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A Short Time Response Stagnation Temperature Probe

By

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A Short Time Response Stagnation Temperature Probe

- By -

R. A. East and J. H. Perry

SUMMARY

A shielded thermocouple, total temperature probe has been developed capable of measuring mainstream and boundary-layer maximum temperatures and temperature - time histories in a hypersonic gun tunnel. Experiments have indicated that temperatures up to a maximum value of 1500°K may be measured with high accuracy. The probe may in principle be miniaturised for boundary-layer measurements so that the outside diameter at the inlet is less than 1/32 in. Response times better than 10 milliseconds have been achieved.

A survey of existing methods of measuring temperatures in short running time facilities is given and a comparison has been made with the results of the thermocouple probe.

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*Replaces A.A.S.U. Report No.264 - A.R.C.27 919.

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1. Introduction

Many of the available hypersonic wind tunnel facilities (e.g. shock tunnels and gun tunnels) have very short running times which makes measurement of the flow total temperature difficult. The authors know of no dependable, easily applied, method by which this quantity may be measured accurately at a given point within the flow mainstream or boundary layer of a tunnel or model respectively. Although this report describes the application of this probe to a gun tunnel facility it would appear possible that it may be used in certain shock tunnel experiments.

These tunnel facilities have running times varying from the order of milliseconds to seconds depending upon the conditions required and the tunnel design. Stagnation temperatures in these facilities range from 800°K upwards.

2. Survey of Existing Methods of Temperature Measurement

Many approaches have been made towards the measurement of mainstream temperature in the gun tunnel. These are summarised below:

(a) Stagnation temperature at the start of the run can be determined, reasonably accurately, from the analysis of the measured stagnation pressure development due to the shock reflection process. East (Ref.13) has used this method to estimate the stagnation temperature. The temperature must be corrected for boundary layer and heat loss effects in the gun barrel as developed by Edney (Ref.14). It is not possible to determine the time variation of temperature over the tunnel run by this method.

(b) The speed of the piston, during the steady running period of the tunnel, is determined by microwave tracking (Ref.15) and this speed is related to mass flow through the nozzle and hence to stagnation temperature. The piston speed cannot be determined to a sufficient accuracy such that the temperature variation with time can be measured.

(c)/

(c) If it can be assumed that reservoir conditions could be related, at any instant, to those during the steady running period of the tunnel by the usual isentropic relations (Ref.15), it is possible, by integrating the mass flow during the running time of the tunnel and equating this to the mass of air initially in the barrel, to determine the average stagnation temperature. The accuracy of this method is low when there is a rapid fall of stagnation temperature with time (Ref.7).

(d) Sodium line reversal techniques can be applied to measuring the temperature between a circular disc, placed normal to the flow, and the bow shock formed about it (Stollery, Ref.16). The sodium line technique measures electronic excitation temperature of the sodium and, as it was realised later, the electronic excitation temperature closely follows the vibrational temperature which was not, probably, in equilibrium with the translational temperature at the measurement point. A correction for this cannot be confidently predicted, with accuracy, at this stage.

(e) A velocity measuring technique, developed by Merritt (Refs. 7 & 8) seems to give the best accuracy and, if sufficient measurements are taken, a time history of temperature can be obtained. This method suffers from a great deal of scatter and only one temperature value can be obtained per run. A cylindrical shock wave is produced, in the test section, by a long spark discharge and the flow velocity is determined by measuring the propagation velocity of the cylindrical shock. Stagnation temperature can be calculated from this velocity. The method is complex in application and the electrode voltage and spacing is sensitive to test section flow density (Ref.2). This method has also been successfully used at N.R.C. Canada (Ref.15).

(f) Bowman (Ref.18) at the R.A.R.D.E. used a streak camera to measure the flow velocity in the tunnel working section. Basically the method uses the small density variations in the flow which are detected by a sensitive schlieren system and photographed with a streak camera scanning at right angles to the flow direction. The inclination of the streaks providing a continuous record of flow velocity during the running time of the tunnel. The stagnation temperature can be calculated from the Mach number, the flow velocity and the thermodynamic constants of the working gas. This method provides quite accurate temperature values and temperature time histories. The possible error is stated at ±3% at $M = 8{\cdot}4$ to ±4% at $M = 12{\cdot}9$.

(g) Brown-Edwards (Ref.17) at the F.F.A. has made measurements in the shock layer at the front of an "end-on" flat faced cylinder using a modified line reversal two-beam optical pyrometer. Working gases were argon, air and nitrogen. The experimental results, for temperatures of the order of 2000°K, agreed reasonably well with theoretical results correlated by Edney (Ref.14) and with Edney's heat transfer gauge results (Ref.14). This is, again, a very complex method to apply although a temperature-time plot can be obtained.

(h) Edney (Ref.14) measured stagnation point heat transfer rates in the tunnel test section using platinum thin film gauges and shell calorimeters.

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The heat transfer rates were related to stagnation temperature. The scatter of results is high (confirmed in the case of platinum thin film gauges by East and Perry (Ref.2) and the importance and difficulties of accurate gauge calibration are obvious. Temperature-time histories can be obtained during a single tunnel run (Ref.2).

(i) Hornung (Ref.3) has developed a stagnation temperature measuring probe of the shielded "hot wire" type. The shield is internally coated with a platinum film which is heated, by a condenser discharge, to fairly high temperatures during the run to reduce radiation loss from the wire. This probe suffers from the usual hot wire calibration problems as modified by the presence of the heated shield. Rise time of the probe was about 1 millisecond and the size about $\frac{1}{4}$ in. outside diameter. The probe would be difficult to miniaturise sufficiently for boundary-layer measurements as (1) the hot wire should be kept as long as possible for sensitive measurements and should also be outside the shield boundary layers; (2) there are manufacturing problems associated with platinum coating internal surfaces of very small shields.

The use of the probe is very sensitive to calibration accuracy. Probe rise time is fast enough to obtain a temperature-time history over the normal gun tunnel run.

None of the above methods give an easily obtainable, reliable, single temperature value or temperature-time history at a given point over a single tunnel run. If sufficient tunnel runs are made methods (e) and (f) give reliable temperature-time histories and method (i) should have good accuracy with detailed calibration.

Of the techniques described, none have sufficient accuracy or spatial resolution for the planned experimental investigation of temperature distributions within the boundary layer developed on the wall of the gun tunnel conical axisymmetric nozzle. It was therefore decided to adopt a different approach.

Considerable progress has been made in the development of shielded thermocouple probes for continuous running tunnel facilities (Refs. 5, 6 and 10.) To date, rise times have been rather long for these thermocouple arrangements, far longer than the 17 milliseconds available for the above boundary-layer measurements (Ref.2). Basically the probes consist of a thermocouple bead surrounded by a radiation shield internally coated with platinum. The use of these probes in a continuous running tunnel depends on the tunnel having a relatively constant stagnation temperature over the run.

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These probes are relative simple to construct and use. Calibration is easily achieved as the recovery factor varies only with Mach number. The manufacturer's calibration charts for the thermocouple can be assumed accurate enough for the temperature/e.m.f. relationship.

It was decided to develop this type of shielded thermocouple probe for use in the gun tunnel operating conditions.

3./

3. Probe Design and Construction Details

3.1 Principle of probe operation

The joining point of the two thermocouple leads (known as the hot junction or bead) is the temperature sensing area. To avoid radiation losses from this area the junction is surrounded by a shield which can be heated to above the temperatures that the probe will be required to measure. It was reasoned that the actual flow temperature was correctly indicated when the thermocouple measured temperature, at the particular time point under examination during the tunnel run, equalled the thermocouple indicated shield temperature before the start of the run.

In the case where the shield is heated, it is important to ensure that the inner wall of the shield, and the thermocouple bead are at the same temperature. If the wall temperature were higher, heat transfer to the sensing junction, from the wall, during the tunnel run would have an unpredictable effect on the temperature indication.

The basic probe design is shown on Fig. 1. Nickel-chromium/nickel-aluminium type thermocouple wires, of 0·001 in. diameter, were used. The joining method is described below. For a temperature of 1000°K this thermocouple* gives about 30 milli-volts signal. The wires were insulated by a small diameter, twin bore, aluminium oxide tube.+

The heat shield was constructed from a single bore tube of aluminium oxide+. Probe vent holes were contained in the stainless steel heat shield support.

3.2 Thermocouple joining method

The thermocouple response time is a function of bead size at the thermocouple junction. The two thermocouple leads were joined by striking an arc across them in an atmosphere of argon. With practice very small joining beads of 0·003 in. diameter could be formed. It was found possible to obtain smaller beads but these proved too fragile for use.

In the manufacture of the thermocouple beads the authors used a simple small glass oval container (Fig.2) with argon feed ports and a carbon rod as one electrode. The thermocouple leads, twisted together, formed the other electrode and were joined when sparked against the carbon electrode. About 36 volts, from a battery source, were necessary to generate a sufficiently intense spark for the gauge of wires used.

3.3 Heat shield construction

An initial attempt was made to use the shield heating methods developed by Hornung (Ref.3). It was not possible to achieve high enough

shield/

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*T_1/T_2 thermocouple wire as supplied by British Driver-Harris Co. Ltd.

+de Gussit sintered aluminium oxide ceramics.

shield temperatures by this method and it proved very difficult to internally coat very small shields with an even film of platinum.

Hence the method was abandoned in favour of heating the shield with platinum resistance wire wrapped about the outside diameter. The shield was a single bore tube of sintered aluminium oxide. For the development probe the shield dimensions were 0·3 in. long and 0·045 in. internal diameter. Platinum wire (0·004 in. diameter wire proved the most successful minimum diameter) was wound around the outside diameter and sealed in position by painting with aluminium oxide powder*, held in suspension in water, over the outside of the wire. The aluminium oxide outer cover was fired in a gas jet. With this powder it was necessary to build up to the required outer cover thickness by using thin layers; firing at each stage.

Platinum proved the best heater wire; others, such as tungsten or nickel, tended to oxidise during the firing process. Platinum allowed heat shield temperatures up to about 1500°K (sufficient for the required experiments). For higher shield temperatures it should be possible to use tungsten by firing in powder in an oxygen free atmosphere. The firing temperature necessary was just under the melting temperature of platinum.

4. Results

The development probe, described in section 3, was installed in the University of Southampton hypersonic gun tunnel. The performance and particulars of this tunnel have been adequately covered in Refs. (2) and (13). The probe was tested in the 4 in. diameter open jet test section at a variety of tunnel breech pressure ratios, probe vent to inlet area ratios and heat shield temperatures.

A preliminary experiment was carried out to ensure that the temperature indicated by the probe thermocouple was the same as the actual shield temperature in the absence of flow, (Section 3·1). To investigate this another thermocouple was placed against the wall of the shield and the two indicated temperatures compared, at ambient pressures within the range 1 mm Hg. to 15 mm Hg. Within the operating range of the shield the temperatures, indicated by the two thermocouples were identical. Hence the shield temperature before a run could be assumed to be equal to the indicated thermocouple temperature.

The development probe was tested with an area ratio of about 20% $\left(\frac{\text{vent area}}{\text{inlet area}}\right)$ and gun tunnel diaphragm pressure ratios of 30 and 60. As the shield temperature was raised, over a number of tunnel runs, from 0°C to above flow temperature three things were noted from the e.m.f. output of the thermocouple (Fig.3) -

(1) The indicated temperature fall with time was very small compared with the amount indicated by Merritt (Ref.7).

(2) Rise time of the probe was about 10 milliseconds from first shock reflection.

(3)/

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*Aluminium oxide V.T. Cat. No. 51020 supplied by Bush Beach and Segner Bayley Limited.

(3) As the shield temperature approached the flow temperature the "peak" thermocouple indicated temperature tended to approach the flow temperature, as determined in Ref.(7) at 5 milliseconds after shock reflection.

As the vent area was increased the indicated thermocouple temperature, during a run, tended to fall more rapidly with time (compare Figs. 3 and 4). Over a single run the thermocouple indicated temperature was still not as great as that indicated in Ref. 7).

When the shield and thermocouple indicated temperatures, during a run, are equal, it is assumed that this is also the flow temperature and this value is plotted on Fig. 6.

Fig. (5) shows the thermocouple indicated shield temperature plotted against thermocouple indicated temperature, for a diaphragm pressure ratio of 60, during the run. A small amount of scatter in the experimental results occurs. This is due to the lack of repeatability of the gun tunnel from run to run in the tunnel configuration used. Four vent/inlet area ratios were investigated as follows: about 20%, 45%, 56% and 75%. The temperature value, during the run, at which shield and thermocouple correspond, for a particular time point, is plotted on Fig. 6. For comparison purposes this figure also shows the measurements made, in the same tunnel, by Merritt (Refs. 7 and 8).

On comparing the results it is noted, for very small vent to inlet area ratios, that the maximum temperature, occurring 5 milliseconds after the first shock reflection, has been accurately measured by the probe. At this area ratio the temperature-time history is not followed. For the much higher vent to inlet area ratios the probe tends to follow the temperature-time history as indicated from the measurements by Merritt. With the vent to inlet area ratio of about 75% the probe tends to give the correct temperature 20 milliseconds after diaphragm burst but reads too low at the 10 and 15 millisecond stations (a factor of response time) and reads about 5% too high at the 40 and 50 millisecond stations (again probably a function of response time). These observations are based on the premise that the results of Merritt are exact.

The probe was used at other temperatures by raising and lowering the diaphragm pressure ratio. The indications, from the previous test, that the small vent area gives maximum temperature was confirmed for a lower diaphragm pressure ratio of 30 (Fig. 7). For a much higher diaphragm pressure ratio of 100 the temperature-time history was again examined for large vent area and in this case (Fig. 8) at the 30, 40 and 50 millisecond stations the probe leads Merritt's results by about 10%.

The results indicate that the probe recovery factor is 1 and the results from a somewhat similar probe described in Ref. (11) confirm this. w 0.99 av 0.98

It has been noticed that the results achieved throughout the test cycle, accounting for tunnel variation in flow properties from run to

run,/

run, have been very repeatable. Hence a cycle of six runs were planned at as close as possible to similar conditions. The temperatures indicated were within ± 3% of the mean.

5. Future Probe Development

As stated earlier in this report the probe has been developed with the view towards measuring boundary-layer temperature profiles as well as mainstream temperature-time history. As only one temperature reading for any given tunnel run is required within the boundary layer, the maximum temperature over the run is the most useful reading. With this in mind, a miniaturised probe of similar design but with 1/64 in. inlet diameter and nose outside diameter of 1/32 in. is currently being evaluated. A rake of four such probes is planned for the boundary-layer measurements.

Shield temperature accuracy is not a severe requirement as, by reference to Figs. 5-8, it may be noted that an error of 10% in shield temperature gives an error in the temperature reading, for a particular temperature-time point, of about 3-8% depending upon vent/inlet area ratio.

The probe operating characteristics are sufficiently encouraging to suggest its use in shock tunnel measurements over running times of 5-10 milliseconds. Since the thermocouple rapidly indicates any difference between the flow temperature and the shield temperature, a "null" method approach might be suitable for the determination of the average temperature during a shock tunnel run.

6. Conclusions

It has proved possible to manufacture a heated shield, stagnation temperature probe of sufficiently small size to measure boundary-layer temperature profiles. Response times can be made short enough to measure the temperatures within the hypersonic gun tunnel running time.

The estimated accuracy of the maximum temperature measurement is high and is limited by the thermocouple calibration accuracy only.

The measurements, which have been carried out in freestreams of Mach numbers 9·7 and 12·5 and Reynolds number of the order of $2 \cdot 2 \times 10^6$ per foot, have suggested that the probe recovery factor is unity. The maximum temperature that may be recorded is limited to 1500°K at the present stage of development.

Acknowledgements

The authors wish to thank Dr. K. N. C. Bray for his encouragement during the development of this probe.

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References/

References

No.	Author(s)	Title, etc.
1	Billing, B. F.	"Thermocouples - a critical survey" R.A.E. Tech. Note CPM 18. May, 1963.
2	East, R. A. and Perry, J. H.	"A study of the characteristics of gun tunnel operation at 10 000 p.s.i." To be published.
3	Hornung, H.	"Principle of operation of stagnation temperature probe for use in short duration flows". Private Communication, 1965.
4	Irvine, F. H., Picken, J. and Greenwood, G. H.	"Measurements of the response of various thermocouple arrangements". A.R.C.26 187. April, 1964.
5	Ladenburg, R. W., Lewis, B., Pease, R. N. and Taylor, H. S.	"Physical measurements in gas dynamics and combustion". Vol.IX. High speed aerodynamics and jet propulsion. O.U.P. 1955.
6	Liepmann, H. W. and Roshko, A.	"Elements of gasdynamics" Wiley, 1957.
7	Merritt, G. E.	"Velocity measurements in the University of Southampton hypersonic gun tunnel". A.R.C.22 873. April, 1961.
8	Merritt, G. E.	"Hypersonic laminar flows over cavities and steps". Ph.D. Thesis: University of Southampton, May, 1964.
9	Roeser, W. F. and Lonberger, S. I.	"Methods of testing thermocouples and thermocouple material". United States Dept. of Commerce - National Bureau of Standards. N.B.S. Circular 590.
10	Winkler, E. M.	"Stagnation temperature probes for use at high supersonic speeds and elevated temperatures". NAVORD Report 3834. October, 1954.

No.	Author(s)	Title, etc.
11	Harkness, J. L.	"Final report on Heat Transfer investigations in supersonic flow". University of Texas Defense Research Laboratory Report 429, 1958.
12	Andrews, S. A.	"Thermocouples for Gas Temperatures up to 2000°C". Proceedings of the Symposium on "Some Developments in Techniques for Temperature Measurement". London 26th April, 1962. Inst. Mech. Eng.
13	East, R. A.	"The performance and operation of the University of Southampton hypersonic gun tunnel". U.S.A.A. Report No. 135. August, 1960.
14	Edney, B. E.	"The correlation of measured and predicted temperatures in the FFA hypersonic gun tunnel." F.F.A. report AU-209:2. 1965.
15	Meyer, R. F., Campbell, W. F. and Jackson, K. P.	"The NAE hypersonic gun tunnel Part I: the compression heater". N.R.C. Aeronautical report LR-432, August, 1965.
16	Stollery, J. L.	"Stagnation temperature measurements in a hypersonic wind tunnel using the sodium line reversal method". Nature vol.190, No.4778, May 27, 1961. pp.778-781.
17	Brown-Edwards, E. G.	"Temperature measurements in the FFA hypersonic gun tunnel". F.F.A. report AE-194:1. 1965.
18	Bowman, J. E.	"A streak camera method for the measurement of flow velocity in a hypersonic gun tunnel". A.R.C.24 823.

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fig. I - PROTOTYPE PROBE DESIGN

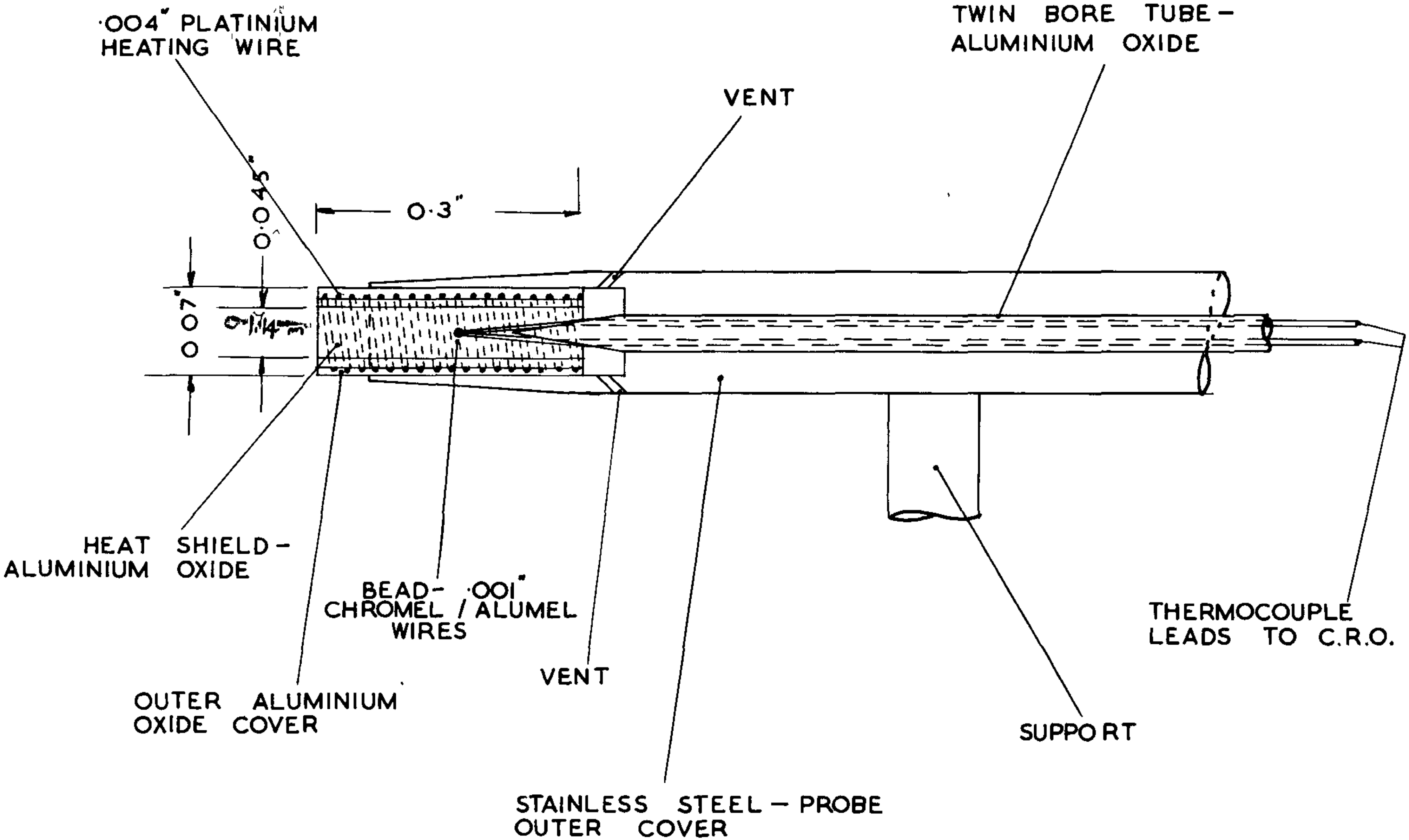

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fig 2 - ARGON ARC DEVICE

FOR JOINING THERMOCOUPLES

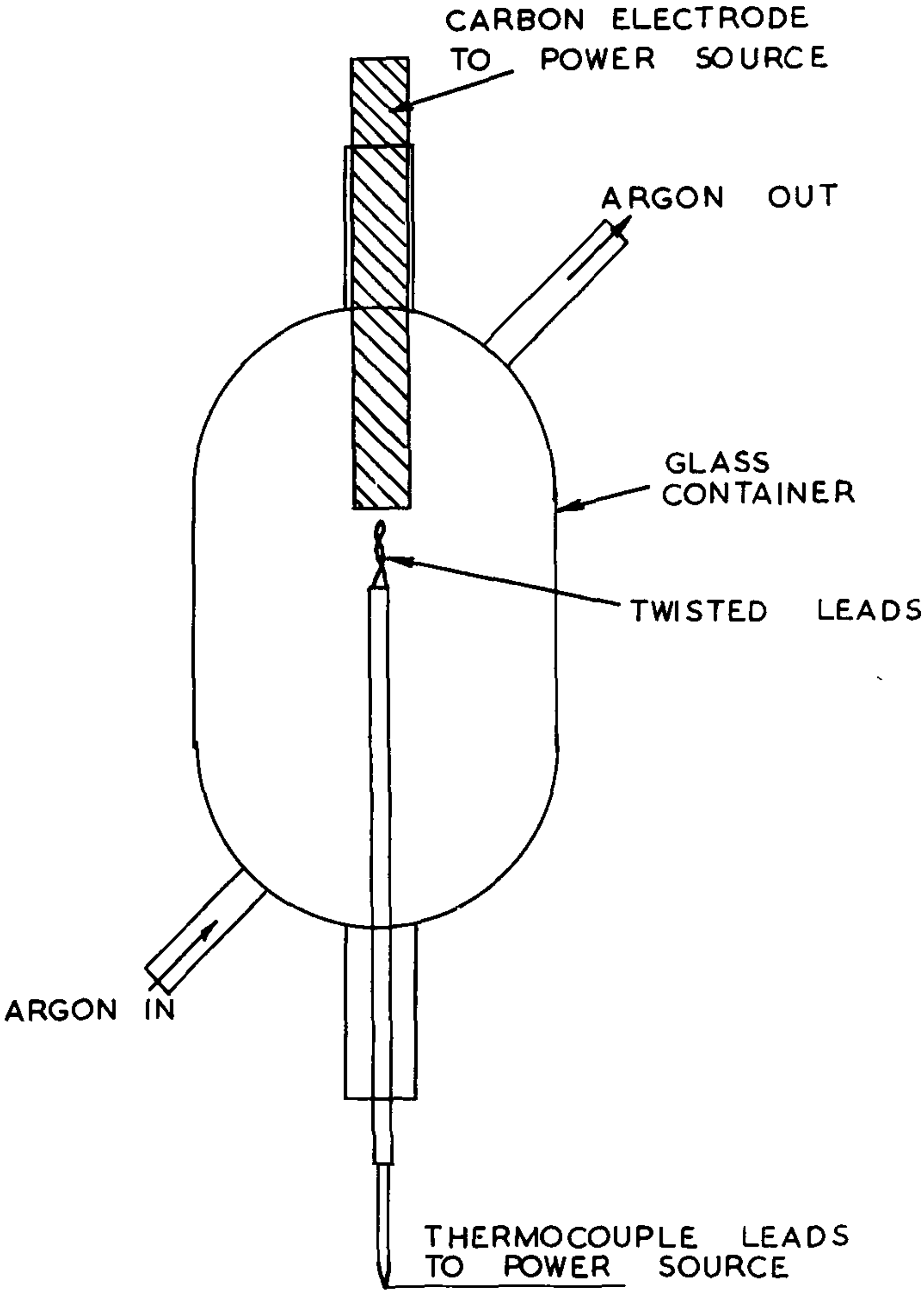
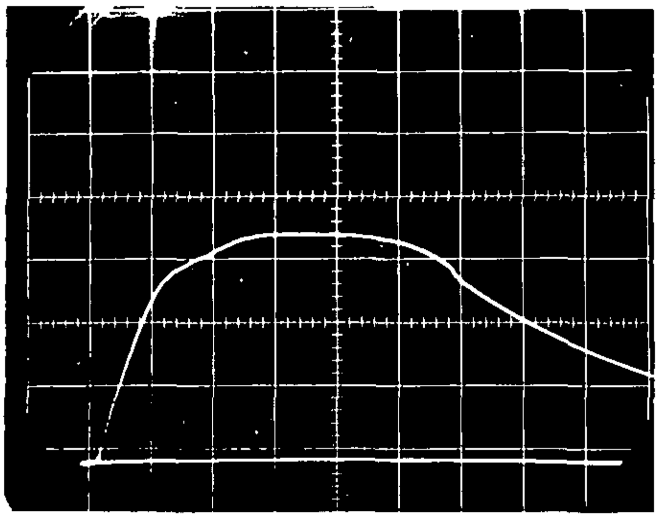


fig. 3 - INFLUENCE OF SHIELD TEMP. ON PROBE INDICATED TEMP.

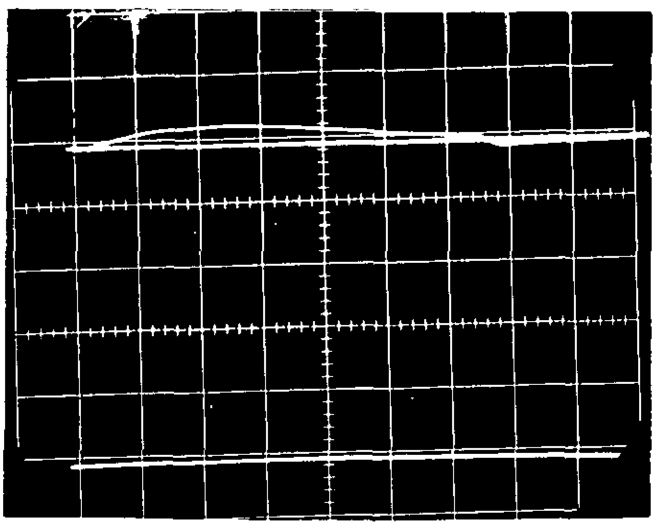
DIAPHRAGM PRESSURE RATIO — 60
PROBE VENT TO INLET AREA RATIO - APPROX. 20%

TIME BASE ·02 SEC./CM.
TEMP. INDICATION — ·005 V./CM.



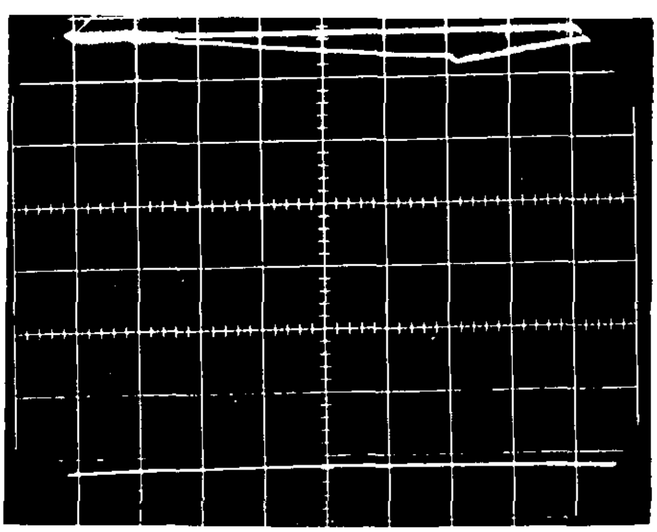
INDICATED TEMPERATURE DURING TUNNEL OPERATION

ZERO SETTING



SHIELD TEMPERATURE
INDICATED TEMPERATURE DURING TUNNEL OPERATION

ZERO SETTING

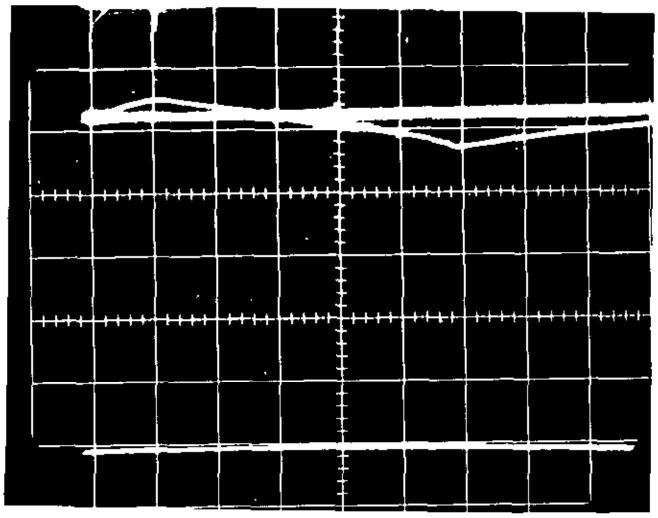


SHIELD TEMPERATURE
INDICATED TEMPERATURE DURING TUNNEL OPERATION

ZERO SETTING

fig4-EFFECT OF ENLARGING THE PROBE VENTS

DIAPHRAGM PRESSURE RATIO — 60



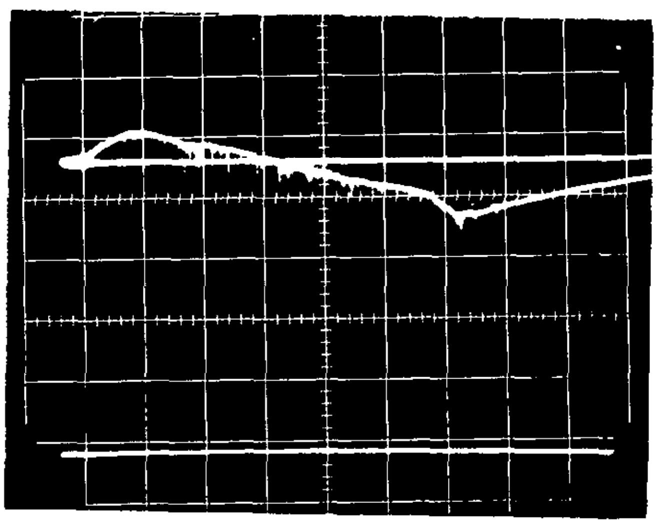
SHIELD TEMPERATURE

INDICATED TEMPERATURE DURING TUNNEL OPERATION

PROBE VENT TO INLET AREA RATIO — 45 %

ZERO SETTING

TIME BASE - 02 SEC /CM
TEMP INDICATION - 005 V. / CM.

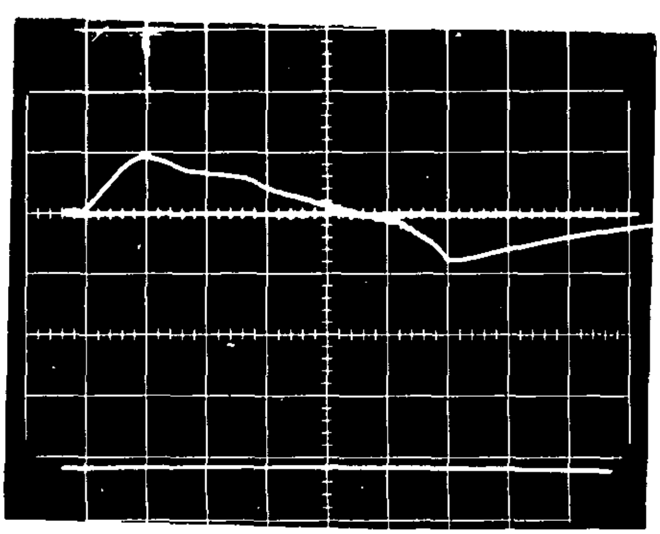


SHIELD TEMPERATURE

INDICATED TEMPERATURE DURING TUNNEL OPERATION

PROBE VENT TO INLET AREA RATIO — 56 %

ZERO SETTING



SHIELD TEMPERATURE

INDICATED TEMPERATURE DURING TUNNEL OPERATION

PROBE VENT TO INLET AREA RATIO — 75 %

ZERO SETTING

fig. 5 - TEMPERATURE ANALYSIS

FOR DIAPHRAGM PRESSURE RATIO OF 60

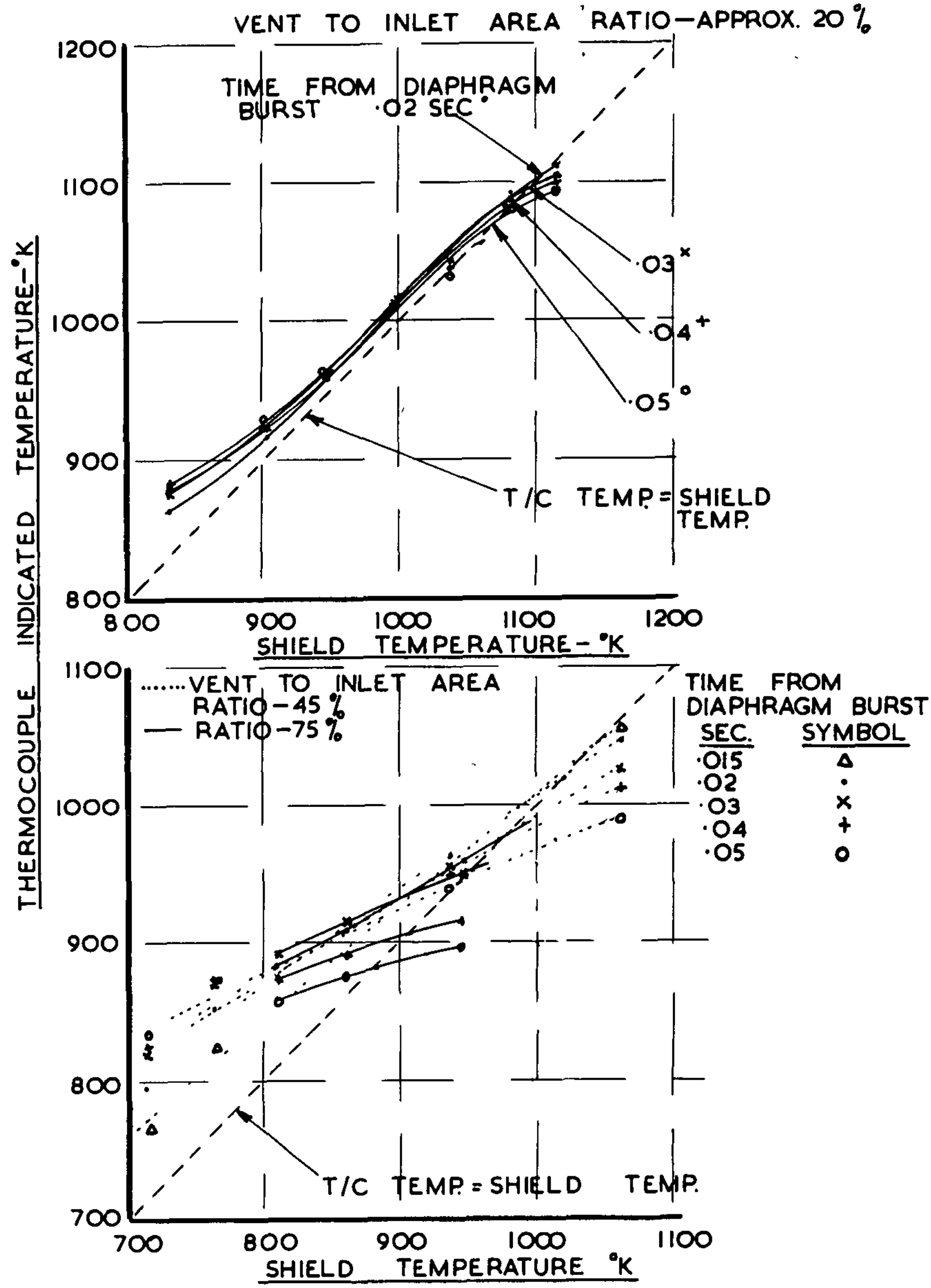


fig. 6 – TEMPERATURE – TIME HISTORY FOR DIAPHRAGM PRESS. RATIO – 60

PROBE VENT TO INLET AREA RATIO – A_v

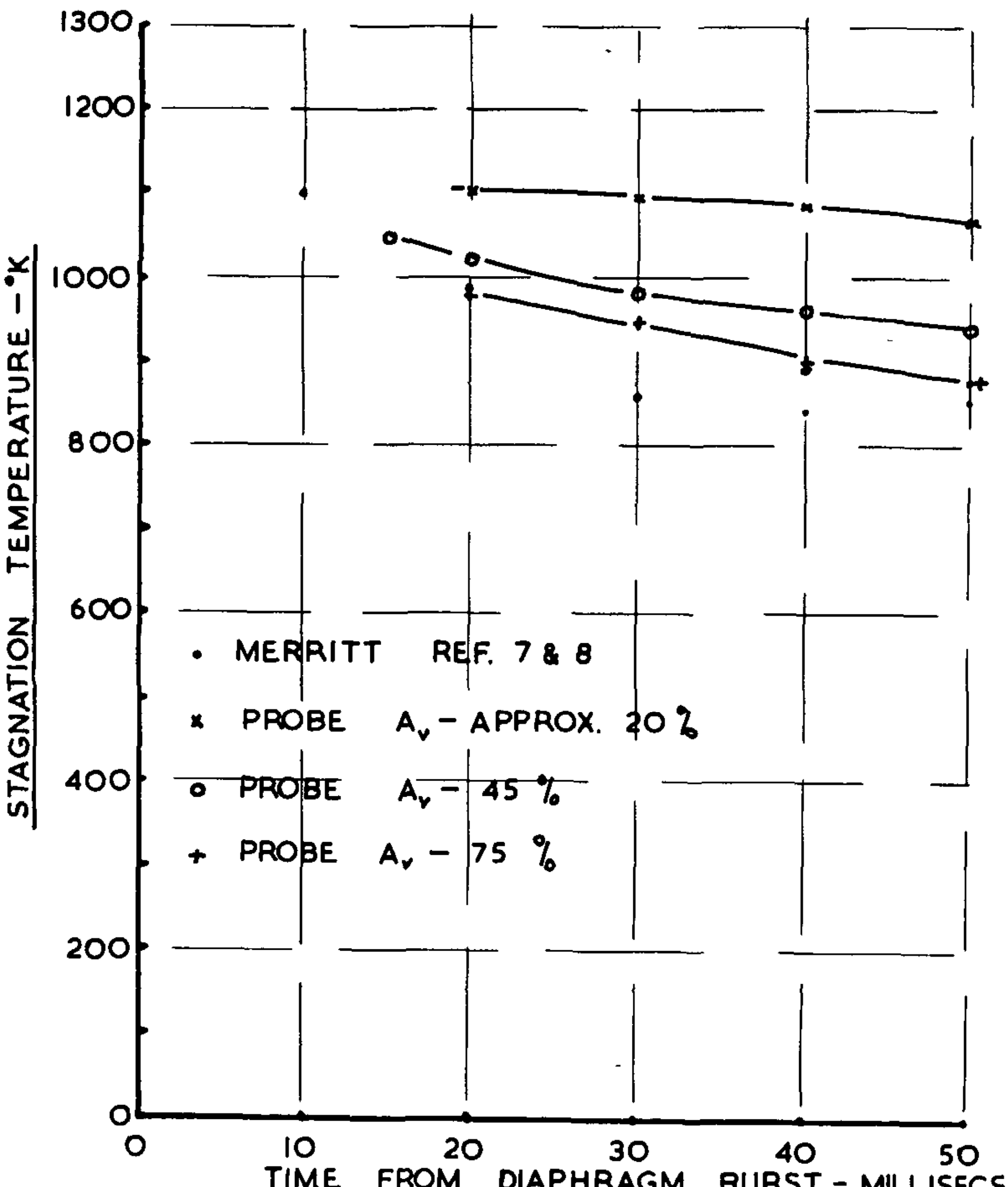


fig. 7 – TEMPERATURE ANALYSIS

FOR DIAPHRAGM PRESSURE RATIO – 30

PROBE INLET TO VENT AREA RATIO – $1/A_v$

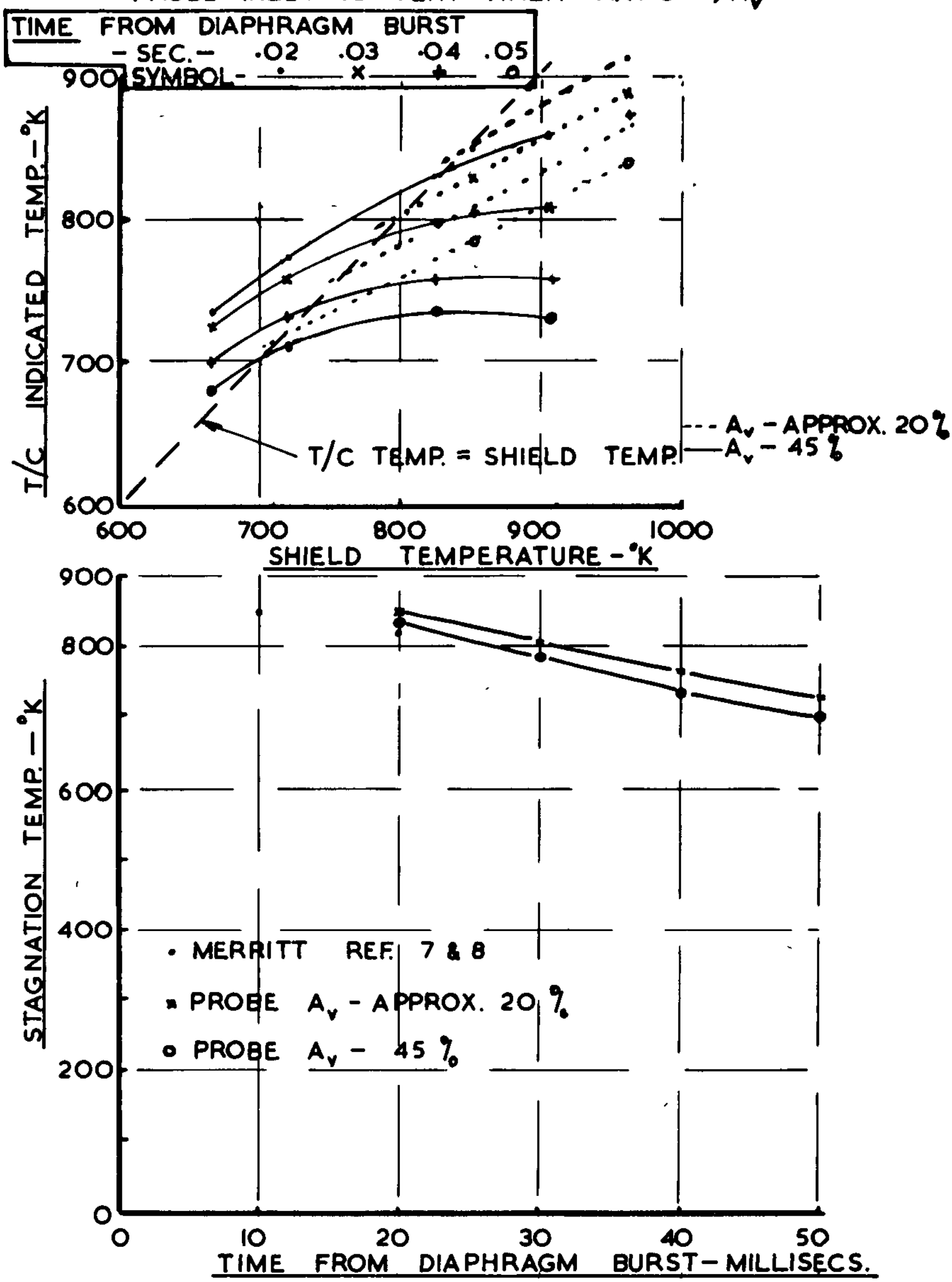
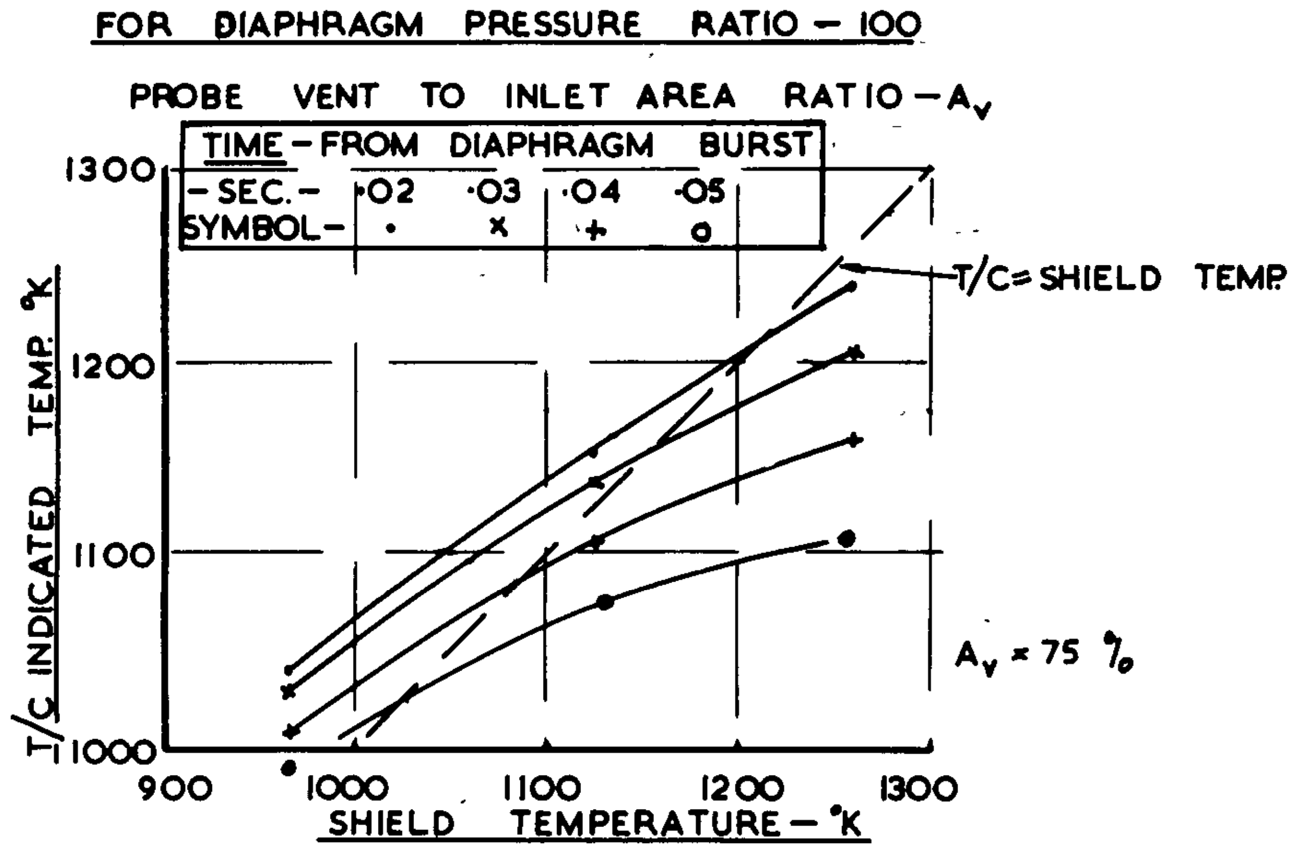
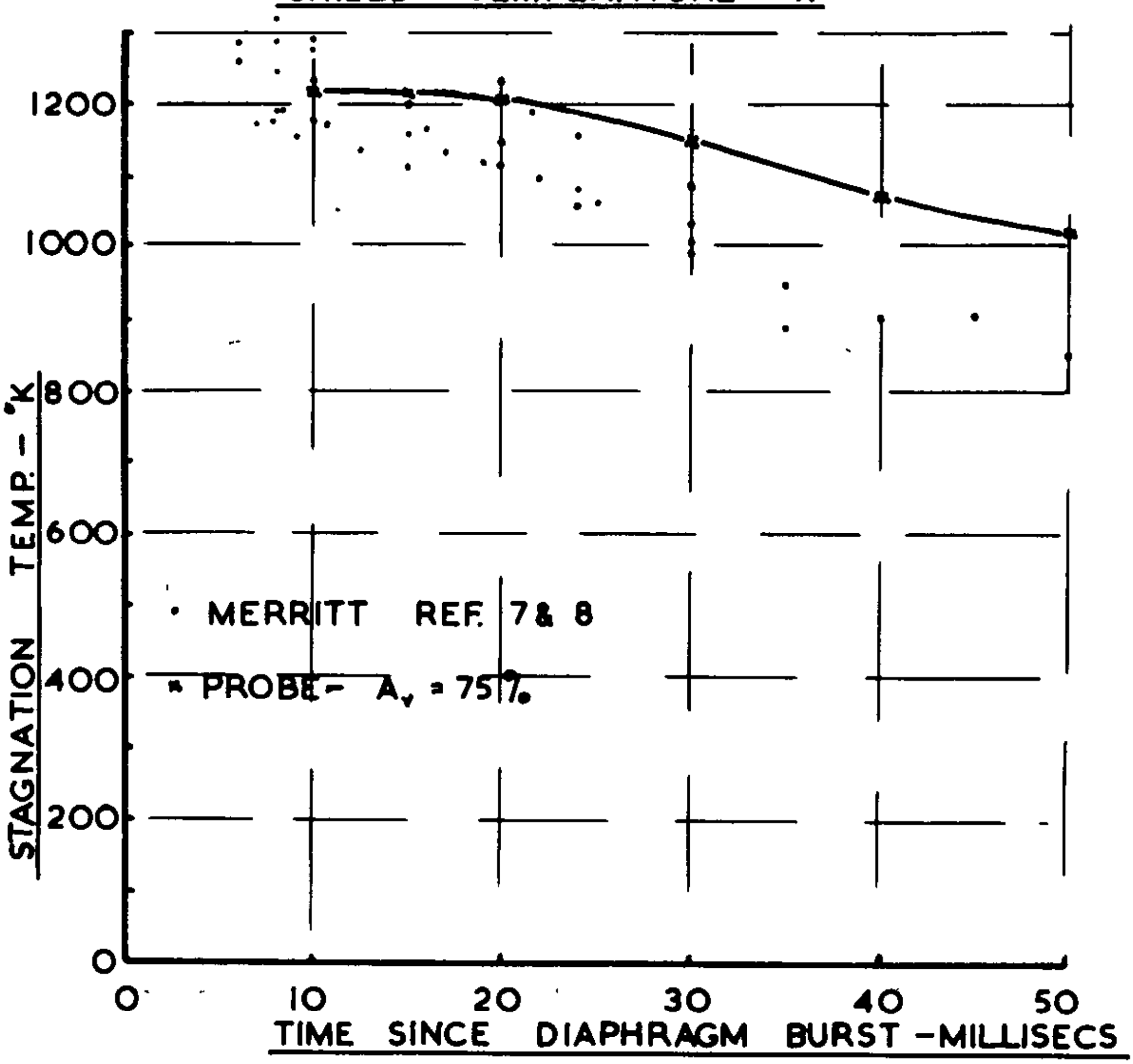


fig. 8.– TEMPERATURE ANALYSIS





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