

C.P. No. 468  
(20,716)  
A.R.C. Technical Report

ROYAL AERONAUTICAL ESTABLISHMENT  
BEDFORD.

C.P. No. 468  
(20,716)  
A.R.C. Technical Report



MINISTRY OF AVIATION  
AERONAUTICAL RESEARCH COUNCIL  
CURRENT PAPERS

Stagnation-Point Heat-Transfer Rate Measurements  
in the Unexpanded Flow of the  
NPL Hypersonic Shock Tunnel

by

*B. D. Henshall, B.Sc., Ph.D.  
of the Aerodynamics Division, N.P.L.*

LONDON: HER MAJESTY'S STATIONERY OFFICE

1960

Price 2s. 0s. net



Stagnation-Point Heat-Transfer Rate Measurements in the  
Unexpanded Flow of the N.P.L. Hypersonic Shock Tunnel

- By -

B. D. Henshall, B.Sc., Ph.D.  
of the Aerodynamics Division, N.P.L.

21st January, 1959

SUMMARY

Thin-film resistance thermometers have been used to determine the heat transfer rate to the stagnation point of  $\frac{3}{4}$ -inch diameter glass spheres in shock tube flows in air with real gas stagnation temperatures up to 6,000°K. The experimental results average 22% lower than the theoretical values predicted by Fay and Riddell.

1. Introduction

The N.P.L. hypersonic shock tunnel was designed as a facility for the investigation of hypersonic aerodynamic problems; the conditions in the working section may be adjusted to correspond to hypersonic flight in the stratosphere with one or more of the following parameters - stagnation enthalpy, altitude, velocity and Mach number - simulated correctly. Some typical operating conditions are discussed in Refs.1 and 2.

One hypersonic flow problem, the stagnation point heat transfer rate to a blunt body, may be studied in the straight channel (unexpanded flow) of a shock tunnel. In this case the difference between the flight and test Mach numbers can be neglected because the flow fields in the neighbourhood of the stagnation point are virtually independent of Mach number. Therefore duplication of stagnation pressure and stagnation enthalpy should be sufficient to define complete simulation of flight conditions in the shock tunnel experiments.

This paper gives a description of an experimental investigation of the heat transfer rates to the stagnation points of  $\frac{3}{4}$ -inch diameter glass sphere models in unexpanded shock tunnel airflow for a range of initial shock tunnel conditions and, therefore, stagnation temperatures and pressures. The experimental results show good agreement with experimental results obtained at the N.A.C.A. Langley Laboratory (Ref.3) and the A.V.C.O. Research Laboratory (Refs.4 and 5). All the experimental results are shown to be significantly lower than the theoretical predictions of Fay and Riddell (Ref.6).

2./

Recommended by the Director, National Physical Laboratory.

## 2. Experimental Methods

The results reported below were made in the 3-inch diameter channel of the N.P.L. hypersonic shock tunnel. In all the experiments the driver gas in the chamber was 'cold', i.e. room temperature, hydrogen and the driven gas in the channel was undried room temperature air. A description of the shock tunnel and its instrumentation is given in Ref.2 and details of the method of shock speed measurement and determination of the duration of the hot flow behind the primary shock wave appear in Ref.7. A schematic diagram of the instrumentation of the N.P.L. hypersonic shock tunnel is shown in Fig.1.  $A_1, B_1, C_1$  etc.  $A_2, B_2, C_2$ , etc. are all thin film resistance thermometer stations. In the current series of tests of heat transfer rate measurements, the  $\frac{3}{4}$ -inch diameter soda glass model was mounted in the shock tunnel at the position labelled  $F_1$  in Fig.1. This station is  $31\frac{1}{2}$  feet from the primary diaphragm. The incident shock Mach number  $M_s^*$  was varied from 6.5 to 10.5 in this series of experiments by variation of the initial channel pressure  $p_1$  and/or the initial chamber pressure.

A photograph of an assembled model and its support appears as Fig.2. The "stagnation point" resistance thermometer consists of a thin film of Hanovia Type 05 Liquid Bright Platinum which has been hand painted on to the model and 'fired' at  $580^\circ\text{C}$  in an oven for 30 minutes. Full details of the methods employed at the N.P.L. in the construction and calibration of resistance thermometer models are given in Ref.8. Here it is sufficient to note that models can be calibrated in some standard repeatable manner and the value of the "calibration constant"  $\frac{\alpha}{\sqrt{\rho c K}}$

determined for each model to  $\pm 5\%$ . Furthermore, Ref.8 gives worked examples of the data reduction methods used at N.P.L., and quantitative estimates of the errors involved in heat transfer measurements in shock tunnels. The stagnation point heat transfer rate measurements reported below would have a probable error of  $\pm 20\%$  according to the estimates of Ref.8.

The models used in these experiments were discarded when the resistance of the element had risen to greater than 125% of the original value, or when the film failed on recalibration. Models were recalibrated when their resistance became 5% greater than the previous value.

## 3. Data Reduction

The following equations were used to determine the stagnation-point heat transfer rate  $\dot{q}$  :-

(a) Constant Heat Transfer Rate  $\dot{q}$

$$\dot{q} = \frac{4.19 \sqrt{\pi}}{2 E_{f0}} \left( \frac{\sqrt{\rho c K}}{\alpha} \right) \left( \frac{E(t)}{\sqrt{t}} \right)$$

or (b) Non-constant Heat Transfer Rate  $\dot{q}(t)$

$$\dot{q}(t) = \frac{4.19}{2\sqrt{\pi} E_{f0}} \left( \frac{\sqrt{\rho c K}}{\alpha} \right) \left\{ \frac{2E(t)}{\sqrt{t}} + \int_0^t \frac{E(t) - E(\tau)}{(t - \tau)^{3/2}} d\tau \right\}$$

where  $E_{f0}$  is the voltage drop across the thin film resistance thermometer of initial resistance  $R_0$  ( $\sim 50 \Omega$ ) carrying a constant current  $I_0$  ( $\sim 20$  milli-amperes).

During/

\* For notation - See Appendix.

During an experiment the temperature rise of the thin film resistance thermometer appears as a voltage variation across the film since the current supplied to the film is constant. This voltage variation  $E(t)$  is displayed on an oscilloscope as a function of time  $t$ , and thus we can calculate the heat transfer rate  $q$  from the above equations if the 'calibration constant'  $\frac{c}{\sqrt{\rho c K}}$  is known.

Two specimen experimental results of this series are shown in Fig.3. The vertical sensitivity of the oscilloscope is 50 millivolts/cm and the horizontal sweep is 50 microseconds/cm. The initial sharp voltage jump as the primary shock hits the model is followed by a parabolic rise of voltage with time until the contact surface arrives and the hot flow ends. A plot of  $[E(t)]^2$  against time was a very good straight line in all these experiments showing the heat transfer rate to be constant throughout the running time. This fact was checked by evaluating some results on the non-constant heat transfer rate analysis. The differences from the constant rate analysis were in all cases less than  $\pm 3\%$  which is much less than the experimental errors, estimated at  $\pm 20\%$ . Therefore all values quoted below have been obtained through the use of the simple constant heat transfer rate analysis. One further correction to the data has been made. This allows for the fact that the heat transfer rate was not measured at the stagnation "point" but over a film of finite area measuring 1 mm by 5 mm approximately. The film covers  $\pm 15^\circ$  from the stagnation point along its larger dimension. Therefore the heat transfer rate as measured is an average over this area and is only 95% of the true stagnation point heat transfer rate assuming a Newtonian pressure distribution over the nose of the model.

#### 4. Discussion of Results

Fig.4 and Table 1 present the results of the present investigation together with corresponding data from similar thin-film resistance thermometer experiments conducted at N.A.C.A. Langley Laboratory (Ref.3) and A.V.C.O. Research Laboratory (Refs.4 and 5). The theoretical values in Table 1 are derived from the theory of Fay and Riddell (Ref.6) and it is clear that this theory gives appreciably higher values of the stagnation point heat transfer rate than the experiments. It should be noted that thick-film or calorimeter gauge experiments made at the A.V.C.O. Research Laboratory agree very well with the theoretical curve of Fig.4. No satisfactory explanation of this discrepancy between thin-and thick-film results has been advanced to date. However, it is clear that the results from thin-film gauges are about 20% lower than those obtained from calorimeter gauges and, furthermore, three separate laboratories have now reported this fact. The experimental values are expressed as a percentage of the corresponding theoretical values for the same shock Mach numbers in Table 1. The % mean and the % standard deviation were calculated for the three series of results and it was found that the A.V.C.O., N.P.L. and N.A.C.A. results gave experimental stagnation point heat transfer rates which were respectively  $15\% \pm 16\%$ ,  $22\% \pm 17\%$  and  $38\% \pm 12\%$  lower than the theoretical values of Fay and Riddell (Ref.6). The % standard deviation (17%) of the N.P.L. results compares favourably with our previous estimate (Ref.8) that the experimental errors would be about  $\pm 20\%$ .

#### 5. Conclusions

Thin-film platinum resistance thermometers have been used to determine the stagnation point heat transfer rates at the nose of  $\frac{3}{4}$ -inch diameter glass models in the unexpanded flow of the N.P.L. hypersonic shock tunnel.

The results of the present tests agree with those reported by N.A.C.A. Langley Laboratory and A.V.C.O. Research Laboratory but are about 22% lower than the values predicted by the theory of Fay and Riddell.

Acknowledgements/

### Acknowledgements

Mr. P. S. Pusey assisted in the experimental work and  
Mrs. N. A. North performed most of the data reduction.

---

### References

| <u>No.</u> | <u>Author(s)</u>                       | <u>Title, etc.</u>                                                                                                                                                                    |
|------------|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1          | B. D. Henshall<br>and<br>G. E. Gadd    | Factors affecting the performance of the nozzle<br>of a hypersonic shock tunnel.<br>A.R.C. C.P.293. February, 1956.                                                                   |
| 2          | D. L. Schultz<br>and<br>B. D. Henshall | Hypersonic shock tunnel equipment at the National<br>Physical Laboratory.<br>NPL/Aero/325. May, 1957.                                                                                 |
| 3          | A. P. Sabol                            | Measurements in a shock tube of heat transfer rates<br>at the stagnation point of a 1 inch diameter sphere<br>for real-gas temperatures up to 7,900°R.<br>NACA TN 4354. August, 1958. |
| 4          | P. H. Rose<br>and<br>W. I. Stark       | Stagnation-point heat transfer measurements in air<br>at high temperature.<br>A.V.C.O. Research Laboratory<br>Research Note 24. December, 1956.                                       |
| 5          | P. H. Rose<br>and<br>W. I. Stark       | Stagnation-point heat transfer measurements in<br>dissociated air.<br>A.V.C.O. Research Laboratory<br>Research Report 3. April, 1957.                                                 |
| 6          | J. A. Fay<br>and<br>F. R. Riddell      | Theory of stagnation-point heat-transfer in<br>dissociated air.<br>A.V.C.O. Research Laboratory<br>Research Report 1. April, 1957.                                                    |
| 7          | B. D. Henshall                         | Shock speed and running time measurements in<br>the N.P.L. hypersonic shock tunnel.<br>C.P.443. January 1959.                                                                         |
| 8          | B. D. Henshall<br>and<br>D. L. Schultz | Some notes on the use of resistance thermometers<br>for the measurement of heat transfer rates in<br>shock tubes.<br>C.P.408. . May, 1958.                                            |

---

APPENDIX/

- 5 -

APPENDIX

Notation

|               |                                                           |
|---------------|-----------------------------------------------------------|
| $a_1$         | speed of sound ahead of incident shock                    |
| $c$           | specific heat cal/gm°C                                    |
| $E$           | voltage                                                   |
| $I_0$         | constant current through thin film resistance thermometer |
| $K$           | thermal conductivity cal/cm °C sec                        |
| $M_{S_1}$     | shock Mach number = (velocity of shock)/ $a_1$            |
| $p_1$         | initial pressure in channel of shock tube                 |
| $R_0$         | initial resistance of thin film                           |
| $R$           | nose radius of model                                      |
| $\dot{q}$     | heat transfer rate watts/cm <sup>2</sup>                  |
| $T$           | temperature, °C                                           |
| $t$ or $\tau$ | time                                                      |
| $U$           | velocity ft/sec                                           |
| $\alpha$      | temperature coefficient of resistance (°C) <sup>-1</sup>  |
| $\rho$        | density gm/cm <sup>3</sup>                                |

Table 1/



Table 1

Stagnation Point Heat Transfer Rates in Unexpanded Shock Tunnel Flow

| A.V.C.O.                      |                                                     |        |            | N.P.L.                        |                                                     |        |            |
|-------------------------------|-----------------------------------------------------|--------|------------|-------------------------------|-----------------------------------------------------|--------|------------|
| Shock<br>Mach<br>No.<br>$M_s$ | Reduced<br>Heat Transfer<br>Rate Kw/cm <sup>2</sup> |        | %<br>Expt. | Shock<br>Mach<br>No.<br>$M_s$ | Reduced<br>Heat Transfer<br>Rate Kw/cm <sup>2</sup> |        | %<br>Expt. |
|                               | Expt.                                               | Theory | Theory     |                               | Expt.                                               | Theory | Theory     |
| 6.15                          | 0.69                                                | 0.79   | 87         | 6.59                          | 0.64                                                | 1.03   | 62         |
| 6.2                           | 0.87                                                | 0.81   | 107        | 6.69                          | 0.72                                                | 1.09   | 66         |
| 6.3                           | 0.77                                                | 0.86   | 90         | 6.71                          | 0.66                                                | 1.10   | 60         |
| 6.7                           | 0.85                                                | 1.10   | 77         | 6.87                          | 0.77                                                | 1.20   | 64         |
| 7.05                          | 1.16                                                | 1.34   | 87         | 6.87                          | 0.84                                                | 1.20   | 70         |
| 7.1                           | 1.31                                                | 1.38   | 95         | 6.91                          | 0.89                                                | 1.23   | 72         |
| 7.2                           | 1.79                                                | 1.45   | 123        | 6.97                          | 0.90                                                | 1.27   | 71         |
| 7.7                           | 2.11                                                | 1.87   | 113        | 7.14                          | 0.99                                                | 1.40   | 71         |
| 8.7                           | 1.87                                                | 2.90   | 64         | 7.16                          | 0.99                                                | 1.42   | 70         |
| 8.7                           | 2.11                                                | 2.90   | 73         | 7.16                          | 1.62                                                | 1.42   | 114        |
| 8.8                           | 2.84                                                | 3.00   | 95         | 7.17                          | 1.06                                                | 1.43   | 74         |
| 8.9                           | 3.09                                                | 3.11   | 99         | 7.19                          | 1.08                                                | 1.44   | 75         |
| 8.9                           | 2.76                                                | 3.11   | 89         | 7.2                           | 1.56                                                | 1.45   | 108        |
| 8.95                          | 3.17                                                | 3.20   | 99         | 7.23                          | 1.56                                                | 1.47   | 106        |
| 9                             | 3.49                                                | 3.25   | 107        | 7.24                          | 1.14                                                | 1.48   | 77         |
| 9                             | 2.68                                                | 3.25   | 82         | 7.31                          | 1.70                                                | 1.52   | 112        |
| 9                             | 1.95                                                | 3.25   | 60         | 7.31                          | 1.16                                                | 1.52   | 76         |
| 9.05                          | 3.17                                                | 3.30   | 96         | 7.32                          | 1.67                                                | 1.54   | 108        |
| 9.1                           | 2.92                                                | 3.38   | 86         | 7.32                          | 1.65                                                | 1.54   | 107        |
| 9.1                           | 2.52                                                | 3.38   | 75         | 7.34                          | 1.75                                                | 1.56   | 112        |
| 9.1                           | 3.09                                                | 3.38   | 91         | 7.34                          | 1.19                                                | 1.56   | 76         |
| 9.1                           | 2.19                                                | 3.38   | 65         | 7.39                          | 1.20                                                | 1.60   | 75         |
| 9.2                           | 2.60                                                | 3.50   | 74         | 7.40                          | 1.12                                                | 1.61   | 70         |
| 9.2                           | 3.01                                                | 3.50   | 86         | 7.41                          | 1.22                                                | 1.62   | 75         |
| 9.2                           | 2.36                                                | 3.50   | 67         | 7.5                           | 1.91                                                | 1.70   | 89         |
| 9.25                          | 2.27                                                | 3.57   | 64         | 7.64                          | 1.70                                                | 1.80   | 94         |
| 9.3                           | 3.25                                                | 3.62   | 90         | 7.74                          | 1.17                                                | 1.90   | 62         |
| 9.4                           | 2.48                                                | 3.78   | 66         | 7.74                          | 1.39                                                | 1.90   | 73         |
| 9.6                           | 2.76                                                | 4.07   | 68         | 7.75                          | 1.39                                                | 1.91   | 73         |
| N.A.C.A.                      |                                                     |        |            | 7.84                          | 1.72                                                | 2.0    | 86         |
| 5.46                          | 0.336                                               | 0.50   | 67         | 7.88                          | 1.35                                                | 2.03   | 67         |
| 5.93                          | 0.57                                                | 0.63   | 84         | 7.95                          | 1.43                                                | 2.10   | 68         |
| 6.38                          | 0.50                                                | 0.91   | 55         | 8.11                          | 1.64                                                | 2.26   | 73         |
| 6.40                          | 0.71                                                | 0.92   | 77         | 8.13                          | 1.90                                                | 2.29   | 83         |
| 6.69                          | 0.61                                                | 1.09   | 56         | 8.25                          | 1.97                                                | 2.40   | 82         |
| 7.24                          | 0.71                                                | 1.48   | 48         | 8.88                          | 1.66                                                | 3.10   | 54         |
| 7.35                          | 0.92                                                | 1.57   | 59         | 8.91                          | 1.71                                                | 3.14   | 54         |
| 7.84                          | 0.90                                                | 2.00   | 45         | 8.97                          | 2.61                                                | 3.20   | 82         |
| 8.32                          | 1.46                                                | 2.48   | 59         | 9.09                          | 2.03                                                | 3.37   | 60         |
| 9.14                          | 2.54                                                | 3.41   | 74         | 9.26                          | 1.69                                                | 3.60   | 47         |
|                               |                                                     |        |            | 9.43                          | 3.29                                                | 3.81   | 86         |
|                               |                                                     |        |            | 10.48                         | 4.69                                                | 5.4    | 87         |

N.A.C.A. Results are  $38\% \pm 12\%$  lower than theory.

A.V.C.O. Results are  $15\% \pm 16\%$  lower than theory.

N.P.L. Results are  $22\% \pm 17\%$  lower than theory.



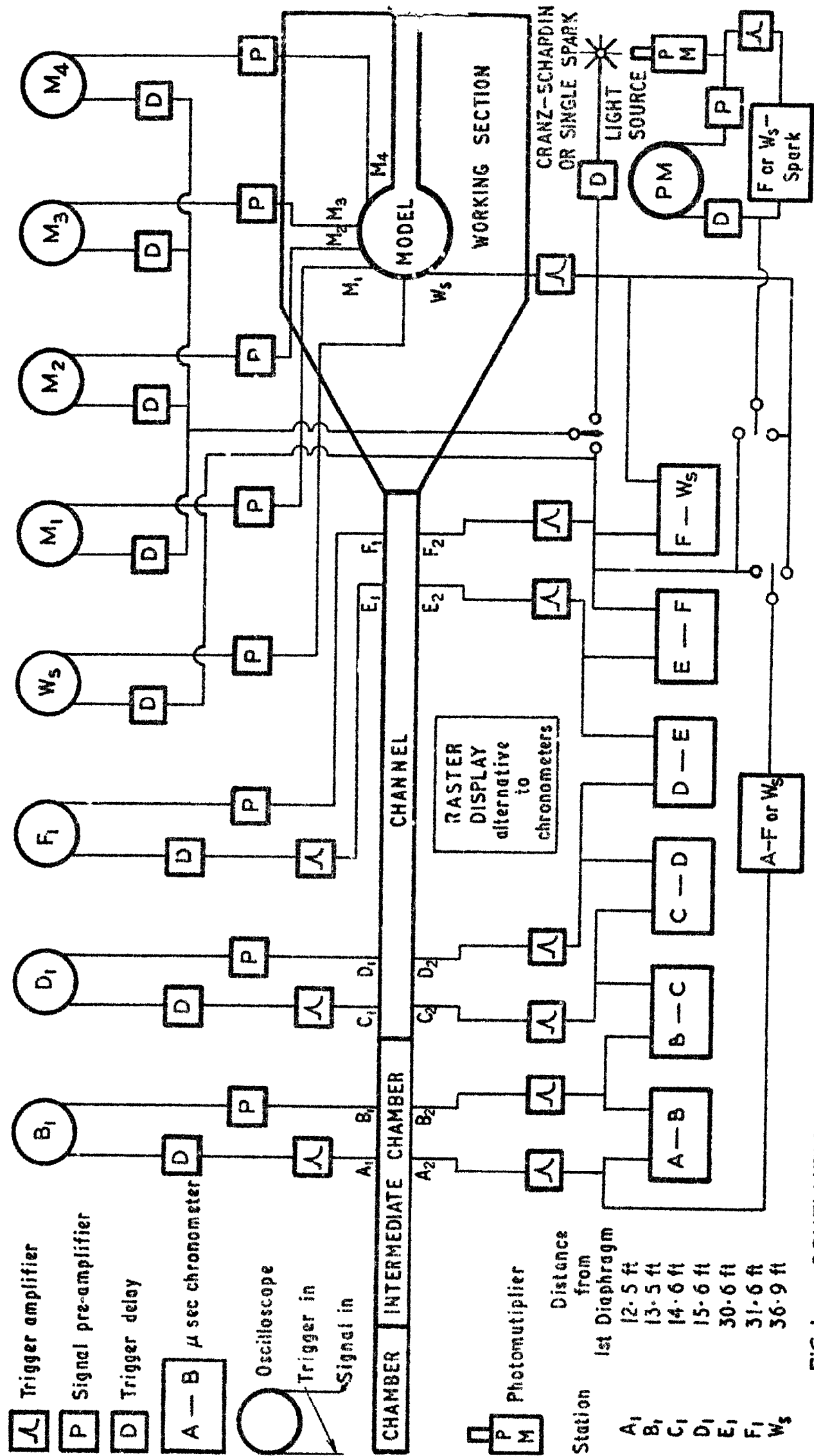
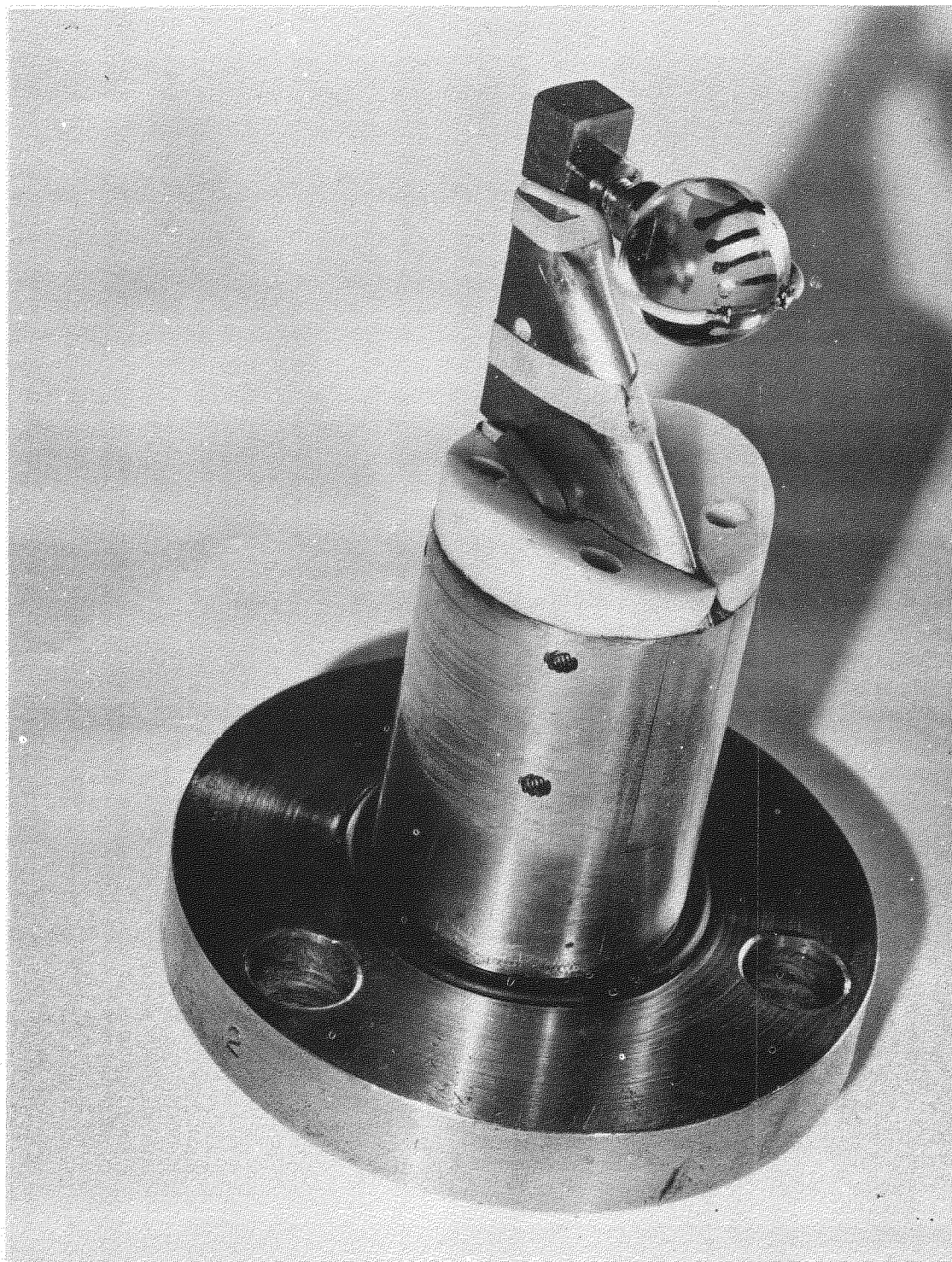


FIG.1. SCHEMATIC DIAGRAM OF INSTRUMENTATION OF NPL HYPERSONIC SHOCK TUNNEL



FIG. 2.

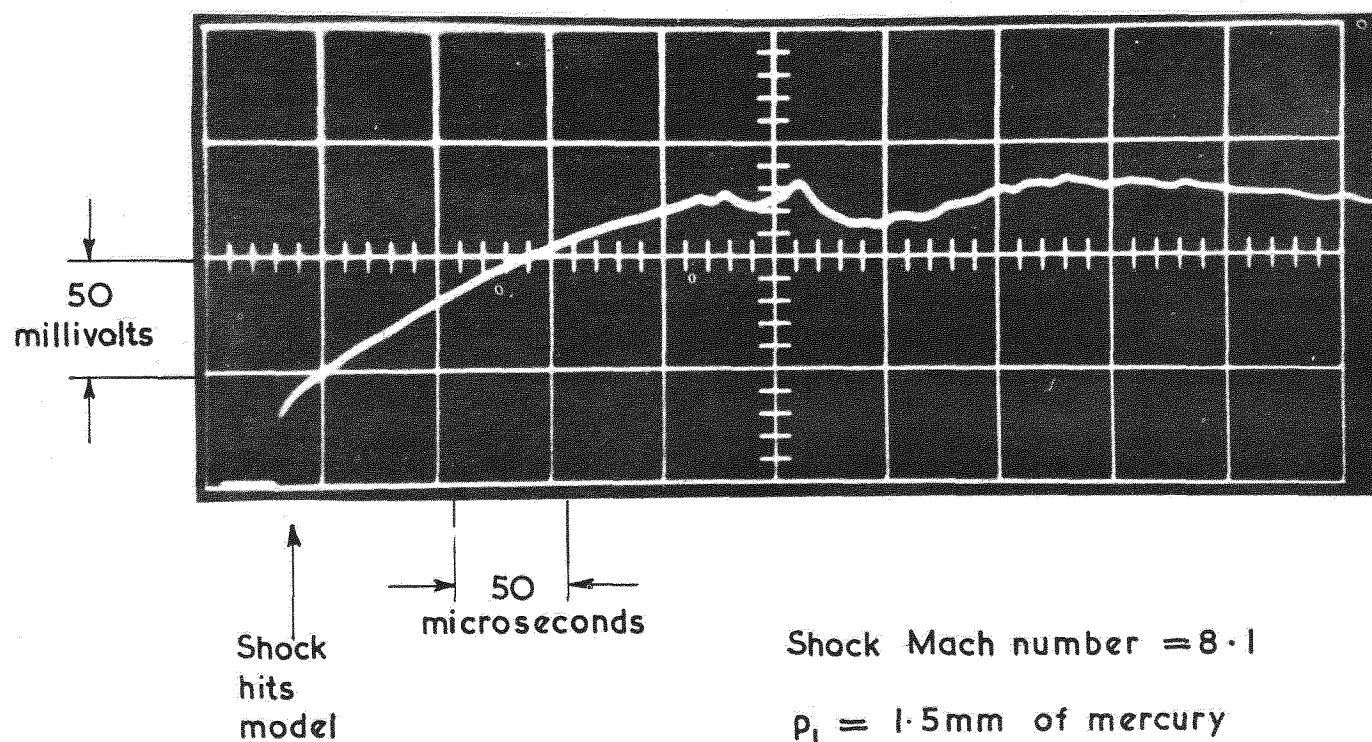


PHOTOGRAPH OF STAGNATION POINT HEAT TRANSFER  
MODEL USED IN UNEXPANDED FLOW OF NPL HYPERSONIC  
SHOCK TUNNEL

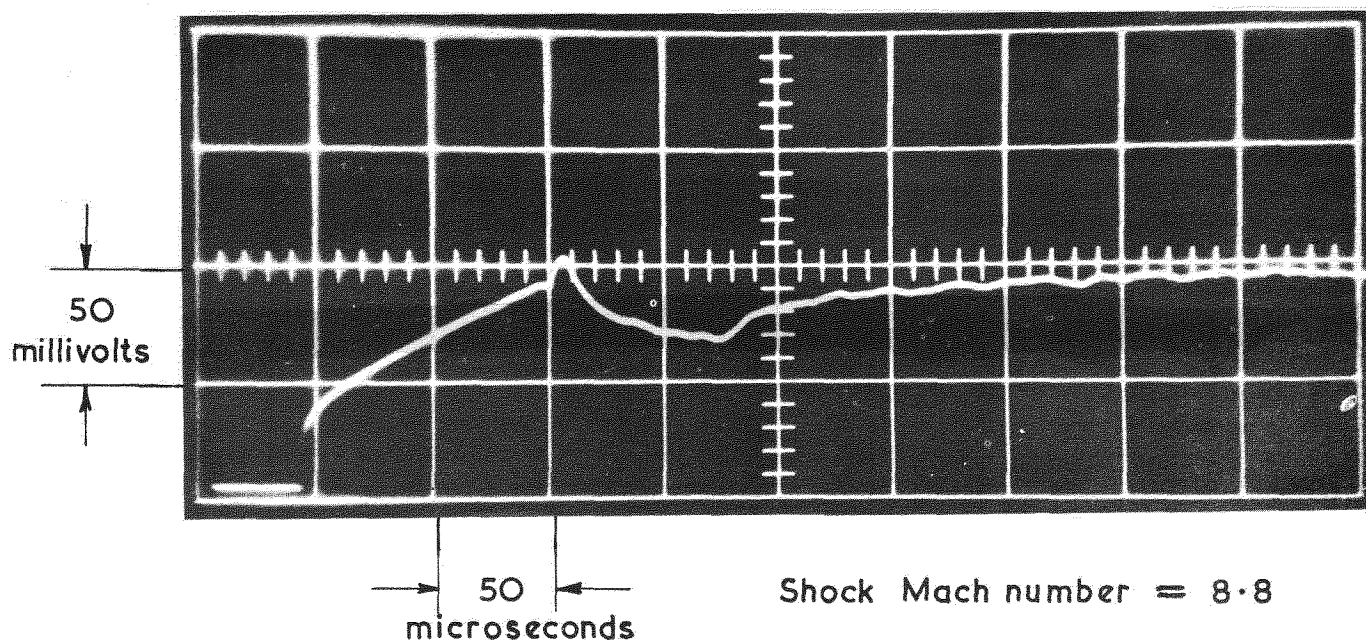


**FIG. 3**

Arrival of contact  
surface

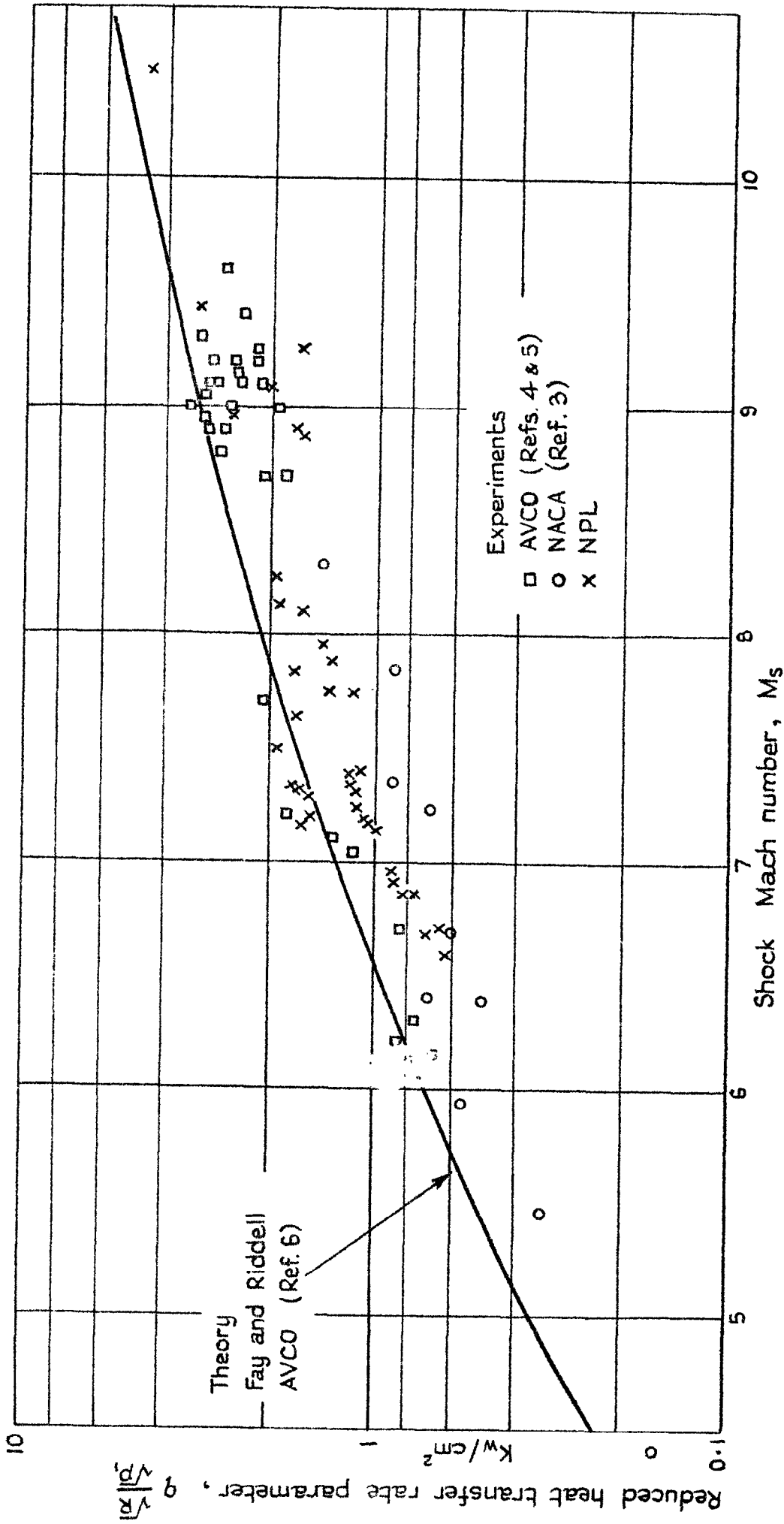


HEAT TRANSFER RATE  $\dot{q}$  (constant for 180  $\mu\text{sec}$ ) = 1.66 KW/cm<sup>2</sup>



HEAT TRANSFER RATE  $\dot{q}$  (constant for 110  $\mu\text{sec}$ ) = 1.70 KW/cm<sup>2</sup>

Fig. 4.



$p_1$  = Channel pressure (mm of mercury)

$R_1$  = Model nose radius (millimetres)

Stagnation point heat transfer rates in unexpanded shock tube flow





**C.P. No. 468**  
(20,716)  
**A.R.C. Technical Report**

© *Crown copyright 1960*

Printed and published by  
**HER MAJESTY'S STATIONERY OFFICE**

To be purchased from  
York House, Kingsway, London w.c.2  
423 Oxford Street, London w.1  
13A Castle Street, Edinburgh 2  
109 St. Mary Street, Cardiff  
39 King Street, Manchester 2  
Tower Lane, Bristol 1  
2 Edmund Street, Birmingham 3  
80 Chichester Street, Belfast 1  
or through any bookseller

*Printed in England*

**S.O. Code No. 23-9011-68**

**C.P. No. 468**