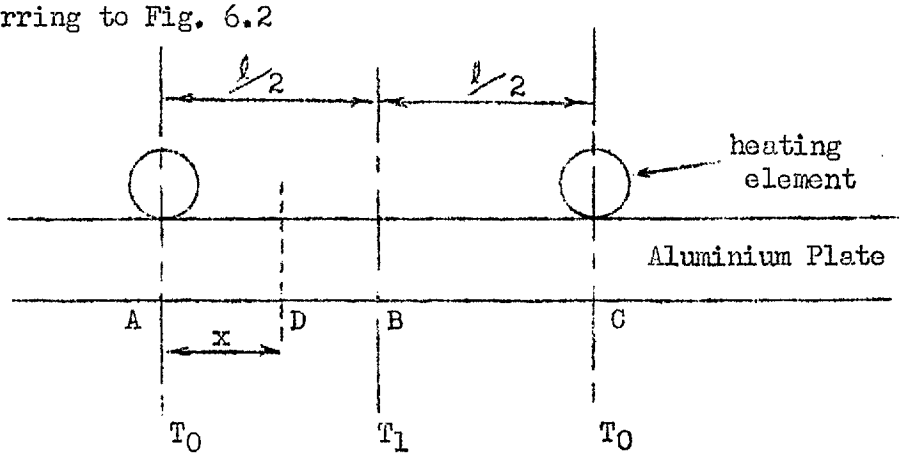
t = thickness of the plate (ft.)

T_0 = temperature at the point of contact of each heating wire ($^\circ$F)

T_1 = temperature of the plate mid-way between heating wires ($^\circ$F)

T = temperature ($^\circ$F) a distance x (ft.) from a heating wire.

Referring to Fig. 6.2



assuming a uniform flow of heat from the surface of the plate and unit distance in the Third dimension, the heat flowing from the plate over the length DB is given by

$$Q\left(\frac{\ell}{2} - x\right)$$

This heat must flow from A through the point D

Thus $$Q\left(\frac{\ell}{2} - x\right) = -k \frac{dT}{dx} . t.$$

$$-kt \int_{T_0}^{T_1} dT = Q \int_0^{\frac{\ell}{2}} \left(\frac{\ell}{2} - x\right) dx$$

$$-kt\left(T_1 - T_0\right) = Q\left[\left(\frac{\ell}{2}\right)^2 - \frac{1}{2}\left(\frac{\ell}{2}\right)^2\right]$$

$$T_0 - T_1 = \frac{Q\ell^2}{8kt}$$

$$= \sqrt{\frac{8k(T_0 - T_1)t}{Q}}$$

for aluminium k = 119 Btu./ft.^{2}hr.(^{o}F/ft.)

$$t = .048 \text{ in. (18 s.w.g.)}$$

so that for Q = 15 Btu./hr. and $(T_0 - T_1) < 0.1^oF$

$$\ell < 1.9 \text{ ins.}$$

One inch. was therefore chosen as the distance between adjacent heating wires.

A guard plate of 16 s.w.g. aluminium heated in a similar way with one heating element having $1\frac{1}{2}$ in. spacing between wires was centrally situated behind the test plate to prevent the leakage of heat in the reverse direction. This plate 52 ins. by 22 ins. was separated from the test plate by a two inch thickness of glass foam. The plate thicknesses were chosen to be as small as possible (to minimise the heat capacity of the system) while being large enough to give reasonable rigidity.

The Cold Plate

The cold plate assembly is shown in Fig. 6.3 and consisted of a 52 ins. by 24 ins. by 16 s.w.g. copper plate with 8 vertical tubes $\frac{3}{8}$ in. O.D. soldered to the rear face. The upper ends of these tubes were soldered into a 4 in. O.D. cylindrical vessel with hemispherical ends supported by two brackets near the top of the plate. (The brackets have been omitted in Fig. 6.3 for clarity) The lower ends were soldered into a $\frac{3}{4}$ in. O.D. horizontal manifold connected to the upper vessel by a 1 in. O.D. vertical downcomer. Three $\frac{3}{8}$ in. O.D. copper tubes were

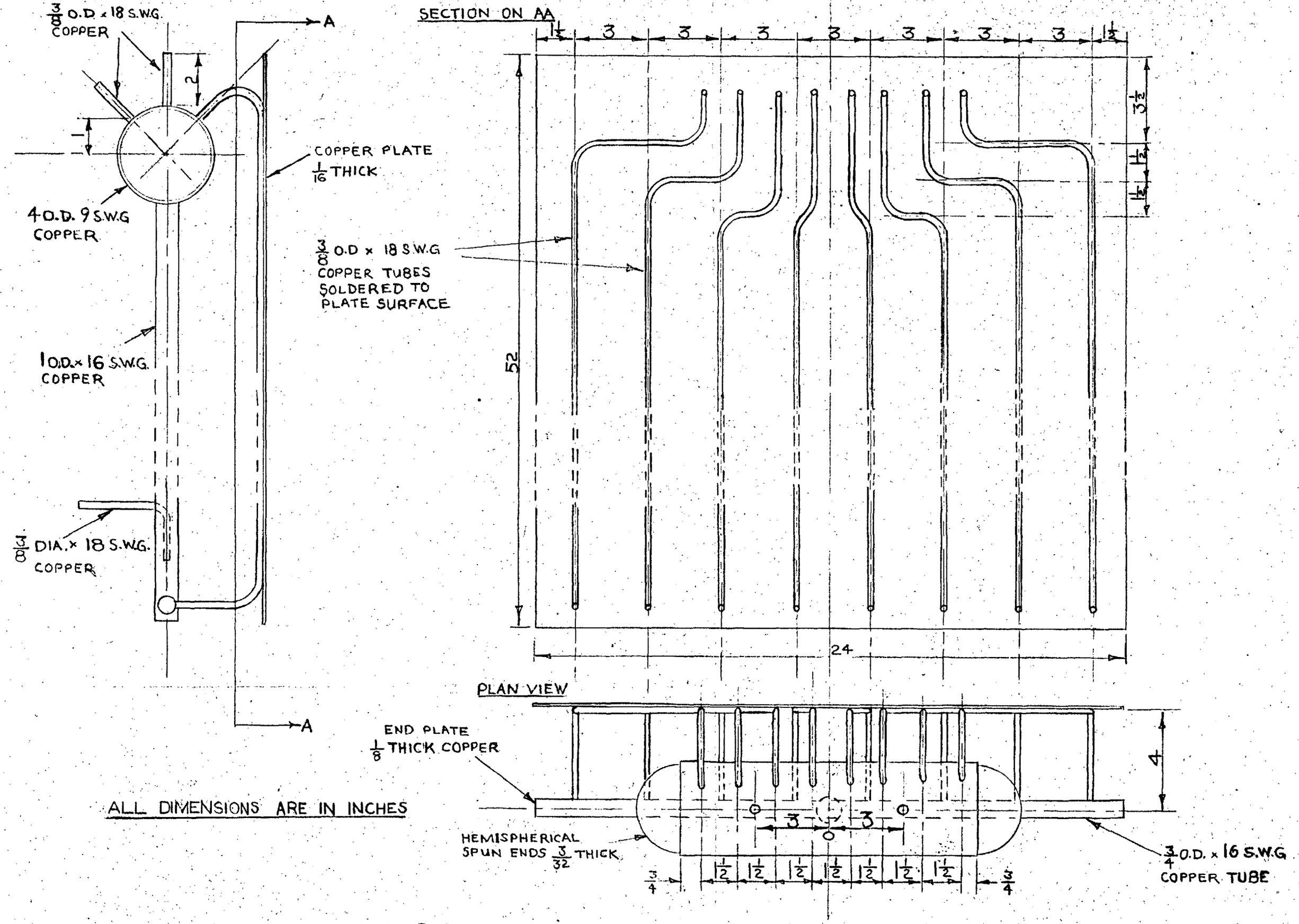


FIG. 6.3 COLD PLATE ASSEMBLY

soldered into the upper vessel and a $\frac{3}{8}$ in. O.D. copper tube was soldered into the downcomer near its lower end as shown.

All joints in the assembly were silver-soldered except those holding the vertical tubes to the plate which were soft soldered. The assembly was designed for working pressures, both internal and external, up to 200 psig and was pressure tested accordingly.

The aim was to maintain a constant level of liquid oxygen in the upper vessel which would be fed via the downcomer and manifold to the vertical tubes. Boiling in the tubes would cool the plate and cause a mixture of liquid and vapour to be forced upwards back into the upper vessel. Vapour would then flow off through one of the $\frac{3}{8}$ in. diameter outlet tubes and liquid would be re-circulated. Of the two remaining $\frac{3}{8}$ in. diameter tubes in the upper vessel, one was used for the level sensing probe (described later) and the other, a spare connection, was blanked off during the experiments. Liquid feed to the system was through the tube projecting into the downcomer. The purpose of this was to assist in circulation of the liquid, particularly in the high temperature runs where cooling was achieved by the circulation of water.

Assembly of the Test Cell

The complete test cell consisted of the hot and cold plates on opposite faces of a box-like structure containing the insulation under test. The other four sides of the assembly were of foamed glass slabs which were impervious to gas flow.

Foamed glass was available in 2 in. thick slabs of maximum dimensions 19 ins. by 19 ins. and it was necessary to make up sections of the

required dimensions by bonding together two or more slabs. Preliminary tests showed that joints between two pieces of foamed glass bonded with Araldite 105 were satisfactory after repeated immersions in liquid nitrogen and subsequent warming to room temperature. Araldite 105 was, therefore, used for all joints in the foamed glass. The joints were reinforced with glass fibre tape impregnated with Araldite 105. Tests on the bonding of aluminium and copper to foamed glass with various adhesives showed that such joints were unsatisfactory where temperature cycling was involved. The whole assembly was, therefore, clamped together without the use of any bonding between metal and foamed glass. Gaskets, consisting of several layers of folded glass tape, were used in these joints to eliminate gaps caused by distortion of the metal plates or irregularities in the foamed glass. The joints were further caulked with asbestos fibre after assembly.

The rear guard plate was bolted into a 25 ins. by 52 ins. frame of aluminium Dexion 112, and Dexion 112 was bolted to the vertical edges and bottom edge of the cold plate. The whole assembly was then drawn together as shown in Fig. 6.4 using 18 swg stainless steel wire between the hot and cold plates. A piece of $\frac{1}{8}$ in. thick hard asbestos board across the base completed the assembly. A lid, constructed from foam glass bonded with Araldite, covered the top of the cell and projected 2 ins. downwards inside the cell. A similar 2 in. layer of foam glass on the base above the hard asbestos ensured that the space for convection was of the same height as the test section of the hot plate.

The complete assembly gave a test cell 48 ins. high 21 ins. wide and 11.9 ins. thick, the actual test plate being 48 ins. high and 12 ins.

wide. This section was packed, as uniformly as possible, with slag wool to a density of 9.1 lb./ft.^{3}

To make possible the variation of gas pressure in the test cell the whole assembly was suspended inside a pressure vessel designed for working pressures of up to 150 psig. The vessel, cylindrical with dished ends, was of $\frac{3}{8}$ in. thick mild steel with an internal diameter of 3 ft. The upper end was flanged to allow the test cell to be lowered into place. The lower end was fitted with a 4 in. nominal bore outlet. Two 2 in. nominal bore outlets were positioned, diametrically opposite, 12 inches below the top flange. The maximum internal height with the lid in place was 6 ft. $5\frac{3}{4}$ ins. and the height of the straight portion of the tank sides was 5 ft. $1\frac{3}{8}$ ins.

The bottom outlet was used as a drain to remove powder insulant from the tank and was fitted with a sliding gate assembly to enable the flow to be controlled. The two 2 in. outlets were used for the connections to the test cell.

The test cell was suspended by 16 s.w.g. stainless steel wires passing underneath it and attached to four bolts screwed into holes tapped in the inside of the main flange of the vessel. Correct positioning was achieved by an additional 18 s.w.g. wire attached to the top and by cable tensioners in the main wires. The assembly is shown in position in Fig. 6.5

The space around the cell was filled with "Perlox", an expanded mineral powder insulation, up to the level of the main flange. Slag wool was placed above this to fill the upper dished end when bolted in position. A $\frac{1}{4}$ in. thick rubber gasket was used to form a seal in

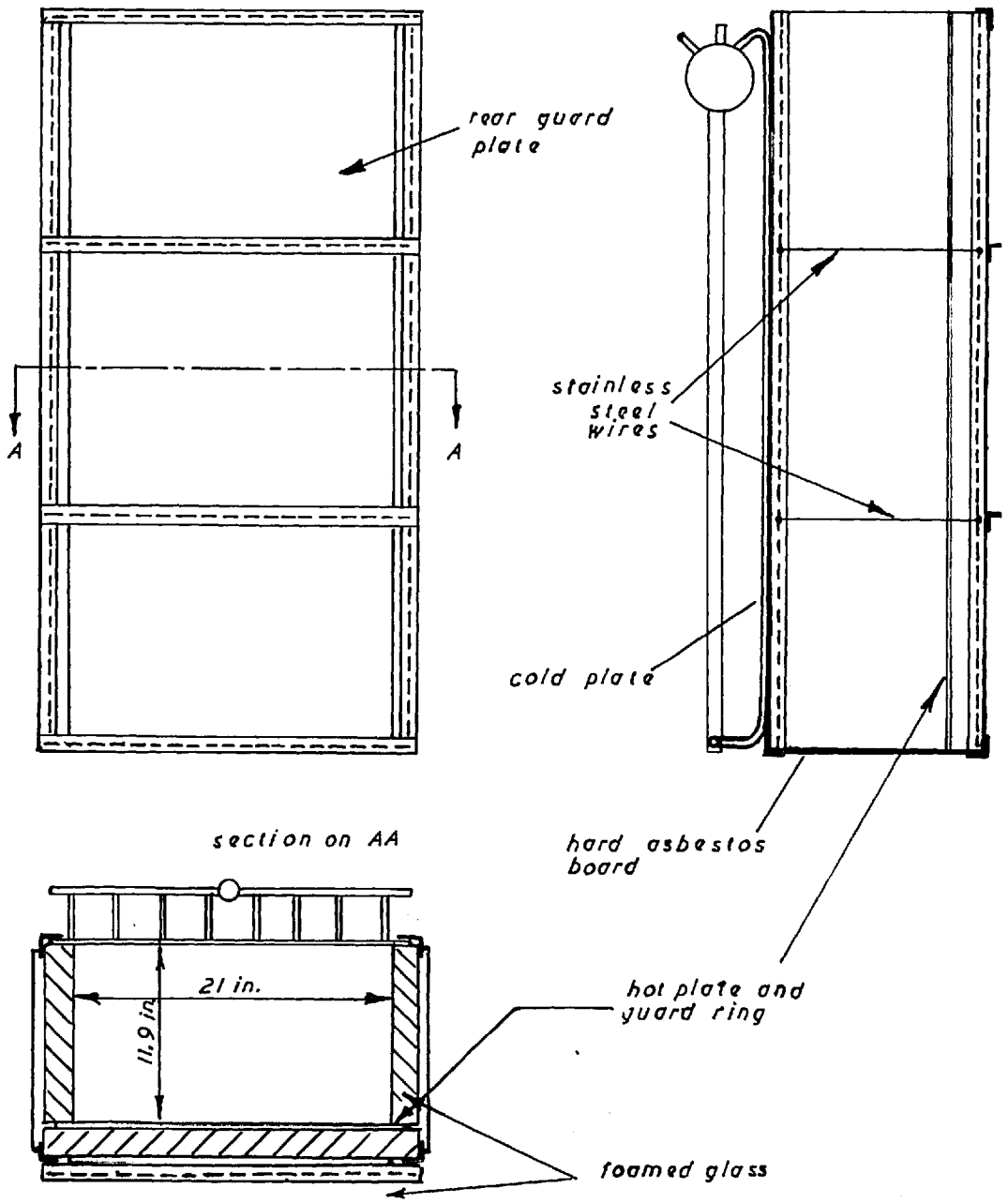


FIG 6.4 ASSEMBLY OF TEST CELL



FIG. 6.5 TEST CELL IN POSITION INSIDE PRESSURE VESSEL

the top flanged joint.

Heating Circuits for Hot Plate and Guard Rings

The main considerations in the design of the heating circuits were

(a) High voltages were to be avoided to minimise the risk of insulation breakdown.

(b) Low current was to be preferred to minimise the necessary diameter of connecting wires.

(c) Resistance of the heating element was to be such that the wire would have reasonable strength without being cumbersome and difficult to keep in close contact with the plate.

Nichrome wire 28 s.w.g. has a resistance of 3 ohms per foot and was available with woven glass insulation.

Distance between adjacent wires = 1 in.

Assuming a uniform coverage of the hot plate surface.

Length of wire required = 12 ft. per sq. ft.

Heat flow = 15 Btu./hr. per sq. ft.

= 4.39 Watts per sq. ft.

∴ Power dissipated in each heater = 1.33 x 4.39

= 5.83 Watts

and resistance of wire = 1.33 x 12 x 3 ohms

= 48 ohms

Voltage required = $\sqrt{48 \times 5.83}$

= 16.7

$$\text{Current} = \frac{5.83}{16.7}$$

$$= 0.35 \text{ amps.}$$

Thus the use of 28 s.w.g. nichrome wire with a 24 volt supply provides ample power without the necessity for large currents.

In the case of the rear guard plate the greatest power will be necessary for high temperature runs where the temperature will be as much as 250°F above that of the pressure vessel shell.

Assuming a mean distance from the tank shell of 5 ins. and a mean conductivity of Perlox of 0.02 Btu./ft.^{2}hr.(°F/ft.) the necessary power will be 28 watts. This would be provided with a voltage of 73 volts and a current of 0.38 amps.

28 s.w.g. nichrome wire was therefore used for all the heating elements. Power for the test plate was obtained from 24 volt batteries which were charged continuously during the tests. The current was adjusted so that there was very little net rate of charge. The power was thus being derived principally from the battery charger; the batteries served simply as a means of keeping the voltage steady at 24 V.D.C. Power for the guard ring circuits was derived from the A.C. mains the voltage being adjusted by "Variac" variable auto-transformers.

Voltmeters were wired so that they could be switched across any of the guard ring heaters.

Power in the three test plate heaters was determined by accurately measuring the voltages across each with a potentiometer. To enable this to be achieved, the actual voltage was reduced by a factor of $\frac{1}{11}$ in a potential dividing circuit using standard resistances of 10,000 ($\pm$ .02%)

and 100,000 (± .02%) ohms. A plug and three sockets were used so that each voltage could be measured in turn.

Fig. 6.6 is a complete circuit diagram for the heaters.

Temperature Measurement

Copper-constantan themocouples were made with 30 s.w.g. wire, glass insulated, and with silver soldered junctions, to determine the temperatures on the test plate and guard plates. The thermocouples were positioned as shown in Fig. 6.7. The junctions were attached by drilling small holes in the plate, inserting the junctions into the hole and "peening" the edges of the hole onto the junctions. The junctionswere then covered with a layer of Araldite to give added support. In addition to these "measuring thermocouples" three pairs of thermocouples were used for control purposes. A and B were positioned as shown in Fig. 6.7 and consisted of two junctions of a themocouple pair, one attached as described above to the aluminium plate, the other similarly attached to the guard ring. The short connecting wire between the two plates was constantan, the longer external leads being copper. The third controlling thermocouple, C, had once junction attached to the test plate in the same way. The other junction was clamped between the rear guard plate and the foamed glass separating this from the main plate.

A Sunvic thermostatically controlled "cold junction" was used for the reference junctions of the measuring thermocouples. Three separate reference junctions were used, insulated from each other by rubber sleeving. They were held firmly in place in the central well of the "cold junction" by a packing of asbestos rope.

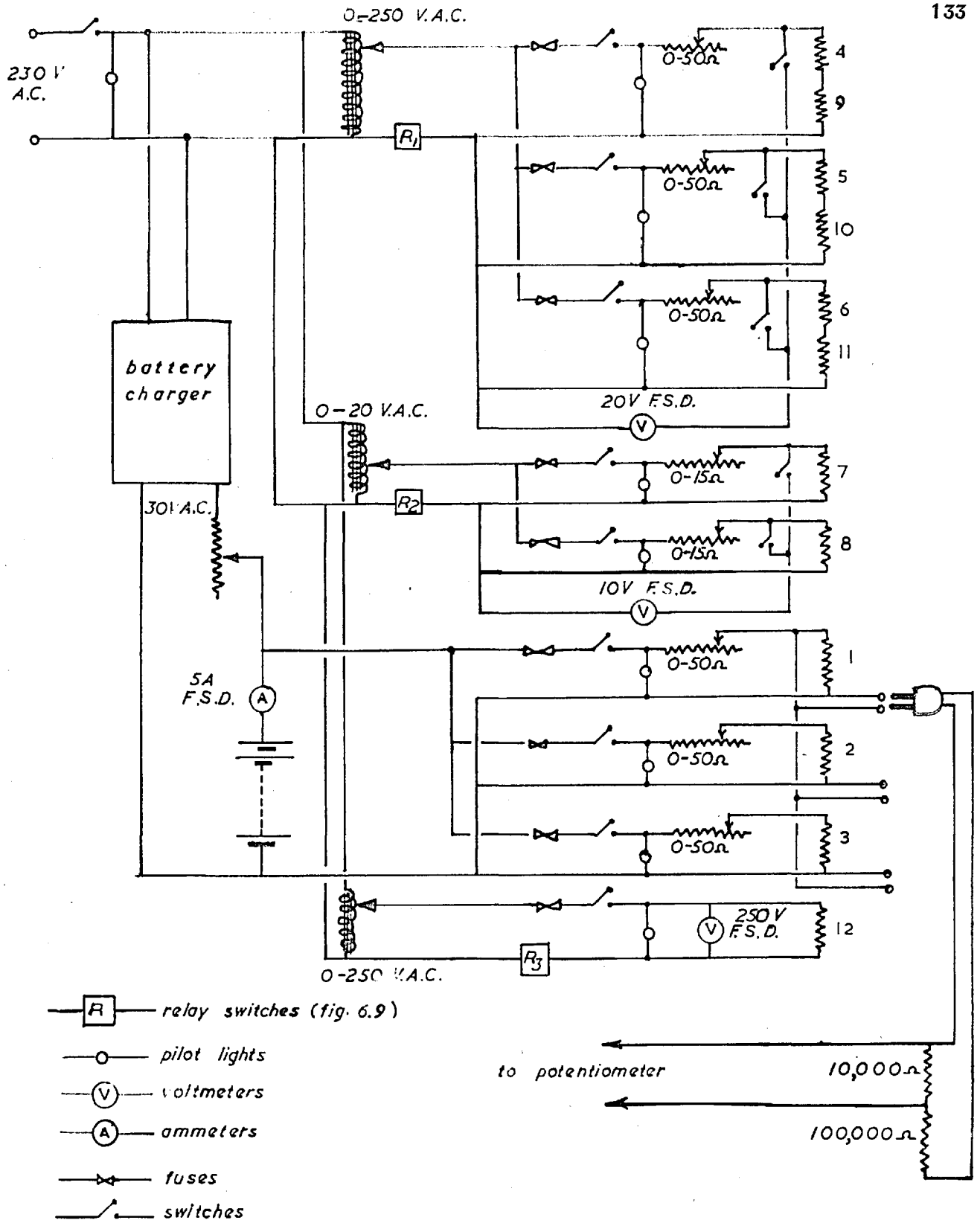


FIG. 6.6 CIRCUIT DIAGRAM FOR HEATERS

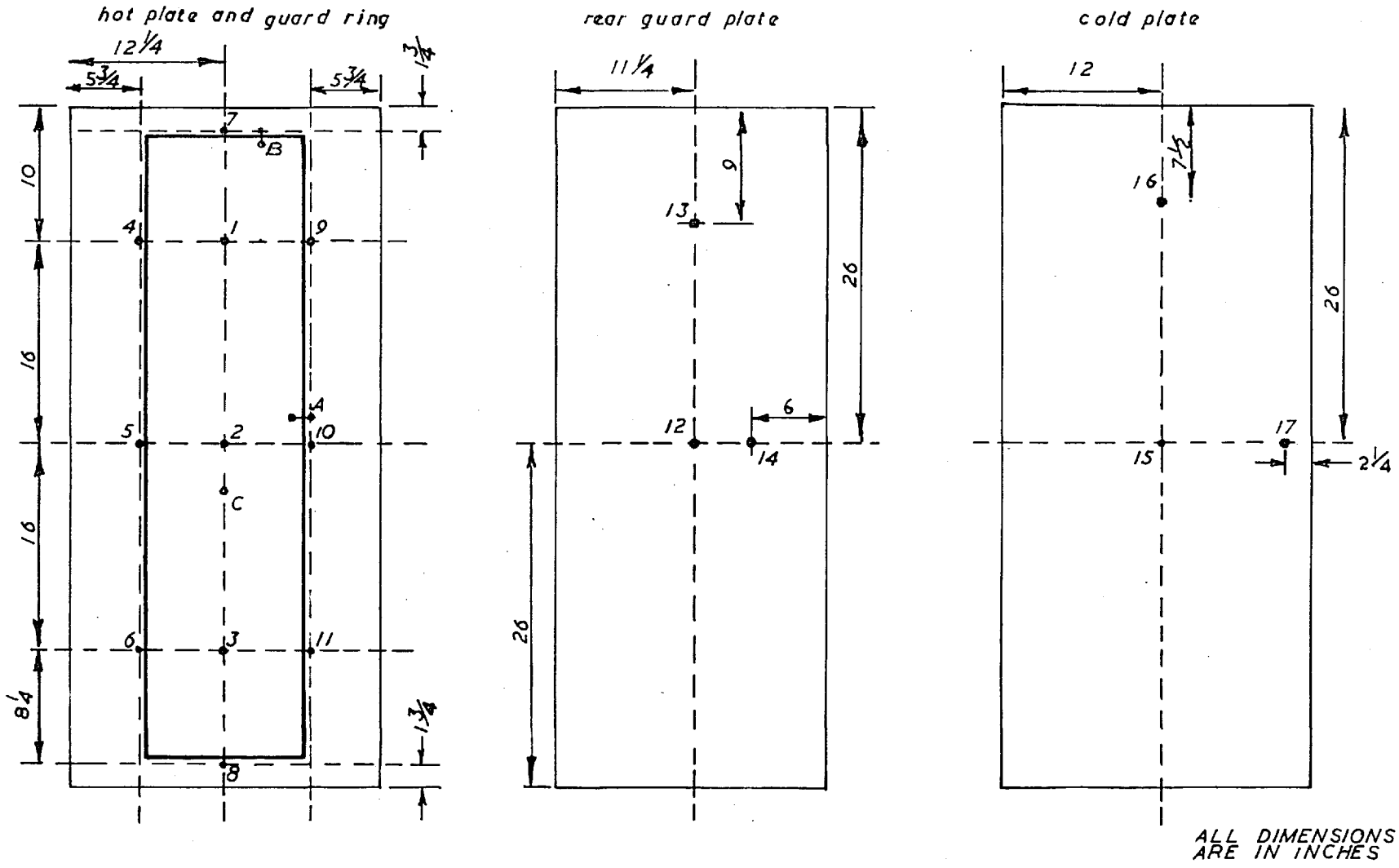


FIG.6.7 POSITION OF THERMOCOUPLES ON PLATES

The eighteen thermocouples were connected for e.m.f. measurement on a Pye potentiometer (Catalogue No. 7568) reading to 1 microvolt. In addition those numbered 1 to 12 in Fig. 6.7 were connected for continuous recording on a 12 point recording potentiometer with a centre zero and ± 5mV full-scale deflection. A reference junction was connected into the switching circuits of this instrument so that the e.m.f. recorded was a direct measure of the difference in temperature between each of the 12 measuring points and the "cold junction". The thermostatically controlled temperature of the "cold junction" was maintained at 43.7°C constant to better than 0.1°C. The circuits of the thermocouples are shown in Fig. 6.8. The constant temperature enclosure consisted of a solder-tag panel held in a recess between two 2 in. thick blocks of Onazote insulation bolted together.

Guard Ring Temperature Control

The e.m.f. from each of the differential thermocouples A, B and C was applied across the coil of a sensitive mirror galvanometer. A phototransistor (Mullard OCP71) connected in the circuit shown in Fig. 6.9 was positioned in the reflected light beam from each galvanometer. Small changes in the e.m.f. of the thermocouple circuit caused the light beam to be directed onto or away from the sensitive spot of the photo-transistor. Connected this way and with 15 volts across the voltmeter (V) the photo-transistor passed about 4mA when in the light beam and less than 1mA in the dark.

4mA was sufficient to trigger the sensitive relays thus switching the current to the guard plate heaters.

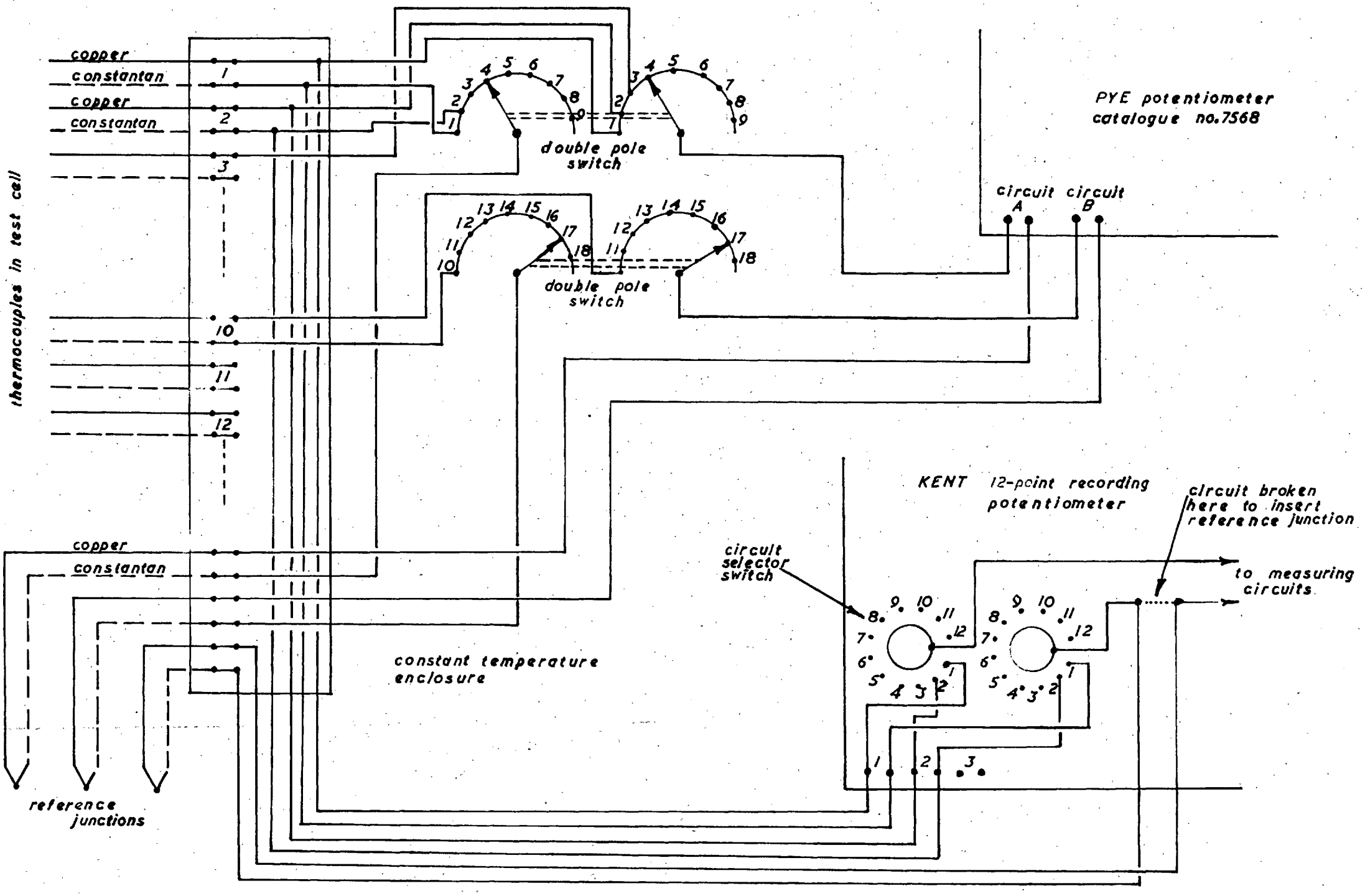
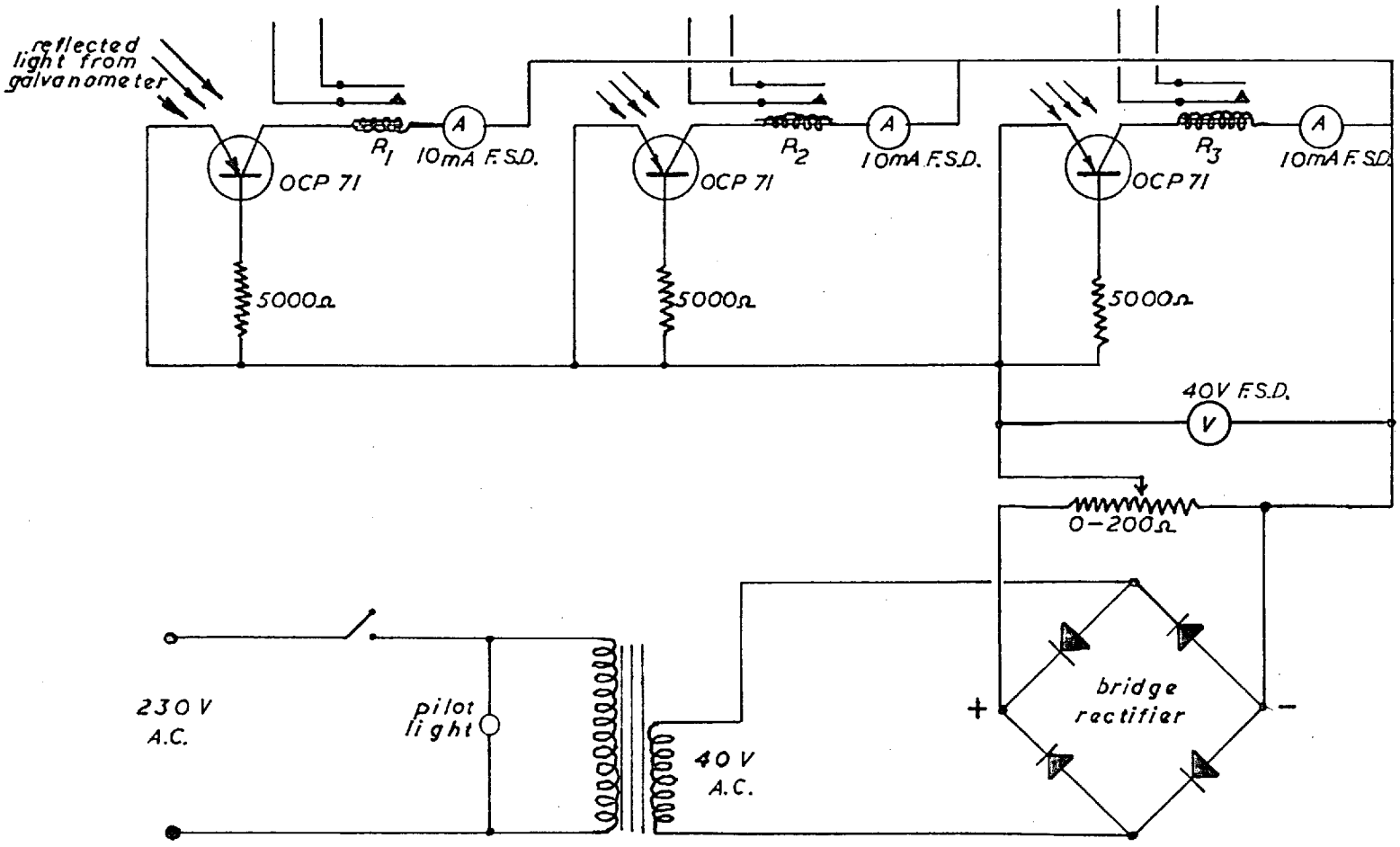


FIG. 6.8 CIRCUIT DIAGRAM FOR THERMOCOUPLES



R_1 R_2 R_3 – relays (approximately 5000Ω) switching current to guard ring heaters (fig. 6.6)

FIG. 6.9 CIRCUIT DIAGRAM FOR PHOTOTRANSISTOR TEMPERATURE CONTROLLERS

The currents to the guard plate heaters were adjusted to give equilibrium temperatures above those of the test plate. The zero position of each galvanometer was then adjusted until, with the temperature of guard plate and test plate equal, the light beam was about to fall on the sensitive surface of the photo-transistor and the relay was on the point of switching. A slight rise in temperature of the guard plates (relative to the test plate) then caused the heaters to be switched off and a slight fall caused them to be switched on again.

The thermocouple pair B was used to switch the current to heaters 7 and 8 (Fig. 6.2), the relative temperatures of 7 and 8 being adjusted manually by the rheostats in these circuits. Similarly, A was used to switch heaters 4,5,6,9,10,11 the relative powers necessary to maintain constant temperature being obtained by manual adjustment of the rheostats in these circuits. C was used for the switching of the current to the rear guard plate heater.

Electrical Connections to the Test Section

All electrical connections to the test section were to be made through the shell of the pressure vessel in such a way as to prevent leakage of gas from the vessel. The connections were made through a flange on one of the 2 in. nominal bore side connections.

The glass insulated thermocouple wires and p.v.c. insulated wires for all other electrical connections were sealed into short lengths of $\frac{3}{8}$ in. O.D. copper tubing with Araldite x83/11 adhesive containing a mica flour filler. These were sealed into Simplifix couplings screwed

into holes in the flange. The assembly is shown in Fig. 6.10. The fittings were pressure tested to 250 psig before being screwed into the flange.

Liquid Oxygen Supply to Cold Plate

Liquid oxygen was supplied to the cold plate from 50 lb. capacity Dewar vessels pressurised with oxygen gas to about 3 psig. A flow diagram is given in Fig. 6.11. The safety valve consisted of a $1\frac{1}{2}$ in. diameter glass column containing eight inches of mercury. A $\frac{3}{8}$ in. diameter glass tube projected to the bottom of this column and was connected to the pressurising line. Any pressures in excess of 8 ins. mercury would have been released by bubbling of the oxygen through the mercury.

The liquid feed lines were $\frac{3}{8}$ in. O.D. copper tubing except at the connection through the flange on the pressure vessel. It was necessary at this point to reduce the diameter to $\frac{1}{4}$ in. O.D. because of space limitations. The lines were insulated with fibre glass "bandage" sealed against moisture inleak with p.v.c. self-adhesive tape. The insulation extended from the flange of the pressure vessel to the connections at the neck of the Dewar vessels. One Dewar vessel could be used alone if necessary by the blanking off of the second feed line. After the connection of full Dewar vessels the fittings at the neck were insulated with slag wool wrapped with polythene strips to prevent the ingress of moisture.

Fig. 6.12 gives details of the flange assembly designed to minimise heat leakage to the liquid oxygen feed and prevent excessive cooling of the pressure vessel side arm at the point of entry of the liquid oxygen feed line.

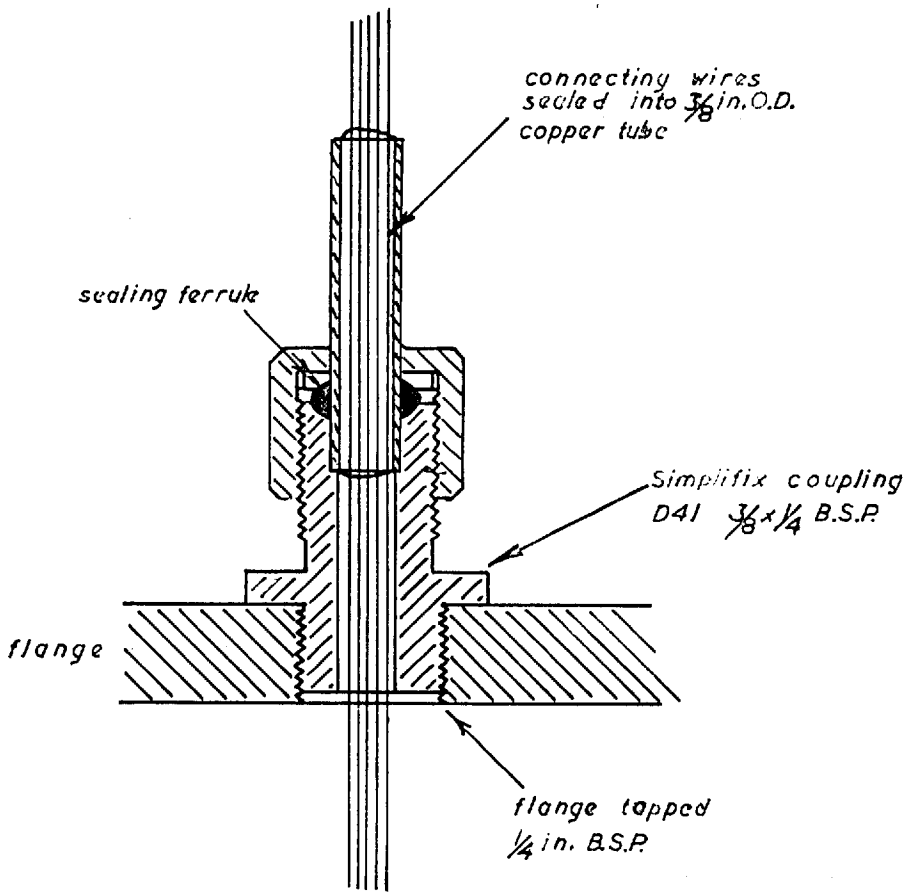
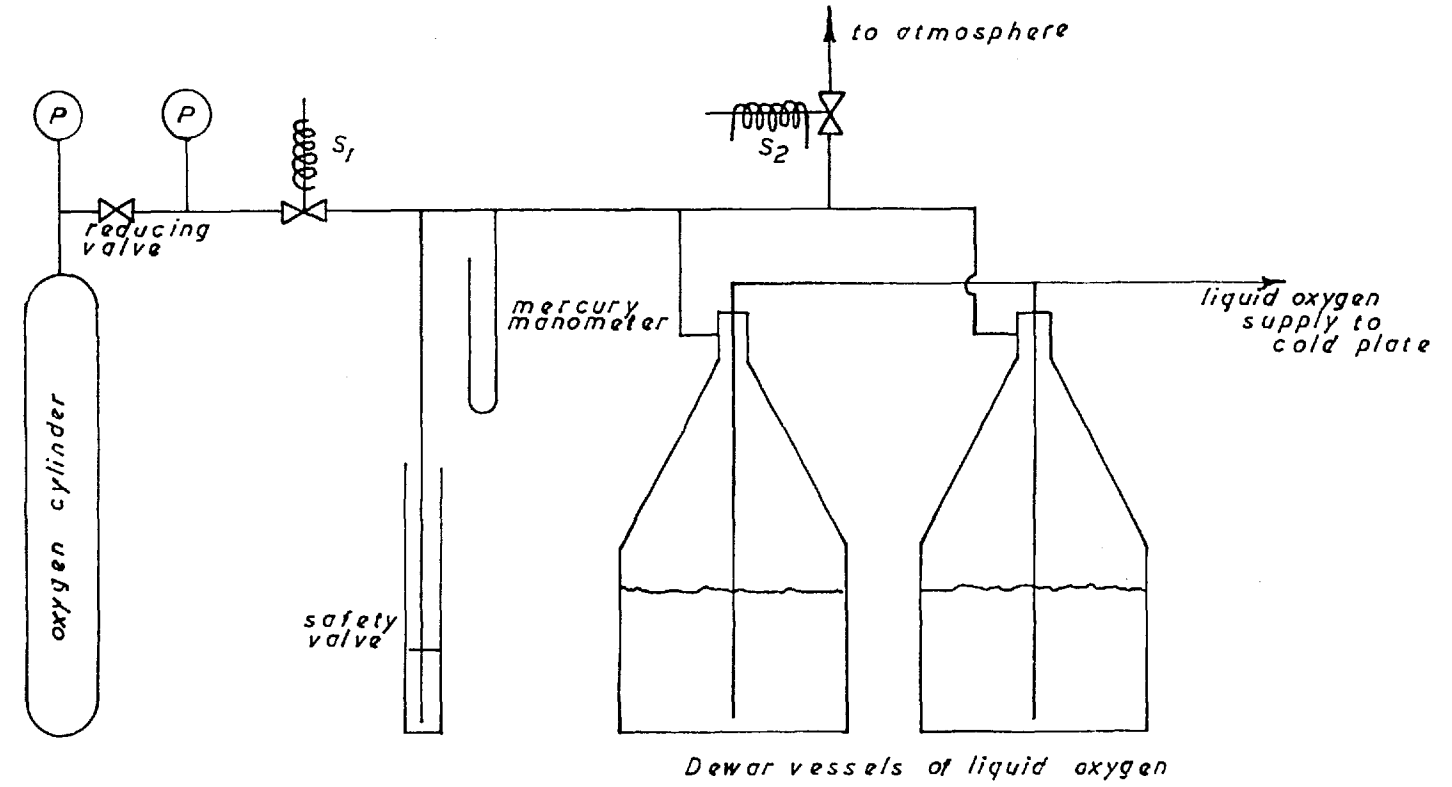


FIG 6.10 SEALING OF CONNECTING WIRES THROUGH FLANGE



(P) pressure gauges

S_1, S_2 solenoid valves

FIG. 6.11 FLOW DIAGRAM FOR LIQUID OXYGEN FEED

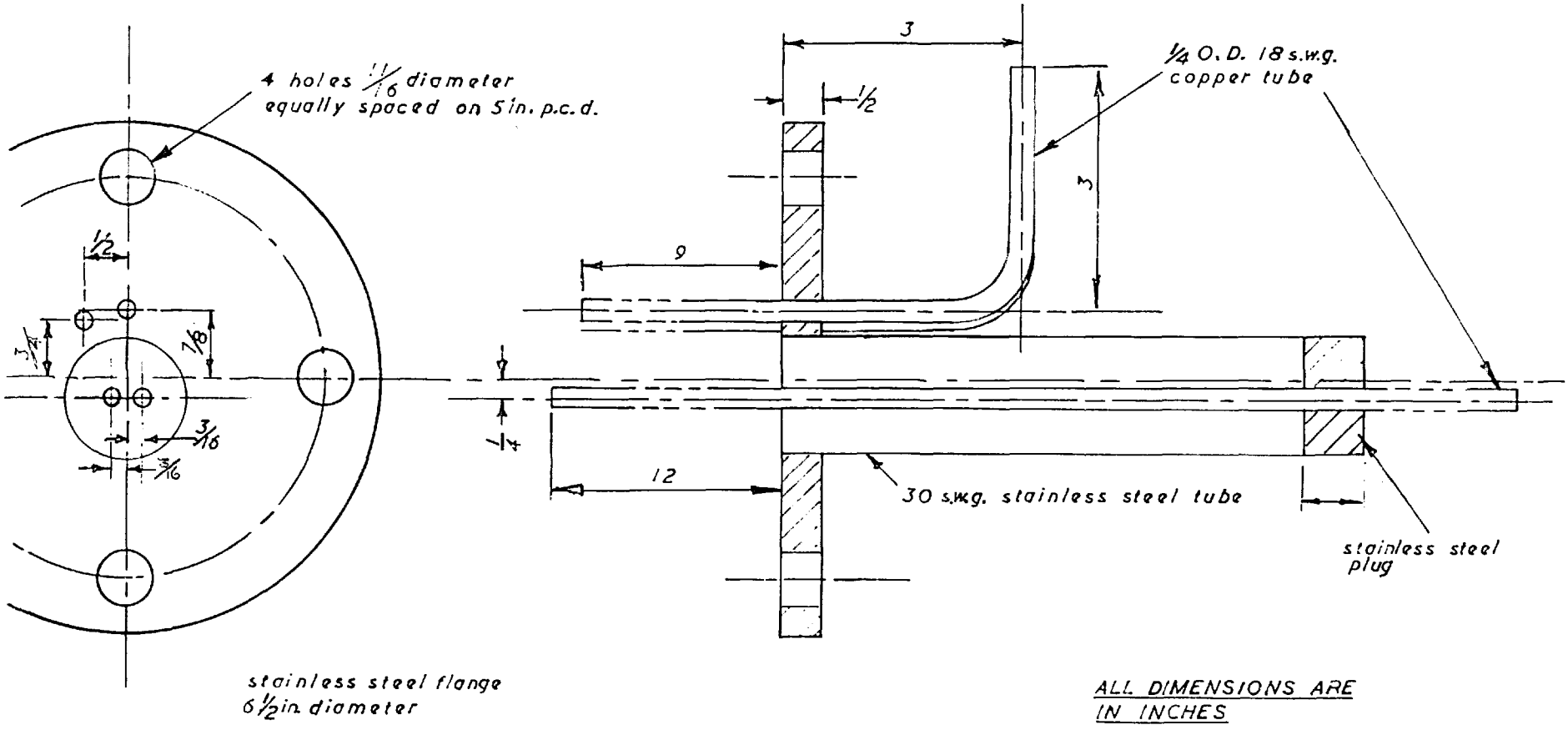


FIG. 6.12 FLANGE FOR LIQUID OXYGEN INLET

The flange was of stainless steel, the 30 s.w.g. stainless steel tube providing a long heat path between the cold oxygen pipes and the pressure vessel shell. Liquid oxygen feed and oxygen gas boil-off passed through the $\frac{1}{4}$ in. O.D. copper tubes at the centre of the stainless steel tube. The other connections were for the pressure and vacuum lines to the pressure vessel.

Liquid Oxygen Level Control

The control of liquid oxygen level in the liquid reservoir on the cold plate was based on the use of a Stantel F.22 thermistor. The thermistor, surrounded by a low wattage heater, was held at the position of the desired level. When immersed in the liquid the heat from the heater was rapidly dissipated by the boiling liquid and the temperature of the thermistor fell to the liquid boiling point. When the liquid level fell the heater caused the temperature of the thermistor to rise. The power was adjusted to warm the thermistor to about -70°F at which temperature its resistance is about 10,000 ohms. At liquid oxygen temperatures the resistance is several megohms. Fig. 6.13 shows the construction of the thermistor level control assembly and the arrangements for sealing it into the top of the liquid oxygen reservoir. The length was adjusted to maintain a liquid level of about $1\frac{1}{2}$ inches in the reservoir.

The heater was wound from about 3 ins. of 36 s.w.g. nichrome wire and had a resistance of about 3 ohms. A current of 0.4 amps was required to give the necessary power input. The change of resistance of the thermistor was used to actuate a relay which caused the operation of solenoid valves S_1 and S_2 (Fig. 6.11). The thermistor circuit including

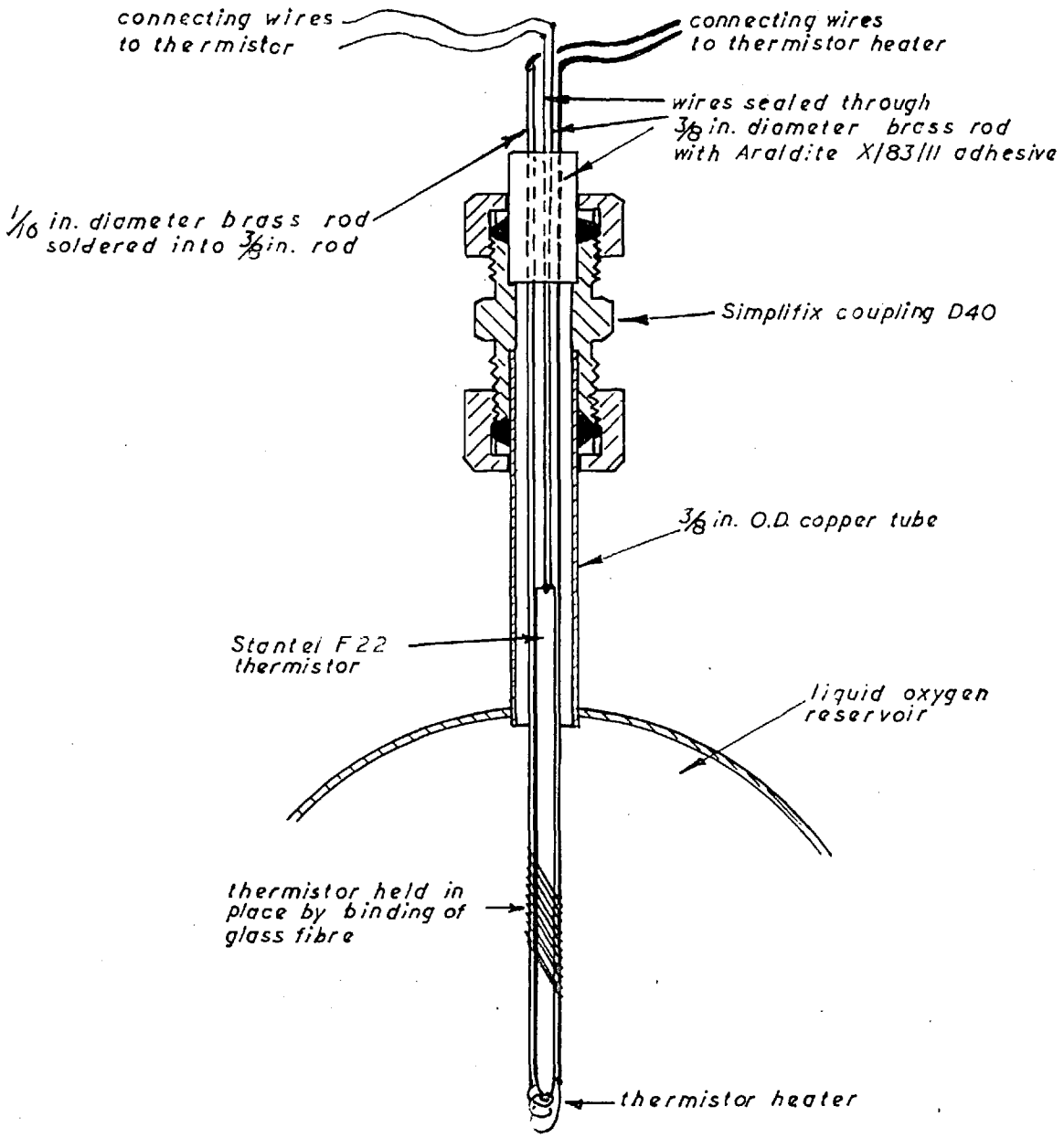


FIG. 6.13 THERMISTOR LIQUID LEVEL CONTROLLER

the associated heater is shown in Fig. 6.14. The solenoid valves were switched through Sunvic hot-wire vacuum switches to reduce sparking at the relay contacts. A 10mA D.C. current was required to operate the relays.

Considering the circuit in Fig. 6.14 in the two positions of control:

a) Liquid level high.

Resistance of thermistor > 2 megohms.

Combined resistance of thermistor and $R_2 > \frac{8}{6}$ megohms.

Potential of A $> \frac{1.33}{3.33} \times 230V$

$> 92V$

If potential of A is 92V

Assume anode current = 13.7mA

then potential of D $= 230 - 1000 \times \frac{13.7}{1000}$

$= \underline{216.3V}$

and potential of C $= 0 + 7,000 \times \frac{13.7}{1000}$

$= \underline{95.9V}$

For the valve,

Anode voltage (D - C) = 120.4V

and Grid bias (A - C) = - 3.9V

Under these conditions the valve characteristic curves show anode current = 13.7mA. Thus, the original estimate of 13.7 was correct.

For a high liquid level, current in the relay is greater than 13.7mA, the relay operates closing S_1 and opening S_2. The pressure

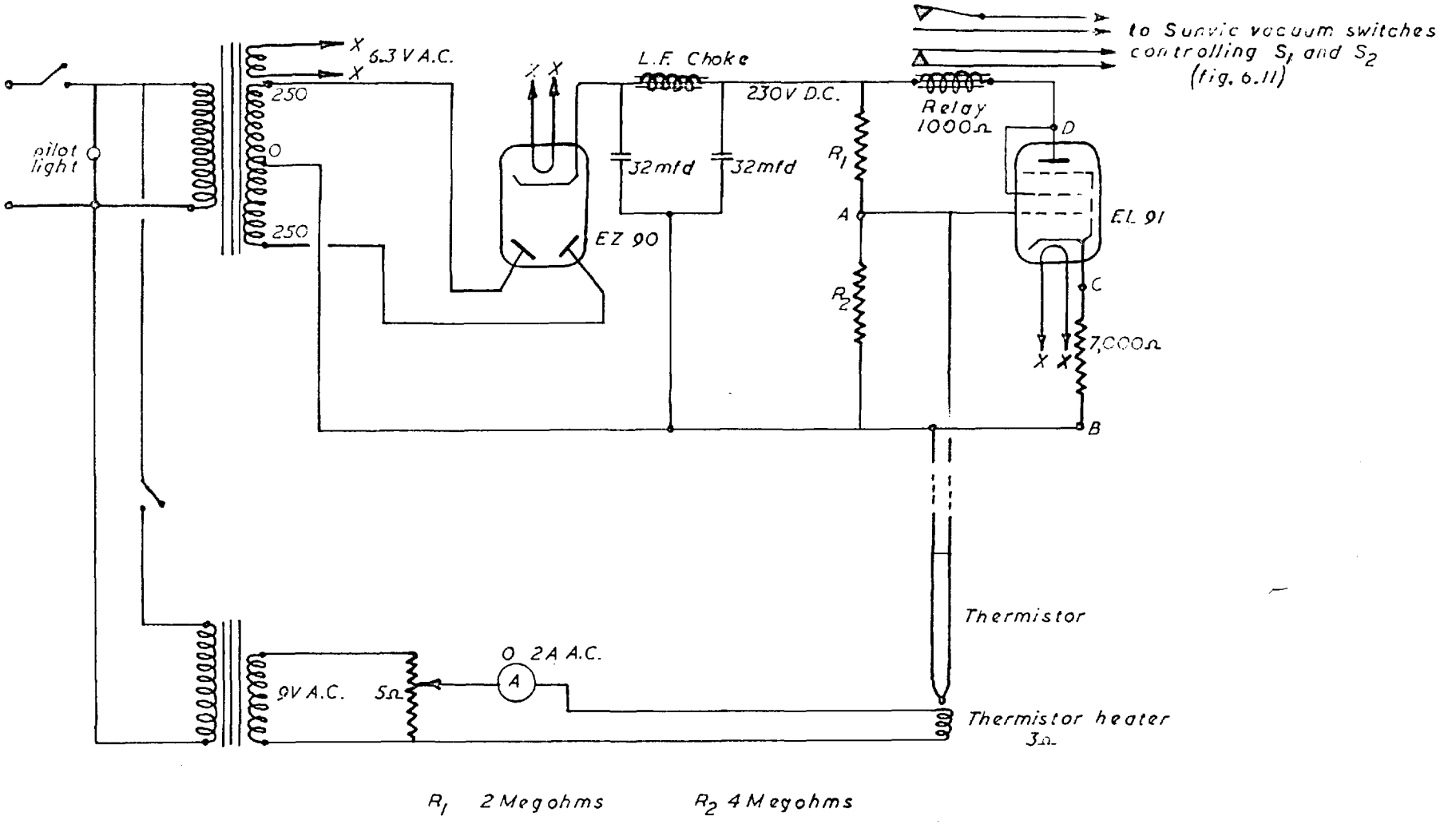


FIG. 6.14 CIRCUIT DIAGRAM FOR LIQUID OXYGEN LEVEL CONTROLLER

in the Dewar vessel is released and the flow of liquid oxygen ceases.

b) Liquid level low.

Resistance of thermistor = 10,000 ohms. (-70°C)

Combined resistance of thermistor and $R_2 = \frac{40,000}{4,010} = 9,980$ ohms.

Potential of $A = \frac{9,980}{2,009,980} \times 230$

$= \underline{1.15V}$

In this case it can be shown that

Current in relay = 3mA

Thus when the liquid level is low the relay closes, S_1 opens and S_2 closes causing the injection of more liquid oxygen.

It can be shown that the maximum power dissipated in the thermistor occurs when its resistance is $\frac{4}{3}$ Megohm. The power must not exceed 10mW.

If resistance is $\frac{4}{3}$ megohm the combined resistance across 230V = 2 + 1 megohm.

= 3 megohm

Total Current = $\frac{230}{3,000}$ mA.

Current in thermistor = $\frac{4 \times 3}{16} \times \frac{230}{3,000} = .0575$mA.

Power dissipated $= 5.75^2 \times 10^{-10} \times \frac{4}{3} \times 10^9$ mW

$= \underline{4.4mW}$

Thus the maximum permissible power is not exceeded with the above circuit.

Pressurisation of Test Cell

A 4 ft. long 4 in. diameter column packed with potassium hydroxide pellets was used to remove moisture and carbon dioxide from the air used

to pressurise the apparatus. Pressures below atmospheric were obtained by using an Edwards Hi-vac rotary vacuum pump. A fine and coarse air bleed into the vacuum line enabled the vacuum to be held constant at intermediate values. A flow diagram of the connections is given in Fig. 6.15.

The oxygen boil-off line was connected via a warming coil of $\frac{3}{8}$ in. diameter 20 s.w.g. copper tubing to a dry gas meter so that an estimate of the rate of consumption of oxygen liquid at any time could be made.

The assembled apparatus is shown in Fig. 6.16.

Auxiliary Apparatus for the Determination of Permeability

A simple apparatus was set up to determine the permeability over a range of bulk densities of the slag wool used in the main tests.

The apparatus consisted essentially of a 3 ft. section of 3 in. diameter "Quickfit" glass pipe bolted at the bottom to a mild steel sheet which served as an end flange and as a stand. A drain cock, an air inlet, and a pressure tapping tube projecting $\frac{3}{4}$ in. into the pipe were welded into this bottom plate. The top cover plate was similarly fitted with an air outlet and a pressure tapping tube projecting into the pipe. Compressed air was passed via a reducing valve through an oil filter and a drying column containing silica gel into the bottom of the 3 in. pipe. Air from the top of the pipe passed through a rotameter to atmosphere. The pressure drop through the pipe was measured on an inclined water manometer. A flow diagram of the system is given in Fig. 6.17. Fig. 6.18 is a general view of the complete apparatus.

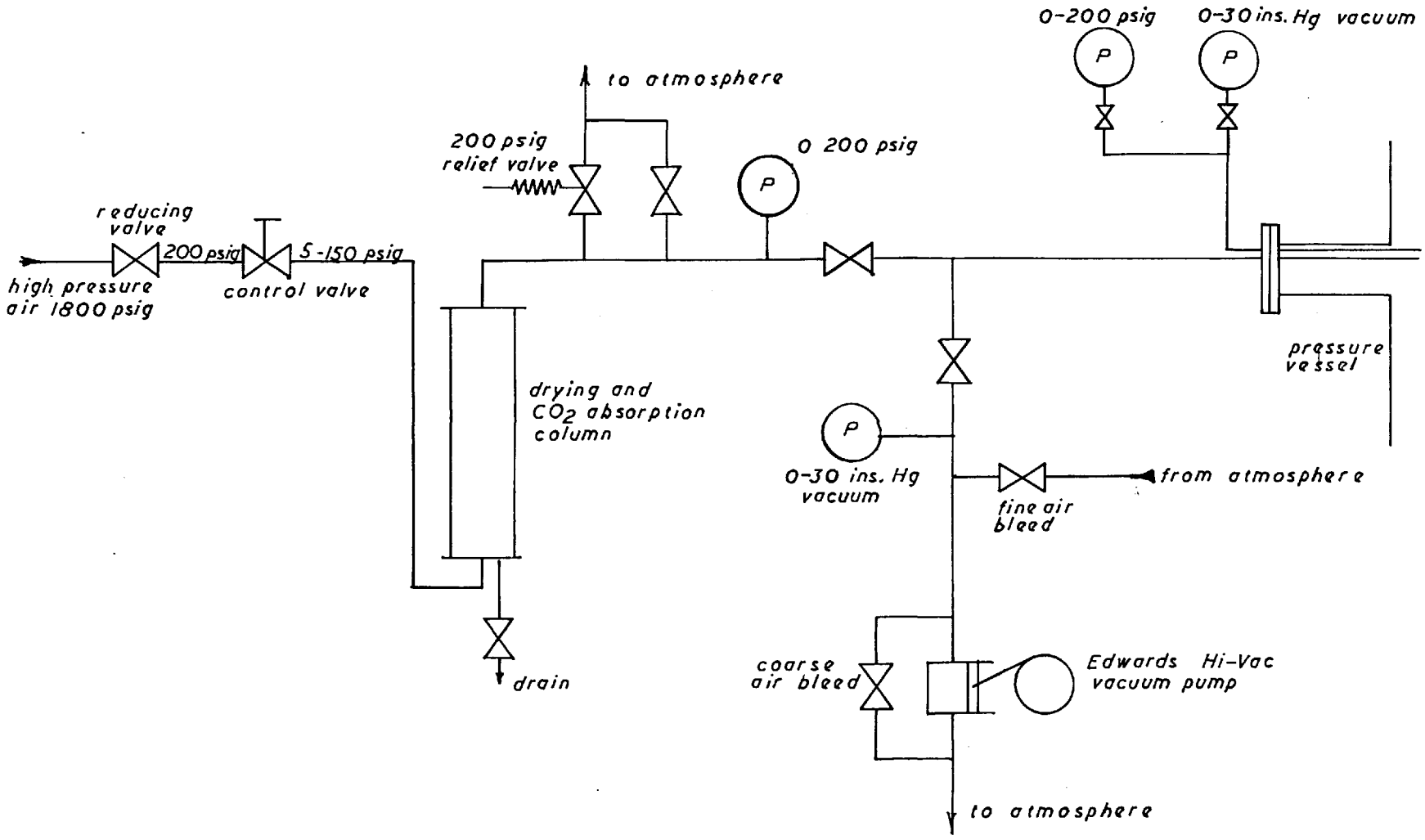


FIG. 6.15 FLOW DIAGRAM FOR PRESSURISING AND VACUUM SYSTEMS

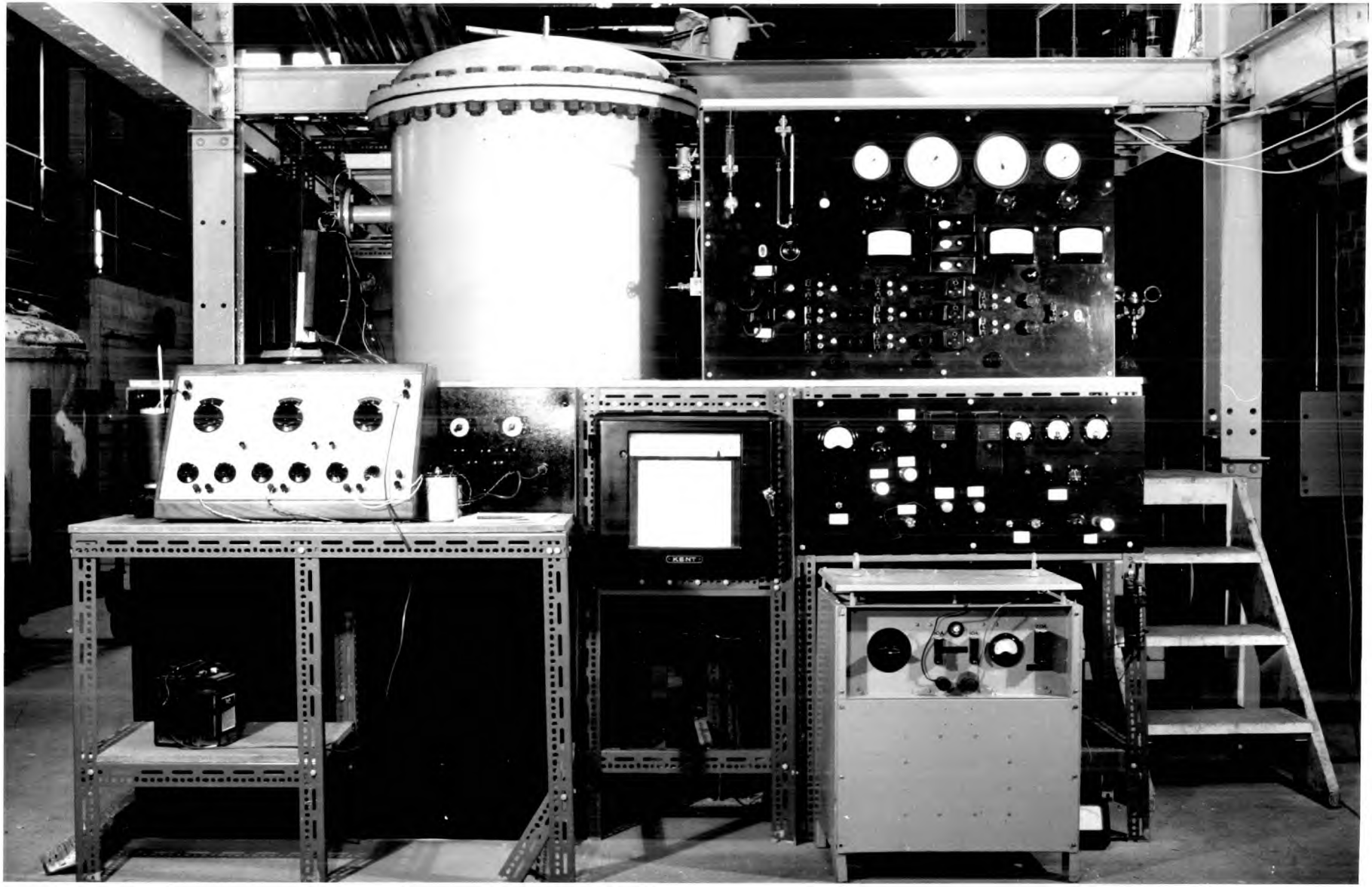


FIG 6.16 LABORATORY APPARATUS FOR THE DETERMINATION OF HEAT TRANSFER BY CONVECTION

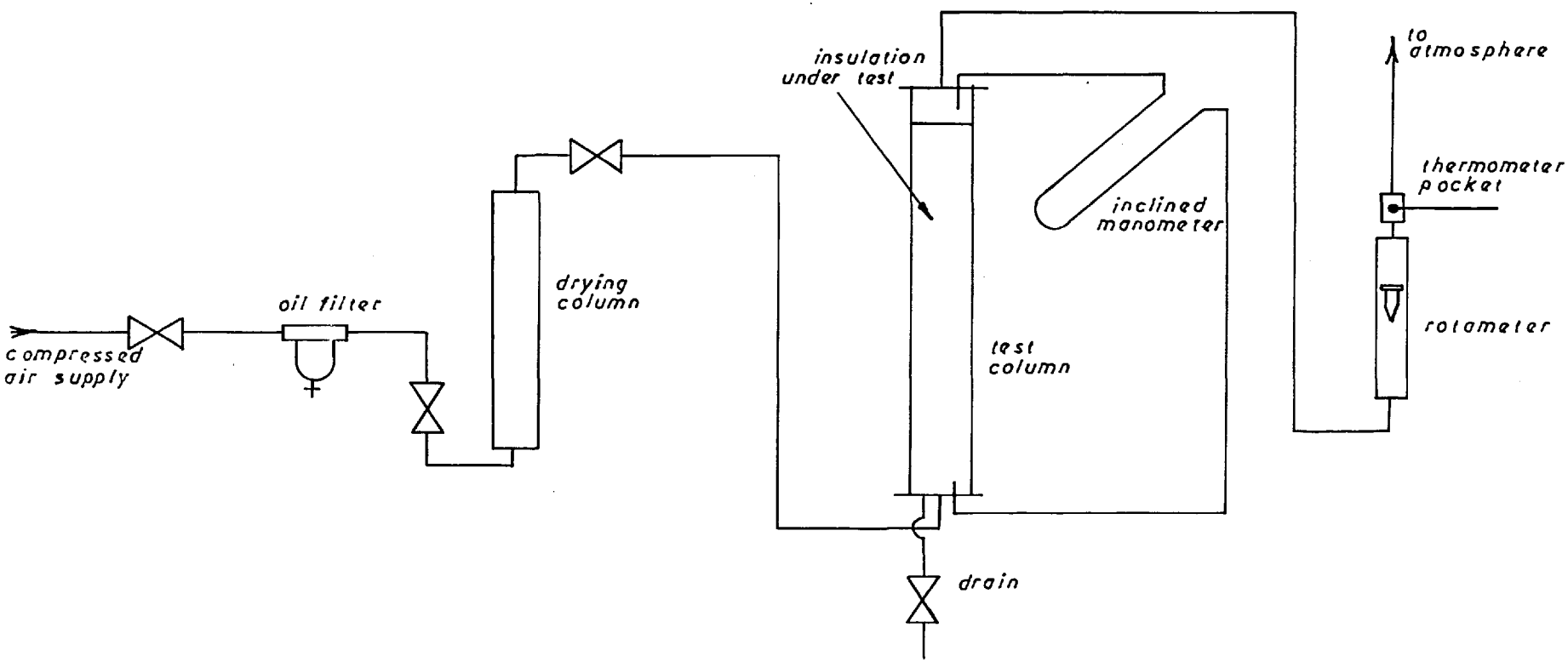


FIG 6.17 FLOW DIAGRAM FOR PERMEABILITY DETERMINATIONS

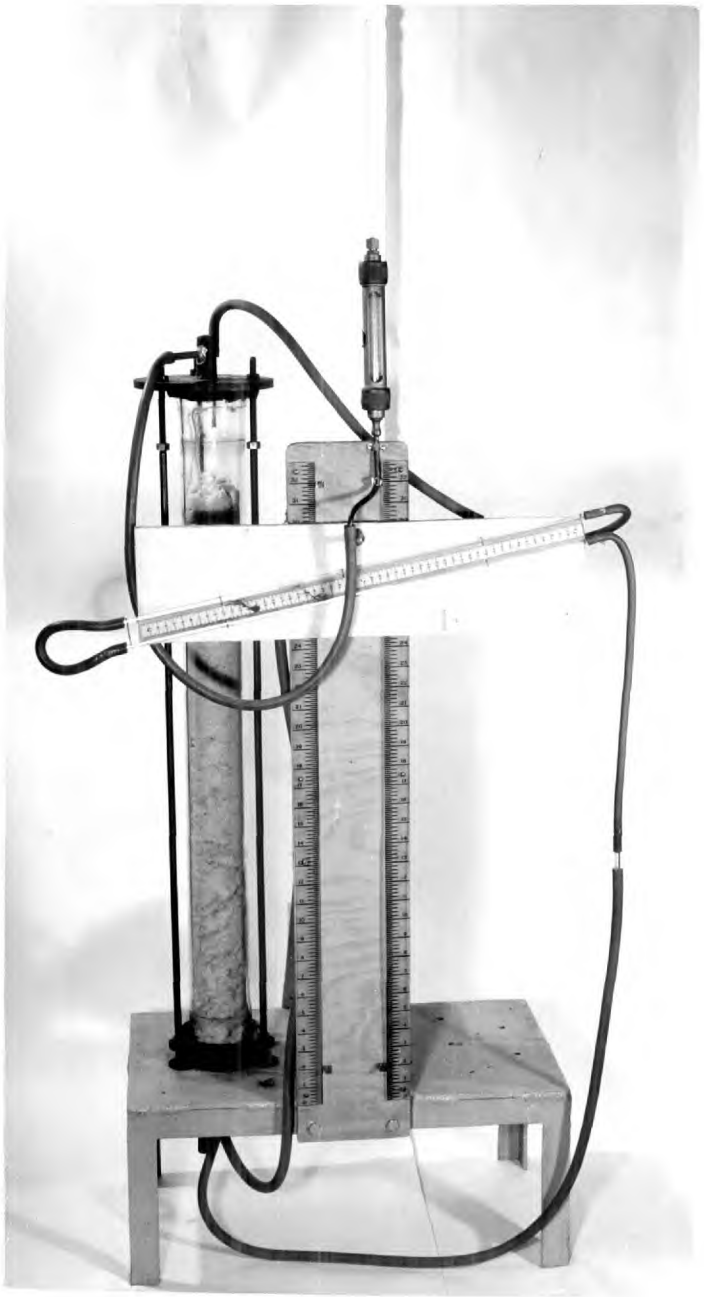


FIG. 6.18 LABORATORY APPARATUS FOR THE DETERMINATION OF PERMEABILITY

6.2 Experimental Procedure

Permeability Measurements

The rotameter used for the determination of air flow rate was first calibrated against an accurate wet gas meter. The outlet of the rotameter (Fig.6.17) was connected to the wet gas meter and air was passed through the system. The flow was held constant at a particular reading of the rotameter for one complete revolution of the wet gas meter (0.1 $ft.^3$). The time for one revolution and the temperature of the air at the gas meter outlet were measured. Table 6.1 gives the readings so obtained. A graph of rotameter reading against gas flow rate calculated from the time for one revolution showed a linear relationship between the two. The slope of the graph gave

$$\text{Flow rate } (ft.^3/hr.) = 2.14 \times \text{Rotameter reading (litres/min.)}$$

In subsequent experiments the rotameter was used since a much quicker reading was possible.

The three-inch diameter pipe was packed as uniformly as possible with different weights of slag wool. The samples were taken from the same batch as that used in the test cell of the main apparatus. Air was passed through the system and the flow rate was held constant at different values while the corresponding pressure drops were measured on the inclined manometer. (In the case of run 2 where the high bulk density caused relatively high pressure drops a vertical manometer was used.) Graphs of pressure drop against rotameter reading were drawn and gave straight lines passing through the origin. The permeability of the insulation was calculated from the slope of the graph for each

packing in the same way as for run 3 calculated below:

Run 3

Weight of slag wool in column = 446 grams

Height of slag wool in column = 2ft. $8\frac{3}{4}$ ins.

Internal diameter of column = $2\frac{27}{32}$ ins.

$\therefore$ Area of cross section of column = $\frac{\pi}{4} \cdot 2.844^2 \times \frac{1}{144}$

$= \underline{.0441 \text{ ft.}^2}$

Volume of packing = $.0441 \times 2.73$

$= \underline{0.120 \text{ ft.}^3}$

Weight of packing = $\frac{446}{454} = \underline{0.984 \text{ lb.}}$

$\therefore$ Bulk Density = $\frac{0.984}{0.120} = \underline{8.18 \text{ lb./ft.}^3}$

Slope of Graph of pressure drop vs rotameter reading

$= 5.73 \frac{\text{cms } H_2O}{\sin 10^\circ} \times \frac{\text{min.}}{\text{litre}}$

$\alpha = \frac{\mu u}{\Delta P/\ell}$ (Chapter 5.1)

$\frac{u}{\Delta P} = \frac{1}{5.73} \times \frac{1}{\sin 10^\circ} \times \frac{2.54 \times 12}{62.4} \times \frac{2.14}{.0441}$ $\frac{\text{ft.}^3}{\text{lb. hr.}}$

$= 23.8$

Mean temperature of gas = 18°C

$\therefore \mu = .0428$ lb. ft.$^{-1}$hr.$^{-1}$

Distance between bottom pressure tapping and top of insulation (ℓ)

= 2ft. $8\frac{3}{4}$ in. $- \frac{3}{4}$ in.

$\ell = 2.67$ ft.

$\therefore \alpha = 23.8 \times 2.67 \times .0428$

$\underline{\alpha = 2.72 \text{ ft.}^3\text{hr.}^{-2}}$

Where the graphs showed a certain amount of scatter the runs were repeated on the same sample. In these cases all the values were plotted together and the best straight line was drawn through the points.

Fig. 6.19 gives typical graphs of pressure drop against flow rate obtained in the experiments using slag wool.

Run 1 was carried out on Perlox insulation to give a comparison of powder insulants with slag wool.

The permeability of Perlox at a density of 3.7 lb./ft.^{3} was found to be 1.32 ft.^{3}/hr.^{2}

The results for slag wool are summarised in Fig. 6.20.

Conductivity Measurements

High Temperature runs (1 to 5)

A few runs in the higher temperature range were carried out in order to check that the heating circuits and control circuits were operating satisfactorily. Water was circulated through the cooling system, in through the liquid oxygen feed line to the downcomer of the cold plate and out through the oxygen vapour outlet. The test plate heaters were switched on and the power was adjusted to a value estimated to give the required temperature difference. The rate of heating of the hot plate was increased by using a large power input to the rear guard plate heater so that it warmed up quickly above the required temperature. It was then controlled manually until the test plate had warmed up to the required temperature. The guard rings were then set on automatic control and the apparatus was allowed to come to equilibrium. Periodically, adjustments were made to the voltages of the guard ring heaters to keep the guard rings at a uniform temperature.

Fig. 6.19 Determination of permeability.
Pressure drop vs flow rate.

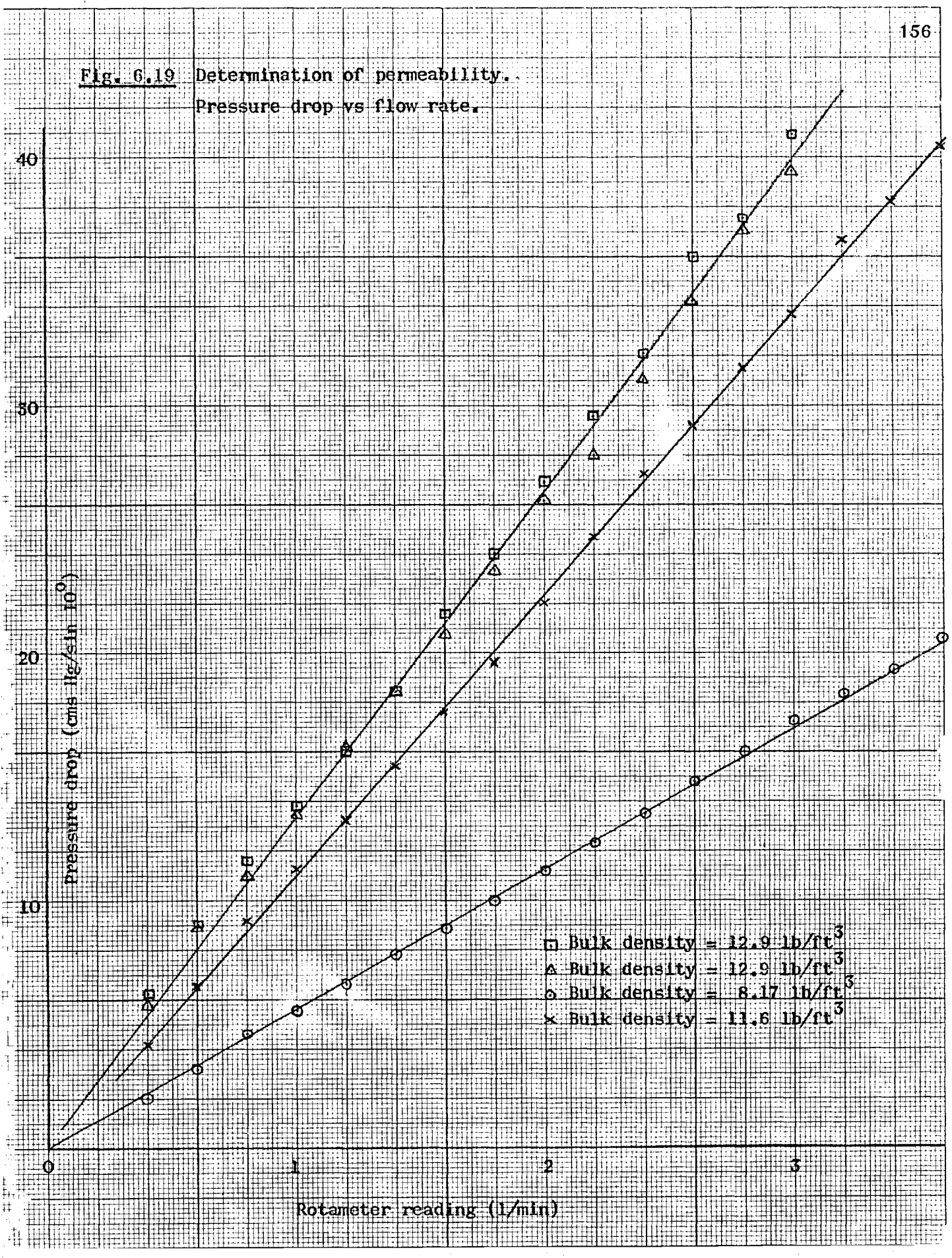
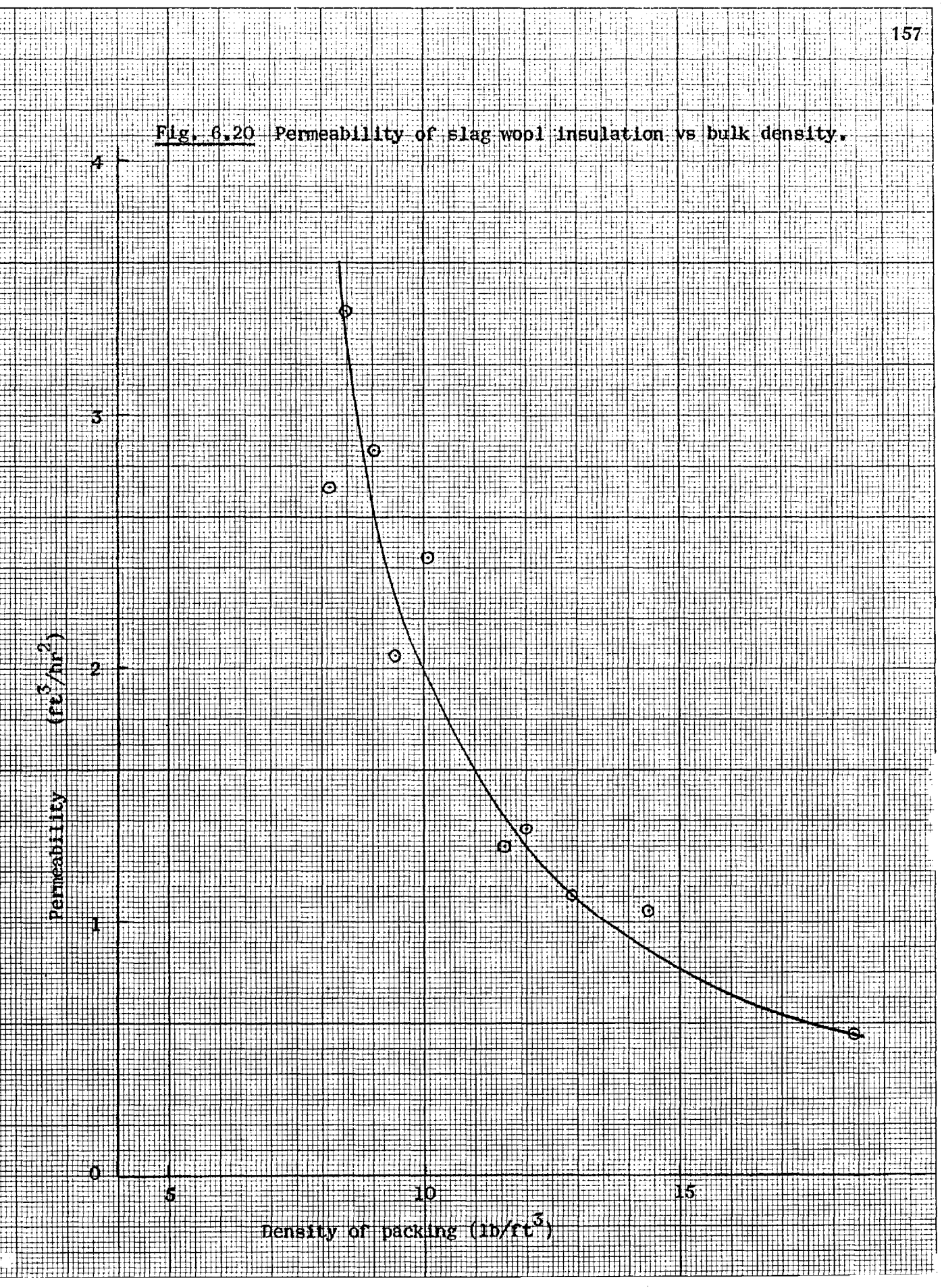


Fig. 6.20 Permeability of slag wool insulation vs bulk density.



Adjustments were also made to the test plate voltages to keep the temperature uniform and in the required temperature range. Temperatures of the hot and cold plates, and the test plate heater voltages were recorded at intervals. Finally when the test plate temperatures were steady and uniform the apparatus was left for three or four days with the temperatures and voltages being measured at intervals. A continuous record was made of all the temperatures 1 to 12 (Fig. 6.7) on the recording potentiometer.

Gas pressure in the pressure vessel was set at different values and adjustments were made to the power input to maintain uniform temperatures. Again the apparatus was allowed to reach equilibrium and the procedure was repeated.

Low Temperature runs (6, 7, 8)

After draining and drying the cold plate assembly, Dewar vessels of liquid oxygen were connected and renewed as necessary to cool down the cold plate and maintain it at the oxygen boiling point. Power input to the test plate heaters was adjusted to maintain a uniform temperature slightly above ambient (so that the guard ring temperatures could be controlled satisfactorily). The apparatus was allowed to reach equilibrium using the same procedure as for the high temperature runs. Other readings which were recorded were atmospheric temperature and pressure, and pressure in the Dewar vessels.

Again, the experiment was repeated for different air pressures in the cell.

Due to the large effects of convection in some of the runs at the higher gas pressures it was necessary to insert additional resistances

in series with the rheostats of some of the heating circuits to achieve the differences in power necessary to maintain uniform temperatures of test plate and guard ring.

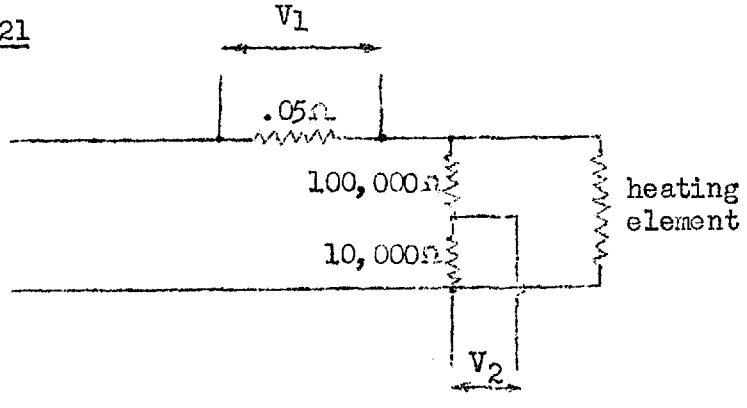
Calibration

Measurement of Heater Resistances

In order that the power input to the main plate could be determined accurately from the voltage of the heater supply, it was necessary to carry out an accurate determination of the resistance of the heating elements. This was done during the course of the high temperature runs. The circuit of each heating element in turn was broken and a standard 0.05 ohm (± 0.02%) resistance was inserted in series.

The modified circuit is shown in Fig. 6.21.

Fig. 6.21



Voltages V_1 and V_2 were measured with the potentiometer and the temperature of the element was determined at the same time from the thermocouple e.m.f.s.

The approximate resistance of the element is 50 ohms so that to an accuracy of about .05% the current flowing in the heating element may be assumed equal to the current flowing in the .05 ohm resistor.

Thus, current in element = $\frac{V_1}{.05}$ amps.

$$\text{Voltage} = V_2 \times 11$$

$$\therefore \text{Resistance} = \frac{V_2}{V_1} \times 11 \times .05$$

$$= 0.55 \frac{V_2}{V_1}$$

The resistance of each heater was calculated in this way. The calibration was carried out with the hot plate at approximately 200°F and at room temperature. The results are given in Table 6.2. A linear change of resistance with temperature was assumed and Fig. 6.22 gives the heater resistance as a function of temperature over the range of hot plate temperatures encountered.

Thermocouple Calibration

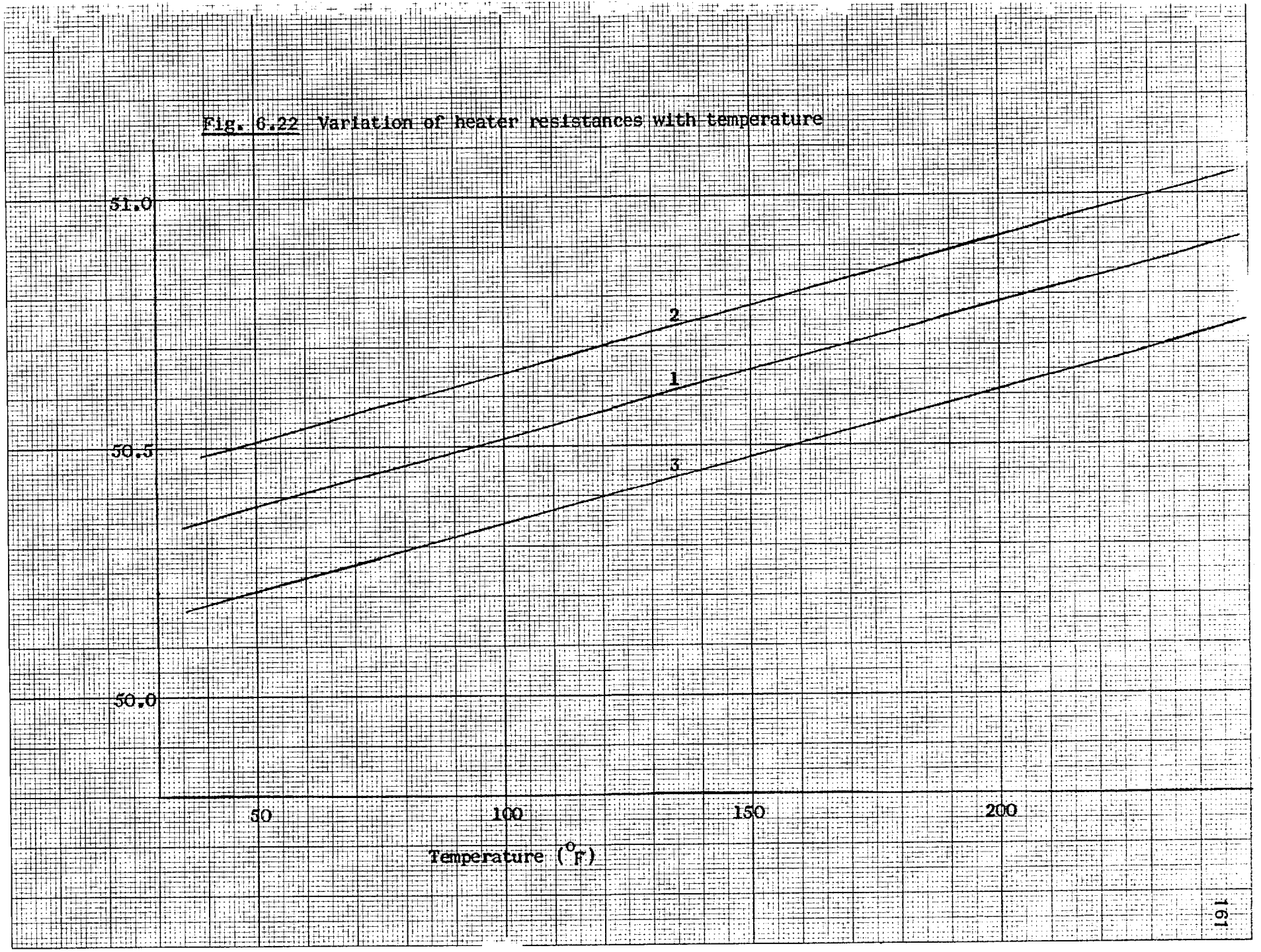
Calibration of the 18 thermocouples in situ was not possible since a constant temperature enclosure large enough to accommodate the whole of the test cell was not available. A sample of the thermocouple wire from the same batch as that used for the thermocouples in the test cell was tested using the reference junction employed in the main experiment (43.7°C). Tests were carried out with the second junction attached to the bulb of a laboratory tested thermometer accurate to ± .05°C. The thermocouple wire was wound around the thermometer stem for a distance of about 3 ins. to eliminate errors due to heat conduction down the wire. The tests were carried out with the thermometer and its attached thermocouple.

a) in an ice-water mixture at 0°C

b) in a Dewar vessel of water at room temperature (20.6°C)

and c) in steam, above boiling water at atmospheric pressure (100.0°C)

Fig. 6.22 Variation of heater resistances with temperature



In each case the measured e.m.f. agreed with that calculated using Adams' table (Ref. 26) to an accuracy of 1part in 1000.

In the range above 0°C, therefore, Adams' table was used to calculate temperatures from the e.m.f. readings.

For the low temperature measurements, where calibration was required over a very small range, the thermocouple wire was calibrated at one point only. The warm junction, attached to the bulb of a laboratory tested thermometer, as described above, was immersed in a Dewar vessel of water at laboratory temperature. The cold junction with a coil of about 1 ft. of the wire was immersed in a Dewar vessel of boiling oxygen.

Warm junction temperature = 19.1°C (66.4°F)

Barometric Pressure = 756 mm Hg.

∴ Liquid oxygen boiling point = -297.5°F

Thermocouple e.m.f. = -6.078 mV

From Adams' table, e.m.f. of 66.4°F above 32°F = 0.751

e.m.f. of 110.7°F above 32°F = 1.766

∴ With a reference junction at 110.7°F the e.m.f. of a junction at -297.5°F is $-(6.078 + 1.766 - 0.751)$

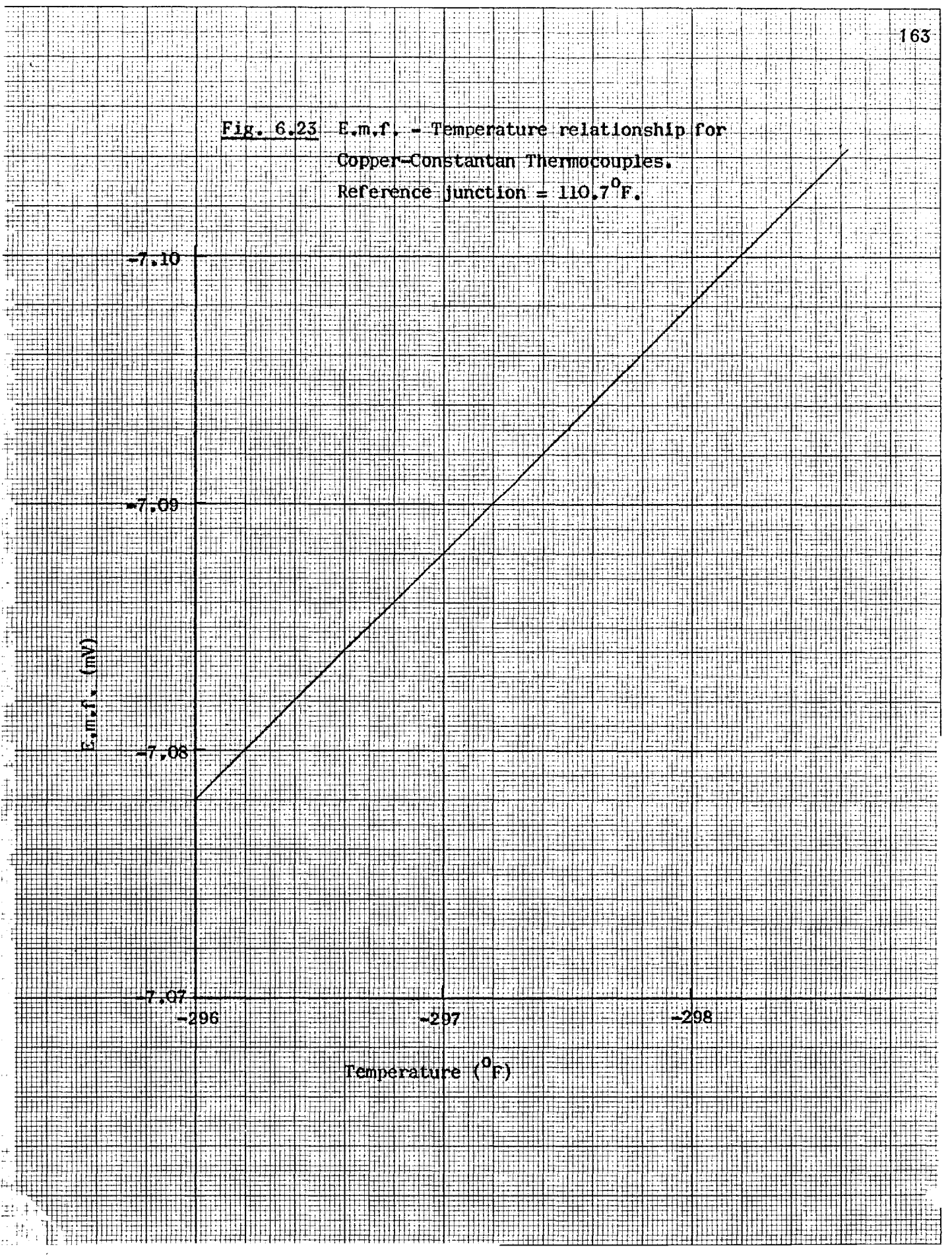
$= -7.093$ mV

Assuming the variation of e.m.f. at this temperature is 17.6 microvolts per °C as given by Scott (Ref. 24) Fig. 6.23 gives the variation of e.m.f. with temperature.

6.3 Treatment of Results

During runs 1 and 2 the recording potentiometer was relied upon to indicate when equilibrium had been reached. A few measurements of hot plate temperature, cold plate temperature and heater voltages were

Fig. 6.23 E.m.f. - Temperature relationship for Copper-Constantan Thermocouples. Reference junction = 110.7 °F.



then made and the thermal conductivity was calculated. Table 6.3 gives the readings for these two runs, the time in hours being measured from the time at which the pressure changes were made for each run. The calculation was carried out as follows:

Run 1. Pressure = 21.3 ins. Hg vacuum.

Time = 45.3 hours. Mean e.m.f. of hot plate thermocouples = 2.624 mV

$\therefore$ Using Adams' tables, Mean temperature of hot plate = 216.4°F

Mean e.m.f. of cold plate thermocouples = -1.020 mV

$\therefore$ Mean temperature of cold plate = 66.1°F

Voltage across heater 1 = 10.2 (in the case of run 1 the voltages were measured directly with a voltmeter, all other runs used the circuit given in Fig. 6.6 with the potentiometer used for measurement. In these cases the potentiometer reading was multiplied by 11 to give the true voltage).

Resistance of heater 1 = 50.8 ohms (Fig. 6.22)

$\therefore$ Power = $\frac{10.2^2}{50.8}$ = 2.05 watts.

Similarly, power in heater 2 = 2.04 watts.

power in heater 3 = 2.10 watts.

Total power = 6.19 watts.

Thickness of element = 11.9 ins.

Area = 4 ft.^{2}

Temperature difference = 150.3°F

$\therefore$ Thermal Conductivity = $\frac{6.19}{150.3} \times \frac{1}{4} \times \frac{11.9}{12}$ watts/ft.°F

$= \frac{6.19}{150.3} \times \frac{1}{4} \times \frac{11.9}{12} \times 3.42$ Btu./ft.^{2}hr.(°F/ft.)

$= \underline{0.0350}$ Btu./ft.^{2}hr.(°F/ft.)

Similarly at time = 54.3 hours

Conductivity = 0.0352 Btu./ft.^{2}hr.$^\circ$F/ft.

$\therefore$ Mean Thermal Conductivity = <u>0.0351 Btu./ft.^{2}hr.$^\circ$F/ft.</u>

Table 6.4 summarises the calculation for run 2.

In the light of experience gained with later runs it appears that sufficient time may not have been allowed to ensure that equilibrium had been reached in these two earlier runs. Runs 3 to 8 were, therefore, allowed a much longer period at their equilibrium settings and more readings were taken during this period. Tables 6.5 to 6.10 give the readings for runs 3 to 8, the time in hours being measured from each pressure change. Hot plate temperature, cold plate temperature and power were calculated as for run 1, given above, and the resulting values were plotted as a function of time. Smooth curves were drawn through the points to eliminate small daily variations of power and cooling water temperature. From these smoothed curves the conductivity was calculated at 12 hour intervals over the whole of the equilibrium period. The calculations are summarised in Tables 6.11 to 6.16.

To enable a better comparison to be made the values were all corrected to the same mean temperature of 158°F for the high temperature results and -113°F for the low temperature results. Graphs of thermal conductivity against temperature for numerous types of insulation in the temperature range 100°K to 320°K (Ref. 27) give a mean slope of 3.8×10^{-5} Btu./ft.hr.$^\circ$F per $^\circ$F. This value was, therefore, used for the correction to the high temperature values. Chow (Ref. 25) gives graphs of the conductivity for slag wool at low temperatures and these

show an increase of conductivity of 4.8×10^{-5} Btu./ft.hr.°F per °F at about -110°F. This value was used for the low-temperature corrections. The corrections were small (maximum 4%) so the absolute accuracy of these assumed correction factors is not important.

The corrected values are given, along with the measured values in Table 6.17.

6.4 Experimental Errors

A constant error in the e.m.f. of all of the thermocouples caused, for example by errors in calibration or failure of the reference junction would lead to very little error in the measured values of conductivity. Even in the worst case an error of 1°F in the thermocouple readings would cause an error of only 0.7% in the conductivity. Should individual thermocouples, however, have failed to retain their calibration larger errors would have been introduced because differences in temperature would be produced between test plate and guard rings.

Before the tests, with no power input to the heaters, the e.m.f.s of all the thermocouples were measured to observe whether any showed significant differences. The temperatures calculated from the e.m.f.s obtained in this way are shown in Fig. 6.24. The differences are small and do not appear to be random, as the highest temperatures occur near the top of the plates. It is likely that the actual cell temperature did vary from top to bottom and the thermocouples could probably be relied upon to about 0.2°F.

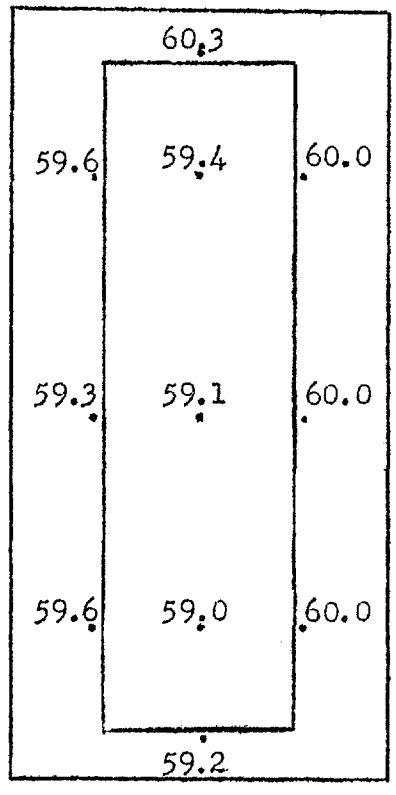
During the low temperature runs it was found possible to control the mean temperature of both guard ring and rear guard plate to within about 0.2°F of the mean test plate temperature. Fig. 6.25 gives the

temperature distribution over plate, guard ring, and rear guard plate measured at one time during the course of run 6. Temperatures of the guard ring and rear guard plate are the mean of extreme values reached as the heaters were switched on and off by the control circuits. During the high temperature runs it was not possible to control the guard rings to within such fine limits. Fig. 6.26 shows the temperature distribution measured during run 5. The upper thermocouple on the rear guard plate recorded a temperature about 2°F lower than that of the test plate. This was observed for all the high temperature runs and is believed to have been a local effect due to heat leakage in the vicinity of the pressure vessel outlet where all electrical connections come from the outer shell to the test cell. In all cases the control circuit was adjusted to maintain the centre of the guard plate at the same temperature as the test plate.

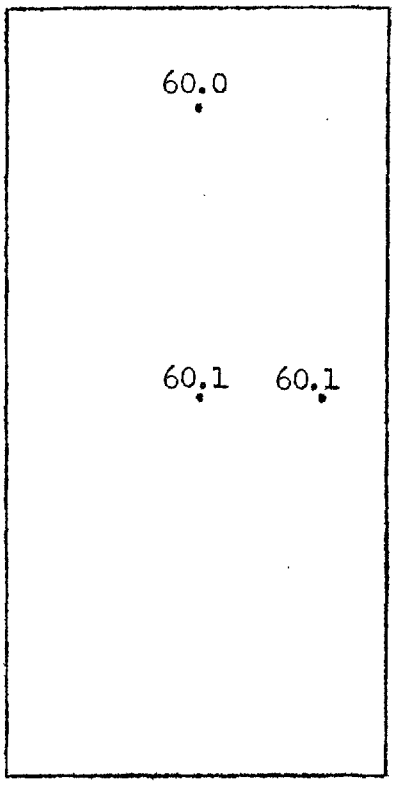
It is impossible to calculate the error caused by heat leakage from the test plate to the guard ring due to temperature inequalities of the order of those given above. Such errors, however, would have been random, since the guard rings were reset for each run, and would have caused a scatter of the measured values on curves of conductivity against pressure. An estimate can be made of the error caused by inequality of temperature between the test plate and the rear guard plate.

Suppose a temperature difference of 1°F exists between the test plate and the rear guard plate. Considering the low temperature runs. Approximate temperature differnce across insulation under test

= 370°F

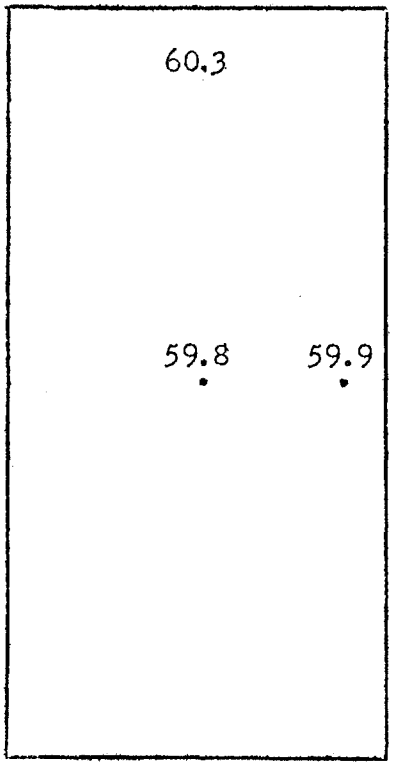


hot plate and guard ring



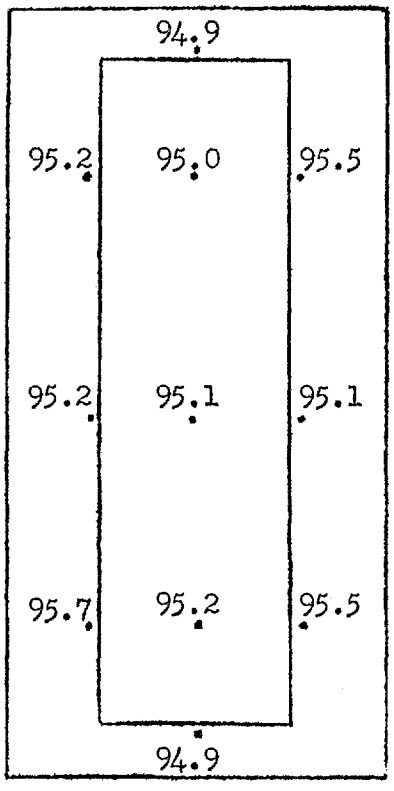
rear guard plate

cold plate

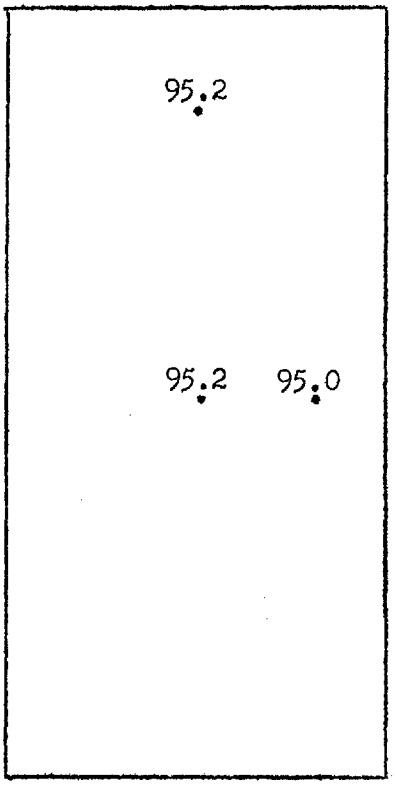


All figures refer to temperatures in °F

Fig. 6.24 Temperature distribution on Plates before experimental runs.



hot plate and guard ring



rear guard plate

cold plate

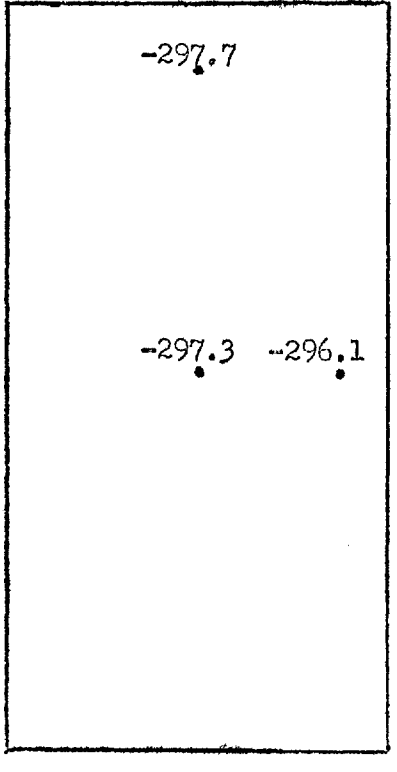
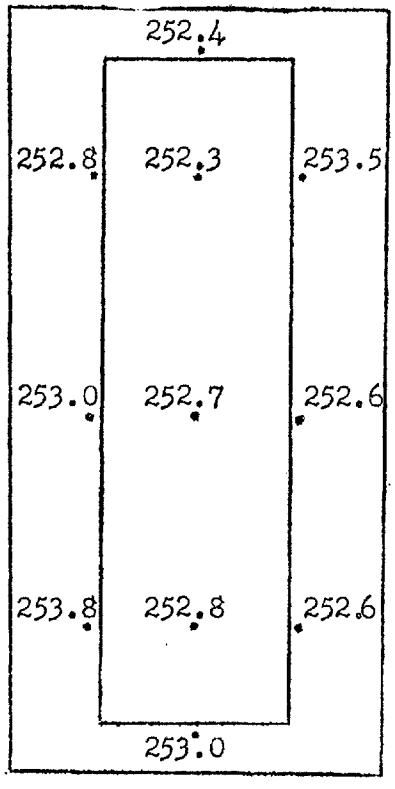
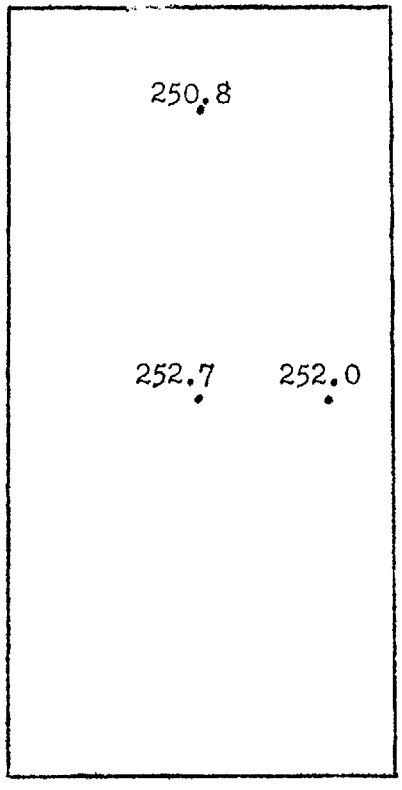


Fig. 6.25 Temperature distribution on Plates during run 8 (time = 130 hrs.)



hot plate and guard ring



rear guard plate

cold plate

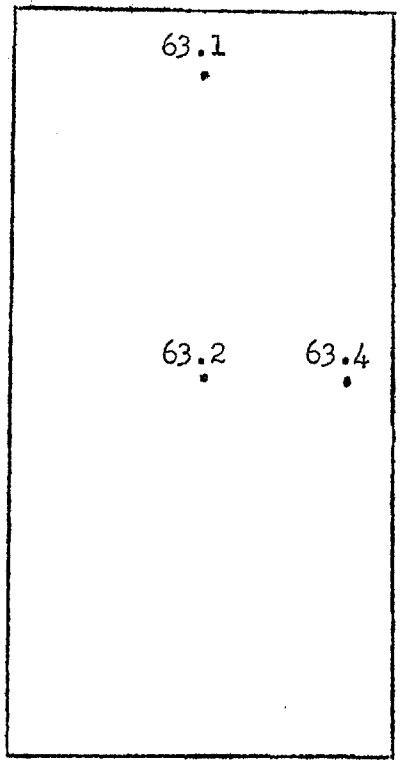


Fig. 6.26 Temperature distribution on Plates during run 5 (time = 195 hrs.)

Conductivity (at mean temperature) = 0.015 Btu/ft.^{2}hr.($^\circ$F/ft.)

Thickness = 11.9 ins.

Conductivity of foam glass separating test plate and rear guard plate $\simeq$ 0.6 milliwatts/cm.$^\circ$K at 330°K (Ref. 29)

$\simeq$ 0.034 Btu/ft.^{2}hr.($^\circ$F/ft.)

Thickness = 2 ins.

$$\therefore \frac{\text{Heat transferred to rear guard plate}}{\text{Heat transferred to cold plate}} = \frac{.034 \times 11.9 \times 1}{.015 \times 2 \times 370}$$

$$= .036$$

i.e. Error is approximately 4%

For the high temperature runs, the error would be greater since the temperature difference across the cell was smaller (approximately 160°F). The ratio of conductivities may be assumed constant since both increase with temperature.

Thus error $\simeq .036 \times \frac{370}{160}$ $\underline{8\%}$

This treatment assumes that the whole of the guard plate is 1°F below the test plate temperature. If we assume that approximately $\frac{1}{4}$ of the plate surface was 2°F below the test plate temperature the error would be approximately 4%.

A more extensive coverage of the guard plate surface with thermocouples would have enabled a better estimate of this error to have been made.

Error due to inadequacy of the area of the guard ring is impossible to determine theoretically but an indication of the relative magnitudes of the effects for runs in the two temperature ranges may be obtained

from a study of the distribution of isotherms in the test cell. Fig. 6.27 is a diagrammatic representation of a plan view of the apparatus showing how, in the ideal case, with no heat leakage to the shell of the pressure vessel, the isotherms would be parallel to the plates and the measured heat input would be a measure of the true conductivity. There are two main factors which could affect this ideal configuration.

a) The conductivity of the foam glass is greater than that of slag wool and may have caused a significant decrease in the temperature at the outer edge of the guard ring. A simplified calculation may be carried out to give an estimate of the magnitude of this effect.

Consider a 1 ft. depth of the test cell. For the low temperature runs the mean conductivity of foam glass may be assumed to be 0.0214 Btu./ft.^{2}hr.(°F/ft.) (Conductivity values for foam glass were obtained from a graph of conductivity against pressure given by Corruccini,) (Ref. 29).

Heat transmitted through foam glass from BC to the cold plate

$$= .0214 \times \frac{1.5}{12} \times 393$$

$$= 1.05 \text{ Btu./hr.}$$

Heat transmitted through slag wool from AB to the cold plate

$$= .0159 \times \frac{4.5}{12} \times 393$$

$$= 2.34 \text{ Btu./hr.}$$

∴ Total heat input necessary = 3.39 Btu./hr.

This heat input is evenly distributed over the surface of the guard ring.

∴ heat input to BC = 0.85 Btu./hr.

and extra heat required = 0.20 Btu./hr.

This must flow out through the aluminium plate.

Conductivity of Aluminium = 119 Btu./ft.^{2}hr.($^\circ$F/ft.)

Thickness = 0.048 in. (18 s.w.g.)

Assuming that this heat flows from the centre of AB to the centre of BC,

path length = 3 ins.

and if ΔT is the temperature difference

$$0.20 = 119 \times \frac{.048}{12} \times \frac{\Delta T}{3} \times 12$$

whence $\underline{\Delta T = 0.105^\circ F}$

This value is negligible. A similar calculation for the high temperature runs also gives a temperature difference of about 0.1°F.

b) There will be some flow of heat between the foam glass and the pressure vessel shell. In the case of the low temperature runs this will have a maximum effect nearest the cold plate and Fig. 6.28 shows the effect on the isotherms. It is unlikely that this would have any appreciable effect on the measured values of conductivity. In the case of the high temperature runs, however, the effect will be a maximum near the hot plate and would cause flow of heat in the direction shown in Fig. 6.29. The net effect would be an increase in the measured heat flux and hence an erroneously high measured conductivity.

Suppose the mean thickness of Perlox insulation between the foam glass and the pressure vessel shell is 4 ins. and has an estimated conductivity of 0.025 Btu./ft.^{2}hr.($^\circ$F/ft.), then heat flowing out

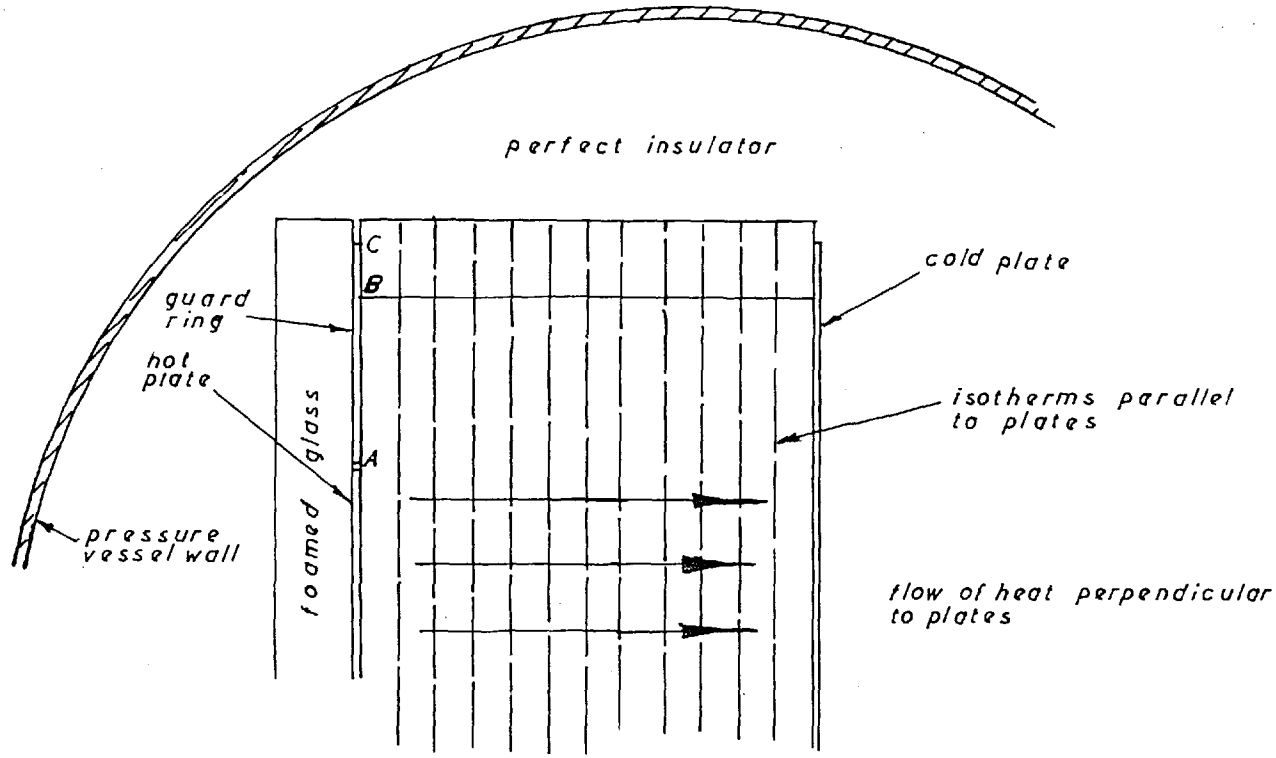


FIG 6.27 DISTRIBUTION OF ISOTHERMS IN TEST CELL IDEAL CASE

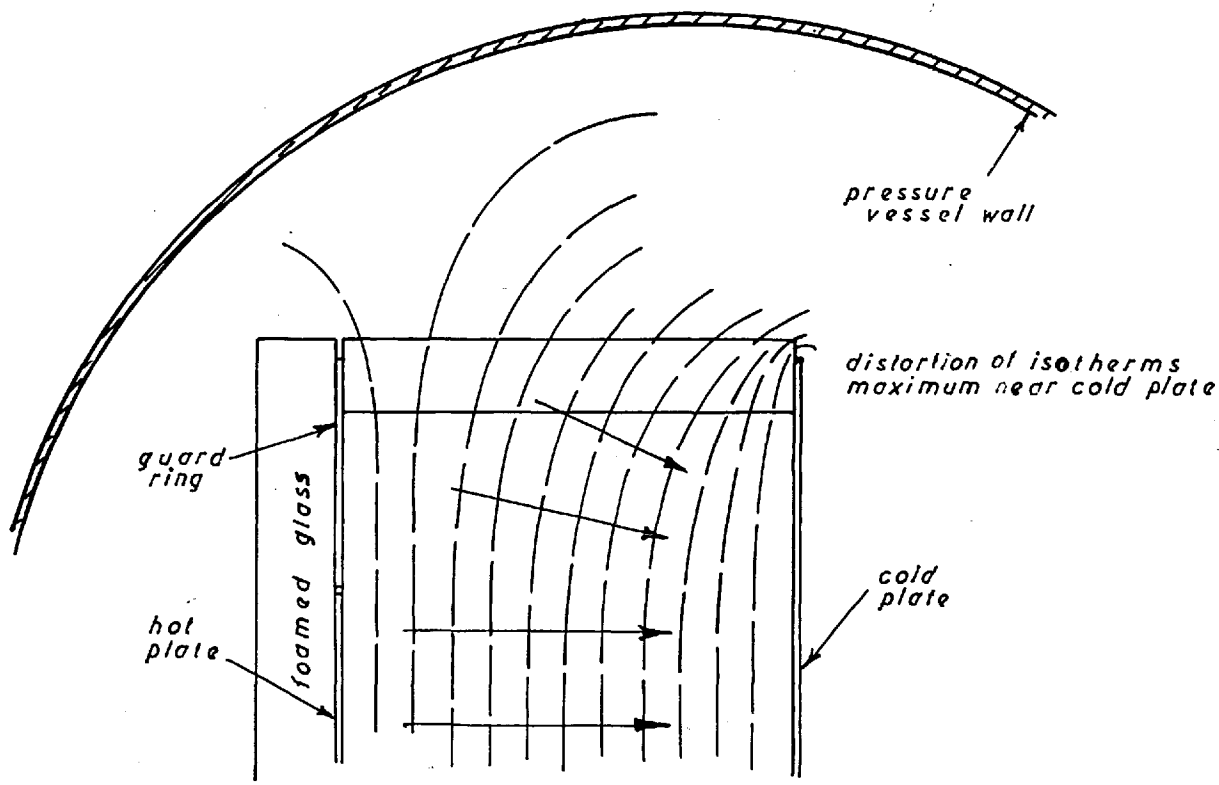


FIG. 6.28 DISTRIBUTION OF ISOTHERMS IN TEST CELL LOW TEMPERATURE RUNS

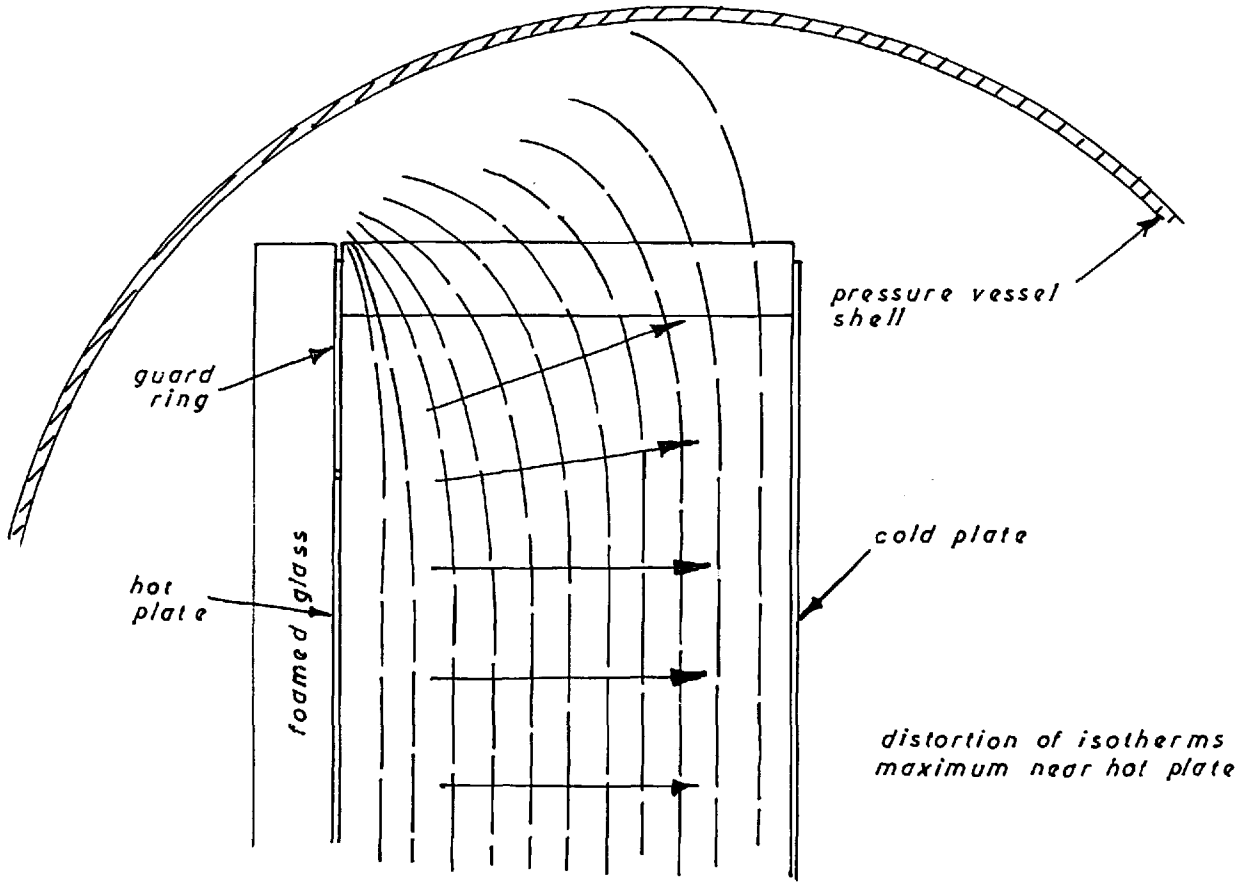


FIG. 6.29 DISTRIBUTION OF ISOTHERMS IN TEST CELL HIGH TEMPERATURE RUNS

from foam glass to the pressure vessel shell $\triangleq 0.025 \times 1 \times \frac{80}{4} \times 12$

$\triangleq$ 6 Btu./hr.

Assuming a mean conductivity of slag wool and foam glass of 0.025 Btu./ft.^{2}hr.$^\circ$F/ft.

The heat flow from the guard plate AC to the cold plate

$$0.025 \times \tfrac{1}{2} \times \frac{160}{1}$$

2 Btu./hr.

A considerable amount of extra heat must therefore be supplied to the guard ring and the distortion of the isotherms shown in Fig. 6.29 will be large. Thus, a fairly large error would be expected in the case of the high temperature runs.

6.5 Discussion of Experimental Results

Graphs of apparent conductivity (corrected to constant mean temperature) against pressure (Figs. 6.30, 6.31) showed an increase of conductivity with gas pressure which was much more significant in the case of the low temperature runs.

If the effects of gas convection are ignored, the flow of heat in porous insulants takes place by radiation, solid conduction and gas conduction. For a given packing density, insulation thickness, and temperature difference, the effects of solid conduction and radiation are independent of gas pressure. Kinetic theory shows that, for perfect gases, thermal conductivity is independent of pressure provided that the mean free path of the gas molecules is small compared with the distance over which thermal conductivity is measured. For air the conductivity is not entirely independent of pressure but the

Fig. 6.30 Measured thermal conductivity vs pressure (High temperature runs)

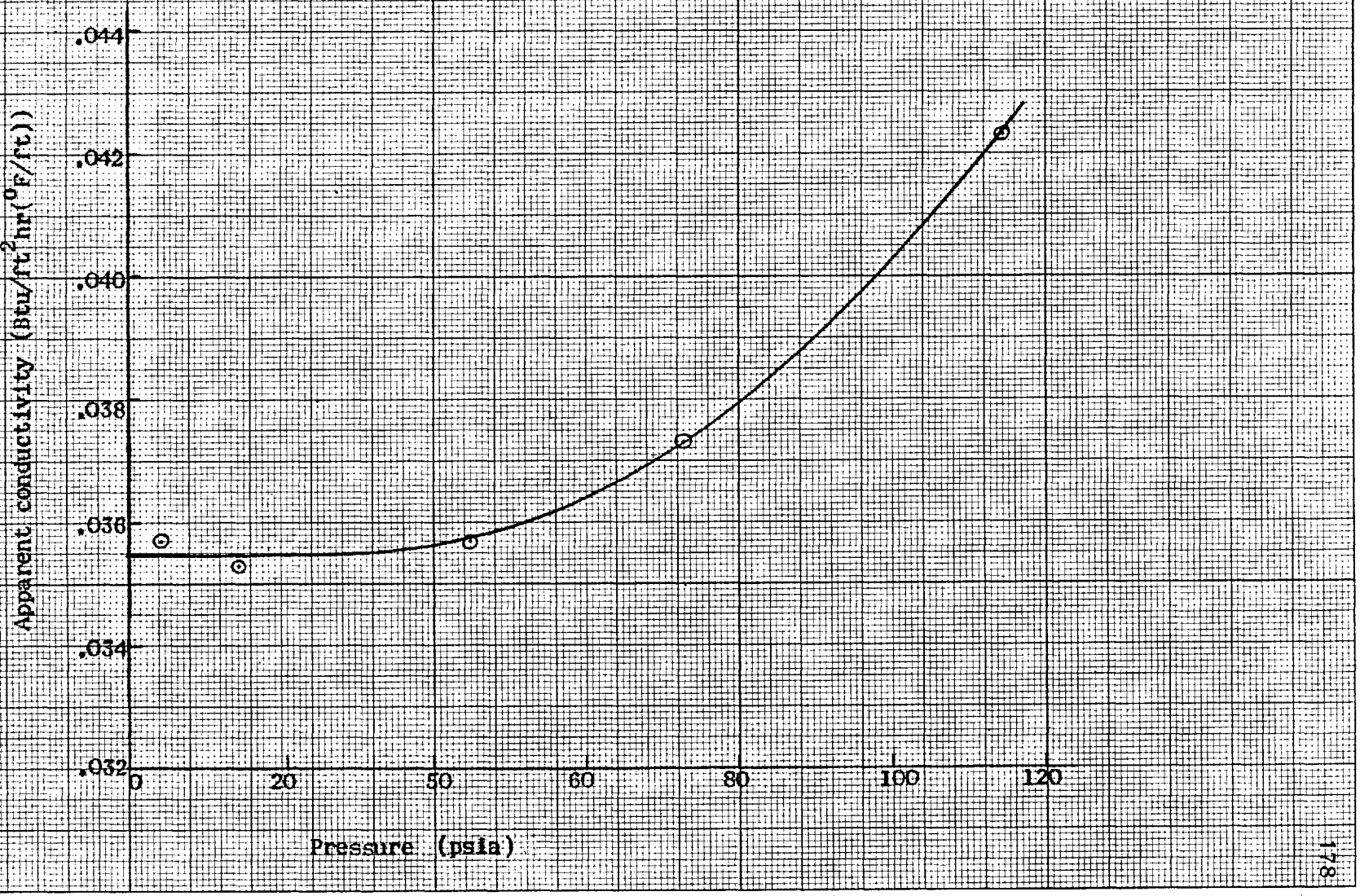
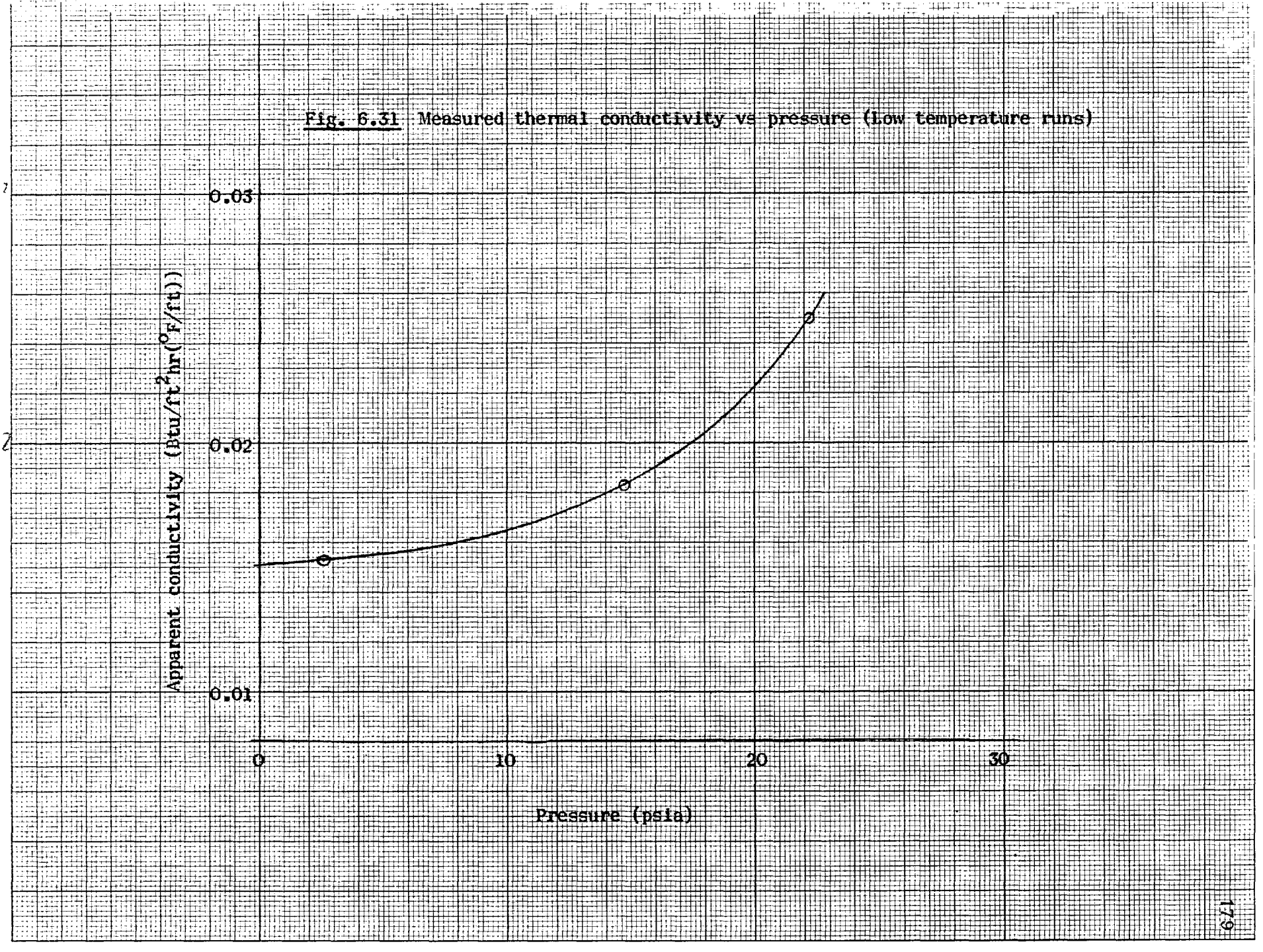


Fig. 6.31 Measured thermal conductivity vs pressure (Low temperature runs)



variation is small. Keyes (Ref. 31) gives the conductivity of oxygen as .0142 Btu./ft.^{2}hr.($^\circ$F/ft.) at 0°C and 1 atmosphere pressure compared with .0144 at 0°C and 10 atmospheres. At low temperatures the variation is greater, .00695 at 1.1 atmospheres and .00715 at 4.9 atmospheres at -145.1°C. Nitrogen shows similar variations. It has been shown, for many types of porous insulation, that thermal conductivities decreases rapidly with gas pressure after a certain critical pressure is reached (Refs. 28,29). This effect occurs when the gas mean free path approaches the size of the pores in the insulant. For all normal insulating materials, this decrease does not occur until vacua better than 10 mm. Hg absolute have been achieved and it may therefore be assumed that, for the range of temperatures and pressures used in the experiments, the true thermal conductivity is independent of gas pressure.

The increase of apparent conductivity with pressure (Figs. 6.30, 6.31) can, therefore, be due only to the influence of gas convection. The readings show that, at the higher gas pressures, the power input to the lower part of the test plate had to be increased considerably while that to the upper part was decreased in order to maintain a constant plate temperature. This effect would be expected if there were considerable convection effects.

Extrapolation of the curves in Figs. 6.30 and 6.31 to zero pressure will, therefore, give the true value of thermal conductivity (Gas convection eliminated). The curves give values of .0150 and .0355 Btu./ft.^{2}hr.($^\circ$F/ft.) at -113°F and +158°F respectively. The value of .0150 at -113°F agrees well with published data for the

conductivity of slag wool at this mean temperature. Chow (Ref 25) gives .0155 for slag wool at 12.3 lb/ft.^{3} and .0145 for slag wool at 7.0 lb./ft.^{3}. Raisch and Weyh (Ref. 30) give .0135 for slag wool at 7.4 lb./ft.^{3} at this temperature. The high temperature value of .0355 Btu./ft.^{2}hr.($^\circ$F/ft.) is undoubtedly high. A sample from the same batch tested at the same bulk density by the National Physical Laboratory had a conductivity of .023 Btu./ft.^{2}hr.($^\circ$F/ft.) at a mean temperature of 122°F. The high value obtained may be attributed to the inadequate width of the guard rings in the high temperature runs.

The results of the experiment as a whole indicate that, for the low temperature runs, gas convection was responsible for about 18% of the total heat transfer at atmospheric pressure. The effect of gas convection increased rapidly with pressure. For the high temperature runs there was no appreciable increase in conductivity at atmospheric pressure, the effects of convection only became noticeable above a pressure of about 50 psig. At 100 psig the heat transfer due to gas convection was about 16% of the total.

6.6 Theoretical Calculation of Results

The contribution of convection to heat transfer for the approximate conditions of the experimental runs was calculated using the computer programme (LN) described in chapter 5.4. Fig. 6.20 shows that at 9.1 lb./ft.^{3} the permeability of the slag wool was 2.5 ft.^{2}/hr. This value was used throughout in the calculations. The true conductivities used were approximately the values obtained by the extrapolation of the curves in Figs. 6.30 and 6.31 to zero pressure. For the high

temperature runs a variation of conductivity with temperature of 3.83×10^{-5} Btu./ft.^{2}hr.($^\circ$F/ft.) per $^\circ$R was assumed. This value was obtained by measuring the mean slope of several curves of the conductivities of various insulating materials against temperature at 150°F. For the low temperature runs a variation of 4.76×10^{-5} Btu./ft.^{2}hr.($^\circ$F/ft.) per $^\circ$R was used. This value is given by Chow (Ref. 25) for slag wool at -113°F. The constants in the viscosity equation (chapter 5.3) were obtained by plotting the viscosity of air against temperature in the two temperature ranges and drawing the best straight lines. The constants μ_0 and μ_1 were obtained from the slope and intercept of each line. Gas density was assumed to be given by

$$\rho = \frac{39.7}{T} \times P_A$$

where ρ = density (lb./ft.^{3})

T = temperature ($^\circ$R)

P_A = absolute pressure (atmospheres)

The specific heat of air was assumed to be 0.25 Btu./lb.$^\circ$F (constant).

Additional calculations were carried out to determine the effects of insulation height and thickness, permeability and temperature difference etc. on the heat transfer. A fairly coarse mesh of 7 x 7 elements was used since limited computing time was available. The calculations lasted an average of about two hours before the required degree of convergence was obtained.

Table 6.18 summarises the data used and the results of all the calculations carried out. Since the calculation uses only pressure differences the absolute value of the pressure set by the warning

sequence PRES is unimportant and in most cases was set at zero. Fig. 6.32 gives the temperature and pressure distribution in the insulation at the end of the calculation I. The pressures are given in lb./ft.^{2} above the arbitrary pressure which was assumed to exist mid way down the insulation at the onset of convection. It shows the distribution of isotherms to be as predicted (Fig. 5.5).

6.7 Discussion

Fig. 6.33 shows the measured values of apparent conductivity (heat transfer per unit area per unit time and per unit temperature gradient) compared with those calculated for similar conditions.

The calculated values given in Table 6.18 were corrected, where necessary, in the same way as the measured values (chapter 6.3) to a mean temperature of 158°F for the high temperature runs and -113°F for the low temperature runs. Again this correction is not strictly correct since it applies only to conduction but in all cases it was small (less than 1.5%). The error introduced by applying it to the total heat transfer by conduction and convection will, therefore, be negligible.

The two sets of results agree well in the case of the high temperature runs and agreement at low temperatures is fair. The discrepancies may be due to one or more of several factors.

a) The coarse mesh used would obviously lead to inaccuracies. A much finer mesh would have been preferred but would have required the use of a faster computer.

b) The assumptions made regarding fluid properties may not have been sufficiently accurate (particularly since one plate was very

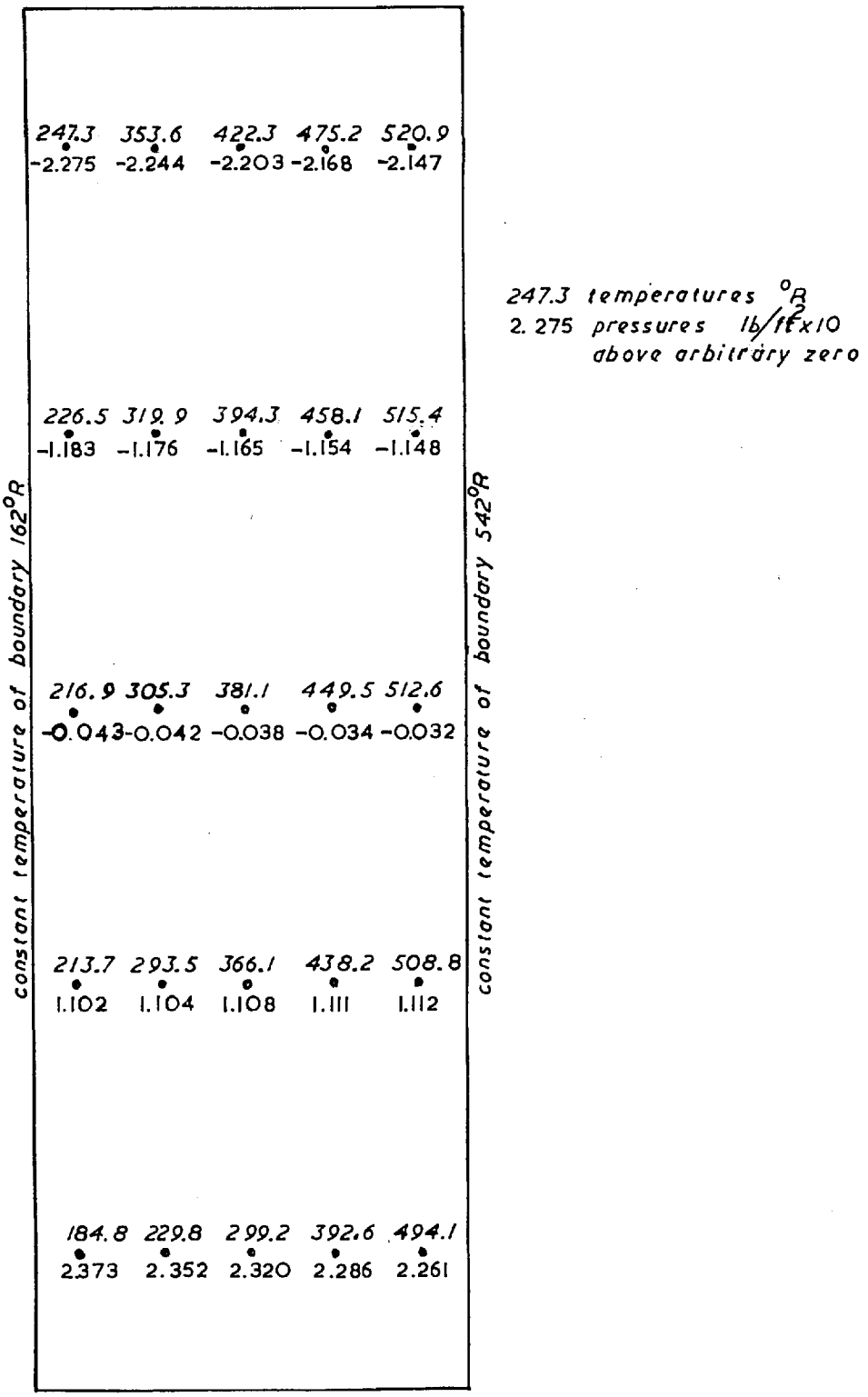
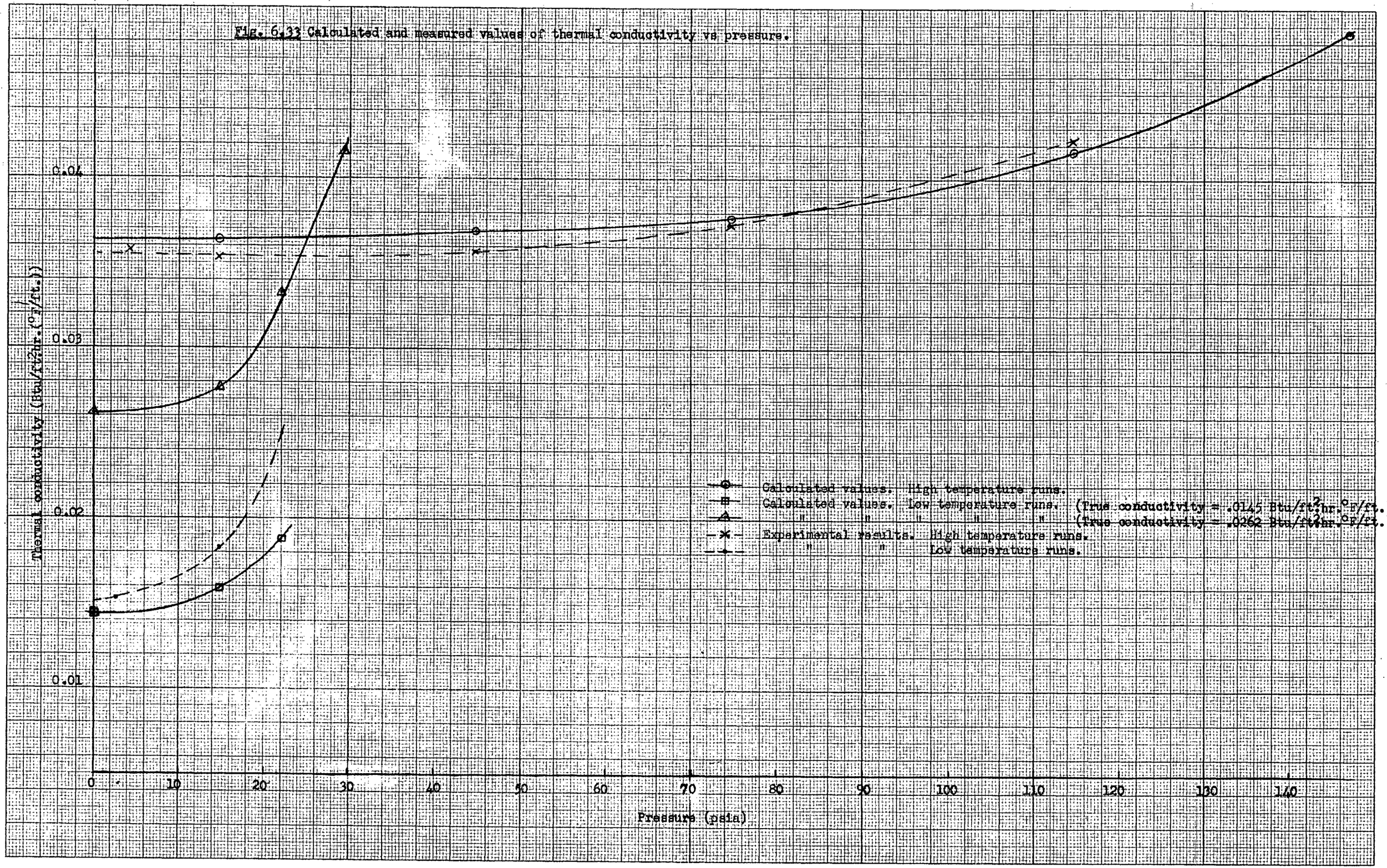


FIG. 6.32 CALCULATED TEMPERATURE AND PRESSURE DISTRIBUTION (I)

Fig. 6.33 Calculated and measured values of thermal conductivity vs pressure.



close to the liquefaction temperature).

c) It was assumed in the theory that, at any position in the insulation, gas temperature was equal to the solid temperature. This assumes perfect heat transfer between solid and gas and would, if in serious error, have given calculated values whichwere too high. It was found, in fact, that the calculated values were lower than the measured values.

d) The calculation assumed perfect insulators above and below the insulation, whereas in practice, the foam glass above and below had appreciable conductivity. This would cause the measured values to be lower than those calculated since the cold gas flowing across the base of the cell from the cold plate would take in heat and would reach the hot plate at a higher temperature than would have been the case had the cell been bounded by perfect insulators. The effect would be compensated for, to some extent, by the fact that gas flowing across the top of the cell would lose heat to the foam glass and so would be cooler in the region of the cold plate. It was observed during the experimental determinations at the higher pressures, that the heat input to the lower heater of the guard ring had to be increased while that to the upper heater was decreased to maintain uniform temperatures. The net effect is not easily calculable but an appreciable error of this kind would have led to the measured values of conductivity being lower than those calculated. This was not observed in practice.

The calculated results, showing the dependence of the convection effect on various factors are given in graphical form in Figs. 6.34 to 6.37. The results show that:

a) Apparent conductivity increases with the permeability of the

Fig. 6.34 Calculated apparent thermal conductivity vs permeability

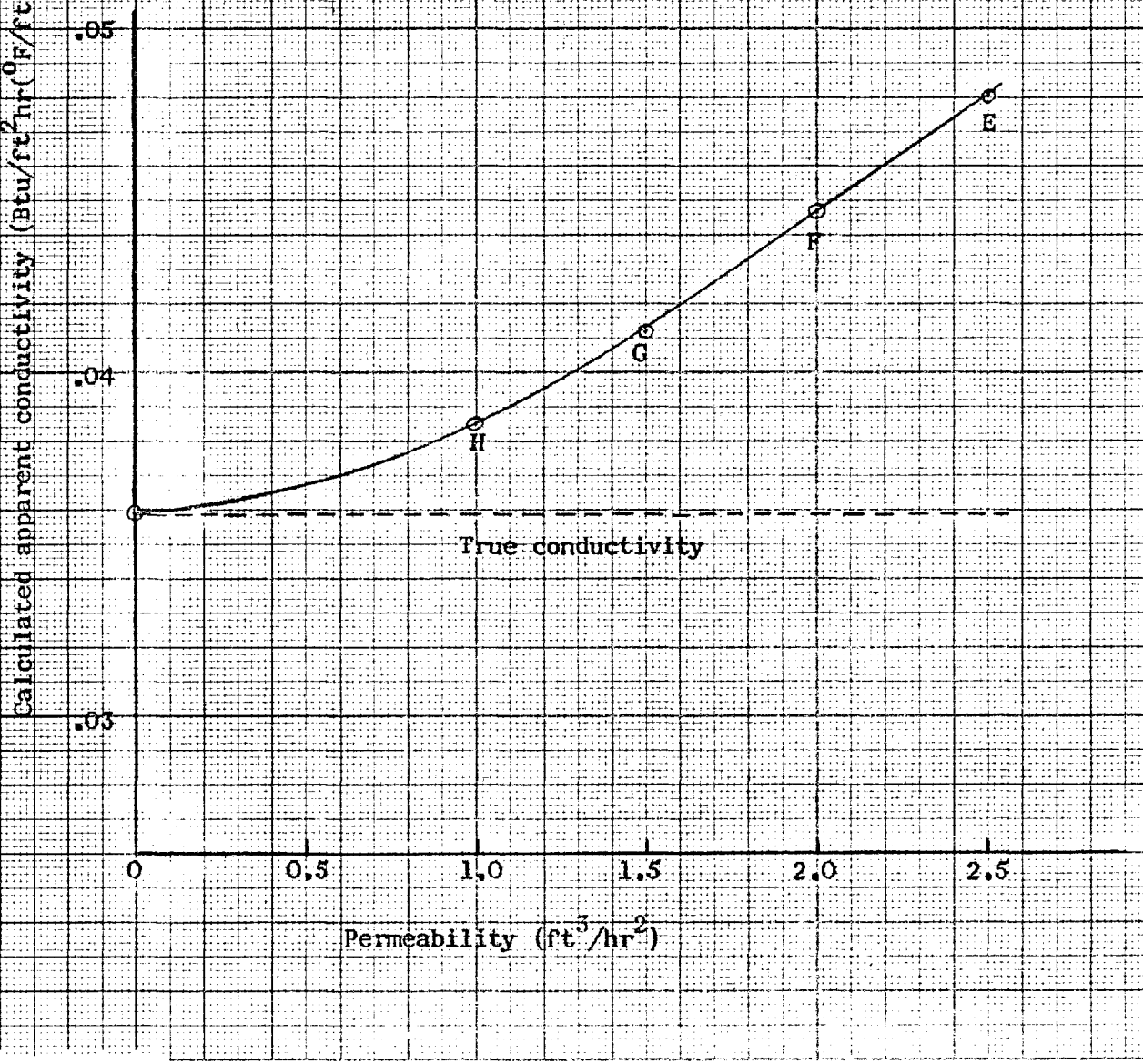


Fig. 6.35 Calculated apparent conductivity vs hot face temperature (constant cold face temperature)

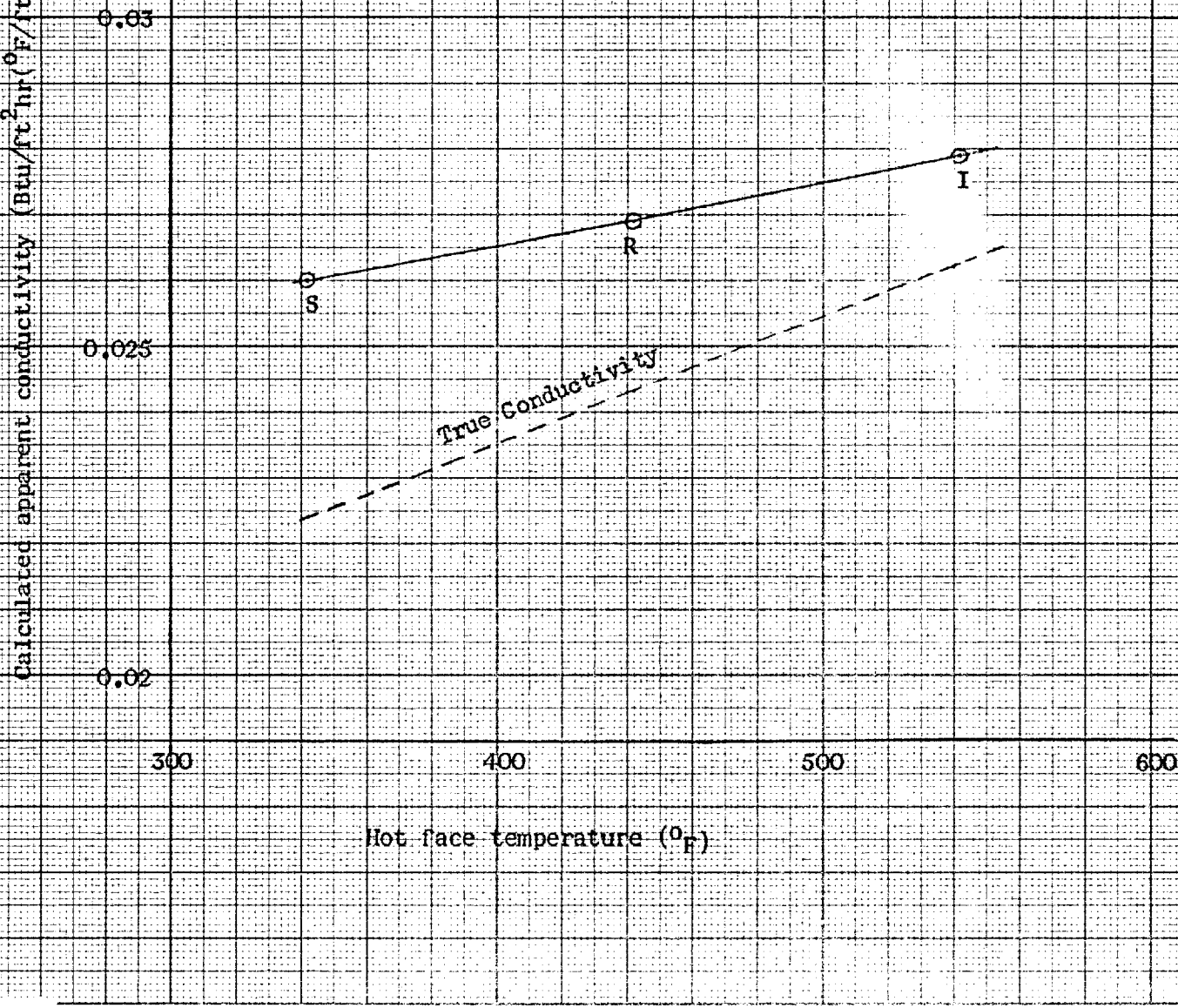


Fig. 6.36 Calculated apparent conductivity vs insulation height (at constant thickness)

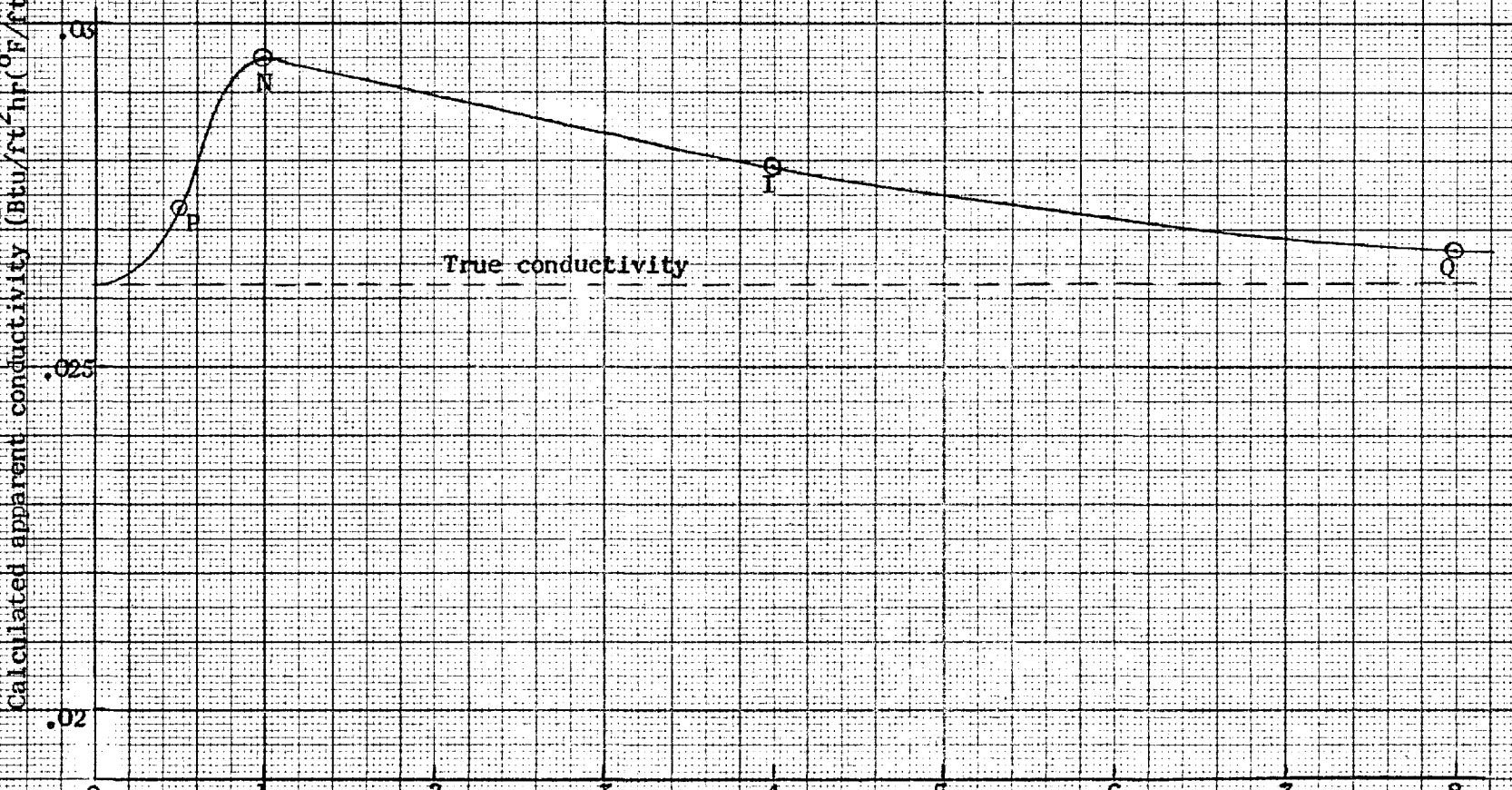
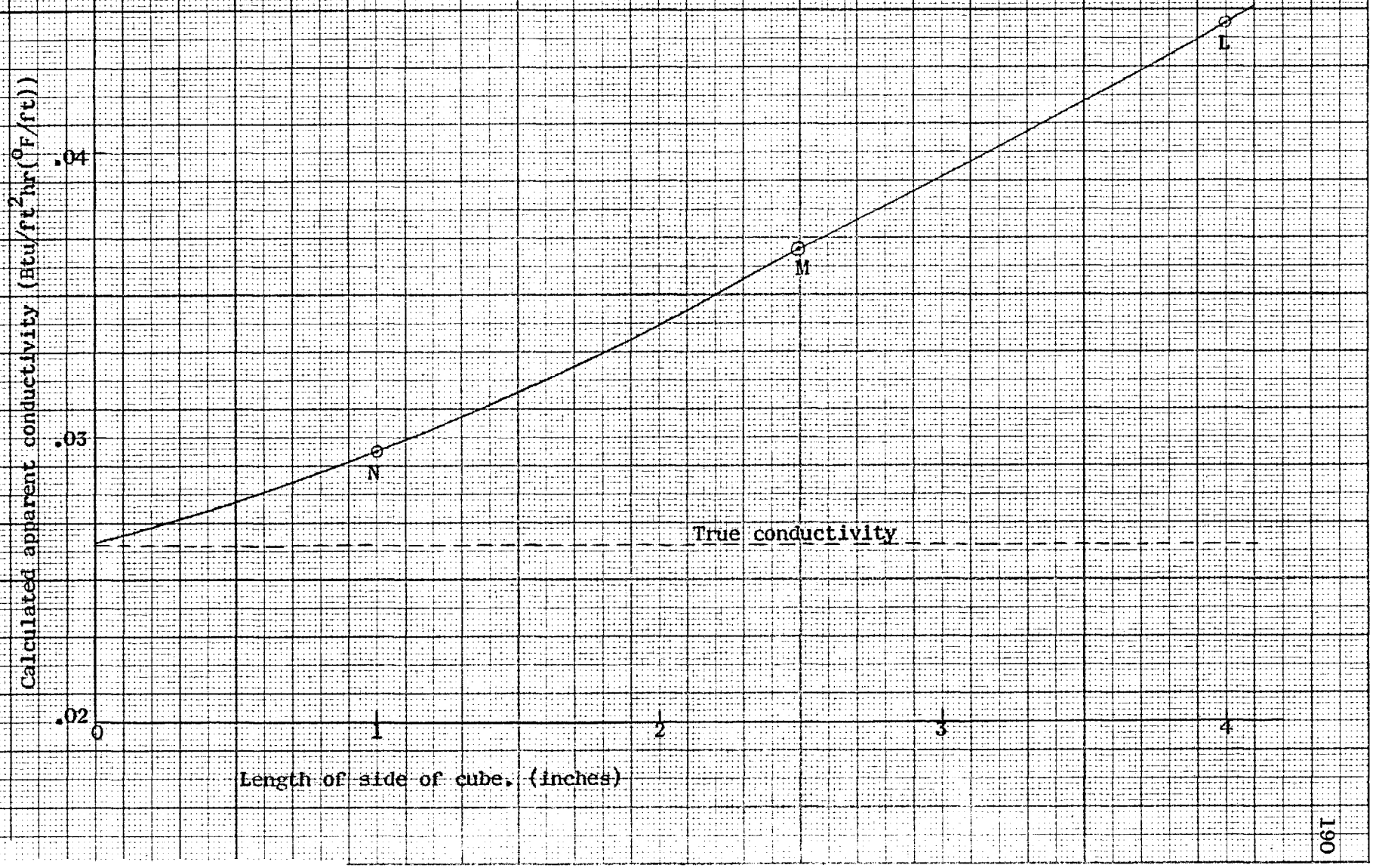


Fig. 637 Apparent conductivity vs Linear Dimension for Cube of insulation.



insulation if other properties are assumed constant (Fig. 6.34). This is to be expected since the reciprocal of permeability is a measure of the resistance of the material to gas flow. For any given insulant the true conductivity decreases as permeability increases at lower packing densities. There will, therefore, for any system, be an aptimum packing density where the apparent conductivity is a minimum.

b) With a constant cold face temperature the contribution of convection to the apparent conductivity decreases with increasing hot face temperature. If the cold face is maintained at a constant temperature an increase of hot face temperature would cause an increased flow of heat because of the increased temperature difference and the increased mean temperature. Convection would be expected to increase because of the increased temperature gradients but this would be compensated for, to some extent, by the increase in mean viscosity. Fig. 6.35 shows that the net effect is a decrease in the contribution of convection.

c) Apparent conductivity increases with the pressure of the gas in the insulation. This is due to the effect of pressure on gas density. (Fig. 6.33).

d) At a constant insulation thickness the apparent conductivity is a maximum for a height equal to the thickness. Additional height decreases the apparent conductivity but in the case of large heights of insulation, particularly where irregularities in the packing occur, the convection may divide into several smaller cells more nearly approaching the cubic configuration. This effect may be enhanced by

uneven temperature changes of the surfaces. For example, in the filling of tanks with liquefied gases, the tank may cool down from the bottom upwards and several successive convection cells may be set up. No direct evidence of this was found during the experimental work but had this occurred during the low temperature runs it would have explained the differences between measured and calculated values. It may be significant to note that during the initial cool-down of the cold plate the cooling was not uniform but took place from the bottom upwards. The splitting of the convection currents into four cells each of 1 ft. depth would have had a similar effect on the relative heat inputs of the three test plate heaters as that of a single convection cell 4 ft. in height.

For a cube of insulation Fig. 6.37 shows that the apparent conductivity is a strong function of the linear dimension.

6.8 Summary and Conclusions

Where porous insulants are used in reasonably large thicknesses the apparent conductivity may increase considerably due to gas convection, particularly if there is an elevated gas pressure in the insulation. Measurements using the apparatus described in chapter 6.1 show the extent of the convection effect and its dependance on gas pressure, in two temperature ranges, for the particular geometry of the test apparatus. The theory developed for the calculation of this effect agreed reasonably well with the measured values and has been used to show the influence of various factors on convective heat transfer. The results show that, for any particular system, the apparent conductivity increases with permeability of the insulation and gas pressure (or gas density) if

the other properties are assumed constant. At a constant cold plate temperature the effect of convection decreases with increasing hot plate temperature. For a constant thickness of insulation the apparent conductivity is a maximum for a height equal to the thickness. Increase in height decreases the apparent conductivity but multiple convection currents may be set up which would increase the apparent conductivity to a figure more closely approaching this maximum. For the "ideal" cubic configuration the apparent conductivity increases rapidly with linear dimension.

The problem of convection is complex and the effects are not always calculable. The above results, however, for the simple case of heat transfer between parallel plates, give an indication of the main factors affecting the heat flow and the magnitude of the effects for the particular insulant properties used in the calculation. The method of calculation is general and may be applied to any insulant pressurised with any gas under any conditions of temperature difference. In many applications concerned with the storage of liquefied gases the heat transfer problems may be simplified to that of heat transfer between parallel plates and the effect of gaseous convection may be estimated from calculations similar to those given in this work.

Table 6.1 Calibration of rotameter with wet gas meter

Rotameter reading litres/min.	Time for flow of 0.1 cu. ft. (T) seconds	Temperature (^{o}F)	Flow rate =360/T (cu. ft./hr.)
4.0	42	62	8.57
3.0	57	62	6.32
2.0	84	62	4.28
1.0	165	62	2.18
0.4	370	62	0.97
1.5	112	62	3.22
2.5	67	62	5.38
3.5	48	62	7.50

Table 6.2 Determination of heater resistances

Heater	V_2 (Volts.)	V_1 (mV)	Thermocouple E.m.f. (mV)	Temperature ($^{\circ}F$)	Resistance (Ohms.)
1	0.7464	8.074	2.306	204.1	50.8
	0.9363	10.133	2.332	205.1	50.8
	1.1418	12.363	2.350	205.8	50.8
2	0.5704	6.151	2.358	206.2	51.0
	0.8465	9.141	2.376	206.8	50.9
	1.1422	12.340	2.415	208.3	50.9
3	0.5569	6.036	2.249	201.9	50.7
	0.8595	9.330	2.362	206.2	50.6
	1.1315	12.294	2.422	208.6	50.6
1	0.1864	2.033	1.006	66.7	50.4
	0.2521	2.750	1.006	66.7	50.4
	0.3365	3.671	1.003	66.8	50.4
2	0.1863	2.027	1.007	66.6	50.6
	0.2515	2.738	1.007	66.6	50.5
	0.3329	3.626	1.004	66.8	50.5
3	0.1817	1.988	1.009	66.6	50.3
	0.2464	2.697	1.007	66.6	50.3
	0.3356	3.673	1.004	66.8	50.3

Table 6.3 Readings for Run 1 and Run 2

Run 1 Pressure = 21.3 in. mercury Vacuum									
Time (hrs.)	Thermocouple E.m.f.s (mV) 1	2	3	15	16	17	Heater volts. 1	2	3
51.25	2.623	2.643	2.614	-1.020	-1.023	-1.018	10.2	10.2	10.3
54.3	2.658	2.672	2.652	-1.022	-1.024	-1.019	10.3	10.3	10.4
Run 2 Pressure = 30 psig.									
Time (hrs.)	Thermocouple E.m.f.s (mV) 1	2	3	15	16	17	Heater volts. ($\times\frac{1}{11}$) 1	2	3
65.25	2.997	2.997	2.979	-0.963	-0.969	-0.968	0.906	0.884	1.121
67.5	3.000	3.003	2.985	-0975	-0.977	-0.971	0.908	0.886	1.1235
68.75	3.008	3.010	2.993	-0.984	-0.988	-0.982	0.907	0.885	1.123
69.75	3.013	3.017	3.000	-1.006	-1.010	-1.004	0.910	0.888	1.126
70.75	3.018	3.022	3.005	-0.997	-1.000	-0.994	0.909	0.887	1.125
73.0	3.025	3.030	3.013	-0.992	-0.996	-0.990	0.907	0.885	1.123
73.6	3.028	3.032	3.015	-0.995	-0.999	-0.993	0.908	0.886	1.124
85.6	3.056	3.059	3.038	-0.949	-0.953	-0.948	0.905	0.884	1.121

Table 6.4 Summary of Calculation for Run 2

Time (hrs.)	Mean Temperature of hot plate ^{o}F	Mean Temperature of cold plate ^{o}F	Total Power (Watts.)	Conductivity Btu./ft.^{2}hr.(^{o}F/ft.)
65.25	230.4	68.4	6.83	0.0358
67.5	230.6	68.1	6.845	0.0356
68.75	230.9	67.6	6.83	0.0354
69.75	231.1	66.6	6.88	0.0352
70.75	231.3	67.1	6.865	0.0354
73.0	231.6	67.3	6.83	0.0352
73.6	231.7	67.2	6.845	0.0352
85.6	232.6	69.2	6.815	0.0353
Mean thermal conductivity = 0.0353 Btu./ft.^{2}hr.(^{o}F/ft.)				

Table 6.5 Readings Run 3 (Air pressure = 100 psig.)

Time	Thermocouple E.m.f.s (mV)						Heater Volts. ($\times\frac{1}{11}$)		
(hrs.)	1	2	3	15	16	17	1	2	3
86.3	3.630	3.633	3.636	-1.065	-1.071	-1.065	0.788	0.734	1.560
95.2	3.599	3.612	3.639	-1.049	-1.056	-1.049	0.789	0.735	1.663
98.3	3.585	3.594	3.606	-1.069	-1.075	-1.068	0.786	0.732	1.659
103.5	3.562	3.572	3.593	-1.069	-1.074	-1.067	0.791	0.737	1.671
108.3	3.553	3.570	3.605	-1.066	-1.071	-1.064	0.785	0.785	1.662
119.2	3.556	3.581	3.625	-1.056	-1.060	-1.055	0.784	0.729	1.664
120.2	3.558	3.579	3.615	-1.087	-1.094	-1.088	0.784	0.729	1.664
122.3	3.548	3.563	3.591	-1.091	-1.096	-1.089	0.783	0.729	1.664
123.3	3.544	3.559	3.586	-1.082	-1.089	-1.083	0.783	0.728	1.662
125.2	3.531	3.543	3.567	-1.123	-1.128	-1.121	0.780	0.726	1.660
126.4	3.517	3.528	3.552	-1.122	-1.129	-1.121	0.780	0.725	1.659
131.3	3.493	3.510	3.548	-1.114	-1.120	-1.113	0.780	0.726	1.663
143.2	3.473	3.487	3.513	-1.115	-1.120	-1.113	0.777	0.723	1.659
144.3	3.475	3.492	3.529	-1.096	-1.101	-1.094	0.782	0.728	1.674
145.2	3.479	3.497	3.535	-1.104	-1.109	-1.100	0.781	0.726	1.670
146.1	3.478	3.498	3.539	-1.093	-	-	-	-	-
148.1	3.490	3.510	3.564	-1.088	-	-	-	-	-
150.1	3.492	3.514	3.557	-1.086	-	-	-	-	-
152.3	3.497	3.520	3.564	-1.069	-1.074	-1.068	0.780	0.726	1.671
153.2	3.500	3.523	3.568	-1.078	-1.082	-1.075	0.780	0.726	1.671
155.8	3.509	3.531	3.576	-1.068	-1.073	-1.066	0.780	0.726	1.672
168.5	3.553	3.582	3.637	-1.056	-1.062	-1.055	0.785	0.731	1.680
170.8	3.559	3.587	3.643	-1.069	-1.073	-1.067	0.786	0.732	1.684
175.5	3.623	3.623	3.679	-1.071	-1.076	-1.069	0.789	0.735	1.687
182.3	3.616	3.639	3.681	-1.073	-1.078	-1.071	0.786	0.732	1.682
191.8	3.617	3.642	3.688	-1.041	-1.045	-1.038	0.784	0.730	1.680

Table 6.6 Readings for run 4 (Air Pressure = 60 psig.)

Time	E.m.f.s of thermocouples (mV)						Heater Volts. ($\times\frac{1}{11}$)		
(hrs.)	1	2	3	15	16	17	1	2	3
218.0	3.605	3.613	3.607	-1.109	-1.113	-1.106	0.915	0.918	1.344
219.8	3.600	3.609	3.605	-1.109	-1.112	-1.105	0.916	0.919	1.345
223.0	3.599	3.606	3.606	-1.105	-1.113	-1.106	0.918	0.920	1.347
226.6	3.597	3.609	3.612	-1.073	-1.077	-1.069	0.921	0.923	1.350
229.1	3.598	3.608	3.602	-1.071	-1.074	-1.068	0.919	0.923	1.349
238.8	3.600	3.613	3.618	-1.051	-1.054	-1.048	0.917	0.921	1.348
240.3	3.596	3.608	3.602	-1.077	-1.081	-1.077	0.917	0.921	1.347
242.4	3.594	3.603	3.596	-1.086	-1.091	-1.084	0.916	0.920	1.346
244.0	3.594	3.604	3.604	-1.097	-1.100	-1.092	0.918	0.922	1.350
246.1	3.591	3.603	3.603	-1.100	-1.104	-1.097	0.917	0.921	1.329
247.0	3.590	3.600	3.603	-1.098	-1.103	-1.095	0.919	0.923	1.351
251.3	3.593	3.605	3.607	-1.070	-1.075	-1.068	0.921	0.925	1.352
263.8	3.611	3.619	3.670	-1.059	-1.062	-1.055	0.919	0.923	1.350
264.7	3.605	3.616	3.616	-1.043	-1.046	-1.040	0.919	0.923	1.350

Table 6.7 Readings for Run 5 (Atmospheric pressure)

Time	Thermocouple e.m.f.s (mV)						Heater Volts. (x $\frac{1}{11}$)		
(hrs.)	1	2	3	15	16	17	1	2	3
101.1	3.651	3.664	3.661	-1.100	-1.103	-1.097	1.026	0.993	1.145
106.6	3.654	3.665	3.659	-1.068	-1.071	-1.064	1.029	0.996	1.146
117.8	3.636	3.649	3.647	-1.040	-1.043	-1.037	1.025	0.992	1.144
119.3	3.642	3.650	3.649	-1.046	-1.048	-1.041	1.042	0.992	1.143
121.2	3.644	3.651	3.648	-1.043	-1.045	-1.039	1.042	0.992	1.144
122.7	3.646	3.653	3.650	-1.047	-1.042	-1.044	1.042	0.992	1.144
124.9	3.648	3.655	3.683	-1.065	-1.067	-1.060	1.042	0.991	1.143
125.8	3.649	3.657	3.653	-1.060	-1.063	-1.058	1.043	0.993	1.144
130.4	3.661	3.667	3.664	-1.033	-1.037	-1.031	1.046	0.995	1.147
141.9	3.648	3.656	3.655	-1.029	-1.032	-1.027	1.037	0.987	1.141
143.3	3.649	3.658	3.656	-1.052	-1.060	-1.054	1.036	0.987	1.140
145.0	3.644	3.654	3.653	-1.052	-1.054	-1.049	1.036	0.985	1.139
147.2	3.652	3.662	3.662	-1.063	-1.066	-1.061	1.048	0.997	1.150
148.0	3.653	3.663	3.662	-1.082	-1.085	-1.078	1.043	0.993	1.146
149.8	3.657	3.667	3.665	-1.082	-1.085	-1.079	1.045	0.996	1.148
154.4	3.645	3.655	3.654	-1.075	-1.079	-1.072	1.033	0.983	1.137
165.8	3.602	3.612	3.612	-1.054	-1.057	-1.052	1.026	0.977	1.134
168.4	3.596	3.603	3.601	-1.071	-1.074	-1.069	1.023	0.974	1.131
169.3	3.595	3.606	3.598	-1.075	-1.080	-1.074	1.028	0.979	1.139
173.8	3.592	3.602	3.600	-1.122	-1.122	-1.119	1.035	0.986	1.141
178.8	3.600	3.611	3.611	-1.118	-1.123	-1.116	1.037	0.988	1.143
190.0	3.578	3.590	3.592	-1.108	-1.114	-1.108	1.031	0.982	1.138
191.3	3.576	3.588	3.591	-1.088	-1.091	-1.086	1.031	0.981	1.137
192.3	3.576	3.588	3.591	-1.088	-1.091	-1.085	1.030	0.981	1.137
193.3	3.576	3.588	3.592	-1.094	-1.097	-1.091	1.031	0.982	1.138
194.9	3.576	3.588	3.591	-1.082	-1.086	-1.079	1.033	0.984	1.139
196.3	3.576	3.588	3.591	-1.093	-1.095	-1.089	1.032	0.982	1.138
198.8	3.575	3.588	3.592	-1.075	-1.079	-1.073	1.036	0.987	1.142
201.8	3.587	3.599	3.605	-1.046	-1.048	-1.042	1.041	0.991	1.146

Table 6.8 Readings for Run 6 (atmospheric pressure)

Time (hrs.)	Atmos. pressure (mm.Hg.)	Pressure in dewar (mm.Hg. gauge)	E.m.f.s of thermocouples (mV)						Heater Volts. ($\times\frac{1}{11}$)		
			1	2	3	15	16	17	1	2	3
94.7	-	150	-0.815	-0.818	-0.818	-7.086	-7.094	-7.074	8.03	8.43	14.01
99.7	-	-	-0.805	-0.808	-0.806	-7.084	-7.093	-7.066	8.03	8.43	14.02
110.9	-	152	-0.795	-0.798	-0.801	-7.084	-7.094	-7.074	8.02	8.42	14.02
111.9	-	140	-0.795	-0.797	-0.801	-7.084	-7.090	-7.070	8.01	8.41	14.00
113.2	-	132	-0.793	-0.795	-0.799	-7.080	-7.082	-7.070	8.01	8.41	13.99
114.3	-	132	-0.792	-0.795	-0.800	-7.080	-7.080	-7.072	8.02	8.42	14.01
117.5	-	141	-0.793	-0.797	-0.807	-7.083	-7.081	-7.071	8.01	8.41	13.99
118.8	756	141	-0.793	-0.797	-0.806	-7.083	-7.080	-7.071	8.04	8.44	14.03
120.6	756	145	-0.794	-0.798	-0.807	-7.085	-7.085	-7.071	8.01	8.41	14.00
122.3	755.5	-	-0.793	-0.799	-0.809	-7.085	-7.085	-7.073	8.02	8.42	14.00
123.8	755.5	131	-0.796	-0.802	-0.811	-7.088	-7.083	-7.074	8.01	8.41	13.99
135.2	755.5	131	-0.822	-0.834	-0.860	-7.073	-7.090	-7.072	8.02	8.42	14.01
136.0	756	137	-0.824	-0.830	-0.837	-7.088	-7.095	-7.071	8.01	8.41	13.99
138.4	756	140	-0.822	-0.827	-0.834	-7.091	-7.097	-7.074	8.01	8.41	14.00
142.0	756	146	-0.821	-0.821	-0.823	-7.016	-6.778	-7.061	8.01	8.40	13.99
142.8	756	146	-0.815	-0.817	-0.816	-7.087	-7.094	-7.073	8.02	8.42	14.01
146.2	756	-	-0.811	-0.818	-0.835	-7.082	-7.094	-7.070	8.00	8.40	13.97
147.3	756	-	-0.812	-0.820	-0.836	-7.075	-7.093	-7.065	8.00	8.40	13.97
159.1	754	140	-0.813	-0.815	-0.824	-7.089	-7.082	-7.074	7.98	8.37	13.93
160.1	753.3	-	-0.811	-0.815	-0.818	-7.040	-7.095	-7.077	7.99	8.39	13.97
161.5	-	134	-0.815	-0.819	-0.827	-7.098	-7.103	-7.081	7.98	8.38	13.93
162.3	-	-	-0.817	-0.819	-0.833	-7.077	-7.101	-7.081	7.98	8.37	13.94
163.3	-	134	-0.814	-0.821	-0.834	-7.096	-7.100	-7.087	7.98	8.38	14.94

Table 6.9 Readings for Run 7 (Approximately 7.5 psig.)

Time (hrs.)	Atmos. Pressure (mm.Hg)	Pressure in dewar (mm. Hg gauge)	Pressure in insulation (mm.Hg gauge)	E.m.f.s of thermocouples (mV)						Heater Volts. ($\times\frac{1}{11}$)		
				1	2	3	15	16	17	1	2	3*
103.5	754	-	382	-0.898	-0.900	-0.909	-7.083	-7.086	-7.065	5.57	5.63	15.81
105.1	754.5	-	382	-0.893	-0.892	-0.911	-7.081	-7.087	-7.065	5.54	5.60	15.71
105.9	755	165	382	-0.893	-0.895	-0.910	-7.082	-7.088	-7.068	5.54	5.60	15.71
112.8	757.5	-	382	-0.908	-0.908	-0.925	-7.080	-7.086	-7.063	5.545	5.605	15.77
114.8	759	164	391	-0.908	-0.907	-0.921	-7.079	-7.085	-7.064	5.55	5.61	15.80
116.5	760.5	190	386	-0.911	-0.907	-0.923	-7.088	-7.094	-7.075	5.56	5.615	15.83
118.5	-	-	385	-0.911	-0.904	-0.190	-7.077	-7.091	-7.061	5.565	5.62	15.85
120.8	762	-	381	-0.902	-0.894	-0.905	-7.072	-7.087	-7.050	5.545	5.605	15.80
122.8	762	-	384	-0.899	-0.892	-0.902	-7.072	-7.080	-7.058	5.545	5.605	15.81
124.8	763	-	384	-0.909	-0.901	-0.901	-6.945	-6.728	-6.819	5.85	5.61	15.83
128.5	764	168	382	-0.915	-0.914	-0.938	-7.077	-7.081	-7.062	5.54	5.595	15.78
139.0	764.5	173	383	-0.961	-0.949	-0.947	-7.079	-7.088	-7.071	5.54	5.59	15.85
141.2	764.5	205	380	-0.949	-0.933	-0.926	-7.082	-7.082	-7.064	5.53	5.59	15.84
142.3	764	209	382	-0.944	-0.927	-0.930	-7.081	-7.084	-7.064	5.53	5.59	15.86
144.8	763	195	382	-0.942	-0.936	-0.949	-7.079	-7.082	-7.062	5.53	5.59	15.84
146.8	763	195	382	-0.947	-0.944	-0.959	-7.078	-7.081	-7.062	5.53	5.59	15.85
148.0	-	-	382	-0.955	-0.953	-0.961	-7.048	-6.938	-7.024	5.54	5.59	15.86
149.0	763	-	382	-0.957	-0.951	-0.952	-7.079	-7.083	-7.061	5.53	5.59	15.85
153.3	763	-	384	-0.955	-0.956	-0.978	-7.079	-7.083	-7.054	5.52	5.58	15.78
162.3	763	-	386	-0.989	-0.985	-0.983	-	-	-	5.52	5.58	15.87

* The voltages of this heater were too high for direct reading on the potentiometer as described. An extra resistance of 26,600 ohms. was, therefore, connected in series with the 100,000 ohm resistance (Fig. 6.6). The true voltage is thus the given reading multiplied by 13.66.

Table 6.10 Readings for Run 8 (reduced pressure)

Time (hrs.)	Atmos. Pressure (mm. Hg)	Pressure in dewar (mm. Hg gauge)	Press. in insulation (ins. H_2O vac.)	E.m.f.s of thermocouples (mV)						Heater Volts. ($\times\frac{1}{11}$)		
				1	2	3	15	16	17	1	2	3
72.0	755	148	24.7	-0.339	-0.339	-0.339	-7.089	-7.096	-7.076	0.985	0.999	1.052
74.2	755	151	24.7	-0.342	-0.341	-0.340	-7.089	-7.095	-7.076	0.983	0.997	1.051
76.8	755	162	24.7	-0.344	-0.343	-0.342	-7.088	-7.089	-7.072	0.984	0.998	1.052
79.1	754	-	24.7	-0.746	-0.344	-0.345	-7.087	-7.087	-7.073	0.985	0.999	1.053
80.2	-	-	24.7	-0.347	-0.345	-0.345	-7.087	-7.098	-7.077	0.985	0.999	1.052
85.3	753.5	-	24.7	-0.345	-0.342	-0.337	-7.088	-7.095	-7.076	0.985	0.999	1.052
95.3	749	-	24.7	-0.353	-0.350	-0.346	-7.093	-7.099	-7.080	0.985	0.999	1.053
79.8	749	-	24.7	-0.356	-0.352	-0.350	-7.086	-7.099	-7.076	0.983	0.997	1.051
100.6	748	-	24.7	-0.356	-0.354	-0.351	-7.091	-7.098	-7.078	0.984	0.997	1.051
103.8	746	-	24.7	-0.356	-0.354	-0.351	-7.088	-7.096	-7.076	0.984	0.997	1.051
105.8	746.5	-	24.6	-0.354	-0.352	-0.350	-7.088	-7.095	-7.076	0.985	0.999	1.053
108.1	747	200	24.6	-0.351	-0.349	-0.346	-7.085	-7.089	-7.071	0.986	1.000	1.054
119.1	745	149	24.6	-0.356	-0.354	-0.354	-7.093	-7.098	-7.081	0.983	0.997	1.052
124.8	744	156	24.6	-0.359	-0.358	-0.357	-7.092	-7.100	-7.080	0.983	0.997	1.052
126.9	744	141	24.6	-0.362	-0.360	-0.359	-7.092	-7.099	-7.097	0.982	0.996	1.051
129.6	744	-	-	-0.362	-0.361	-0.359	-7.091	-7.095	-7.079	0.984	0.998	1.053
133.6	744	-	24.6	-0.360	-0.357	-0.355	-7.091	-7.097	-7.079	0.986	1.000	1.055
143.8	748	-	-	-0.365	-0.363	-0.362	-7.091	-7.097	-7.078	0.982	0.996	1.051
146.0	749.5	-	24.6	-0.370	-0.366	-0.362	-7.089	-7.102	-7.074	0.982	0.996	1.052

Table 6.11 Summary of conductivity calculations (run 3).

Time (hrs.)	Hot plate temperature °F	Cold plate temperature °F	Power (watts)	Thermal conductivity $\left(\frac{Btu.}{ft^2.\ hr.\ ^\circ F/ft.}\right)$
86	253.4	64.1	9.34	.0419
98	252.4	63.7	9.35	.0420
110	251.2	62.7	9.28	.0417
122	250.2	62.0	9.25	.0417
134	249.9	62.2	9.32	.0420
146	251.0	63.5	9.41	.0425
158	252.8	64.0	9.47	.0425
170	254.5	64.2	9.50	.0423
			Mean conductivity =	.0421

Table 6.12 Summary of conductivity calculations (run 4)

Time (hrs.)	Hot plate temperature °F	Cold plate temperature °F	Power (watts)	Thermal conductivity $\left(\frac{Btu}{ft.hr.^\circ F/ft.}\right)$
218	253.5	62.8	8.34	.0371
230	253.3	63.2	8.34	.0372
242	253.3	63.5	8.35	.0373
254	253.4	63.7	8.37	.0374
266	253.5	63.7	8.39	.0374
			Mean conductivity =	.0373

Table 6.13 Summary of conductivity calculations (run 5).

Time (hrs.)	Hot plate temperature (°F)	Cold plate temperature (°F)	Power (watts)	Thermal conductivity $\left(\frac{\text{Btu}}{\text{ft.}^2\text{hr.}\,^\circ\text{F/ft.}}\right)$
100	255.3	64.0	7.94	.0352
112	255.3	64.7	7.99	.0355
124	255.3	65.0	8.01	.0356
136	255.3	64.9	8.02	.0356
148	255.2	64.8	8.00	.0356
160	254.3	63.9	7.88	.0351
172	253.3	62.4	7.87	.0350
184	252.8	62.3	7.91	.0351
196	252.7	63.3	7.96	.0356
			Mean conductivity =	.0354

Table 6.14 Summary of conductivity calculations (run 6)

Time (hrs.)	Hot plate temperature (°F)	Cold plate temperature (°F)	Power (watts)	Thermal conductivity $\left(\frac{\text{Btu}}{\text{ft.}^2\text{ hr.}\,^\circ\text{F/ft.}}\right)$
100	70.5	-297.2	7.96	.0184
112	71.1	-297.3	7.96	.0184
124	70.9	-297.4	7.95	.0183
136	69.8	-297.4	7.94	.0183
148	70.1	-297.5	7.92	.0182
160	70.1	-297.6	7.89	.0182
			Mean conductivity=	.0183

Table 6.15 Summary of conductivity calculations (run 7)

Time (hrs.)	Hot plate temperature (^{o}F)	Cold plate temperature (^{o}F)	Power (watts)	Thermal conductivity ($\frac{Btu.}{ft.^2\ hr.\ ^{o}F/ft.}$)
114	71.1	-296.5	10.76	.0248
126	70.7	-296.4	10.77	.0249
138	69.8	-296.3	10.78	.0250
150	69.0	-296.2	10.78	.0251
162	67.8	-296.1	10.78	.0251
			Mean conductivity =	.0250

Table 6.16 Summary of conductivity calculations (run 7).

Time (hrs.)	Hot plate temperature (^{o}F)	Cold plate temperature (^{o}F)	Power (watts)	Thermal conductivity ($\frac{Btu.}{ft.^2\ hr.\ ^{o}F/hr.}$)
72	96.0	-297.4	7.37	.0159
84	95.8	-297.5	7.37	.0159
96	95.7	-297.5	7.37	.0159
108	95.6	-297.5	7.37	.0159
120	95.4	-297.5	7.37	.0159
132	95.3	-297.5	7.37	.0159
146	95.1	-297.6	7.36	.0159
			Mean conductivity =	.0159

Table 6.17 Summary of measured values of apparent conductivity

Run Number	Pressure (psia)	Temperature difference (°F)	Mean temperature (°F)	Apparent conductivity $\frac{\text{Btu.}}{\text{ft}^2\text{hr.}^\circ\text{F/ft.}}$	Corrected mean temperature (°F)	Corrected conductivity $\frac{\text{Btu.}}{\text{ft}^2\text{hr.}^\circ\text{F/ft.}}$
1	4.3	151	141	.0351	158	.0357
5	14.7	190	160	.0354	158	.0353
2	44.7	163	150	.0354	158	.0357
4	74.7	190	158	.0373	158	.0373
3	114.7	189	158	.0423	158	.0423
8	2.6	393	-101	.0159	-113	.0153
6	14.7	368	-114	.0183	-113	.0183
7	22.1	366	-113	.0250	-113	.0250

TABLE 6.18 CALCULATION OF APPARENT CONDUCTIVITY USING COMPUTER PROGRAMME LN

	Cold plate temperature T_0 °F	Hot plate temperature T_1 °F	Air pressure P psia	Thickness of element L ft	Height of element H ft	Density Constant ρ_0 lb°R/ft³	Conductivity constants $k_0 \times 10^2$ Btu/ft²hr°F/ft	Conductivity constants $k_1 \times 10^5$ Btu/ft²hr°F/ft°R	Viscosity constants $\mu_0 \times 10^3$ lb/ft hr	Viscosity constants $\mu_1 \times 10^5$ lb/ft hr°R	Heat Capacity Cp Btu/lb°F	Permeability α ft³/hr²	Calculated total heat transfer Btu/hr	Apparent Conductivity Btu/ft²hr°F/ft	True Conductivity Btu/ft²hr°F/ft	% of total heat transfer due to Convection
A	530	680	14.7	1	4	39.7	1.27	3.83	1.42	5.46	0.25	2.5	21.5	.0359	.0359	0
B	529	691	44.7	1	4	120.6	1.27	3.83	1.42	5.46	0.25	2.5	23.6	.0364	.0362	0.5
C	529	708	74.7	1	4	202.0	1.27	3.83	1.42	5.46	0.25	2.5	27.0	.0377	.0364	3.5
D	529	680	114.7	1	4	309.5	1.27	3.83	1.42	5.46	0.25	2.5	24.8	.0411	.0359	12.7
E	530	680	147.0	1	4	397.0	1.27	3.83	1.42	5.46	0.25	2.5	28.9	.0481	.0359	25.4
F	530	680	147.0	1	4	397.0	1.27	3.83	1.42	5.46	0.25	2.0	26.8	.0447	.0359	19.7
G	530	680	147.0	1	4	397.0	1.27	3.83	1.42	5.46	0.25	1.5	24.8	.0412	.0359	12.8
H	530	680	147.0	1	4	397.0	1.27	3.83	1.42	5.46	0.25	1.0	23.1	.0385	.0359	6.8
I	162	542	14.7	1	4	39.7	1.27	3.83	3.40	7.73	0.25	2.5	42.4	.0279	.0262	6.1
J	162	542	22.1	1	4	59.5	1.27	3.83	3.40	7.73	0.25	2.5	50.9	.0335	.0262	21.8
K	162	542	29.4	1	4	79.4	1.27	3.83	3.40	7.73	0.25	2.5	63.5	.0418	.0262	37.3
L	162	542	14.7	4	4	39.7	1.27	3.83	3.40	7.73	0.25	2.5	16.9	.0445	.0262	41.1
M	162	542	14.7	2.5	2.5	39.7	1.27	3.83	3.40	7.73	0.25	2.5	13.9	.0366	.0262	28.4
N	162	542	14.7	1	1	39.7	1.27	3.83	3.40	7.73	0.25	2.5	11.2	.0295	.0262	11.2
P	162	542	14.7	1	0.5	39.7	1.27	3.83	3.40	7.73	0.25	2.5	5.18	.0273	.0262	4.0
Q	162	542	14.7	1	8	39.7	1.27	3.83	3.40	7.73	0.25	2.5	81.0	.0267	.0262	1.9
R	162	442	14.7	1	4	39.7	1.27	3.83	3.40	7.73	0.25	2.5	30.2	.0269	.0243	9.7
S	162	342	14.7	1	4	39.7	1.27	3.83	3.40	7.73	0.25	2.5	18.7	.0260	.0224	13.8
T	162	530	14.7	1	4	39.7	−0.15	4.76	3.40	7.73	0.25	2.5	23.4	.0159	.0145	8.8
U	162	530	22.1	1	4	59.5	−0.15	4.76	3.40	7.73	0.25	2.5	27.6	.0188	.0145	22.9

CHAPTER VII

Summary of Conclusions and Suggestions for Future Work

Pressure drops encountered in the flow of liquid methane through a ten inch diameter pipeline have been measured. It was found, for the system investigated, that flow in the pipeline would be entirely single phase (provided that the pipeline was precooled before the unloading). In this case the pressure drops experienced could be predicted sufficiently accurately for all normal design purposes using the pipe friction chart method normally employed for liquids. It would be of interest to carry out similar measurements on systems where the thickness of insulation and flow rate are such that two phase flow occurs.

Transient atmospheric conditions have been shown to exert a large influence on the rate of evaporation of liquefied gases in large storage tanks and a procedure has been developed to enable the best analysis of insulation performance to be made from evaporation rate measurements. The method was applied to the calculation of heat inleak to a storage tank for liquid methane. Much interesting work remains to be done, in particular, on the influence of pressure changes on the rate of evaporation. The provision of temperature measuring points within the liquid would enable a study to be made of the convection effects associated with changes of pressure. Artificial pressure changes could be introduced to enable a more complete study to be made. It would be desirable, for work of this nature, to have some direct measure of the vapour flow rate from the tanks. A direct means of determining the wall temperatures of the inner tank would be useful, particularly for investigations involving partially filled tanks.

Measured rates of heat inleak to the storage tank were about 25% higher than those calculated using insulation properties measured in the laboratory. It is considered that the discrepancy may be due, in part, to the effects of gas convection within the porous insulation of the tank sides and roof. The problem of convection within porous insulants has been studied both theoretically and in the laboratory. A method of calculation, involving the use of an electronic digital computer has been developed and used to predict the effects of convection for various systems. The effect of air pressure within the insulation was used to demonstrate the extent of convection in two temperature ranges. Computed values of heat transfer, at various pressures, agreed reasonably well with measured values for slag wool. A more extensive study of the identity of calculated and experimental values remains to be carried out. In addition to the investigation of the effects of air pressure, the apparatus lends itself particularly to studies involving the use of gases of different properties and the inclusion of membranes dividing the cell into smaller convection regions. The inclusion of themocouples in the bulk of the insulation would allow valuable information on the temperature distribution to be obtained. Suggested improvements to the existing apparatus are the provision of independent temperature control on the heaters of the upper and lower sections of the guard ring and the provision of a more stable power supply to the heaters. This could be achieved using a constant voltage transformer.

Many more calculations using the computer programme need to be carried out before general relationships showing the effects of convection can be obtained. A suggested method of approach is the substitution of

values calculated by the computer method in the general relationship which has been derived from dimensional analysis. Slight modifications to the existing programme would allow different systems to be investigated. For example, the setting up of the boundary conditions could be modified to calculate convection effects under the same conditions but with the upper and lower edges of the cell bounded by conducting materials instead of perfect insulators. Similarly, the condition of uniform heat flux instead of uniform temperature for the hot and cold plates could be investigated.

List of Symbols used in Main Calculations

A, B, C, D	Constants	
C	Constant	
Cp	Heat capacity	(Btu./lb.^{o}R)
d	Length; used to denote pipe diameter (Chapter 2) and length of element of insulation in the vertical direction (Chapter 5.6)	(ft.)
e	Absolute roughness of pipe surface	(ft.)
g	Acceleration due to gravity	(ft./hr^2.)
G	Temperature gradient	(^{o}F/ft.)
H	Insulation height	(ft.)
k	Thermal conductivity	(Btu./ft^2.hr.(^{o}F/ft.)
k_0, k_1	Constants in equation $k = k_0 + k_1T$	
K	Thermal Diffusivity	(ft^2./hr.)
K_1, K_2	Constants used in finite-difference equations	
ℓ	Length of element in the horizontal direction	(ft.)
L	Total length in the horizontal direction	(ft.)
m, M	Constants	
P	Absolute pressure	(lb./ft^2.)
Q	Heat transfer per unit area per unit time	(Btu./hr.ft^2.)

R	Electrical resistance	(ohms)
t	Time (General)	(hrs.)
t'	Student's t	
T	Absolute Temperature	(^{o}R)
u	Velocity of flow	(ft./hr.)
v	Specific volume	(ft^3/lb.)
V	Potential difference	(volts.)
x	Distance (General)	
X	Length of one distance step used in finite-difference formulae	(ft.)
Y	Length of one time step used in finite-difference formulae	(hrs.)
z	Height above some arbitrary level	(ft.)
μ	Fluid viscosity	(lb./ft.hr.)
μ_0/μ_1	Constants in equation $\mu = \mu_0 + \mu_1 T$	
ρ	Density	(lb./ft^3)
α	Insulation permeability	(ft^3/hr^2)
γ	Constant used in finite-difference calculations	(^{o}R)
βg	Product of co-efficient of cubical expansion and the acceleration due to gravity	($^{o}F^{-1}$.ft./hr^2)

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APPENDIX 1

1.0 Computer programme LG

1.1 List of indices and variables used in LG

1.2 Data tape for step change test case

1.3 Data tape for linear change test case

1.4 Data tapes for runs 1 to 6

1.5 Calculated mean outside temperatures for runs 1 to 6

1.6 Output tapes for runs 1 to 6

APPENDIX 1.0

Computer programme LG

```
DN
LG MK5
J837.0
N
METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
N
TEMPERATURE GRADIENTS (DEG F/FT)
N
BOIL-OFF (IN.) =
N
EMFS NOT MULTIPLE OF 12 - REMAINDER =
N
WRONG NUMBER OF JUNCTION
TEMPERATURES - SURPLUS =


N
(SUMMARY AND ERROR PUNCH)
N
```

```
L
T843.0
6688 --0
I6777181
797 -50
I6777178
32
I6777186
32
I6777187
32
I6777188
32
I6777204
32
I6775476

32
I6777188
32
I6775475
32
I6776499
1034 --0 .
I6777185
1046 --0 .
I6777192
1060 --0 .
I6777195
1030 --0 .
I6777208
1038 --0 .
I6775332

1049 --0 .
I6775344
```

```
1047 --o .
16775397
1048 --o .
16775404
1042 --o .
16775408
1050 --o .
16665907
1055 --o .
16665844
1053 --o .
16731362
1051 --o .
16731364

1054 --o .
16731365
1052 --o .
16731376
1060 --o .
16777195
6679 --o
16777189
6680 --o
16777202
6682 --o
16777201
6681 --o
16777213


X805.6+
46
J1.0
```

```
9)no=0
COND
no=6
TEXT
no=0
TEXT
no=8
COND
no=6
TEXT
no=0
TEXT
no=5
TEXT


0)no=1
COND
no=600
10)SIXWAYS
n5=no*12
n4=no/12
→10,n5=0
n24=3
12)no=9
COND
no=n24
TEXT
PRINTn5,4000
STOP
→0


1)no=500
SIXWAYS
n5=no-n4
→11,n5=0
n24=4
→12
11)n1=0
```

```
16)n2=12Xn1
vo=v(609+n2)+v(610+n2)
```

```
vo=vo/2
vo=voXv27
v(200+n1)=vo+v(500+n1)
vo=v(604+n2)+v(605+n2)
vo=vo+v(607+n2)
vo=vo/3
vo=voXv27
v(275+n1)=vo+v(500+n1)
vo=v(600+n2)+v(601+n2)
vo=vo+v(602+n2)
vo=vo/3
vo=voXv27
v(350+n1)=vo+v(500+n1)
vo=v(608+n2)
vo=voXv27
v(425+n1)=vo+v(500+n1)

→10,n1=n4
n1=n1+1
→16
2)n3=0
13)n12=75Xn3
vo=12Xv(22+n3)
vo=voXv(18+n3)
vo=voXv31
vo=voXv(10+n3)
vo=voXv(10+n3)
v1=v(40+n3)Xv30
v1=v1Xv35
v1=v1Xv35
v(50+n3)=v1/vo
vo=1+v(50+n3)
vo=2Xvo

v56=vo/v(50+n3)
```

```
v0=v(50+n3)-1
v0=2Xv0
v57=v0/v(50+n3)
n7=v31
n8=v32
n9=n4Xn7
n9=n9+1
n6=1
v0=v29-v(200+n12)
v55=v0/v35
v0=v35+1
n14=v0
n13=0
15)v1=n13
v0=v1Xv55
v(80+n13)=v(200+n12)+v0
n13=n13+1
>15,n13≠n14
v120=0
v121=1
v161=0
14)n0=n6/n7
n15=n0Xn7
n17=n15+n7
n16=n6*n7
v0=n16/n7
n0=n12+n15
v1=v(200+n0)
n0=n12+n17
v2=v(200+n0)-v1
v2=v0Xv2


v80=v1+v2
v160=v80
n13=2
17)v0=v56Xv(119+n13)
v(120+n13)=v0-v(118+n13)
v0=v57Xv(79+n13)
v0=v0-v(80+n13)
v58=v0-v(78+n13)
v0=v56Xv(159+n13)
v0=v0-v(158+n13)
v(160+n13)=v0+v58
n13=n13+1
```

```
→17,n13≠n14
vo=v29-v(159+n13)
v81=vo/v(119+n13)

n13=3
18)vo=v(119+n13)xv81
v(79+n13)=vo+v(159+n13)
n13=n13+1
→18,n13≠n14
vo=25xv(79+n14)
v1=-48xv(78+n14)
vo=vo+v1
v1=36xv(77+n14)
vo=vo+v1
v1=-16xv(76+n14)
vo=vo+v1
v1=3xv(75+n14)
vo=vo+v1
vo=voxv35
v1=12xv(10+n3)

no=4xn6
no=no+n3
v(600+no)=vo/v1
n6=n6+1
→14,n6≠n9
n3=n3+1
→13,n3≠4
→10
3)no=1
TEXT
n6=0
4)vo=v30/v31
19)no=4xn6
v1=n6
v1=v1xvo
PRINTv1,3061

PRINTv(600+no),4101
PRINTv(601+no),4061
PRINTv(602+no),4061
PRINTv(603+no),4061
n6=n6+n8
→19,n9≥n6
→10
```

```
(>10)
T844.7
1080 --0 .
16775344
T846.6
6684 --0
16775343
 41 -00
16774433

T805.6
840 -70 .
49
T840.3
 72 3723
3.4 060
  3 470
  1 141
  3 471
  0
 27 3723
3.4 060
840 -30
16777178

L

ALTER9,54
n1=n1+1
ALTER9,55
>16,n1≠n4
ALTER9,56
>10
ALTER9,76
>32
```

```
32)no=n4-1
n9=noxn7
→33
ALTER9,77
33)n9=n9+1

ALTER13,12
SPv56=vo/v(50+n3)
ALTER13,15
SPv57=vo/v(50+n3)
ALTER13,21
vo=v(60+n3)-v(200+n12)
ALTER17,10
vo=v(60+n3)-v(159+n13)

ALTER14,1
n15=no
ALTER14,2
n17=n15+1
ALTER10,2
XPn4=no/12
ALTER18,18
XPn6=n6+1
ALTER18,20
SPn3=n3+1

5)no=2
TEXT
n19=v33
n20=v34
n3=0
v72=0
30)vo=v31x12
vo=voxv26
vo=voxv28
v1=v30xv(14+n3)
v1=v1xv(40+n3)
v2=v1/vo
n6=n19
v(64+n3)=0
31)no=4xn6
no=no+n3
v(64+n3)=v(64+n3)+v(600+no)
n6=n6+1
→31,n6≠n20
```

```
v(68+n3)=v(64+n3)xv2
PRINTv(68+n3),4024
v72=v72+v(68+n3)
n3=n3+1
→30,n3≠4
PRINTv72,4064
→10

(→10)
N
LG (X6)
J755.0-846.7
  →A X42.0
LL
ALTER9,80
→34
34)v(600+n3)=-v0/v(10+n3)
v55=v0/v35
→35
ALTER9,81
35)v0=v35+1
ALTER9,135
v(600+n0)=-v0/v1

(→9)


N
QQ

→A

ALTER3
46)n0=1
3)n8=v32
n7=v31
n0=n4-1
n9=n0xn7
→46
(→10)

N
REGRESSION MK1

→10
```

```
X805.6+
 54
J755.0-847.0
  TL v29
  CS *
 CST →7
  P≠ *
 P≠3 v599
LL

→A

7)PRINTv29,1023
n1=v29
n0=n1*3
→60,n0=0
STOP
SIXWAYS
60)n1=n1/3
n2=0
61)n3=v599
→62,n2≠3
n3=4
62)n7=n4-n1
n5=75Xn2
n5=200+n5
n6=n1Xn3
n6=n6+n2
n6=n6+600
n0=0
v44=n7
v45=0
v46=0
v47=0
v48=0
v49=0

63)v45=v45+vn5
v46=v46+vn6
v0=vn5Xvn5
v47=v47+v0
v0=vn5Xvn6
v48=v48+v0
v0=vn6Xvn6
```

```
v49=v49+v0
n0=n0+1
n5=n5+1
n6=n6+n3
→63,n0≠n7

v0=v45Xv45
v1=v44Xv47
v47=v1-v0
v0=v45Xv46
v1=v44Xv48
v48=v1-v0
v0=v46Xv46
v1=v44Xv49
v49=v1-v0
v0=v47Xv49
v0=1/v0
v0=SQRTv0
v0=v0Xv48
v0=ARCSINv0
v0=TANv0
v1=v44-2
v2=SQRTv1
v0=v0Xv2
PRINTv0,4062
PRINTv1,4040

n2=n2+1
→61,n2≠4
→10

(→10)

P≠3 8

N
PHASESWITCH MK1
→A
52)n12=75Xn3
→50
ALTER13,1
50)v0=12Xv(22+n3)
ALTER18,20
51)n3=n3+1
55)v0=v31X12
```

```
→53
ALTER30,1
53)v0=v0×v26
ALTER31,8
54)n3=n3+1
(→10,2392)

0.3 110
5.4 100
115 2701
5.7 110
5.5 010
0.3 100
J2392-13
```

```
 52 740
124 370
 15 600
  1 6521
5.5 662
 51 740
 14 640
 16 610
  0 1401
 16 110
 25 752
115 2707
  2 141
 34 103
  1 200
3.4 060

J2392-30
```

```
 55 740
I24 370
 I5 600
  I 652I
5•5 662
 54 740
 I4 640
 I6 6I0
  0 I40I
 I6 II0
 25 752
II5 2707
  2 I4I
 34 I03
  I 200
3•4 060

L
49)n3=v599
→47
ALTER6I,I
47)→62,n2≠3
ALTER63,32
48)n2=n2+I
(→I0
→I0)
J2392-6I
```

```
 49 740
124 270
 15 600
  1 6521
5.5 662
 48 740
 14 640
 16 610
  0 1401
 16 110
 25 752
115 2707
  2 141
 34 103
  1 200
3.4 060

L

N
M-C-THETA METHOD MK1

>A
ALTER9,89
>20

20)v0=v57Xv81
v0=v0-v80
XPv58=v0-v82
SPv122=v56

14)n0=n6/n7
n15=n0
n17=n15+1
n16=n6*n7
v0=n16/n7
n0=n12+n15
v1=v(200+n0)
n0=n12+n17
v2=v(200+n0)-v1
v2=v0Xv2
v80=v1+v2
SPv162=v58-v80
```

```
vo=v57Xv82
vo=vo-v83
XPv58=vo-v81
n13=3

17)vo=1/v(119+n13)
XPv(120+n13)=v56-vo
vo=v(159+n13)/v(119+n13)
SPv(160+n13)=vo+v58
vo=v57Xv(80+n13)
vo=vo-v(81+n13)
SPv58=vo-v(79+n13)
n13=n13+1
→17,n13≠n14

vo=v(60+n3)-v(159+n13)
XPv(78+n13)=vo/v(119+n13)
n13=n13-1

18)vo=v(79+n13)-v(159+n13)
v(78+n13)=vo/v(119+n13)
n13=n13-1
→18,n13≠2

vo=v(60+n3)-v(78+n14)
vo=voXv35
no=4Xn6
no=no+n3
v(600+no)=-vo/v(10+n3)
n6=n6+1
→20,n6≠n9
→51

(→10)

N
USE TSD IN REGRESSION
→A


ALTER49
n3=v31
ALTER61,1
n3=4Xn3
```

```
ALTER6,2
no=no
(→10)

N
LINEFIT MK1
→A
ALTER9,122
→59
59)vo=v(78+n14)-v(79+n14)
vo=-voxv35
→58
ALTER9,132
58)v1=v(10+n3)
(→10)

(COPY OF SIXCODE INTEREAD INSERTED HERE)

→A
ALTER14,2
n25=n15+1
ALTER14,3
n24=n6*n7
ALTER14,4
vo=n24/n7
ALTER14,7
no=n12+n25
ALTER9,162
n27=v34
ALTER9,171
n6=n26
ALTER9,177
→31,n6≠n27
ALTER9,161

n26=v33
(→10)

Z
```

Appendix 1.1

List of Indices and Variables used in LG

Variables

ν 0 to 9	Workspace
10, 11, 12, 13	Thickness of insulation for phases 0, 1, 2, 3
14, 15, 16, 17	Area for heat flow for phases 0, 1, 2, 3
18, 19, 20, 21	Density of insulation for phases 0, 1, 2, 3
22, 23, 24, 25	Heat capacity
26	Latent heat of methane H
27	E.m.f. constant CE
28	Level conversion factor CL
29	Time lag TL
30	DTS
31	TSD
32	TSP
33	TSB
34	TSE
35	DST
40, 41, 42, 43	Thermal conductivity for phases 0, 1, 2, 3
44	TSD($\equiv \nu 31$)
45, 46, 47, 48, 49	Intermediate sums used in regression calculation $\sum T, \sum G, \sum T^2, \sum GT, \sum G^2$
50, 51, 52, 53	Constant K for phases 0, 1, 2, 3
54	Outside wall temperature $T_{t,n}$
55	Temperature increase per integration step at time 0

Variables

56	K_1
57	K_2
58	γ_x
60,61,62,63	Aluminium tank temperatures for phases 0,1,2,3
80 - 119	T_0 to T_{39} Temperatures at each distance step
120 - 159	m_0 to m_{39} Constant, m, at each distance step
160 - 189	C_0 to C_{39} Constant, C, at each distance step
200 - 274	Average temperatures of outer shell for phase 0
275 - 349	Average temperatures of outer shell for phase 1
350 - 424	Average temperatures of outer shell for phase 2
425 - 499	Average temperatures of outer shell for phase 3
500 - 599	Reference junction temperatures
600 - 1369	E.m.f. readings and calculated temperature gradients

Indices

n0	Workspace
1	Time in data steps from start
2	12 x n1
3	Phase number
4	Total number of data steps + 1 (Equal to number of
5	dozens of e.m.f. readings)
6	Time in integration steps from start
7	TSD
8	TSP
9	Total number of integration steps + 1

Indices	
n 12	$75 \times n_3$
13	Number of distance steps from outside
14	Total number of distance steps in thickness + 1
15	Number of data steps up to last data step
16	Number of integration steps since last data step
17	Number of data steps up to next data step
19	TSB
20	TSE

APPENDIX 1.2

Data tape for step change test case



E.m.f.s(mV)	Time(hrs.)
	0
	3
	6
	9
	12
	15
	18
	21
	24
	27
	30
	33
	36
	39
	42
	45
	48
	51
	54
	57
	60
	63
	66
	69
	72
	75
	78

```
N
TEST CASE 1
STEP CHANGE

X   3   ===
BD   3   ===
CP 0.1   ===
K 0.16   ===
CE45.7
BP-260

YE
-0.22   ==== ==== ===
===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==

1.31   ===== ===== =
===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==

===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==

===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==

===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==
===== ===== ==

===== ===== ==
===== ===== ==
```

```
 =====  =====  ==
=====  =====  ==
=====  =====  ==

=====  =====  ==
L

R


40  ====  =====  =====
=====  =====  =====  =
L

Y
DTS3
DST5
TSD5
TSP10

Y?

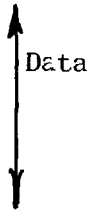
YQ

YBO

Z
```

APPENDIX 1.3

Data tape for linear change test case



E.m.f.s(mV)	Time(hrs.)
	0
	3
	6
	9
	12
	15
	18
	21
	24
	27
	30
	33
	36
	39
	42
	45
	48
	51
	54
	57
	60
	63
	66
	69
	72
	75
	78
	81

```
N
TEST CASE 2
LINEAR CHANGE

 X2.875  ===
BD  3.5  ===
CP  .13  ===
 K 0.18  ===
CE 45.7
BP -260

YE
-.33   ==== ===== ==
-.28   ==== ===== ==
-.23   ==== ===== ==
-.18   ==== ===== ==
-.13   ==== ===== ==

-.08   ==== ===== ==
-.03   ==== ===== ==
 .02   ==== ===== ==
 .07   ==== ===== ==
 .12   ==== ===== ==

 .17   ==== ===== ==
 .22   ==== ===== ==
 .27   ==== ===== ==
 .32   ==== ===== ==
 .37   ==== ===== ==

 .42   ==== ===== ==
 .47   ==== ===== ==
 .52   ==== ===== ==
 .57   ==== ===== ==
 .62   ==== ===== ==

 .67   ==== ===== ==
 .72   ==== ===== ==
 .77   ==== ===== ==
 .82   ==== ===== ==
 .87   ==== ===== ==
 .92   ==== ===== ==
 .97   ==== ===== ==
1.02   ==== ===== ==
```

```
I.07  ==== ===== ==
I.12  ==== ===== ==

I.17  ==== ===== ==
I.22  ==== ===== ==
I.27  ==== ===== ==
I.32  ==== ===== ==
I.37  ==== ===== ==

I.42  ==== ===== ==
I.47  ==== ===== ==
I.52  ==== ===== ==
I.57  ==== ===== ==
I.62  ==== ===== ==

I.67  ==== ===== ==
I.72  ==== ===== ==
I.77  ==== ===== ==
I.82  ==== ===== ==
I.87  ==== ===== ==

I.92  ==== ===== ==
I.97  ==== ===== ==
2.02  ==== ===== ==
2.07  ==== ===== ==
2.12  ==== ===== ==

2.17  ==== ===== ==
2.22  ==== ===== ==
2.27  ==== ===== ==
2.32  ==== ===== ==
2.37  ==== ===== ==

2.42  ==== ===== ==
2.47  ==== ===== ==
2.52  ==== ===== ==
2.57  ==== ===== ==
2.62  ==== ===== ==

2.67  ==== ===== ==

L

YR
   45 v==== ===== ======
```

```
 =====  =====  =====
=====  =====  =====
=====  =====  =====
=

L

Y
DTS 3
DST10
TSD10
TSP50

Y?

YQ

Z
```

APPENDIX 1.4

Data tapes for runs 1 to 6

Time (hrs.)	E.m.f.s of thermocouples (mV 100)											
	1	2	3	4	5	6	7	8	9	10	11	12
0												
3												
6												
9												
12												
15												
18												
21												
24												
27												
30												
33												
36												
39												
42												
45												
48												
51												
54												
57												
60												
63												
66												
69												
72												
75												
78												
81												

N
E/R RUN1

E

→n

21	18	17	19	16	15	0	16	0	15	16	12
11	6	2	3	8	5	0	5	0	5	5	6
-9	-9	-9	-9	-10	-9	-9	-10	-8	-9	-10	-8
-8	-7	-6	-6	-7	-8	-8	-8	-5	-8	-8	-5
-4	-3	-3	-3	-4	-3	0	-4	-3	-3	-4	-3
1	1	2	2	1	0	0	0	0	0	0	0
12	12	19	18	13	13	0	13	0	13	13	12
37	72	52	33	33	58	0	33	2	58	33	38
47	40	34	34	38	37	0	37	4	37	37	33
17	16	14	13	13	13	0	13	4	13	13	15

→v

5	9	8	8	5	6	0	5	4	6	5	9
1	2	2	2	2	2	0	2	2	2	2	4
3	3	3	3	3	3	0	3	3	3	3	8
3	3	3	3	3	3	7	3	3	3	4	
=10	10	10	10	10	10	0	10	3	10	10	8

→n

24	24	24	23	23	22	0	22	4	22	22	24
32	29	27	27	27	27	0	27	4	27	27	27
32	17	16	15	28	18	0	18	4	18	18	17
4	4	4	3	3	3	0	3	0	3	3	5
-3	-3	-3	-4	-4	-4	0	-4	-3	-4	-4	-3
-2	-2	-2	-3	-3	-3	0	-3	-2	-3	-3	-2
-1	-1	-1	-2	-2	-2	0	-2	-1	-2	-2	-1
13	24	173	19	13	21	0	21	-1	21	21	29
27	54	63	29	26	44	0	26	0	44	26	36
46	62	37	36	42	51	0	42	2	51	42	31
20	18	12	12	18	17	0	17	2	17	17	13
-2	-2	-2	-3	-3	-3	0	-3	-2	-3	-3	-2
-2	-2	-2	-2	-2	-2	0	-2	-2	-2	-2	0

3	4	4	4	4	4	0	4	0	4	4	4
6	6	6	6	6	6	0	6	2	6	6	6
21	21	28	26	22	21	0	21	4	21	21	21
18	18	18	8	16	16	9	17	8	16	10	14
14	14	14	7	14	14	8	13	7	14	9	12
10	10	10	7	10	10	8	10	6	7	7	10
4	4	4	4	3	3	4	3	2	2	2	4
-1	-1	-1	-1	-1	-2	0	-3	-3	-5	-5	0
-6	-6	-6	-3	-4	-4	-3	-4	-5	-7	-7	-2
-8	-8	-8	-3	-4	-5	-4	-6	-6	-7	-7	-1
13	14	20	-1	9	11	1	13	0	16	19	8
22	22	22	3	21	21	2	23	2	22	25	12
18	19	23	4	17	17	4	19	3	16	18	16
12	11	12	4	10	10	3	11	0	7	9	11
3	3	2	2	2	1	1	1	1	0	0	3
-3	-3	-3	-2	-2	-2	-2	-1	-3	-4	-4	-3
-3	-3	-5	-4	-5	-4	-3	-9	-7	-8	-8	-2
-6	-6	-7	-3	-5	-6	-4	-9	-8	-9	-9	-3
2	9	21	-4	0	7	0	1	-5	9	12	0
40	128	99	-4	31	97	-1	30	-3	97	96	10
56	40	33	-3	42	39	-2	13	-1	33	31	2
-2	-2	-2	-2	-2	-2	-2	-2	-3	-3	-3	-2
-2	-2	-2	-2	-3	-3	-3	-3	-3	-4	-4	-1
-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-5	-5

→v

L

R

→n

42	42	42	43	43	43	42	43	43	44	44	44
44	44	44	45	45	46	46	46	46	45	46	46
48	48	49	47	47	47	47	48	49	50	52	50
50	50	50	50	50	50	50	52	51	51	51	51
52	52	52	52								

→v

```
L
Y

     A 2305    6310    2160    2205
    BD  3.5    3.75    4.0    70.0
    CE  .457
    CL 4280
    CP 0.13    0.13    0.13    0.20
     X  4.6   2.875   2.875   4.875
     H2 19.5

BP  -244   -254   -248   -247
K   0.18   0.18   0.18    1.0
DST 10
TSD  1
TSB 11
TSE 44
TSP  1
n ? Q BO PAGE Z
```

N
RUN 2

E

→n

16	15	14	6	13	12	3	11	2	7	8	9
-1	-1	-1	-1	-1	-2	-2	-3	-3	-3	-3	0
-11	-11	-13	-4	-10	-11	-5	-15	-11	-17	-17	-9
-15	-15	-19	-9	-16	-17	-9	-22	-13	-20	-22	-13
-15	-15	-15	-10	-13	-14	-10	-18	-13	-16	-16	-14
-4	-4	0	-6	-5	-5	-2	-6	-6	-6	-4	-4
11	11	24	-4	7	7	0	16	0	20	22	5
53	53	26	4	47	40	1	17	6	37	38	16
19	13	6	5	16	10	4	1	1	1	0	6
-3	-3	-10	-1	-2	-2	-1	-10	-3	-8	-12	0
-12	-13	-17	-6	-14	-15	-6	-18	-9	-20	-22	-10
-11	-12	-12	-9	-10	-10	-7	-14	-11	-13	-13	-10
-4	-4	-5	-5	-5	-5	-5	-8	-8	-8	-8	-4
4	7	29	-1	0	6	0	3	0	10	14	4
19	30	43	2	17	21	3	19	4	28	34	8
17	17	19	6	13	13	6	13	5	12	13	10
13	3	0	0	7	2	0	-1	-2	-2	-3	0
-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
-3	-3	-4	-4	-4	-5	-4	-5	-5	-5	-5	-2
-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
-12	-12	-12	-10	-10	-10	-9	-10	-10	-15	-17	-10
-3	10	110	-7	-7	2	-1	-3	-5	12	32	-1
8	35	35	-2	7	18	0	2	0	28	39	-1
24	48	22	2	20	22	2	2	0	18	18	4
16	13	4	2	12	7	2	0	0	0	-1	1
-12	-12	-16	-6	-13	-14	-3	-11	-9	-19	-27	-10
-14	-15	-18	-9	-17	-18	-6	-14	-11	-21	-28	-12
-15	-15	-19	-9	-16	-17	-6	-20	-11	-21	-23	-13
-16	-16	-15	-11	-12	-13	-9	-16	-13	-19	-19	-16
3	6	21	-7	2	2	-1	3	-2	4	9	3
19	45	50	0	14	32	2	21	6	34	38	9
7	7	16	3	3	3	2	10	3	7	10	7
1	1	1	1	0	0	0	0	0	0	0	1

```
  2     2     2     2     2     2     2     2     2     2     2     2
  3     3     3     3     3     3     3     3     3     3     3     3
  6     5     5     4     4     4     4     3     3     3     3     6

  6     6     5     5     5     4     4     3     3     4     5     6
  9     9    10     8     8     7     6     5     6     8     9     9
 13    14    19     6    12    12     9    16     7    16    19    13
→v
L

R
→n
 52    52    54    52    52    50    51    52    53    53    52    52
 50    50    51    51    52    52    51    51    50    49    49    50
 50    50    50    49    48    47    48    49    49    50    50    50
 50    50    50
→v
L

BP   -178   -236   -251   -250
K    0.18   0.18   0.18    1.0
DST  10
TSD   1
TSB  21
TSE  37
TSP   1

n ? Q BO PAGE Z
```

N
RUN3

E
→n

50	64	46	17	45	58	16	36	20	57	55	39
63	47	32	22	50	42	20	27	19	23	23	28
3	3	3	11	6	2	8	12	8	-4	-4	10
-13	-13	-13	3	-9	-13	7	-9	-2	-26	-26	0
-13	-15	-15	-2	-9	-17	2	-11	-9	-24	-23	-11
-14	-14	3	0	-11	-14	-1	-8	-8	-17	-17	-13
9	39	89	0	6	32	1	11	3	47	53	9
27	87	52	2	20	87	3	14	5	71	67	8
116	62	18	3	79	58	3	7	3	48	33	4
116	9	4	3	82	12	2	6	1	1	0	0
-6	-6	-6	-2	-6	-7	-1	-8	-5	-13	-13	-1
-19	-20	-23	-6	-19	-21	-1	-20	-10	-29	-31	-12
-17	-17	-22	-7	-18	-18	-4	-21	-11	-22	-25	-12
-12	-12	-10	-10	-13	-13	-4	-10	-9	-13	-13	-10
3	28	122	-6	2	19	1	3	-1	30	44	2
33	140	97	3	29	92	1	24	7	90	91	19
52	145	52	10	76	102	9	33	12	86	73	29
64	46	27	12	50	39	11	20	9	19	19	21
-1	-1	-1	1	-1	-2	-4	1	1	-5	-4	1
-14	-14	-16	-2	-12	-13	0	-12	-10	-20	-20	-12
-10	-10	-15	-4	-11	-11	-1	-16	-9	-17	-18	-7
-12	-12	-12	-7	-10	-11	-3	-11	-10	-14	-14	-11
2	2	2	-2	-2	-2	-2	-2	-6	9	9	-4
17	16	15	-1	10	10	0	4	0	13	13	2
31	29	18	-2	19	20	0	7	-2	22	21	-1
61	4	1	-2	41	4	0	-2	-5	-5	-5	-5
-13	-13	-13	-8	-14	-14	-3	-14	-9	-18	-18	-6
-14	-14	-20	-9	-17	-17	-7	-22	-12	-23	-25	-12
-12	-12	-18	-9	-13	-14	-7	-19	-11	-17	-19	-11
-11	-10	0	-6	-12	-12	-9	-10	-10	-11	-10	-10
4	27	160	-5	3	18	0	8	-1	39	52	3
36	101	89	4	32	62	3	25	8	66	71	17
16	22	22	8	16	16	8	15	3	15	16	16
2	2	2	2	1	1	1	1	1	1	1	2

```
 -2   -2   -2   -2   -2   -3    0   -1   -2   -3   -3   -1
-12  -12  -12   -5   -8   -8   -5  -10  -10  -20  -19  -10

-21  -21  -22   -8  -18  -21   -5  -20  -12  -27  -27  -19
-18  -18  -18   -9  -13  -17   -6  -16  -14  -20  -19  -17
 10   16   17   -7    4    8   -2    2   -8   13   13   -7
 40   52   54   -5   31   36   -2   22   -5   58   62    6
 14   22   22   -2   12   13    1    8   -1   16   17    6
  7    9    9    0    7    7    3    5   -1    4    5    5

 -5   -5   -5   -4   -5   -5   -3   -4   -5   -5   -5   -5
-10  -11  -11   -8   -9  -10   -5   -7   -8  -13  -13   -9
-12  -12  -13   -9  -10  -11   -5  -11  -11  -17  -18  -10
 -8   -9   -9   -9   -9   -9   -8   -9   -9  -10  -10   -8
  9   32   89   -6    6   22   -1    8   -2   40   47    2
 14   19   19    0   10   12    2   11    1   23   23    9

 -7   -7   -7   -6   -5   -5   -4   -8   -8   -8   -8   -8
→v
L

R
→n
 47   50   50   50   49   48   48   48   48   50   49   48
 48   49   48   48   50   51   51   50   50   50   50   50
 50   49   49   49   49   48   48   48   50   49   49   49
 49   48   48   48   48   48   49   48   48   48   48   48
 48
→v
L

BP   -100   -172   -256   -254
K    0.18   0.18   0.18    1.0

DST 10
TSD  1
TSB 20
TSE 44
TSP  1

n ? Q BO PAGE Z
```

N
RUN4

E
→n

0	1	6	1	-2	1	1	-1	-4	0	0	1
26	58	45	1	19	43	1	16	2	49	49	1
25	33	24	1	20	29	1	15	5	28	28	1
2	2	2	1	2	2	1	1	1	1	1	1
0	0	0	1	0	0	1	0	0	0	0	1
-11	-12	-12	1	-7	-8	1	-8	-8	-17	-17	1
-20	-20	-20	1	-18	-20	1	-19	-13	-30	-30	1
-13	-12	-12	1	-12	-12	1	-12	-12	-12	-12	1
8	30	51	1	7	26	1	9	1	40	41	1
32	58	31	1	25	46	1	14	2	50	48	1
26	26	20	1	19	19	1	13	3	19	19	1
16	14	11	1	11	9	1	5	1	2	2	1
-3	-3	-3	1	-3	-3	1	-3	-3	-7	-7	1
-17	-17	-17	1	-12	-14	1	-16	-10	-28	-28	1
-14	-14	-14	1	-10	-13	1	-14	-12	-22	-21	1
-12	-12	31	1	-11	-12	1	-1	-6	-16	-10	1
13	39	108	1	11	35	1	14	0	65	73	1
42	96	68	1	33	71	1	23	1	86	84	1
33	72	29	1	93	69	1	16	3	62	48	1
78	27	21	1	57	24	1	14	2	10	10	1
1	1	-2	1	-1	-1	1	-2	-2	-5	-6	1
-2	-3	-2	1	-2	-3	1	-1	-3	-8	-11	1
-11	-11	-12	1	-7	-12	1	-10	-10	-23	-23	1
-8	-9	-3	1	-6	-6	1	-7	-7	-9	-9	1
2	3	2	1	0	0	1	0	-2	1	1	1
-1	-1	-1	1	-2	-1	1	-2	-5	-4	-4	1
2	3	3	1	2	3	1	2	-2	2	2	1
0	1	0	1	-2	-1	1	-2	-2	-5	-4	1
-8	-8	-8	-8	-8	-8	-7	-8	-8	-9	-9	1
-11	-11	-11	-10	-11	-11	-9	-10	-10	-13	-13	-10
-13	-13	-13	-10	-11	-13	-10	-13	-12	-20	-20	-12
-10	-10	-9	-9	-10	-10	-9	-10	-10	-10	-10	-10
9	10	24	-6	7	7	1	9	-4	2	8	3
27	27	27	-3	22	37	0	27	-3	54	58	2

```
 10   11   24   -3    9    9    3   17   -1   12   18    6
 23   20   17    2   18   16    3    9    0    2    3    3

 -2   -2   -2   -2   -2   -2   -3   -2   -3   -9  -11    0
 -7   -7   -9   -8   -9   -9   -4  -10  -10  -10  -10   -7
 -7   -7   -7   -7   -7   -7   -6   -7   -7   -7   -7   -7
 -5   -5   -5   -5   -5   -5   -5   -5   -5   -5   -5   -5
 12   26  118   -2   12   22    2   24    0   34   49    9
 49  136  136    4   42   61    3   47    6  125  126   24

 66   60   43    5   56   55    7   37    8   55   56   20
 13   14   14    7   10   10    9   10    6    8   12   12
  5    5    5    5    5    5    5    5    4    4    3    7
 -3   -3   -7   -1   -2   -3   -1   -5   -4   -8   -9    0
 -4   -5   -9   -4   -5   -5   -3   -9   -7  -10  -10   -3
 -8   -8   -3   -3   -5   -5   -4   -5   -5   -8   -8   -8

  3   21  141   -3    3   18    2   17   -3   39   58    1
 49   91  109    0   43   66   -2   44    1   83   88   18
 79   79   64    8   67   66    4   48    9   68   67   26
 44   39   38   11   39   36    8   27   12   21   21   24
 11   11   11   10   10   10    9    8    6    6    6   11
  4    3    2    3    3    3    3    2    1    1    1    5

  2    2    1    2    2    2    1    0   -1   -1   -1    3
  2    2    2    1    1    1    1    1   -2    0    0    2
 22   23   31    0   19   19    3   20   -1   34   29    9
→υ
L

R
→n
 44   44   46   46   45   45   44   44   44   44   45   46
 45   45   45   45   44   44   44   46   47   47   46   46
 46   46   46   46   45   45   44   44   44   44   45   46
 45   45   44   44   44   45   47   48   47   47   47   47
 47   47   48   50   50   50   50   50   50
→υ
L

BP   -62  -113  -243  -257
K   0.18  0.18  0.18   1.0

DST 10
```

```
TSD  I
TSB 29
TSE 47
TSP  I

n ? Q BO PAGE Z
```

N
RUN 5

E
→n

33	72	29	1	93	69	1	16	3	62	48	1
78	27	21	1	57	24	1	14	2	10	10	1
1	1	-2	1	-1	-1	1	-2	-2	-5	-6	1
-2	-3	-2	1	-2	-3	1	-1	-3	-8	-11	1
-11	-11	-12	1	-7	-12	1	-10	-10	-23	-23	1
-8	-9	-3	1	-6	-6	1	-7	-7	-9	-9	1
2	3	2	1	0	0	1	0	-2	1	1	1
-1	-1	-1	1	-2	-1	1	-2	-5	-4	-4	1
2	3	3	1	2	3	1	2	-2	2	2	1
0	1	0	1	-2	-1	1	-2	-2	-5	-4	1
-8	-8	-8	-8	-8	-8	-7	-8	-8	-9	-9	1
-11	-11	-11	-10	-11	-11	-9	-10	-10	-13	-13	-10
-13	-13	-13	-10	-11	-13	-10	-13	-12	-20	-20	-12
-10	-10	-9	-9	-10	-10	-9	-10	-10	-10	-10	-10
9	10	24	-6	7	7	1	9	-4	2	8	3
27	27	27	-3	22	37	0	27	-3	54	58	2
10	11	24	-3	9	9	3	17	-1	12	18	6
23	20	17	2	18	16	3	9	0	2	3	3
-2	-2	-2	-2	-2	-2	-3	-2	-3	-9	-11	0
-7	-7	-9	-8	-9	-9	-4	-10	-10	-10	-10	-7
-7	-7	-7	-7	-7	-7	-6	-7	-7	-7	-7	-7
-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
12	26	118	-2	12	22	2	24	0	34	49	9
49	136	136	4	42	61	3	47	6	125	126	24
66	60	43	5	56	55	7	37	8	55	56	20
13	14	14	7	10	10	9	10	6	8	12	12
5	5	5	5	5	5	5	5	4	4	3	7
-3	-3	-7	-1	-2	-3	-1	-5	-4	-8	-9	0
-4	-5	-9	-4	-5	-5	-3	-9	-7	-10	-10	-3
-8	-8	-3	-3	-5	-5	-4	-5	-5	-8	-8	-8
3	21	141	-3	3	18	2	17	-3	39	58	1
49	91	109	0	43	66	-2	44	1	83	88	18
79	79	64	8	67	66	4	48	9	68	67	26
44	39	38	11	39	36	8	27	12	21	21	24

11	11	11	10	10	10	9	8	6	6	6	11
4	3	2	3	3	3	3	2	1	1	1	5
2	2	1	2	2	2	1	0	-1	-1	-1	3
2	2	2	1	1	1	1	1	-2	0	0	2
22	23	31	0	19	19	1	20	-1	34	29	9
66	99	97	0	57	79	-1	51	0	100	100	13
71	52	47	1	56	53	1	26	6	46	47	15
53	26	24	4	38	27	4	13	4	15	15	13
3	2	3	2	2	2	2	2	0	1	0	3
-6	-5	-5	-4	-5	-5	-5	-4	-4	-11	-11	0
-15	-15	-16	-8	-4	-5	-8	-14	-12	-23	-23	-11
-14	-14	19	-8	-13	-14	-10	-4	-10	-7	-6	-10
12	34	164	-4	12	24	-4	29	-6	57	73	6
49	104	100	-1	41	98	-2	32	1	97	94	16
99	60	37	1	70	61	-1	20	4	47	44	10
53	19	16	2	33	22	2	4	2	5	6	7
1	1	1	1	1	1	1	1	6	-3	-3	4
-8	-8	-8	-7	-8	-8	-6	-6	-6	-10	-9	-1
-13	-13	-13	-9	-11	-11	-6	-10	-10	-18	-18	-9
-12	-12	-12	-9	-10	-10	-8	-10	-10	-14	-14	-11
11	29	104	-6	11	26	-2	23	-6	46	58	3
44	76	79	-3	36	70	-3	23	1	78	73	7
113	70	37	1	82	71	-1	20	4	59	49	11
67	21	19	3	47	21	4	8	4	10	10	9
-1	-1	-1	-1	-2	-1	-1	-2	-2	-6	-6	0

>v
L

R
>n

44	46	47	47	46	46	46	46	46	46	45	45
44	44	44	44	45	46	45	45	44	44	44	45
47	48	47	47	47	47	47	47	48	50	50	50
50	50	50	51	51	52	52	52	52	52	51	52
54	54	54	54	54	52	52	53	53	54	55	

>v
L

BP	-58	-109	-238	-257
K	0.18	0.18	0.18	1.0

```
DST IO
TSD  I
TSB34
TSE 55
TSP  I

n ? Q BO PAGE Z
```

N
RUN6

E
→n

3	21	141	-3	3	18	2	17	-3	39	58	1
49	91	109	0	43	66	-2	44	1	83	88	18
79	79	64	8	67	66	4	48	9	68	67	26
44	39	38	11	39	36	8	27	12	21	21	24
11	11	11	10	10	10	9	8	6	6	6	11
4	3	2	3	3	3	3	2	1	1	1	5
2	2	1	2	2	2	1	0	-1	-1	-1	3
2	2	2	1	1	1	1	1	-2	0	0	2
22	23	31	0	19	19	3	20	-1	34	29	9
66	99	97	0	57	79	-1	51	0	100	100	13
71	52	47	1	56	53	1	26	6	46	47	15
53	26	24	4	38	27	4	13	4	15	15	13
3	2	3	2	2	2	2	2	0	1	0	3
-6	-5	-5	-4	-5	-5	-5	-4	-4	-11	-11	0
-15	-15	-16	-8	-4	-5	-8	-14	-12	-23	-23	-11
-14	-14	19	-8	-13	-14	-10	-4	-10	-7	-6	-10
12	34	164	-4	12	24	-4	29	-6	57	73	6
49	104	100	-1	41	98	-2	32	1	97	94	16
99	60	37	1	70	61	-1	20	4	47	44	10
53	19	16	2	33	22	2	4	2	5	6	7
1	1	1	1	1	1	1	1	6	-3	-3	4
-8	-8	-8	-7	-8	-8	-6	-6	-6	-10	-9	-1
-13	-13	-13	-9	-11	-11	-6	-10	-10	-18	-18	-9
-12	-12	-12	-9	-10	-10	-8	-10	-10	-14	-14	-11
11	29	104	-6	11	26	-2	23	-6	46	58	3
44	76	79	-3	36	70	-3	23	1	78	73	7
113	70	37	1	82	71	-1	20	4	59	49	11
67	21	19	3	47	21	4	8	4	10	10	9
-1	-1	-1	-1	-2	-1	-1	-2	-2	-6	-6	0
-10	-10	-10	-6	-7	-8	-5	-7	-6	-13	-13	-6
-18	-18	-18	-8	-14	-16	-7	-16	-12	-27	-26	-14
-10	-13	-3	-4	-12	-13	-7	-8	-9	-11	-10	-10
9	28	111	-4	8	23	-3	17	-2	39	44	3
36	64	63	-2	27	70	-1	18	2	67	66	10

```
101   60   32    1   72   59    0   16    3   49   41    8

 27   21   19    2   17   18    3   11    3   11   11   11
  0    0    0    0    0   -1    0    0   -1   -2   -2    1
 -4   -4   -4   -4   -4   -5   -3   -4   -4   -7   -7   -2
 -7   -7   -6   -6   -6   -7   -5   -6   -6  -11  -11   -3
 -1   -1    0   -2   -2   -2   -2   -2   -5   -5   -2   -1
 19   19   29   -1   13   18    0   10    2   20   21    4

 40   63   59   -2   30   57   -2   17    2   62   58    4
 28   24   24    3   19   21    1   10    4   21   21   10
 22   21   20    3   16   17    3   11    3   13   13   13
  5    6    6    4    5    5    5    2    2    3    4    5
  1    1    1    1    1    1    1   -3   -3   -5   -5    2
 -9   -9   -9   -5   -7   -7   -5   -8   -7  -10  -10   -4

-11  -11  -10   -6   -7   -8   -6   -8   -8  -17  -16   -7
 11   34  142   -3   11   27   -2   24   -2   51   59    3
 31   57   56   -3   22   58   -3    8   -1   61   58    2
100   61   26    0   67   71    1   13    4   52   42    8
 88   28   16    6   59   30    2    9    5   12   12   12
 -3   -3   -3   -2   -3   -4   -2   -4   -3   -9   -9   -2

 -4   -4   -3   -2   -3   -4   -2   -3   -3   -6   -6    0
 -7   -8   -7   -7   -7   -8   -7   -8   -8  -10  -10   -6
 -8   -8   -8   -8   -8   -8   -8   -8   -8   -9   -9   -9
  8    8   22   -6    4    9   -1    2   -2   12   12    0
 29   27   23   -3   17   31   -4    7   -1   27   27    0
 49   28   23    1   33   33    0   13    4   31   30    1

 18   12   12    2   10   10    3    3    2    4    5    5
 -2   -2   -2   -2   -2   -2   -1   -2   -2   -2   -2   -1
→v
L

R
→n
 47   47   48   50   50   50   50   50   50   51   51   52
 52   52   52   52   51   52   54   54   54   54   54   52
 52   53   53   54   54   55   54   53   53   53   54   54
 54   54   54   54   54   55   55   56   56   56   56   55
 55   56   56   56   58   58   57   56   56   56   56   57
 58
→v
L
```

```
BP    -54   -109   -241   -257
K    0.18  0.18  0.18   1.0

TSD   1
DST  10
TSB  39
TSE  55
TSP   1

n ? Q BO PAGE Z
```

APPENDIX 1.5

Calculated mean outer shell temperatures for runs 1 to 6

Time (hrs.)	Phase 0	1	2	3

RUN 1

AVERAGE TEMPERATURES (DEG F)

0.0	49	49	51	42
3.0	44	45	45	42
6.0	38	38	38	38
9.0	39	39	40	41
12.0	41	41	41	42
15.0	43	43	44	43
18.0	48	48	49	42
21.0	64	62	68	44
24.0	60	60	61	45
27.0	50	50	51	46
30.0	47	46	47	46
33.0	45	45	45	45
36.0	45	45	45	45
39.0	46	45	45	45
42.0	49	49	49	45
45.0	55	55	56	47
48.0	57	57	58	47
51.0	54	56	56	48
54.0	47	47	48	46
57.0	44	44	45	45
60.0	45	45	45	45
63.0	44	44	45	45
66.0	56	54	78	46
69.0	62	61	68	46
72.0	69	69	70	49
75.0	56	56	56	49
78.0	48	48	48	48
81.0	46	46	46	46
84.0	49	49	49	47
87.0	50	50	50	48
90.0	57	57	58	49
93.0	54	55	56	52
96.0	54	55	55	52
99.0	53	55	55	53
102.0	53	53	54	53
105.0	48	49	50	49
108.0	47	48	47	48
111.0	47	48	46	47
114.0	58	55	57	50
117.0	61	60	60	51

120.0	58	58	59	51
123.0	54	55	55	50
126.0	50	51	51	50
129.0	50	51	51	51
132.0	47	48	49	48
135.0	47	48	48	47
138.0	56	52	56	49
141.0	95	75	92	50
144.0	67	66	72	52
147.0	51	51	51	51
150.0	50	51	51	51
153.0	49	49	50	49

RUN 2

AVERAGE TEMPERATURES (DEG F)

0.0	55	57	59	53
3.0	51	51	52	51
6.0	46	49	49	49
9.0	42	44	45	46
12.0	45	45	45	46
15.0	48	48	49	47
18.0	61	56	58	51
21.0	69	68	72	55
24.0	53	57	59	53
27.0	48	51	51	52
30.0	42	45	46	48
33.0	46	47	47	47
36.0	46	47	48	46
39.0	55	51	56	50
42.0	65	60	65	53
45.0	57	57	59	53
48.0	51	53	54	51
51.0	51	51	51	51
54.0	49	49	49	49
57.0	49	49	49	49
60.0	43	45	45	45
63.0	59	48	67	47
66.0	64	53	61	49
69.0	58	57	64	50
72.0	50	53	55	50
75.0	39	44	44	46
78.0	39	43	43	45
81.0	39	41	42	44
84.0	39	42	41	42
87.0	50	48	52	46
90.0	64	58	65	51
93.0	53	51	54	50
96.0	49	49	49	49
99.0	51	51	51	51
102.0	51	51	51	51
105.0	51	52	52	51
108.0	52	52	53	51
111.0	54	53	54	53
114.0	58	56	57	53

RUN 3

AVERAGE TEMPERATURES (DEG F)

0.0	44	44	45	42
3.0	66	56	64	45
6.0	59	56	58	48
9.0	46	47	47	46
12.0	45	45	45	45
15.0	37	41	40	41
18.0	30	35	35	38
21.0	39	39	38	39
24.0	63	50	58	44
27.0	66	57	62	45
30.0	54	53	56	46
33.0	47	50	52	46
36.0	42	44	44	44
39.0	32	39	37	40
42.0	35	39	39	40
45.0	39	41	46	42
48.0	76	53	68	44
51.0	83	63	75	44
54.0	69	71	64	45
57.0	51	60	65	47
60.0	44	46	47	46
63.0	43	46	46	46
66.0	35	42	41	41
69.0	42	43	43	43
72.0	46	46	47	45
75.0	44	45	46	44
78.0	47	47	47	45
81.0	44	45	46	45
84.0	41	41	41	41
87.0	39	40	40	40
90.0	35	38	38	39
93.0	39	39	40	39
96.0	46	48	51	42
99.0	70	57	56	43
102.0	52	50	52	45
105.0	47	53	55	46
108.0	40	44	44	44
111.0	40	41	41	40
114.0	41	41	41	41
117.0	42	42	42	42

120.0	63	53	68	44
123.0	102	68	94	48
126.0	72	70	73	51
129.0	53	53	54	51
132.0	49	49	49	49
135.0	43	45	45	45
138.0	42	44	44	44
141.0	43	45	44	45
144.0	69	53	72	46
147.0	86	70	85	47
150.0	79	76	82	52
153.0	60	66	68	55
156.0	53	54	55	53
159.0	50	51	51	50
162.0	50	51	51	50
165.0	50	50	51	49
168.0	64	59	62	50

RUN 4

AVERAGE TEMPERATURES (DEG F)

0.0	73	68	71	56
3.0	61	68	72	59
6.0	48	53	51	54
9.0	38	45	44	49
12.0	38	43	42	45
15.0	40	43	44	44
18.0	71	55	69	49
21.0	80	66	73	50
24.0	67	70	78	49
27.0	50	65	70	50
30.0	43	46	46	47
33.0	34	39	39	43
36.0	37	39	39	43
39.0	43	44	44	45
42.0	65	52	71	48
45.0	89	70	89	51
48.0	86	82	88	55
51.0	60	68	72	55
54.0	49	51	51	51
57.0	41	44	43	45
60.0	42	44	45	46
63.0	44	45	45	45
66.0	54	49	51	47
69.0	56	54	57	50
72.0	60	57	62	49
75.0	47	56	59	47
78.0	41	43	43	45
81.0	38	40	42	44
84.0	41	42	43	44
87.0	43	43	45	43
90.0	69	52	77	48
93.0	79	66	82	52
96.0	57	57	59	51
99.0	49	49	50	49
102.0	48	48	48	48
105.0	40	45	44	44
108.0	37	40	39	44
111.0	39	41	40	42
114.0	54	50	55	44
117.0	75	62	70	46

120.0	56	53	57	48
123.0	50	51	52	48
126.0	47	47	47	47
129.0	42	44	43	44
132.0	40	43	42	43
135.0	43	44	44	44
138.0	68	53	68	47
141.0	59	53	56	48
144.0	44	45	45	44

RUN 5

AVERAGE TEMPERATURES (DEG F)

0.0	69	71	64	45
3.0	51	60	65	47
6.0	44	46	47	46
9.0	43	46	46	46
12.0	35	42	41	41
15.0	42	43	43	43
18.0	46	46	47	45
21.0	44	45	46	44
24.0	47	47	47	45
27.0	44	45	46	45
30.0	41	41	41	41
33.0	39	40	40	40
36.0	35	38	38	39
39.0	39	39	40	39
42.0	46	48	51	42
45.0	70	57	56	43
48.0	52	50	52	45
51.0	47	53	55	46
54.0	40	44	44	44
57.0	40	41	41	40
60.0	41	41	41	41
63.0	42	42	42	42
66.0	63	53	68	44
69.0	102	68	94	48
72.0	72	70	73	51
75.0	53	53	54	51
78.0	49	49	49	49
81.0	43	45	45	45
84.0	42	44	44	44
87.0	43	45	44	45
90.0	69	53	72	46
93.0	86	70	85	47
96.0	79	76	82	52
99.0	60	66	68	55
102.0	53	54	55	53
105.0	50	51	51	50
108.0	50	51	51	50
111.0	50	50	51	49
114.0	64	59	62	50
117.0	97	79	91	51

120.0	72	72	77	54
123.0	59	64	68	54
126.0	52	53	53	52
129.0	47	50	50	50
132.0	41	48	45	47
135.0	49	47	51	47
138.0	81	61	83	48
141.0	96	78	91	52
144.0	75	77	84	56
147.0	57	63	67	55
150.0	53	54	54	57
153.0	50	51	50	51
156.0	46	49	48	49
159.0	46	47	47	47
162.0	76	61	74	49
165.0	88	73	83	53
168.0	78	79	87	55
171.0	59	66	70	56
174.0	52	54	55	54

RUN 6

AVERAGE TEMPERATURES (DEG F)

0.0	69	53	72	46
3.0	86	70	85	47
6.0	79	76	82	52
9.0	60	66	68	55
12.0	53	54	55	53
15.0	50	51	51	50
18.0	50	51	51	50
21.0	50	50	51	49
24.0	64	59	62	50
27.0	97	79	91	51
30.0	72	72	77	54
33.0	59	64	68	54
36.0	52	53	53	52
39.0	47	50	50	50
42.0	41	48	45	47
45.0	49	47	51	47
48.0	81	61	83	48
51.0	96	78	91	52
54.0	75	77	84	56
57.0	57	63	67	55
60.0	53	54	54	57
63.0	50	51	50	51
66.0	46	49	48	49
69.0	46	47	47	47
72.0	76	61	74	49
75.0	88	73	83	53
78.0	78	79	87	55
81.0	59	66	70	56
84.0	51	53	54	53
87.0	49	52	50	52
90.0	42	47	46	49
93.0	48	48	49	49
96.0	72	60	76	52
99.0	83	71	78	54
102.0	75	76	83	55
105.0	59	61	64	55
108.0	53	54	54	54
111.0	51	52	52	52
114.0	49	51	51	51
117.0	52	53	54	52

120.0	63	60	64	55
123.0	82	71	80	56
126.0	65	63	67	57
129.0	62	63	66	57
132.0	58	58	59	57
135.0	54	56	56	55
138.0	51	53	52	53
141.0	47	51	50	51
144.0	80	64	83	54
147.0	83	69	78	56
150.0	77	79	84	58
153.0	61	71	76	58
156.0	54	56	57	57
159.0	55	56	56	57
162.0	52	53	54	53
165.0	52	52	52	52
168.0	61	58	62	55
171.0	68	64	68	56
174.0	70	68	71	58
177.0	59	61	63	58
180.0	57	57	57	57

APPENDIX 1.6

Computer output for runs 1 to 6

Time (hrs.)	Calculated temperature gradients for phases			
	0	1	2	3

RUN 1

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG FFT)

0.0	63.7	105.4	103.8	59.3
3.0	63.7	105.4	103.8	59.3
6.0	63.7	105.4	103.8	59.3
9.0	63.7	105.4	103.8	59.3
12.0	63.7	105.4	103.8	59.3
15.0	63.7	105.3	103.7	59.3
18.0	63.7	105.2	103.6	59.3
21.0	63.7	105.0	103.4	59.3
24.0	63.7	104.9	103.3	59.3
27.0	63.7	104.8	103.1	59.3
30.0	63.7	104.7	103.1	59.3
33.0	63.6	104.8	103.1	59.3
36.0	63.6	104.9	103.2	59.3
39.0	63.6	105.0	103.3	59.3
42.0	63.6	105.1	103.4	59.3
45.0	63.6	105.1	103.4	59.3
48.0	63.6	105.1	103.4	59.3
51.0	63.6	105.1	103.4	59.3
54.0	63.6	105.1	103.4	59.3
57.0	63.6	105.2	103.4	59.3
60.0	63.6	105.3	103.5	59.3
63.0	63.6	105.4	103.6	59.3
66.0	63.6	105.4	103.6	59.3
69.0	63.6	105.5	103.6	59.3
72.0	63.6	105.5	103.7	59.3
75.0	63.6	105.4	103.7	59.3
78.0	63.6	105.5	103.8	59.3
81.0	63.6	105.6	104.1	59.3
84.0	63.6	105.8	104.3	59.3
87.0	63.6	106.0	104.6	59.3
90.0	63.7	106.1	104.8	59.3
93.0	63.7	106.2	104.8	59.3
96.0	63.7	106.2	104.9	59.3
99.0	63.7	106.2	104.8	59.3
102.0	63.8	106.2	104.8	59.3
105.0	63.8	106.3	104.8	59.3
108.0	63.8	106.3	104.9	59.3
111.0	63.8	106.4	104.9	59.3
114.0	63.9	106.5	104.9	59.3

117.0	63.9	106.5	104.9	59.3
120.0	63.9	106.5	104.8	59.3
123.0	63.9	106.4	104.8	59.3
126.0	64.0	106.5	104.7	59.3
129.0	64.0	106.5	104.7	59.3
132.0	64.0	106.6	104.8	59.3
135.0	64.0	106.6	104.8	59.3
138.0	64.0	106.7	104.9	59.3
141.0	64.0	106.7	104.9	59.3
144.0	64.1	106.7	104.9	59.3
147.0	64.1	106.7	104.9	59.3
150.0	64.1	106.7	104.9	59.3
153.0	64.1	106.8	105.1	59.3

BOIL-OFF (IN.) = 0.2321 1.0546 0.3555 1.1479

RUN 2

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG F/FT)

0.0	50.7	102.1	107.8	62.1
3.0	50.7	102.1	107.8	62.1
6.0	50.7	102.1	107.8	62.1
9.0	50.7	102.1	107.8	62.1
12.0	50.7	102.0	107.7	62.1
15.0	50.7	101.9	107.7	62.1
18.0	50.7	101.8	107.5	62.1
21.0	50.7	101.6	107.3	62.1
24.0	50.7	101.4	107.1	62.1
27.0	50.7	101.2	106.9	62.1
30.0	50.7	101.1	106.8	62.1
33.0	50.7	101.0	106.8	62.1
36.0	50.6	101.0	106.7	62.1
39.0	50.6	101.0	106.7	62.1
42.0	50.6	100.9	106.7	62.1
45.0	50.6	100.8	106.6	62.1
48.0	50.6	100.7	106.4	62.1
51.0	50.5	100.6	106.4	62.1
54.0	50.5	100.6	106.3	62.1
57.0	50.5	100.6	106.3	62.1
60.0	50.5	100.6	106.4	62.1
63.0	50.5	100.5	106.4	62.1
66.0	50.4	100.5	106.3	62.1
69.0	50.4	100.4	106.2	62.1
72.0	50.4	100.3	106.2	62.1
75.0	50.4	100.2	106.2	62.1
78.0	50.4	100.2	106.2	62.1
81.0	50.4	100.1	106.3	62.1
84.0	50.3	100.1	106.3	62.1
87.0	50.3	100.0	106.3	62.1
90.0	50.3	99.9	106.2	62.1
93.0	50.3	99.7	106.0	62.1
96.0	50.3	99.5	105.9	62.1
99.0	50.3	99.4	105.7	62.1
102.0	50.2	99.3	105.6	62.1
105.0	50.2	99.3	105.6	62.1

108.0	50.2	99.3	105.5	62.1
111.0	50.1	99.4	105.5	62.1
114.0	50.1	99.4	105.5	62.1

BOIL-OFF (IN.) = 0.0889 0.4833 0.1756 0.5834

RUN 3

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG F/FT)

0.0	37.5	83.5	113.9	63.6
3.0	37.5	83.5	113.9	63.6
6.0	37.5	83.5	113.9	63.6
9.0	37.5	83.5	113.9	63.6
12.0	37.5	83.5	113.8	63.6
15.0	37.5	83.4	113.7	63.6
18.0	37.5	83.2	113.6	63.6
21.0	37.5	82.9	113.2	63.6
24.0	37.5	82.5	112.8	63.6
27.0	37.4	82.1	112.4	63.6
30.0	37.4	81.7	112.1	63.6
33.0	37.3	81.4	111.9	63.6
36.0	37.2	81.3	111.7	63.6
39.0	37.1	81.1	111.6	63.6
42.0	37.0	81.0	111.5	63.6
45.0	36.9	80.7	111.2	63.6
48.0	36.8	80.3	110.9	63.6
51.0	36.7	80.0	110.6	63.6
54.0	36.6	79.7	110.4	63.6
57.0	36.5	79.6	110.4	63.6
60.0	36.4	79.7	110.6	63.6
63.0	36.3	79.8	110.7	63.6
66.0	36.2	79.9	110.8	63.6
69.0	36.1	79.8	110.8	63.6
72.0	36.0	79.7	110.6	63.6
75.0	35.9	79.5	110.4	63.6
78.0	35.8	79.3	110.1	63.6
81.0	35.8	79.1	109.9	63.6
84.0	35.7	79.0	109.7	63.6
87.0	35.6	78.8	109.5	63.6
90.0	35.5	78.7	109.3	63.6
93.0	35.4	78.4	109.0	63.6
96.0	35.3	78.2	108.8	63.6
99.0	35.2	78.0	108.6	63.6
102.0	35.1	77.9	108.5	63.6
105.0	35.0	77.8	108.6	63.6
108.0	34.9	77.8	108.7	63.6
111.0	34.8	77.8	108.7	63.6

114.0	34.8	77.8	108.7	63.6
117.0	34.7	77.7	108.6	63.6
120.0	34.6	77.6	108.4	63.6
123.0	34.5	77.4	108.2	63.6
126.0	34.5	77.3	108.0	63.6
129.0	34.4	77.3	107.9	63.6
132.0	34.3	77.3	107.9	63.6
135.0	34.3	77.3	107.8	63.6
138.0	34.2	77.3	107.8	63.6
141.0	34.1	77.2	107.7	63.6
144.0	34.1	77.1	107.5	63.6

BOIL-OFF (IN.) = 0.0937 0.5695 0.2714 0.8959

RUN 4

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG FFT)

0.0	23.0	54.5	100.2	61.4
3.0	23.0	54.5	100.2	61.4
6.0	23.0	54.5	100.2	61.4
9.0	23.0	54.5	100.2	61.4
12.0	23.0	54.6	100.3	61.4
15.0	23.0	54.7	100.4	61.4
18.0	23.1	54.8	100.6	61.4
21.0	23.1	55.0	100.7	61.4
24.0	23.1	55.0	100.8	61.4
27.0	23.1	55.0	100.8	61.4
30.0	23.1	55.0	100.7	61.4
33.0	23.1	55.0	100.7	61.4
36.0	23.2	55.0	100.7	61.4
39.0	23.2	55.0	100.8	61.4
42.0	23.2	55.1	100.9	61.4
45.0	23.2	55.2	101.0	61.4
48.0	23.2	55.3	101.1	61.4
51.0	23.3	55.3	101.1	61.4
54.0	23.3	55.2	101.1	61.4
57.0	23.3	55.2	101.1	61.4
60.0	23.3	55.3	101.2	61.4
63.0	23.3	55.5	101.4	61.4
66.0	23.4	55.7	101.7	61.4
69.0	23.4	56.0	102.0	61.4
72.0	23.4	56.2	102.3	61.4
75.0	23.5	56.4	102.4	61.4
78.0	23.5	56.4	102.4	61.4
81.0	23.6	56.4	102.4	61.4
84.0	23.6	56.3	102.3	61.4
87.0	23.7	56.2	102.2	61.4
90.0	23.7	56.1	102.0	61.4
93.0	23.7	56.0	101.9	61.4
96.0	23.7	55.9	101.7	61.4
99.0	23.8	55.7	101.5	61.4
102.0	23.8	55.6	101.3	61.4
105.0	23.7	55.4	101.2	61.4
108.0	23.7	55.3	101.0	61.4
111.0	23.7	55.3	101.0	61.4

114.0	23.7	55.4	101.0	61.4
117.0	23.7	55.4	101.0	61.4
120.0	23.7	55.5	101.1	61.4
123.0	23.7	55.5	101.1	61.4
126.0	23.7	55.4	101.1	61.4
129.0	23.7	55.4	101.1	61.4
132.0	23.6	55.5	101.3	61.4
135.0	23.6	55.7	101.6	61.4
138.0	23.7	55.9	102.0	61.4
141.0	23.7	56.2	102.3	61.4
144.0	23.7	56.4	102.6	61.4
147.0	23.8	56.5	102.8	61.4
150.0	23.8	56.5	102.9	61.4
153.0	23.9	56.6	102.9	61.4
156.0	23.9	56.7	103.1	61.4
159.0	24.0	56.9	103.3	61.4
162.0	24.0	57.2	103.7	61.4
165.0	24.1	57.5	104.1	61.4
168.0	24.2	57.7	104.4	61.4

BOIL-OFF (IN.) = 0.0471 0.3026 0.1888 0.6482

RUN 5

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG F/FT)

0.0	27.6	62.6	105.2	62.0
3.0	27.6	62.6	105.2	62.0
6.0	27.6	62.6	105.2	62.0
9.0	27.6	62.6	105.2	62.0
12.0	27.6	62.5	105.2	62.0
15.0	27.6	62.4	105.1	62.0
18.0	27.6	62.1	104.9	62.0
21.0	27.6	61.6	104.7	62.0
24.0	27.6	61.1	104.4	62.0
27.0	27.5	60.5	104.0	62.0
30.0	27.5	59.9	103.6	62.0
33.0	27.4	59.3	103.2	62.0
36.0	27.3	58.8	102.8	62.0
39.0	27.2	58.3	102.4	62.0
42.0	27.1	57.8	102.0	62.0
45.0	27.0	57.3	101.6	62.0
48.0	26.8	56.8	101.3	62.0
51.0	26.7	56.4	100.9	62.0
54.0	26.5	56.1	100.7	62.0
57.0	26.4	55.8	100.5	62.0
60.0	26.2	55.7	100.4	62.0
63.0	26.1	55.6	100.3	62.0
66.0	25.9	55.5	100.2	62.0
69.0	25.8	55.3	100.1	62.0
72.0	25.7	55.1	100.0	62.0
75.0	25.5	55.0	100.0	62.0
78.0	25.4	55.0	100.1	62.0
81.0	25.3	55.1	100.4	62.0
84.0	25.2	55.3	100.7	62.0
87.0	25.1	55.4	101.0	62.0
90.0	25.1	55.6	101.3	62.0
93.0	25.0	55.6	101.4	62.0
96.0	25.0	55.6	101.4	62.0
99.0	24.9	55.6	101.5	62.0
102.0	24.9	55.6	101.6	62.0
105.0	24.9	55.8	101.8	62.0
108.0	24.9	56.1	102.2	62.0
111.0	24.9	56.4	102.5	62.0

114.0	24.9	56.6	102.8	62.0
117.0	24.9	56.8	103.0	62.0
120.0	24.9	56.9	103.1	62.0
123.0	24.9	56.9	103.1	62.0
126.0	24.9	57.1	103.2	62.0
129.0	24.9	57.3	103.3	62.0
132.0	25.0	57.5	103.6	62.0
135.0	25.0	57.7	103.8	62.0
138.0	25.0	57.9	104.0	62.0
141.0	25.0	57.9	104.0	62.0
144.0	25.1	57.9	103.9	62.0
147.0	25.1	57.8	103.9	62.0
150.0	25.1	57.8	104.0	62.0
153.0	25.2	58.0	104.2	62.0
156.0	25.2	58.1	104.4	62.0
159.0	25.2	58.3	104.7	62.0
162.0	25.3	58.4	104.8	62.0
165.0	25.3	58.5	104.9	62.0
168.0	25.3	58.4	104.8	62.0
171.0	25.4	58.3	104.7	62.0
174.0	25.4	58.3	104.6	62.0

BOIL-OFF (IN.) = 0.0580 0.3635 0.2247 0.7643

RUN 6

METHANE BOIL-OFF CALCULATIONS
BY THETA-M-C METHOD
TEMPERATURE GRADIENTS (DEG F/FT)

0.0	26.8	56.3	108.9	62.1
3.0	26.8	56.3	108.9	62.1
6.0	26.8	56.3	108.9	62.1
9.0	26.8	56.3	108.9	62.1
12.0	26.8	56.4	109.0	62.1
15.0	26.8	56.6	109.0	62.1
18.0	26.8	56.8	109.1	62.1
21.0	26.8	57.1	109.1	62.1
24.0	26.8	57.3	109.0	62.1
27.0	26.8	57.4	108.8	62.1
30.0	26.8	57.4	108.5	62.1
33.0	26.8	57.5	108.2	62.1
36.0	26.8	57.5	107.9	62.1
39.0	26.7	57.7	107.7	62.1
42.0	26.7	57.9	107.6	62.1
45.0	26.7	58.1	107.6	62.1
48.0	26.6	58.2	107.5	62.1
51.0	26.6	58.2	107.3	62.1
54.0	26.6	58.1	107.0	62.1
57.0	26.5	58.1	106.8	62.1
60.0	26.5	58.1	106.7	62.1
63.0	26.4	58.1	106.7	62.1
66.0	26.4	58.3	106.8	62.1
69.0	26.3	58.5	106.9	62.1
72.0	26.3	58.6	107.0	62.1
75.0	26.3	58.6	106.9	62.1
78.0	26.2	58.5	106.7	62.1
81.0	26.2	58.4	106.5	62.1
84.0	26.1	58.4	106.4	62.1
87.0	26.1	58.4	106.4	62.1
90.0	26.1	58.5	106.5	62.1
93.0	26.0	58.7	106.6	62.1
96.0	26.0	58.8	106.6	62.1
99.0	26.0	58.8	106.6	62.1
102.0	25.9	58.6	106.4	62.1
105.0	25.9	58.5	106.2	62.1
108.0	25.9	58.4	106.1	62.1
111.0	25.8	58.5	106.1	62.1

114.0	25.8	58.5	106.2	62.1
117.0	25.7	58.6	106.3	62.1
120.0	25.7	58.7	106.3	62.1
123.0	25.7	58.6	106.2	62.1
126.0	25.7	58.6	106.1	62.1
129.0	25.6	58.5	105.9	62.1
132.0	25.6	58.4	105.8	62.1
135.0	25.6	58.4	105.8	62.1
138.0	25.5	58.5	105.8	62.1
141.0	25.5	58.5	105.8	62.1
144.0	25.5	58.6	105.8	62.1
147.0	25.5	58.6	105.8	62.1
150.0	25.4	58.5	105.7	62.1
153.0	25.4	58.5	105.6	62.1
156.0	25.4	58.5	105.6	62.1
159.0	25.4	58.6	105.8	62.1
162.0	25.4	58.8	106.0	62.1
165.0	25.3	59.0	106.2	62.1
168.0	25.3	59.1	106.4	62.1
171.0	25.3	59.1	106.4	62.1
174.0	25.3	59.1	106.4	62.1
177.0	25.3	59.1	106.3	62.1
180.0	25.3	59.0	106.2	62.1

BOIL-OFF (IN.) = 0.0451 0.2832 0.1753 0.5829

APPENDIX 2

2.0 Computer programme LN

2.1 List of indices and variables used in LN

2.2 Specimen data tape for LN

2.3 Specimen output tape for LN

APPENDIX 2.0

Computer programme LN

```
Q7901

Q7850

DN
LN  MK2
@837.0
G.MARTIN  JN1327
 HEAT TRANSFER BY
 NATURAL CONVECTION
N

DATAN

ALPHAL

J755.0-843.0
   @ →3
   ? →7
VISC @80
DENS @82
COND @83
  CP @85
  AL @896.0
 PHA @86
  XH @87
  XV @88
  SV @00
  SH @91
PRES @92
 TEM @896.0
  PS @05

  CD →1
  →6 →6
   V *
  VI *
 VIS *
   D *
  DE *
 DEN *
   C *
  CO *
```

```
 COM *
   A *
  PH *
   X *
   S *
  PR *

 PRE *
   T *
  TE *
   P →5
LX805.6+
 5I
JI.0
6)SINGLE
v86=v0
n0=2
TEXT
PRINTv0,2025
→I9



3)n0=0
TEXT
SIXWAYS
7)n4=v90
n5=n4-I
n7=v9I
n6=n7/2
n8=n7-I
n9=n4+I
n10=n0Xn7
n11=n7+I
vI=v95-v96
v2=v9I-I
v3≡vI/v2
n2=I

8)v(700+n2)=v95+v2
n2=n2+I
→8,n2≠n4
n3=I
```

```
9)n2=1
10)n0=n3X20
n0=n0+n2
n1=n0-v9
v(700+n0)=v(680+n0)-v1
n2=n2+1
→10,n2≠n4
n3=n3+1
→9,n3≠n7
v0=v01-1
v93=v87/v0
v0=v90-1

v93=v87/v0
v0=v90-1
v94=v82/v0
n3=1
13)n2=n4/2
n1=n3X20
n0=n1+n2
v(100+n0)=v92
v0=v82/v(700+n0)
v0=v0Xv94
11)n0=n1+n2
v(101+n0)=v(100+n0)+v0
n2=n2+1
→11,n2≠n5
n2=n4/2
12)n0=n1+n2

v(99+n0)=v(100+n0)-v0
n2=n2-1
→12,n2≠1
n3=n3+1
→13,n3≠n7
5)10)n2=1
14)n1=n2+n0
v(100+n2)=v(120+n2)
v0=aXv95
v(700+n2)=v0-v(720+n2)
n2=n2+1
→14,n2≠n4
n2=1
15)n0=n7X20
n0=n0+n2
```

```
v(100+n0)=v(80+n0)

v0=2×v96
v(700+n0)=v0-v(680+n0)
n2=n2+1
⇒15,n2≠n4
n0=1
16)n1=n0×20
v(700+n1)=v(701+n1)
v(100+n1)=v(101+n1)
n0=n0+1
⇒16,n0≠n7
n0=1
22)n1=n0×20
n1=n1+n4
v(100+n1)=v(99+n1)
v(700+n1)=v(699+n1)
n0=n0+1

⇒22,n0≠n7
v15=0
v97=v93/v94
n3=1
17)v0=v90-1
n2=v0
v0=v91-1
n3=v0
⇒4096
(⇒10,4096,512)
```

```
124 270
 25 153
 21 240
 25 252
  1 201
124 370
 25 153
 33 300
  1 301
```

```
   0  100
2.5  400
  25 -714
  97 -704
2.3  110
   4 4723
   5 5723

2.4  400
   2 4011
  20 -704
   1 6000
  19 -704
1.4  540
  32 5066
2.7+5666
   1 6433
   6 1000
2.5  400
   6 -714
   0 0000
   6 0723
   7 1723
0.0  0600

                +0
                +0
                +0
                +0
  26 4400
  32 5066
  15 7400
  25 4522
2.5  4011
  32 5066
   0 0704
   1 7000




   5 1000
   6 4000
3.6  6055
```

```
   6 403
   7 500
3.6 705
   7 503
4.2+1631
3.5 501
3.7 0601
                -256
                -512
   7 620
4.2 060
```

```
   7 701
   7 626
   7 600
   1 544
   5 401
5.1+162
   7 702
   4 504
4.7 562
   5 403
   7 606
   6 706
   7 606
   5 502
  28 543
5.0+562
```

```
  25 550
  28 7515
   7 601
5.7 660
  36 456
3.5 603
   2 456
5.6+463
3.6 605
   4 601
3.6 405
5.7 460
   0 075
   0 600
```

```
  25 152
   0 0601

0.0 110
  82 -704
   1 600
0.0 700
0.3 140
3.0+166
2.5 400
   6 100
  10 -714
0.0 600
  84 400
0.6+540
2.4+060
  83 440
1.0 540
2.5+566

2.5 400
   6 100
  14 -714
0.0 600
  81 440
1.3+540
2.4+060
  80 440
1.5 540
2.5+566
2.5 400
   6 100
  18 -714
   8 0723
   9 1723
0.0 060

2.4 400
   2 401
  20 -704
   1 600
   0 -704
0.4 540
  32 506
2.7+566
```

```
   I 643
   6 100
2.5 400
   7 -714
0.0 110
  32 -704
   I 600
0.0 700

I.I 140
3.0+166
2.5 400
   6 100
  II -714
0.0 600
  8I 440
I.4+540
2.4+060
  80 440
I.6 540
2.5+566
0.0 700
  I0 0723
  II 1723
0.0 060

2.5 400
   6 100
  I9 -714
  84 -704
   I 600
0.3+140
3.0+060
  93 440
0.5 540
2.5+566
2.5 400
   6 100
  I5 -714
2.4 400
   2 40I
  20 -704

   I 600
  40 -704
```

```
1.2+540
 32 506
2.7+566
   1 643
   6 100
2.5 400
   8 -714
0.0 110
 82 -704
   1 600
0.0 700
 12 0723
 13 0723
0.0 060

0.0 710
0.1+140
3.0+166
2.5 400
   6 100
 12 -714
0.0 600
 81 440
0.5 540
2.4+060
 80 440
0.6+540
2.5+566
2.5 400
   6 100
 20 -714

0.0 600
 84 440
1.2 540
2.4+060
 83 440
1.3+540
2.5+566
2.5 400
   6 100
 16 -714
2.4 400
   2 401
 20 -704
```

```
 I4 0723
 I5 I723
0.0 060

  I 600
 2I -704
0.2+540
 32 506
2.7+566
  I 643
  6 I00
2.5 400
  9 -7I4
0.0 II0
 82 -704
  I 600
0.0 700
0.7+I40
3.0+I66
2.5 400

  6 I00
 I3 -7I4
0.0 600
 8I 440
I.3 540
2.4+060
 80 440
I.4+540
2.5+566
2.5 400
  6 I00
 2I -7I4
0.0 600
 I6 0723
 I7 I723
0.0 060

 84 440
0.I+540
2.4+060
 83 440
0.3 540
2.5+566
2.5 400
```

```
   6 100
 17 -714
   0 000
   0 000
   0 000
2.5 400
   2 401
  80 -704
   1 600

  11 400
1.1+540
2.4+060
2.0 610
2.5 400
   2 401
120 -704
   1 600
  12 440
1.5+540
2.4+060
2.0 700
0.1 140
  18 0723
  19 1723
0.0 060

  32 106
3.0+166
2.3 700
0.2+140
3.0+166
2.0 610
2.5 400
   2 401
  99 -704
0.0 110
101 -704
0.1 110
0.0 600
  10 440
1.0 540
2.4+060

2.1 610
```

```
0.1 600
 13 440
1.2+540
2.4+060
2.1 700
1.4 140
 32 106
3.0+166
2.3 700
1.6 140
3.0+060
2.0 700
 20 0723
 21 1723
0.0 060

0.1+140
 32 106
3.0+166
2.0 610
2.5 400
 10 -704
0.0 110
 13 -704
0.1 110
0.1 600
0.1 700
0.6+140
3.0+060
2.1 610
0.0 600
0.0 700

1.1 140
3.0+060
2.2 610
   0 000
   0 000
   0 000
2.1 700
1.5 140
 32 106
3.0+060
 03 440
1.6+540
```

```
2.4+060
 22 0723
 23 1723
0.0 060

2.0 700
0.2 140
 32 106
3.0 166
2.0 610
2.5 400
 12 -704
  1 600
 11 440
0.5+540
2.5+566
2.3 700
0.7 140
3.0+166
2.1 610
2.5 400

 10 -704
 13 440
1.2 540
2.5+566
2.3 700
1.3+140
3.0+060
2.1 700
1.5+140
 32 106
3.0+166
  6 700
2.0 600
 24 0723
 25 1723
0.0 060

0.1 140
3.0+166
2.5 400
  2 401
  6 100
100 -714
```

```
   6 700
  99 -704
   I 600
0.6 I40
  32 I06
3.0 060
  94 440
0.7+540
2.4+566
  I0 440

I.I 540
2.5+566
   6 440
I.2+540
2.4+060
  I0 440
I.4 540
2.4+060
  I8 440
I.5+540
2.4+566
2.0 6I0
2.5 400
  40 0723
  27 I723
0.6+060

I0I -704
   I 600
I00 -704
   I 700
0.3+I40
  32 I06
3.0+060
  94 440
0.5 540
2.4+566
  I3 440
0.6+540
2.5+060
   9 440
I.0 540
2.4+060
```

```
   13  440
1.1+540
2.4+060
  21  440
1.3  540
2.4+566
2.0  700
1.5  140
  32  106
3.0+166
  93  440
1.6+540
2.4+060
  28  0723
  29  1723
0.0  060

2.0  610
2.5  400
   2  401
  80  -704
0.0  110
100  -704
0.1  110
120  -704
0.2  110
0.0  600
0.1  700
0.7  140
  32  106
3.0+060
   7  440
1.0+540

2.4+060
  11  440
1.2  540
2.4+060
  19  440
1.3+540
2.4+566
2.1  610
0.2  600
0.1  700
1.6+140
```

```
 32 106
3.0+060
 30 0723
 31 1723
0.0 060

  8 440
0.1+540
2.4+060
 12 440
0.3 540
2.4+060
 20 440
0.4+540
2.4+566
2.1 700
0.6+140
 32 106
3.0+166
2.3 700
1.0 140
3.0+166

2.0 700
1.2 140
 32 106
3.0+166
 85 440
1.3+540
2.4+060
 86 440
1.5 540
2.4+060
2.0 610
  0 000
  0 000
 32 0723
 33 1723
0.4 060

1034 --0 .
1719
1037 --0 .
1721
1035 --0 .
```

```
I700
I036 --o .
I740
0.4 310
  4 340
0.0 4003
  0 0704
  I 600
 25 452
  3 401
I.0+540

2.7 060
0.0 6103
 35 301
0.5 367
0.4 300
0.I 600
0.0 700
I.5 I40
 32 I06
3.0+I66
2.3 700
I.6+I40
3.0+060
2.I 610
 34 I723
I.0 060

0.3 600
0.2 700
I.2+I40
 32 I06
3.0+I66
2.3 700
I.4 I40
3.0+I66
2.I 700
I.6 I40
 32 I06
3.0+I66
  I 641
2.0 700
 35 I723
I.0 060
```

1.1+140
32 106
3.0+166
1 643
2.0 610
2.5 400
14 -704
1 600
17 440
1.5+540
2.5+566
2.1 610
2.3 700
36 0723
37 1 723
0.0 060

0.1 140
3.0+060
2.1 610
2.5 400
15 -704
16 440
0.4 540
2.5+566
2.3 700
0.5+140
3.0+166
2.1 700
0.7+140
32 106
3.0+166
6 700

2.0 600
1.1+140
3.0+166
3.4 400
2 401
6 100
20 -714
3 400
127 445
1 443

```
 I.7 461
 38 0723
 39 I723
0.0 060
 39 I723
I.2 060

2.4 400
   2 401
 40 -704
   I 600
 20 -704
0.4 540
 32 506
2.7+060
2.3 700
0.5+I40
3.0+I66
 I6 440
0.7 540
2.4+060
 25 440
I.0+540

2.5+566
3.5 400
   6 I00
 25 -7I4
 35 20I
I.7 267
I24 270
 25 I53
 25 253
   I 203
 20 24I
 25 252
 40 0723
0.0 060
   I I723
I.0 060

   I 20I
0.4 367
   2 I00
 25 I52
```

```
 I24 37I
 6I 240
 40 472
4.4 060
  I I723
I.0 060
  0 000
  0 000
  0 000
  2 40I
 26 0723
0.0 060

 I5 300
0.3 363
I00 340
 I7 0I0
 I7 0I0
0.I+367
 I5 300
 I3 352
0.6 363
 I9 240
 40 472
4.4 060
  4 072
0.3 060
B
JI.2

6I)vI=v9I-I
v0=vIX20
v0=v0+vI
n0=v0
62)PRINTv(700+n0),3062
n0=n0+I
n2=n2-I
→62,n2≠0
PRINTv25,4065
→M4424
I)n0=I
TEXT
n0=80
2)PRINTvn0,I025
n0=n0+I
```

```
→2,⍝o=89

X⍝o=o
PRINTυ90,1025
PRINTυ91,1025
PRINTυ92,1025
X⍝o=o
PRINTυ95,1025
PRINTυ96,1025
o)SIXWAYS
(→o)
```

```
N
LH   (X3)
→10
X518.5
 84 440
X523.7
 13 1723
X539.o
 11 440
X531.3
1.4+140
X534.1+
3.o+166
X536.5+
3.o+o6o
L

N
LH   (X4)
→10
J755.o-847.3
   →A X42.o
   PL *
  PLO *
PLOT →4
L
```

```
X805.6+
 56
S512.0
T554.0



   0 300
   0 074
  15 740
  17 010
0.1+767
  77 740
  13 640
  17 610
0.3+767
  38 740
  17 010
0.5 767
    8 074
  32 306
0.1 363
1.0 110

L →A
ALTER6,38
n3=1
ALTER6,39
n3=1
ALTER61,2
Xv0=v0+1
4)→114432
v0=v90-1
n14=v0
v0=v91-1
n15=v0
n12=0
50)n0=0
COND
Xn0=8

Xn0=8
COND
Xn13=0
```

```
Xm13=0
51)→52,12≥m13
m0=8
→53
52)m0=0
53)COND
m0=20Xm13
m0=m0+m12
PRINTv(721+m0),4060
m13=m13+1
→51,m13≠m15
m0=0
COND

Xm0=8
COND
Xm13=0
54)m0=0
→55,12≥m13
m0=8
55)COND
m0=20Xm13
m0=m0+m12
v0=100Xv(121+m0)
PRINTv0,4060
m13=m13+1
→54,m13≠m15
m12=m12+1
→50,m12≠m14
m0=0

COND
SIXWAYS
(→0)
```

```
N
LH  (X5)
⇒10
X533.7
 43 1723
X555.0-555.1+
 10 -704
  1 600
 23 1723
1.0+060
X548.2-548.2+
 43 0723
0.3 060
X555.2-555.4+
 15 -704
  1 600

 16 440
  0 000
 36 0723
0.3 060
L
⇒A
ALTER5
⇒18
18)⇒M4424
5)19)@2=1
⇒14
(⇒0)
⇒10
G5123.0
G5551.2
L

N
LH  (X6)
⇒10
T556.0
```

```
0.0 310
  4 340
2.5 400
  3 401
 10 -704
  1 600
 18 -704
0.4+540
2.7+566
2.5 400
  3 401
  6 100
 30 -714
 35 301
0.1 367
 99 172

X528.5-528.5+
 44 0723
0.0 060
T99.0
0.0 300
2.5 400
  2 401
 80 -704
  1 600
  0 000
 17 1723
1.0 060
T528.6
-1.0
-1.0


X529.0
 31 440
```

```
X529.4
 32 440
X530.6+
 30 440
X531.1
 33 440
X534.3
 32 -704
X534.4
 31 440
X555.0
 30 -704
X535.0-535.0+
  0 000

 33 440
T532.2
2.5 400
 13 -704
  1 600
 33 440
0.5 540
2.4+060
2.1 610
2.5 400
 10 -704
  1 600
 30 440
2.3 540


2.4+060
  0 000
  0 000
  0 000
X537.0
1.4 540
X538.5+
1.1+540
X540.5+
1.2 540
X541.7+
0.3 060
X543.4
```

```
0.0  540
X542.0-543.1


 82  440
1.5  540
2.4+060
X546.6
  0 000
X547.1+
  0 000
L
```

```
N
LN   (X7)
÷10
X532.7+
1.3  540
X540.5+
1.2  140
L
```

```
N
LN(X8)

÷10
T553.6
12  340
34  352
```

```
II 4723
4.4 060

L
N
LN  (X10)

>A

ALTER7,8
>46

(TAPE6,258)

46)v30=v83/v84
v0=0.5Xv84
v0=v0Xv05
v0=v0+v83
v31=v0Xv95

v0=v95+v96
v0=v0Xv84
v0=v0X0.5
v0=v0+v83
v1=v96-v95
v1=v1/v87
v32=v1Xv0
v0=v91-1
v2=v87/v0

n3=0
44)n2=1
v0=v2/2
v1=n3
v1=v1Xv2
v0=v0+v1
v0=v0Xv32
v0=v0+v31
v0=v0X2
v0=v0/v84
v1=v30Xv30
v0=v0+v1
v0=SQRTv0

n1=n3X20
45)n0=n1+n2
v(720+n0)=v0-v30
n2=n2+1
```

```
 →45,n2≠n4
n3=n3+1
→44,n3≠n8
→45
ALTER10,8
45)v0=v91-1

(→0)

N
LN  (X10*)

→A
ALTER44,13
45)n0=n1+n2
ALTER45,6
→47
ALTER10,8
47)v0=v91-1
(→0)

N
LN(X11)

→10
T537.0
1.1 540
2.5+566
 15 100
  2 152
1.4 162
  0 000
 39 1723
1.2 060
L

N
LN(X12)

→A

ALTER16
→48

48)n1=n0X20
```

```
 v(700+n1)=v(701+n1)
v0=v82/v(700+n1)
v0=v0Xv94
v(100+n1)=v(101+n1)-v0
n0=n0+1
→48,n0≠n7

n0=1
49)n1=n0X20
n1=n1+n4
v(700+n1)=v(600+n1)
v0=v82/v(700+n1)
v0=v0Xv94
v(100+n1)=v(99+n1)+v0
n0=n0+1
→49,n0≠n7
→39

ALTER22,5
39)v0=0

(→0)

Z
```

Appendix 2.1

List of Indices and Variables used in LN

Variables

0 to 5	Workspace
6, 7, 8, 9	T_{TN} T_{LN} T_{RN} T_{BN} (Temperatures of faces of element)
10, 11, 12, 13	ρ_{TN} ρ_{LN} ρ_{RN} ρ_{BN}
14, 15, 16, 17	k_{TN} k_{LN} k_{RN} k_{BN}
18, 19, 20, 21	μ_{TN} μ_{LN} μ_{RN} μ_{BN}
25	Total heat transfer across right hand boundary
30	k_0/k_1
31	$T_0(k_0 + \frac{1}{2}k_1T_0)$
32	$\frac{T_1 - T_0}{L}\left[k_0 + \frac{1}{2}k_1T_0 + T_1\right]$
80, 81	Viscosity constants, μ_0, μ_1
82	Density constant, ρ_0
83, 84	Conductivity constants, k_0, k_1
85	Specific heat, Cp
86	Permeability, α
87	Thickness of insulation, L
88	Height of insulation, H
90	Number of steps in height, m
91	Number of steps in thickness, n
92	Pressure at datum

Variables

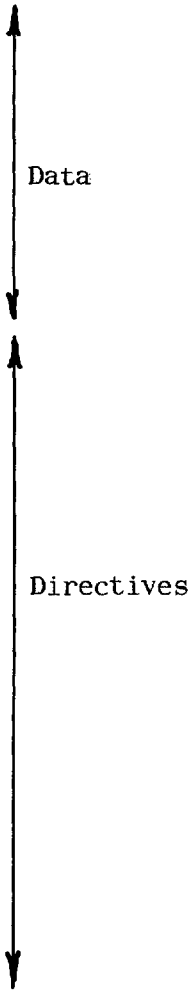
93	Thickness of element, $\ell = \frac{L}{n - 1}$
94	Height of element, $d = \frac{H}{m - 1}$
95, 96	Temperatures of boundaries T_0, T_1
100 to 119	Pressure in elements 0 to m
120 to 139	Pressure in elements m + 1 to 2m + 1
etc. to 699	
700 to 719	Temperature in elements 0 to m
720 to 739	Temperature in elements m + 1 to 2m + 1
etc. to 1299	

Indices

n0 to 3	Workspace
4	number of steps in height, m (v_{90})
5	m - 1
6	n/2
7	number of steps in thickness, n (v_{91})
8	n - 1
9	m + 1
10	(m + 1)n
11	n + 1

APPENDIX 2.2

Specimen data tape for computer programme LN



```
SPECIMEN DATA TAPE FOR LN


N
DATA 3

COND      .0127      .0000383
DENS      39.7
VISC      .0034      .0000773
CP        .25
ALPHA     0
XH        1      XV        4
SH        6      SV        6
PRES      0
TEMPS     162      542

n
CD
?
RRRRRRRRRR
→6  0.2
→6  0.4
→6  0.6
→6  0.8
→6  1.0
→6  1.2
→6  1.4
→6  1.6
→6  1.8
→6  2.0
→6  2.2
→6  2.4
→6  2.5

RRRRRRRRRRRRRRRRRRR
PLOT

Z
```

APPENDIX 2.3

Specimen output tape for computer programme LN

μ_0
μ_1
ρ_0
k_0
k_1
C_p
α
L
H

m
n
P_c

T_0
T_1

Temperatures Heat transfer
^0F Btu/hr

```
G.MARTIN  JN1327
 HEAT TRANSFER BY
 NATURAL CONVECTION


DATA
 3.40000,   -3
 7.73000,   -5
 3.97000,   +1
 1.27000,   -2
 3.83000,   -5
 2.50000,   -1
 0.00000,   +0
 1.00000,   +0
 4.00000,   +0

 6.00000,   +0
 6.00000,   +0
 0.00000,   +0

 1.62000,   +2
 5.42000,   +2



 512.32
 512.35
 512.35
 512.35
 512.35    40.09435

 512.23
 512.23
 512.23
 512.23
 512.23    39.76858

 512.31
 512.32
 512.32
 512.32
 512.32    39.78531
```

512.32	
512.32	
512.32	
512.32	
512.32	39.72259
512.34	
512.34	
512.34	
512.34	
512.34	39.70584*
512.35	
512.35	
512.35	
512.35	
512.35	39.68604
512.36	
512.36	
512.36	
512.36	
512.36	39.67574
512.36	
512.36	
512.36	
512.36	
512.36	39.66783
512.36	
512.37	
512.37	
512.37	
512.37	39.66290
512.37	
512.37	
512.37	
512.37	
512.37	39.65947
512.37	
512.37	
512.37	

```
 512.37
 512.37    39.65722

ALPHA  2.00000,  -1

 513.31
 512.71
 512.37
 512.06
 511.37    39.66053

ALPHA  4.00000,  -1

 514.14
 512.96
 512.35
 511.76
 510.39    39.69405

ALPHA  6.00000,  -1

 515.02
 513.22
 512.32
 511.44
 509.23    39.77189

ALPHA  8.00000,  -1

 515.81
 513.43
 512.30
 511.14
 508.03    39.89001

ALPHA  1.00000,  +0

 516.55
 513.62
 512.27
 510.84
 506.77    40.04663

ALPHA  1.20000,  +0
```

```
 517.22
 513.79
 512.25
 510.56
 505.47    40.23676

ALPHA  1.40000,  +0

 517.84
 513.95
 512.23
 510.29
 504.10    40.45764

ALPHA  1.60000,  +0

 518.42
 514.09
 512.21
 510.02
 502.68    40.70755

ALPHA  1.80000,  +0

 518.96
 514.24
 512.20
 509.75
 501.17    40.98622

ALPHA  2.00000,  +0

 519.47
 514.39
 512.19
 509.48
 499.59    41.29419

ALPHA  2.20000,  +0

 519.96
 514.54
 512.19
 509.20
 497.92    41.63238
```

```
ALPHA  2.40000,  +0

 520.42
 514.70
 512.18
 508.90
 496.17   42.00159
ALPHA  2.50000,  +0

 520.71
 514.82
 512.17
 508.65
 494.94   42.33710

 520.83
 514.90
 512.18
 508.50
 494.38   42.54698

 520.91
 514.97
 512.19
 508.43
 494.05   42.64641

 520.95
 515.03
 512.21
 508.41
 493.93   42.68297

 520.97
 515.08
 512.24
 508.42
 493.91   42.67495

 520.98
 515.13
 512.27
 508.45
```

493.95 42.64252

520.98
515.16
512.30
508.49
494.00 42.59861

520.98
515.20
512.34
508.53
494.07 42.55216

520.97
515.23
512.37
508.58
494.12 42.50840

520.97
515.26
512.40
508.61
494.16 42.47009

520.96
515.28
512.43
508.64
494.19 42.43827

520.95
515.30
512.46
508.67
494.21 42.41299

520.95
515.32
512.48
508.69
494.22 42.39368

520.94

515.33
512.50
508.71
494.22 42.37951

520.93
515.34
512.52
508.72
494.21 42.36956

520.92
515.35
512.54
508.73
494.20 42.36295

520.92
515.36
512.55
508.73
494.19 42.35890

520.91
515.37
512.56
508.74
494.18 42.35676

520.90
515.37
512.58
508.74
494.16 42.35597

520.89
515.38
512.59
508.75
494.15 42.35610

520.89
515.38
512.60
508.75

494.13 42.35685

520.88
515.39
512.61
508.75
494.12 42.35797

247	354	422	475	521
-23	-22	-22	-22	-21
227	320	394	458	515
-12	-12	-12	-12	-11
217	305	381	449	513
-0	-0	-0	-0	-0
214	294	366	438	509
11	11	11	11	11
185	230	299	393	494
24	24	23	23	23