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A.R.C. Technical Report

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by

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

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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).

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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°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 ± 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 ± 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 $\dot{q}$

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

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

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

where E_{fo} is the voltage drop across the thin film resistance thermometer of initial resistance R_o (~ 50 Ω) carrying a constant current I_o (~ 20 milli-amperes).

During/

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* 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 $\dot{q}$ from the above equations if the 'calibration constant' $\frac{\alpha}{\sqrt{\rho cK}}$ 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 ± 3% which is much less than the experimental errors, estimated at ± 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 ± 15° 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% ± 16%; 22% ± 17% and 38% ± 12% <u>lower</u> 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 ± 20%.

5. Conclusions

Thin-film platinum resistance thermometers have been used to determine the stagnation point heat transfer rates at the nose of ¾-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.

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APPENDIX/

APPENDIX

Notation

a_1	speed of sound ahead of incident shock
c	specific heat cal/gm°C
E	voltage
I_o	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_o	initial resistance of thin film
R	nose radius of model
$\dot{q}$	heat transfer rate watts/cm^2
T	temperature, °C
t or τ	time
U	velocity ft/sec
α	temperature coefficient of resistance $(°C)^{-1}$
ρ	density gm/cm^3

Table 1/

Table 1

Stagnation Point Heat Transfer Rates in Unexpanded Shock Tunnel Flow

A.V.C.O.

Shock Mach No. M_s	Reduced Heat Transfer Rate Kw/cm²		% Expt. / Theory
	Expt.	Theory	
6.15	0.69	0.79	87
6.2	0.87	0.81	107
6.3	0.77	0.86	90
6.7	0.85	1.10	77
7.05	1.16	1.34	87
7.1	1.31	1.38	95
7.2	1.79	1.45	123
7.7	2.11	1.87	113
8.7	1.87	2.90	64
8.7	2.11	2.90	73
8.8	2.84	3.00	95
8.9	3.09	3.11	99
8.9	2.76	3.11	89
8.95	3.17	3.20	99
9	3.49	3.25	107
9	2.68	3.25	82
9	1.95	3.25	60
9.05	3.17	3.30	96
9.1	2.92	3.38	86
9.1	2.52	3.38	75
9.1	3.09	3.38	91
9.1	2.19	3.38	65
9.2	2.60	3.50	74
9.2	3.01	3.50	86
9.2	2.36	3.50	67
9.25	2.27	3.57	64
9.3	3.25	3.62	90
9.4	2.48	3.78	66
9.6	2.76	4.07	68

N.A.C.A.

Shock Mach No. M_s	Expt.	Theory	% Expt. / Theory
5.46	0.336	0.50	67
5.93	0.57	0.68	84
6.38	0.50	0.91	55
6.40	0.71	0.92	77
6.69	0.61	1.09	56
7.24	0.71	1.48	48
7.35	0.92	1.57	59
7.84	0.90	2.00	45
8.32	1.46	2.48	59
9.14	2.54	3.41	74

N.P.L.

Shock Mach No. M_s	Reduced Heat Transfer Rate Kw/cm²		% Expt. / Theory
	Expt.	Theory	
6.59	0.64	1.03	62
6.69	0.72	1.09	66
6.71	0.66	1.10	60
6.87	0.77	1.20	64
6.87	0.84	1.20	70
6.91	0.89	1.23	72
6.97	0.90	1.27	71
7.14	0.99	1.40	71
7.16	0.99	1.42	70
7.16	1.62	1.42	114
7.17	1.06	1.43	74
7.19	1.08	1.44	75
7.2	1.56	1.45	108
7.23	1.56	1.47	106
7.24	1.14	1.48	77
7.31	1.70	1.52	112
7.31	1.16	1.52	76
7.32	1.67	1.54	108
7.32	1.65	1.54	107
7.34	1.75	1.56	112
7.34	1.19	1.56	76
7.39	1.20	1.60	75
7.40	1.12	1.61	70
7.41	1.22	1.62	75
7.5	1.91	1.70	89
7.64	1.70	1.80	94
7.74	1.17	1.90	62
7.74	1.39	1.90	73
7.75	1.39	1.91	73
7.84	1.72	2.0	86
7.88	1.35	2.03	67
7.95	1.43	2.10	68
8.11	1.64	2.26	73
8.13	1.90	2.29	83
8.25	1.97	2.40	82
8.88	1.66	3.10	54
8.91	1.71	3.14	54
8.97	2.61	3.20	82
9.09	2.03	3.37	60
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% ± 12% lower than theory.

A.V.C.O. Results are 15% ± 16% lower than theory.

N.P.L. Results are 22% ± 17% lower than theory.

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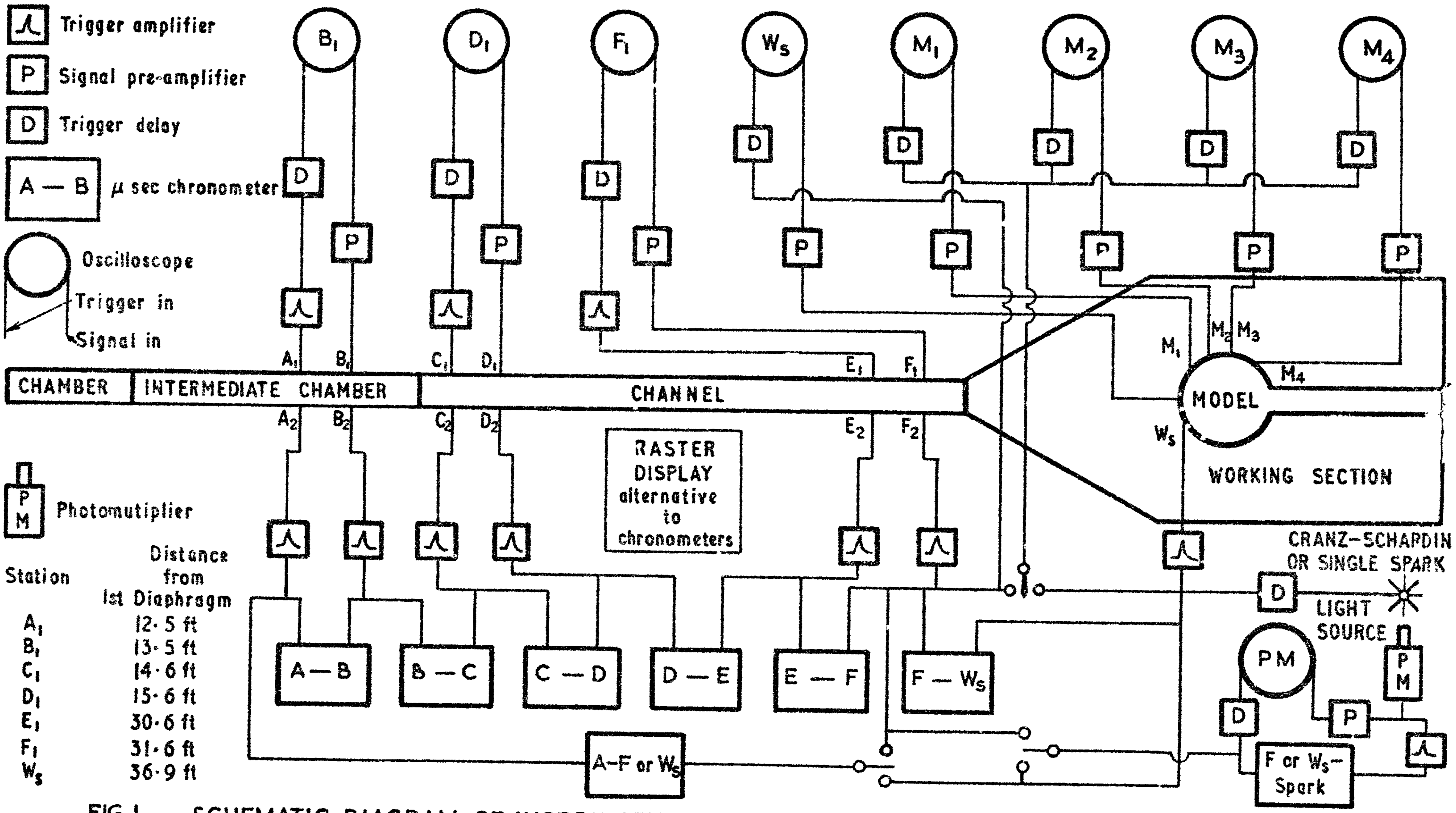
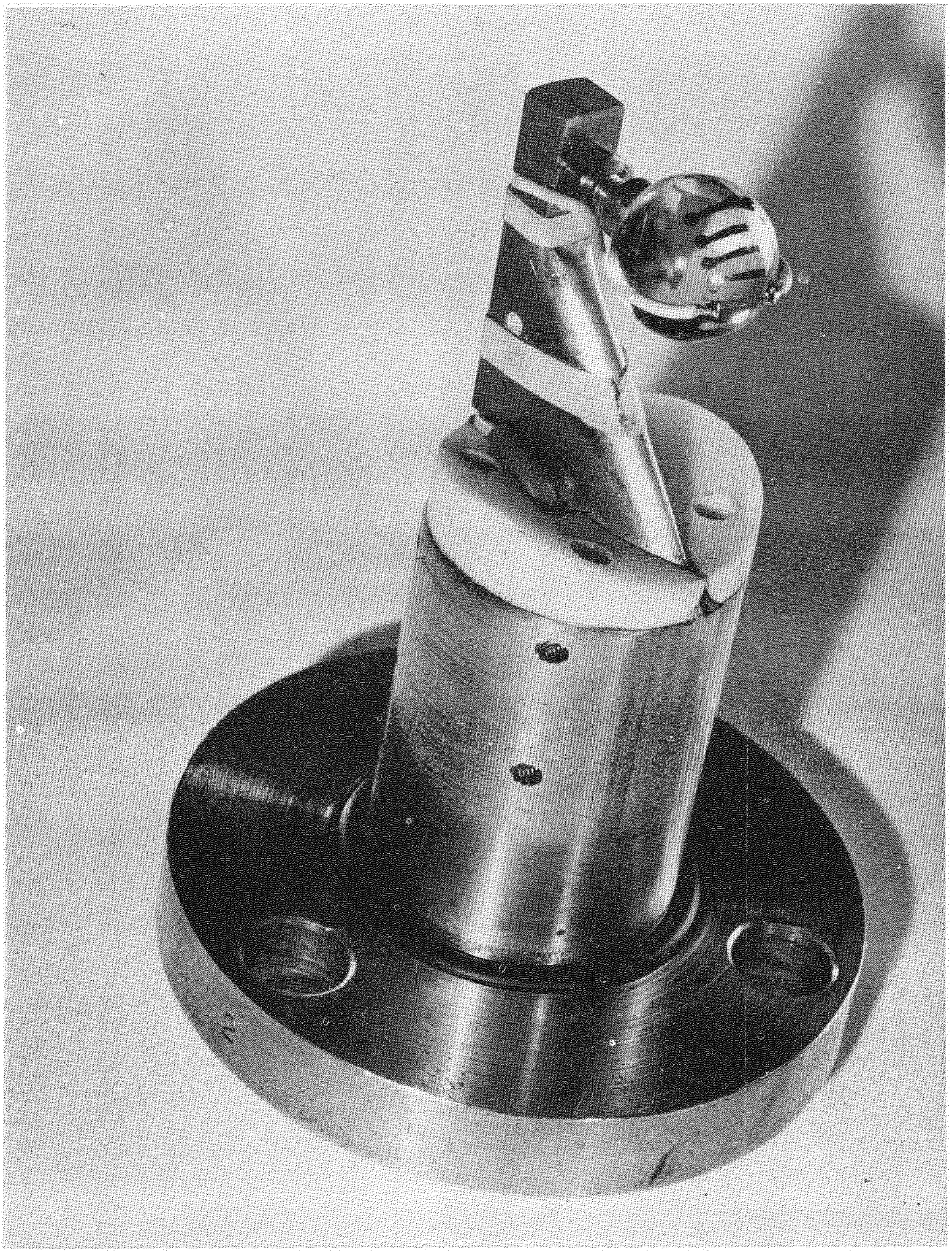


Station	Distance from 1st Diaphragm
A_1	12·5 ft
B_1	13·5 ft
C_1	14·6 ft
D_1	15·6 ft
E_1	30·6 ft
F_1	31·6 ft
W_s	36·9 ft

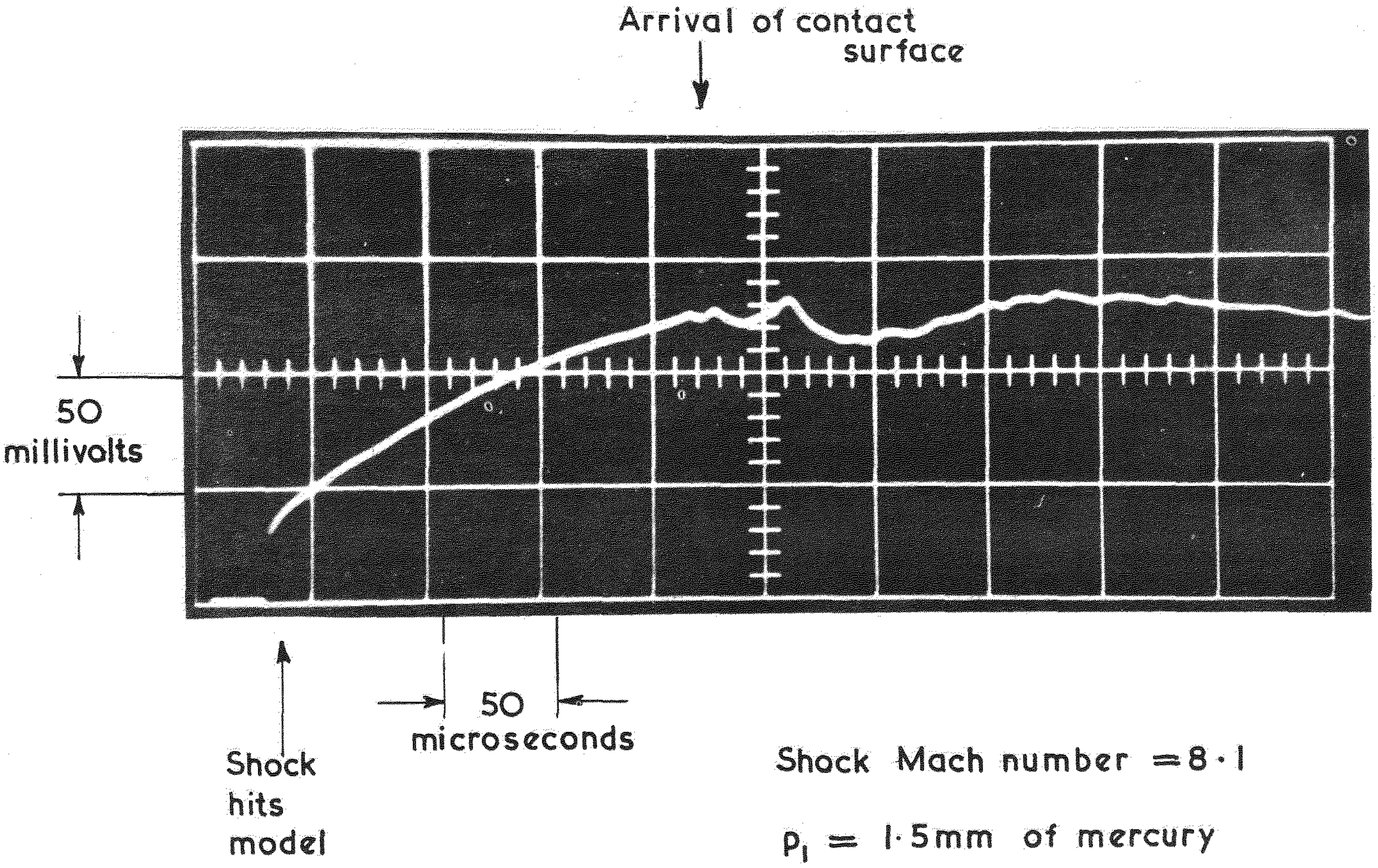
FIG.1. SCHEMATIC DIAGRAM OF INSTRUMENTATION OF NPL HYPERSONIC SHOCK TUNNEL

FIG. 2.



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

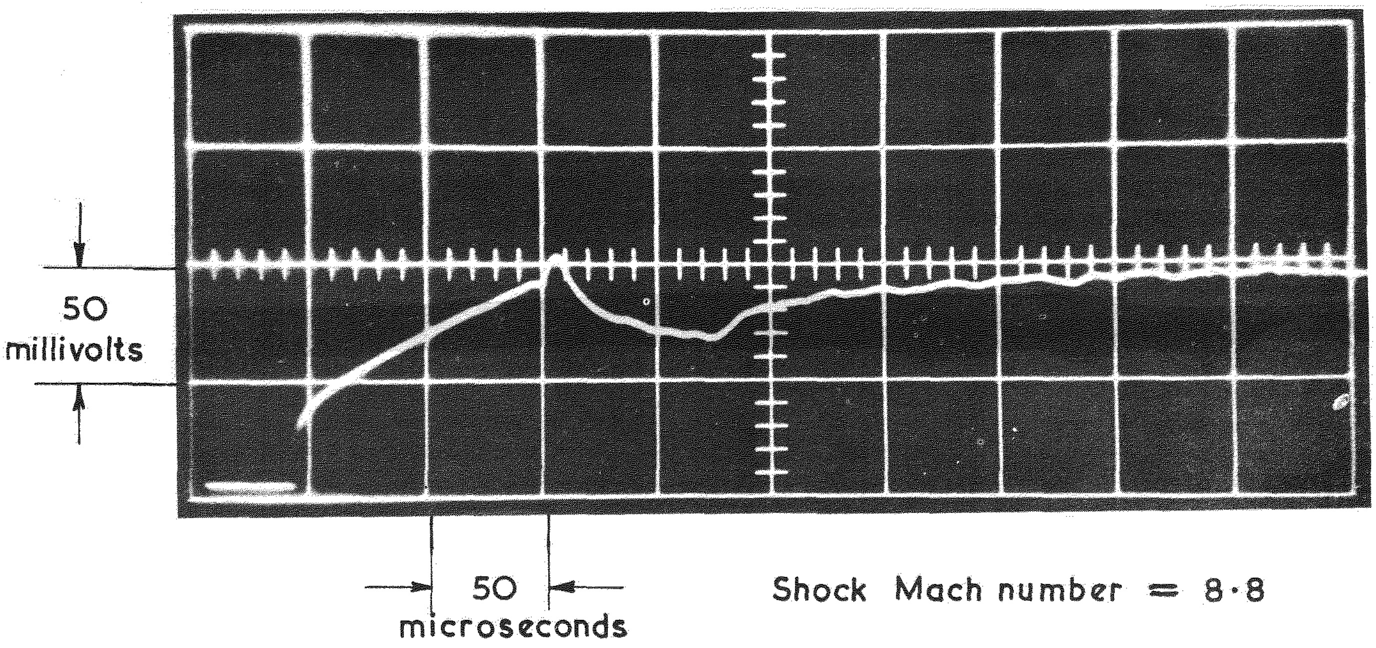
FIG. 3



Shock Mach number $= 8 \cdot 1$

$p_1 = 1 \cdot 5$mm of mercury

HEAT TRANSFER RATE $\dot{q}$ (constant for 180 μsec) = 1·66 KW/cm^2



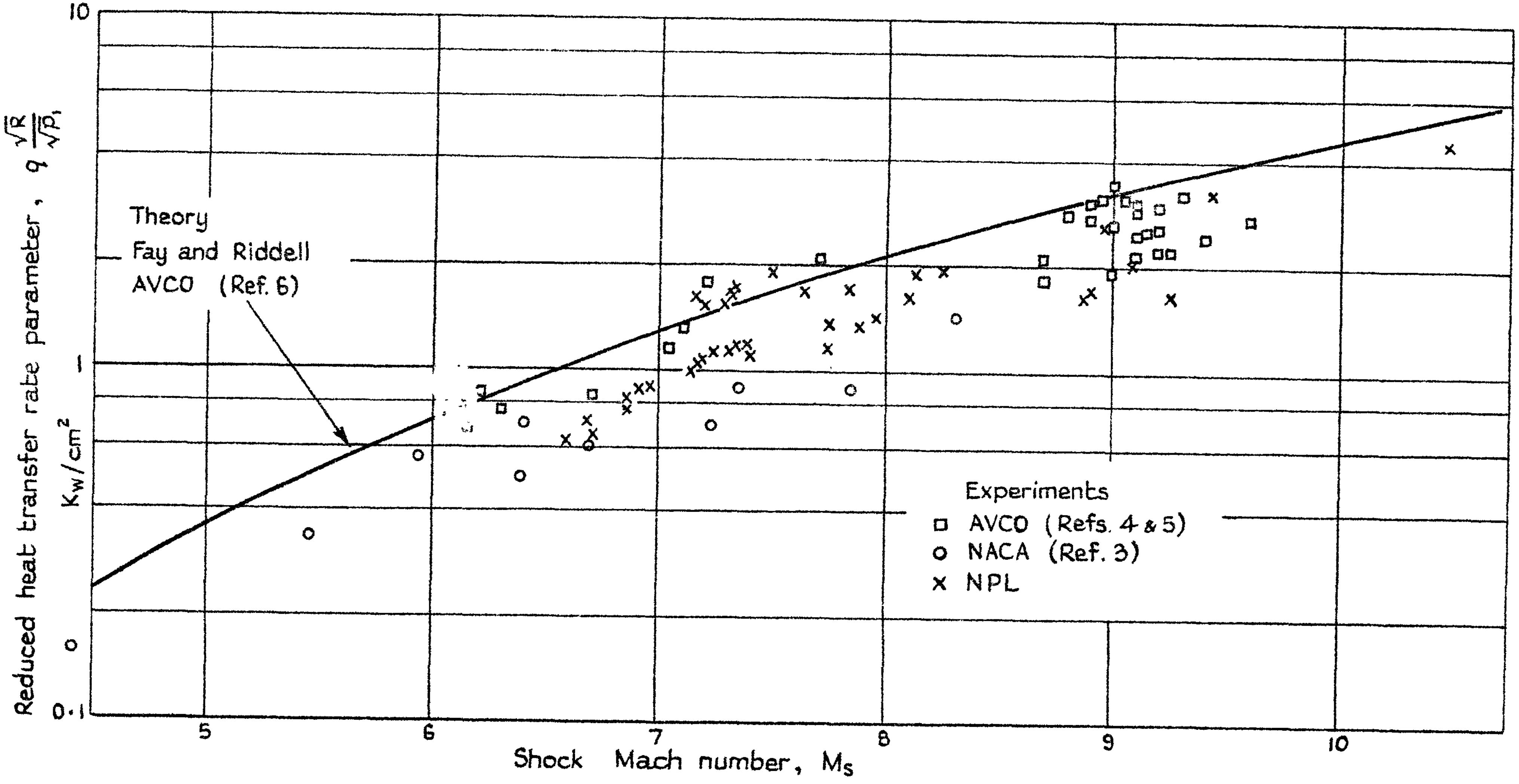
Shock Mach number $= 8 \cdot 8$

$p_1 = 0 \cdot 65$mm of mercury

HEAT TRANSFER RATE $\dot{q}$ (constant for 110 μsec) = 1·70 KW/cm^2

OSCILLOSCOPE TRACES FROM A STAGNATION POINT RESISTANCE

FIG. 4.



p_1 = Channel pressure (mm of mercury)
R_1 = Model nose radius (millimetres)

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