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Determination of Stagnation Temperatures in the R.A.R.D.E. Hypersonic Gun Tunnel from Streak Camera Measurements of Flow Velocity

By

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Determination of Stagnation Temperatures in the R.A.R.D.E. Hypersonic Gun Tunnel from Streak Camera Measurements of Flow Velocity

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SUMMARY

Flow velocities in the working section of the R.A.R.D.E. hypersonic gun tunnel have been measured by a streak camera method for flow Mach numbers of 8·4, 10·4 and 12·9 and initial breech/barrel pressure ratios ranging from 25 to 300, using nitrogen as the driving gas and both air and nitrogen as working gases. Stagnation temperatures calculated from the measured flow velocities ranged from about 750°K to 1600°K and were up to 15% higher than corresponding real-gas isentropic temperatures. Cooling rates were of the order 2°K per millisecond for stagnation temperatures around 750°K. Results for air and nitrogen were generally similar near the beginning of a run, but towards the end of the run a marked increase in flow velocity was observed with air. This was attributed to partial combustion of the nylon piston.

List of Symbols

M	Mach number
P	stagnation pressure
P_A	initial breech pressure
P_B	initial barrel pressure
T	stagnation temperature
t	time from start of flow
V	flow velocity
γ	ratio of specific heats

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*Replaces R.A.R.D.E. Memo.2/66 - A.R.C.27 768.

1. Introduction

The stagnation temperature in a hypersonic gun tunnel is difficult to measure directly but it may be calculated from the Mach number, the flow velocity and the thermodynamic constants of the working gas[1] if the flow process is known. In the R.A.R.D.E. hypersonic gun tunnel[2] the flow Mach number is obtained in the conventional way from the ratio of measured pitot and stagnation pressures[3] and a method has been developed at R.A.R.D.E. for measuring the flow velocity by using a streak camera in conjunction with a sensitive schlieren system to obtain streak records of small density variations in the flow[4].

Using this method a comprehensive velocity calibration was carried out for flow Mach numbers of 8•4, 10•4 and 12•9 and initial breech/barrel pressure ratios ranging from 25 to 300. As usual, nitrogen was used for both driving and working gases, and the effect of changing the working gas to air was also investigated.

Stagnation temperatures were calculated from the measured flow velocities by a method given by Wilson and Regan[5], which takes into account real-gas effects but assumes the gas to be in equilibrium, and a calibration curve was constructed which is independent of Mach number and applies to the first 20 milliseconds of the run.

2. Description of Tests

The R.A.R.D.E. hypersonic gun tunnel[2] has a closed-jet working section of mean diameter 11 in. which forms part of the continuous 4° semi-angle conical expansion extending from the nozzle throat to the diffuser. Three interchangeable throats give average flow Mach numbers of 8•4, 10•4 and 12•9 respectively, with either air or nitrogen as the working gas[3].

The use of a streak camera to measure the flow velocity in the working section is described in Ref. 4. The basis of the method is that small density variations in the flow 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 provides a continuous record of flow velocity during the running time of the tunnel. Direct comparison with a spark disturbance method for measuring flow velocity[4] has shown that the streak method measures the mainstream velocity with an estimated maximum error of about ±3% at $M = 8{\cdot}4$ and ±4% at $M = 12{\cdot}9$, when the working section density is about an order lower and the streak records are correspondingly fainter.

In the present tests a conventional single-pass schlieren system was used (Fig. 1), with a long-focus ($f = 20$ ft) second schlieren mirror (M3) to ensure high sensitivity. An Acmade 35 mm high-speed cine camera was converted to a streak camera by removing the optical compensating block. Part of a typical streak record is shown in Fig. 2.

Stagnation pressures were measured during each run with a quartz piezo transducer (S.L.M. Type PZ14) mounted in the gun barrel near the nozzle end, and static pressures with a capacitance transducer (Southern Instruments Type G247C) mounted in the wall of the working section. The static pressure

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records served to indicate the flow duration, which was always found to be in excellent agreement with the duration of the streak record. Both stagnation and static pressures were recorded on a multi-channel U.V. galvanometer recorder (N.E.P. Type 1050).

The driving gas was nitrogen at a constant initial breech pressure of 4015 psia. Initial barrel pressures ranging from 14·5 psia to 165 psia were used to vary the compression ratio and thus provide a range of stagnation temperatures. The tunnel was run at each barrel pressure in turn with nitrogen as the working gas; then the whole test schedule was repeated with air. A streak schlieren record of each run was analysed to find the variation of flow velocity with time by making enlargements similar to Fig. 2 for a number of points during the run and then measuring the average streak angle on each enlargement with a simple cursor and calculating the corresponding flow velocity.

3. Results

Flow velocity/time graphs are shown in Figs. 3 to 8 for each of the three Mach numbers with both nitrogen and air as working gases. Flow velocities were related to corresponding stagnation temperatures by using the calculations given in Ref. 6, based on a method due to Wilson and Regan[5] which takes into account real-gas effects but assumes the gas to be in equilibrium. Temperature scales so obtained are included in Figs. 3 to 8. These graphs clearly show the correspondence between the initial breech/barrel pressure ratio in the gun tunnel and the resulting stagnation temperature, which increases progressively as the compression ratio is increased.

3.1 Comparison of results for nitrogen and air

The most striking feature of the empirical velocity/time graphs is the difference between corresponding graphs for nitrogen and air. At the beginning of the run the agreement is generally quite good, but towards the end of the run all the air results show a marked increase in flow velocity, accompanied by a slight increase in flow duration which increases with increasing Mach number and averages about 10% over the present Mach number range. Even with nitrogen there is some indication of a terminal rise in flow velocity for temperatures above 1100°K (Fig. 5) but this may be due partly to the variation of stagnation pressure during the run (see paragraph 3.2 below).

The terminal rise in flow velocity and the increase in flow duration with air are considered to be due to partial combustion of the nylon piston, with an associated increase in the temperature of the gas near the piston face. Since the piston had to be drilled and tapped in order to extract it from the gun barrel after the run it was not possible to weigh the piston after firing and so find the weight of nylon lost by combustion, but Fig. 9 clearly shows the increased charring which occurs when air is used as the working gas.

At the lowest stagnation temperatures (Fig. 9A) no charring of the piston occurs with either nitrogen or air, whilst if the temperature is sufficiently high (Fig. 9C) there is some charring even in an atmosphere of nitrogen, presumably because nylon contains some combined oxygen. In general, however, air produces very much more charring than nitrogen under the same

conditions/

conditions (Fig. 9B). The only way to overcome this problem would be to make the piston of some suitably refractory material, or possibly to attach a heat-resistant coating to the front face. Since nitrogen is normally used as the working gas in the R.A.R.D.E. gun tunnel the question was not pursued further, but the results emphasise that the choice of piston material may be important if air is used as the working gas in a gun tunnel.

It should be noted that the temperature scales in Figs. 4, 6 and 8 do not necessarily apply to the terminal rise in flow velocity with air, since the velocity/temperature relations computed for air may not apply to the products of combustion of nylon which probably include CO_2, water vapour, etc.

3.2 Rate of cooling

At the lowest stagnation temperatures the records are not affected by nylon combustion and the flow velocity decreases fairly steadily during the run, indicating an approximately constant rate of cooling of the working gas. This is most clearly shown by the lowest curves in Figs. 5 and 6.

In estimating the cooling rate it is necessary to take into account the effect of variations in the stagnation pressure during the run. A simple isentropic approximation suggests that the flow velocity should be proportional to $P^{1/7}$ when $\gamma = 1{\cdot}4$, thus $T \propto P^{2/7}$ and the correction for pressure variations should be small.

Fig. 10 shows a typical graph of stagnation pressure during a run at $M = 8{\cdot}4$ and velocity measurements for four similar runs at $M = 8{\cdot}4$ using different schlieren arrangements. The velocity has a peak at about 26 milliseconds corresponding to the peak in stagnation pressure and the general variation of velocity during the run suggests a rather stronger dependence on stagnation pressure than a 1/7 power law. Failing definite evidence to the contrary, however, a 1/7 power correction was applied and cooling rates were then found to lie between about 1·5°K and 2·5°K per millisecond for stagnation temperatures around 750°K.

3.3 Relation between stagnation temperature and initial pressure ratio

The main object of the present work was to establish the relation between initial breech and barrel pressures in the gun tunnel and the resulting stagnation temperature. The initial breech pressure is normally set at a constant value of 4015 psia so the stagnation temperature is determined by the initial barrel pressure. Since the working gas is normally nitrogen and the air results were to some extent affected by nylon combustion only the nitrogen results (Figs. 3, 5 and 7) were used. Cooling corrections were avoided by considering only the first 20 milliseconds of the run. Average stagnation temperatures during the first 20 milliseconds (or the length of the run if this was less than 20 milliseconds) were estimated from the graphs and are plotted in Fig. 11 against initial barrel pressures. The points lie on a reasonably smooth curve which is independent of Mach number and may be used as a general calibration curve for the R.A.R.D.E. hypersonic gun tunnel.

One important use for this curve is to define the minimum compression ratio for any Mach number in order to avoid condensation of the working gas. In practice some degree of supersaturation is usually acceptable;

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this is discussed in a forthcoming publication[7] in which it is shown that the minimum stagnation temperature to avoid any appreciable condensation effects is approximately 800°K at M = 8·4, 900°K at M = 10·4 and 1200°K at M = 12·9.

3.4 Comparison of stagnation temperatures and isentropic temperatures

Since the working gas in a gun tunnel is heated by a shock process the final stagnation temperature should be higher than that produced in an equivalent isentropic compression. The gain over isentropic heating will depend on the shock system set up in the particular gun tunnel, i.e., on the gun geometry, piston mass, etc., and various attempts have been made to predict the temperatures produced by shock heating, by calculating the performance of a representative model of the system[8,9]. In practice these calculated temperatures are never fully realised probably because it is difficult to make adequate allowance for various dissipative factors such as piston friction, heat transfer to the gun barrel and boundary-layer growth behind the piston and shock waves.

Results for the R.A.R.D.E. gun tunnel are shown in Fig. 12. Average stagnation temperatures for the first 20 milliseconds of the run are plotted against compression ratios and are compared with equivalent real-gas isentropic temperatures obtained from the Mollier diagram for nitrogen in Ref. 10. At the lowest compression ratios the stagnation temperature calculated from the flow velocity approaches the corresponding isentropic temperature but as the compression ratio is increased the difference between observed and isentropic temperatures increases until for a compression ratio of 300 the observed temperature is some 15% higher.

These results are consistent with stagnation temperatures measured in comparable facilities by different methods[11,12,13].

4. Conclusions

A streak camera method has been used to measure flow velocities in the working section of the R.A.R.D.E. hypersonic gun tunnel for flow Mach numbers of 8·4, 10·4 and 12·9, using nitrogen as the driving gas and both air and nitrogen as working gases. For initial breech/barrel pressure ratios ranging from 25 to 300, real-gas stagnation temperatures calculated from these flow velocities ranged from 750°K to 1600°K and were up to 15% higher than corresponding real-gas isentropic temperatures. Cooling rates were of the order 2°K per millisecond for stagnation temperatures around 750°K.

Results for air and nitrogen were generally similar near the beginning of a run, but with air as the working gas a marked increase in flow velocity occurred towards the end of the run, accompanied by increased charring of the nylon piston and an increase in flow duration of the order 10%. It was concluded that some gas had been evolved by combustion of the nylon; the choice of piston material may accordingly be restricted when air is used as the working gas in a hypersonic gun tunnel.

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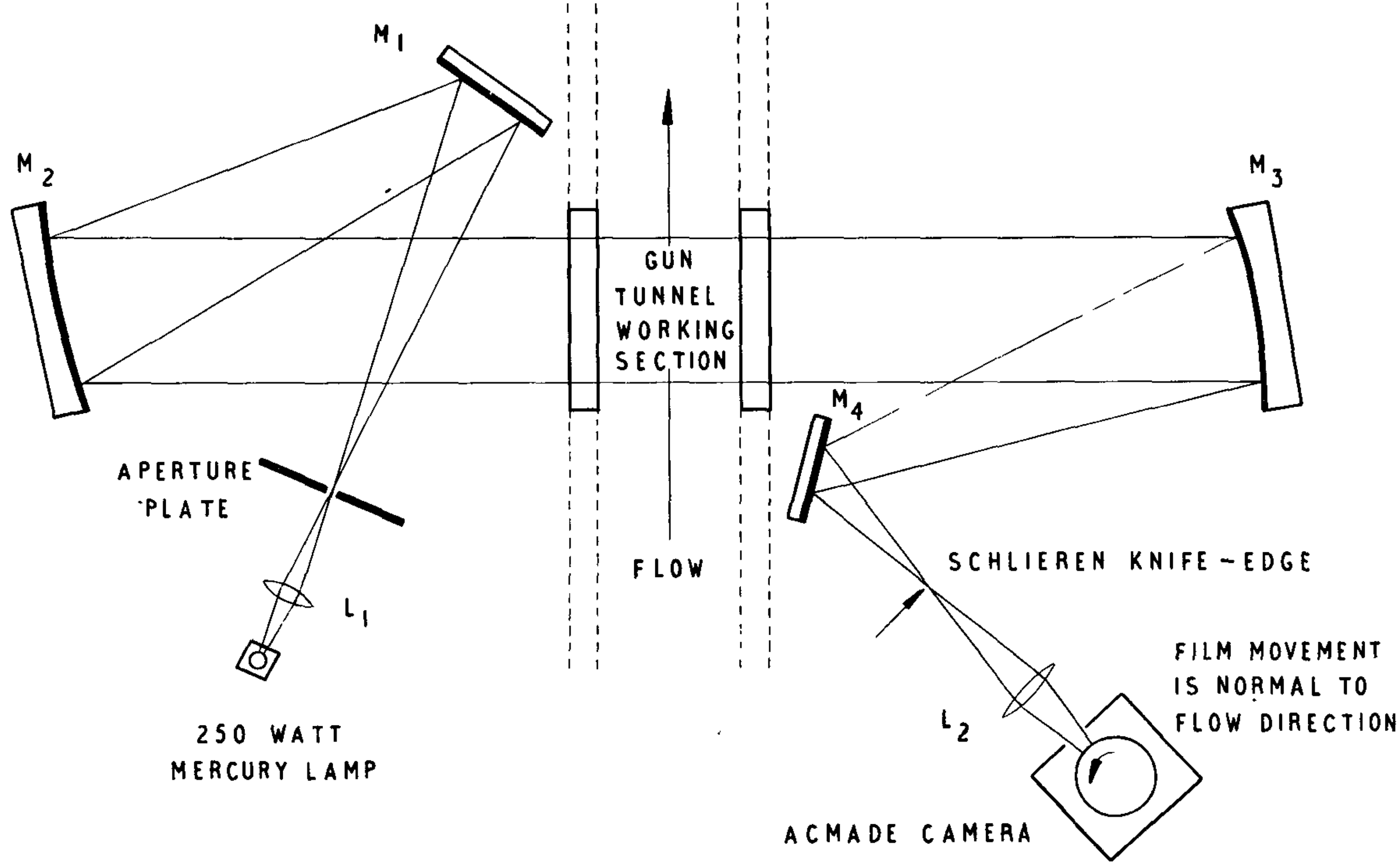

FIG 1 OPTICAL SYSTEM FOR STREAK CAMERA MEASUREMENT OF FLOW VELOCITY

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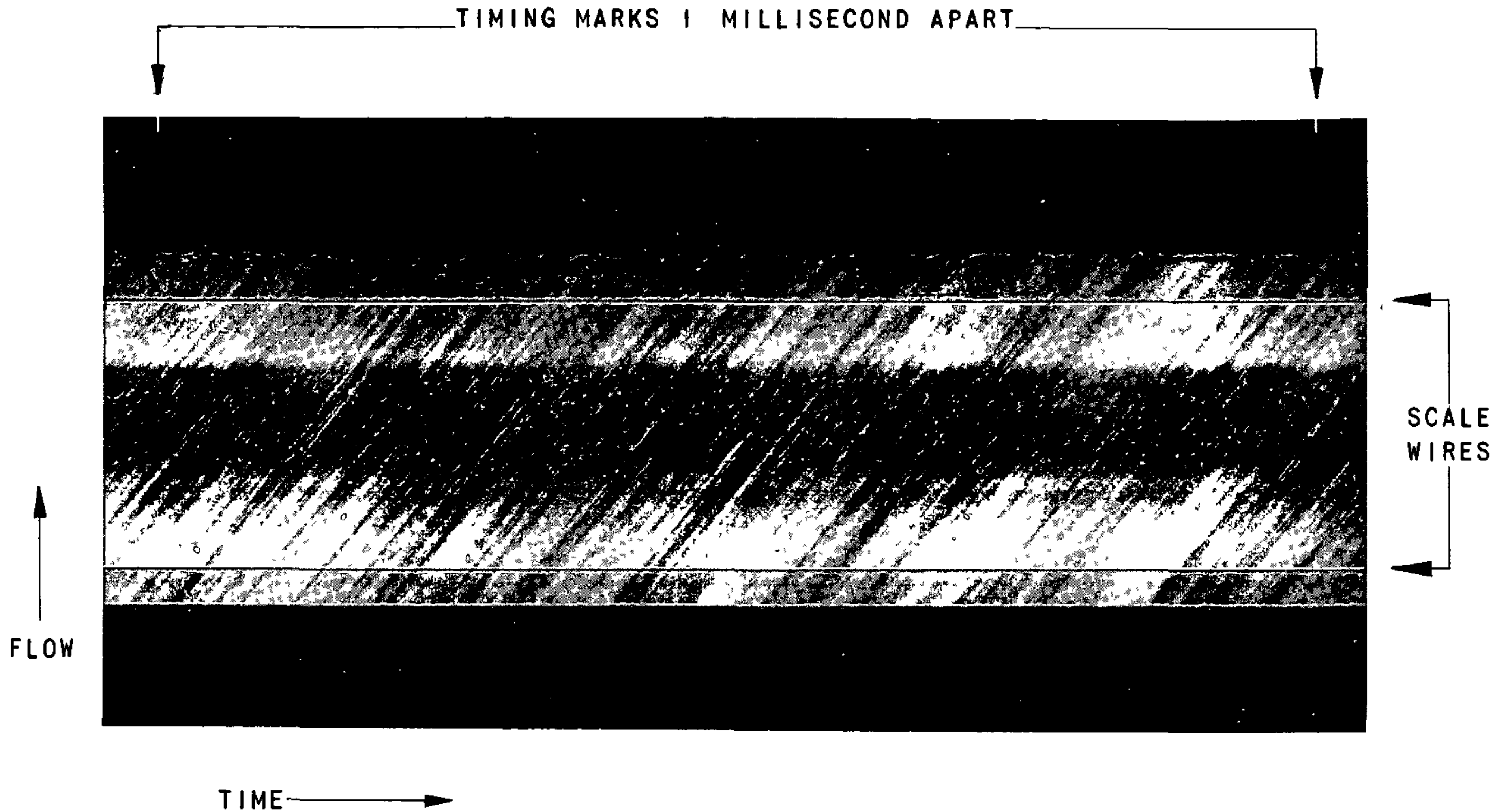

FIG. 2 STREAK RECORD OF FLOW AT M = 8 · 4

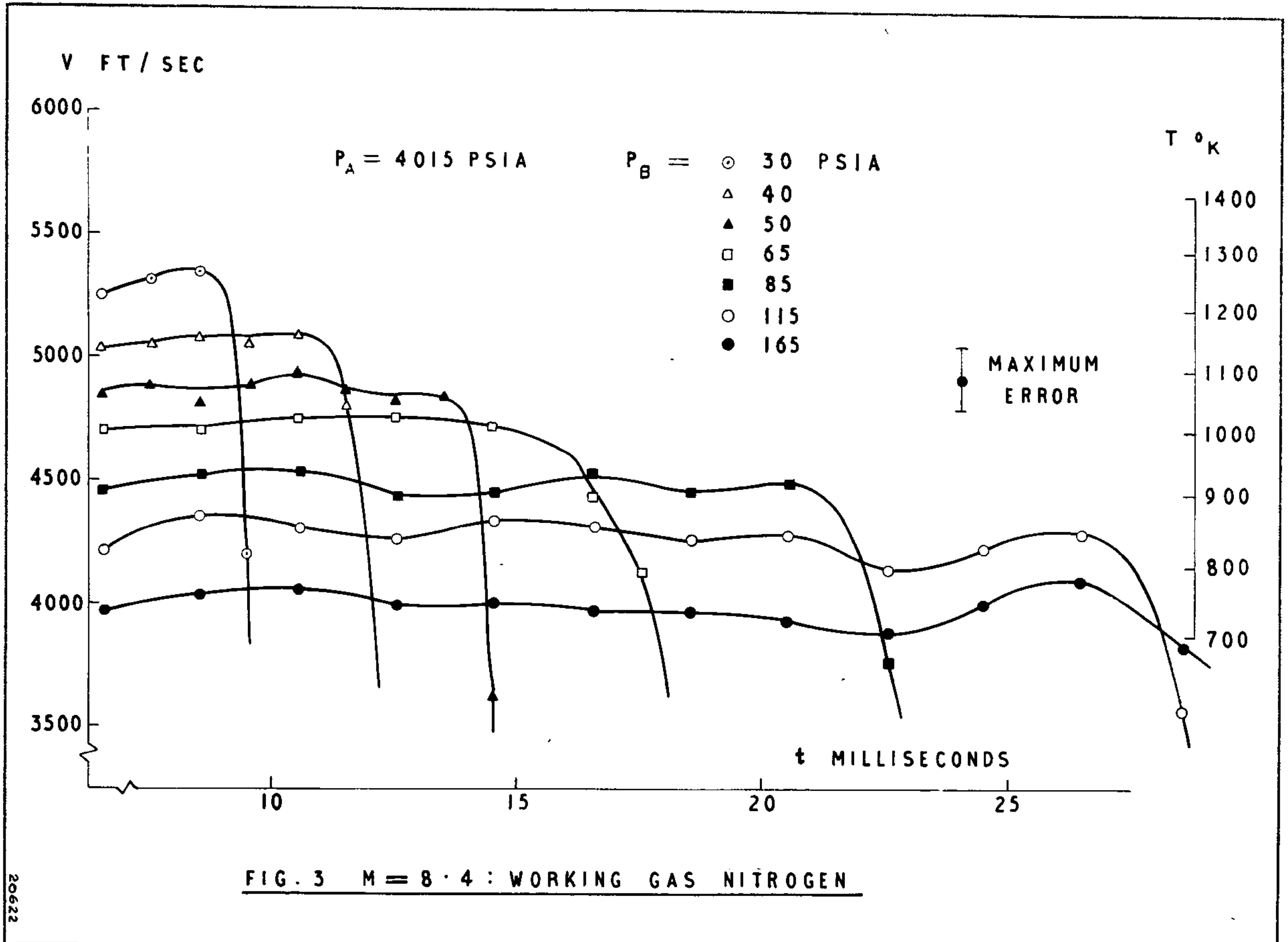

FIG. 3 M = 8·4 : WORKING GAS NITROGEN

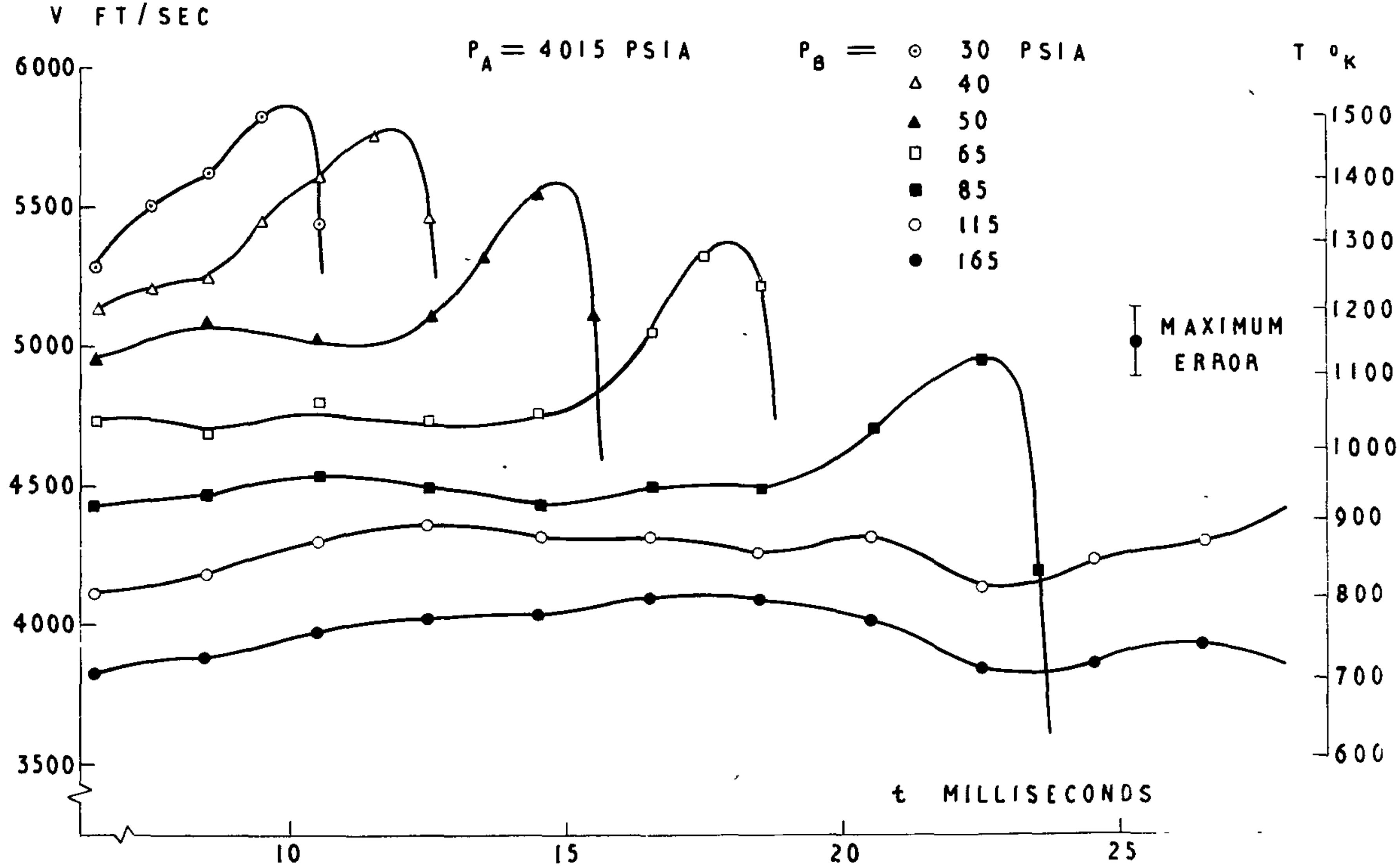

FIG 4 M = 8·4 : WORKING GAS AIR

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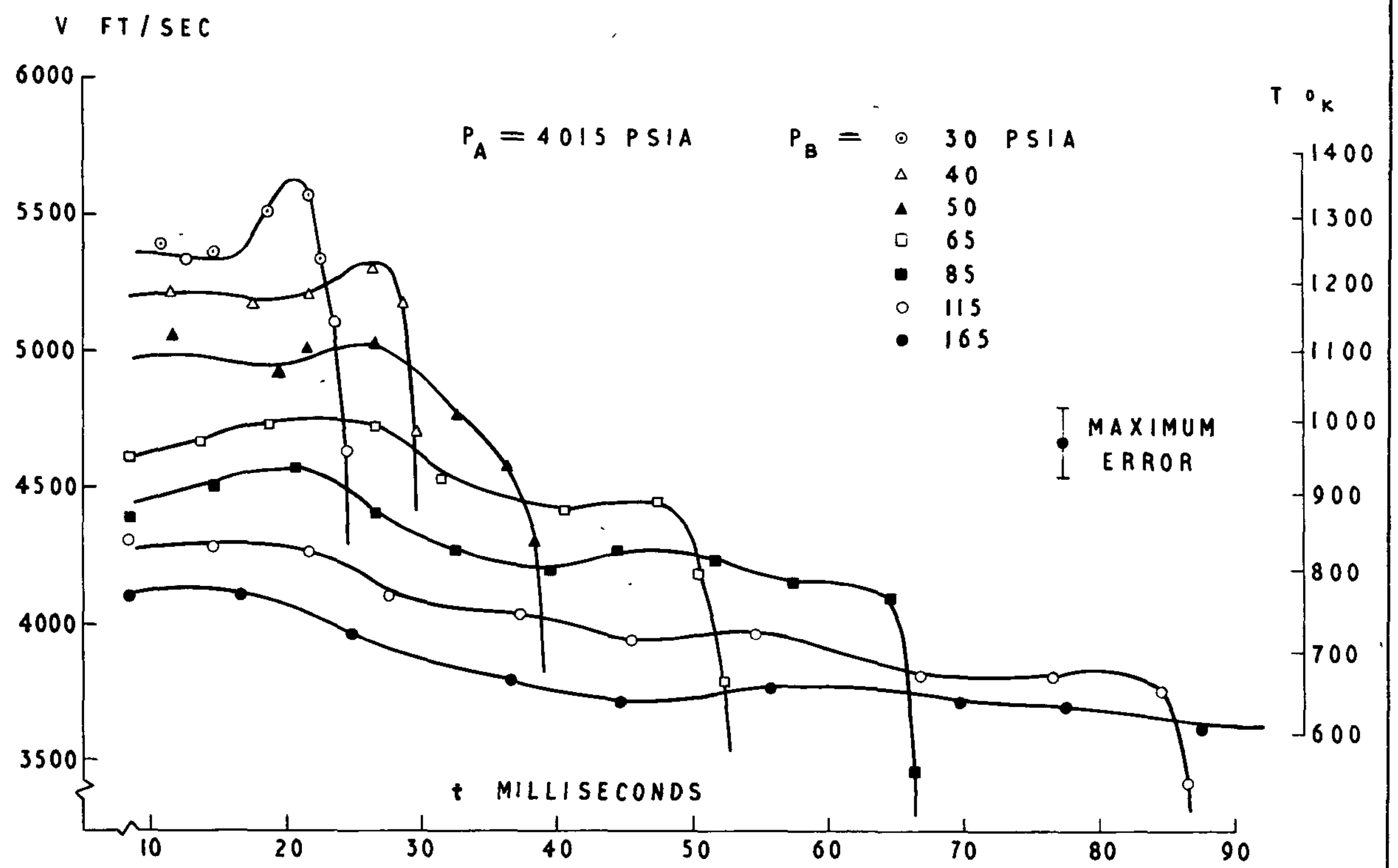

FIG. 5 M = 10·4 : WORKING GAS NITROGEN

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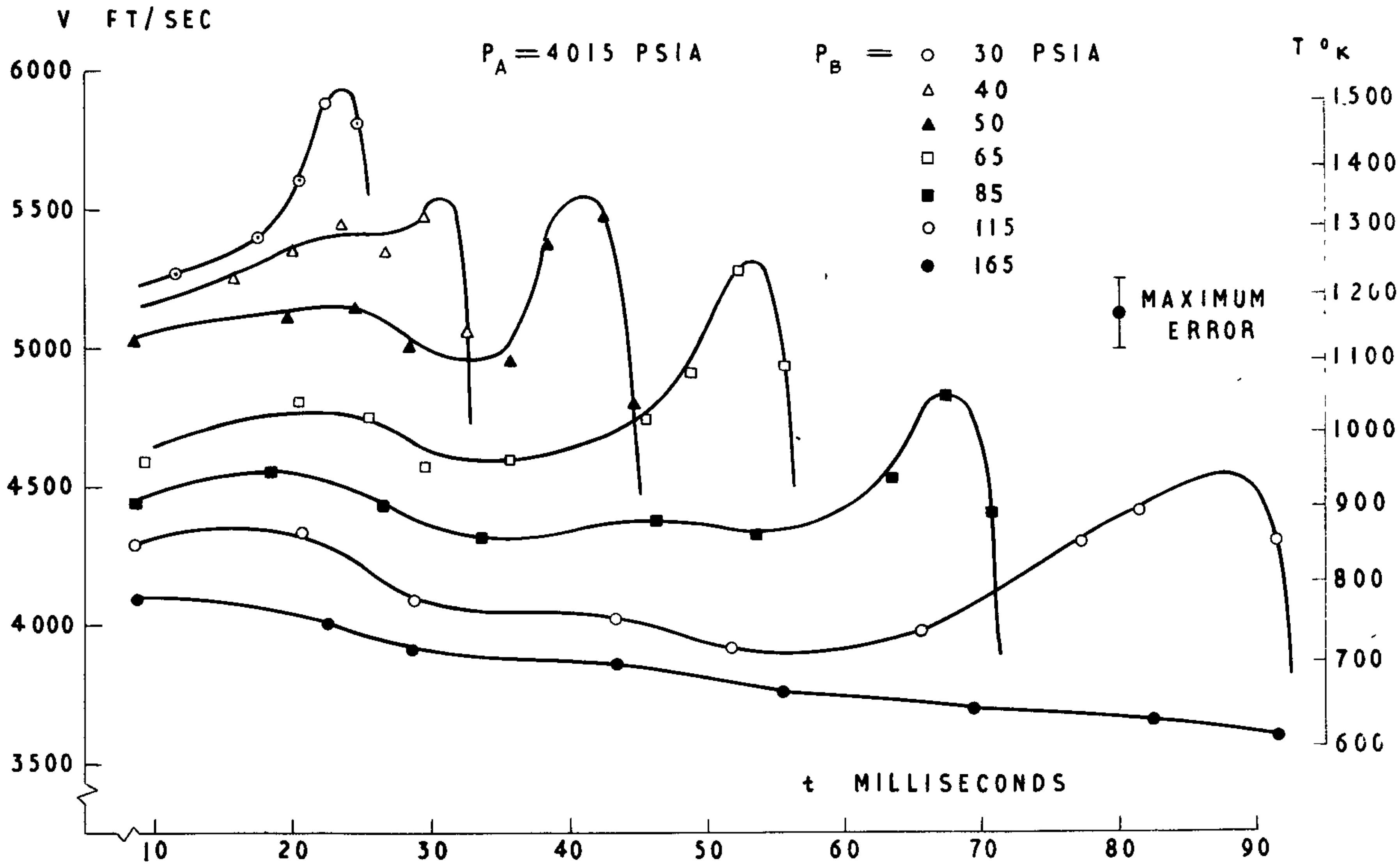

FIG. 6 M = 10·4 : WORKING GAS AIR

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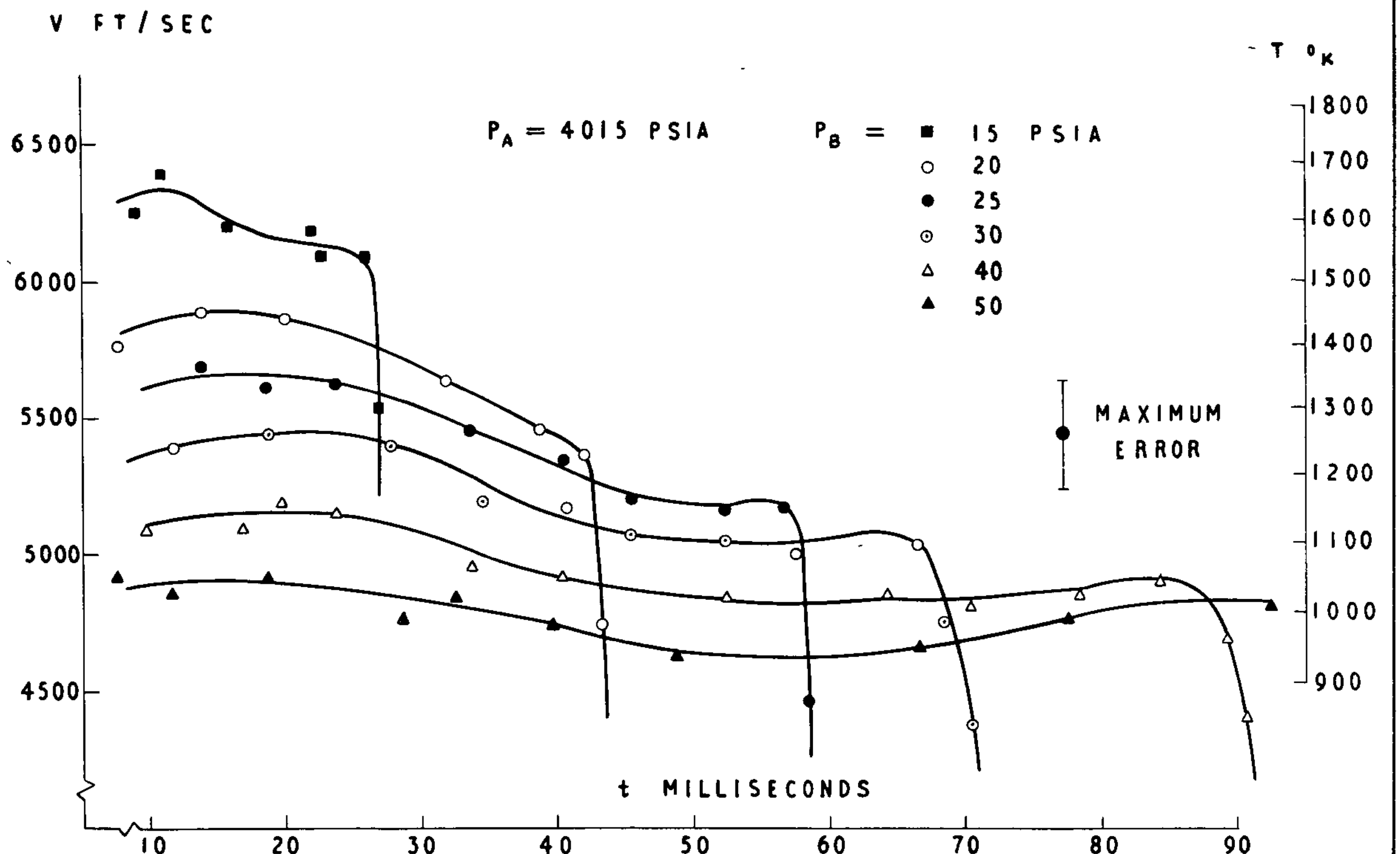

FIG. 7 M = 12·9 : WORKING GAS NITROGEN

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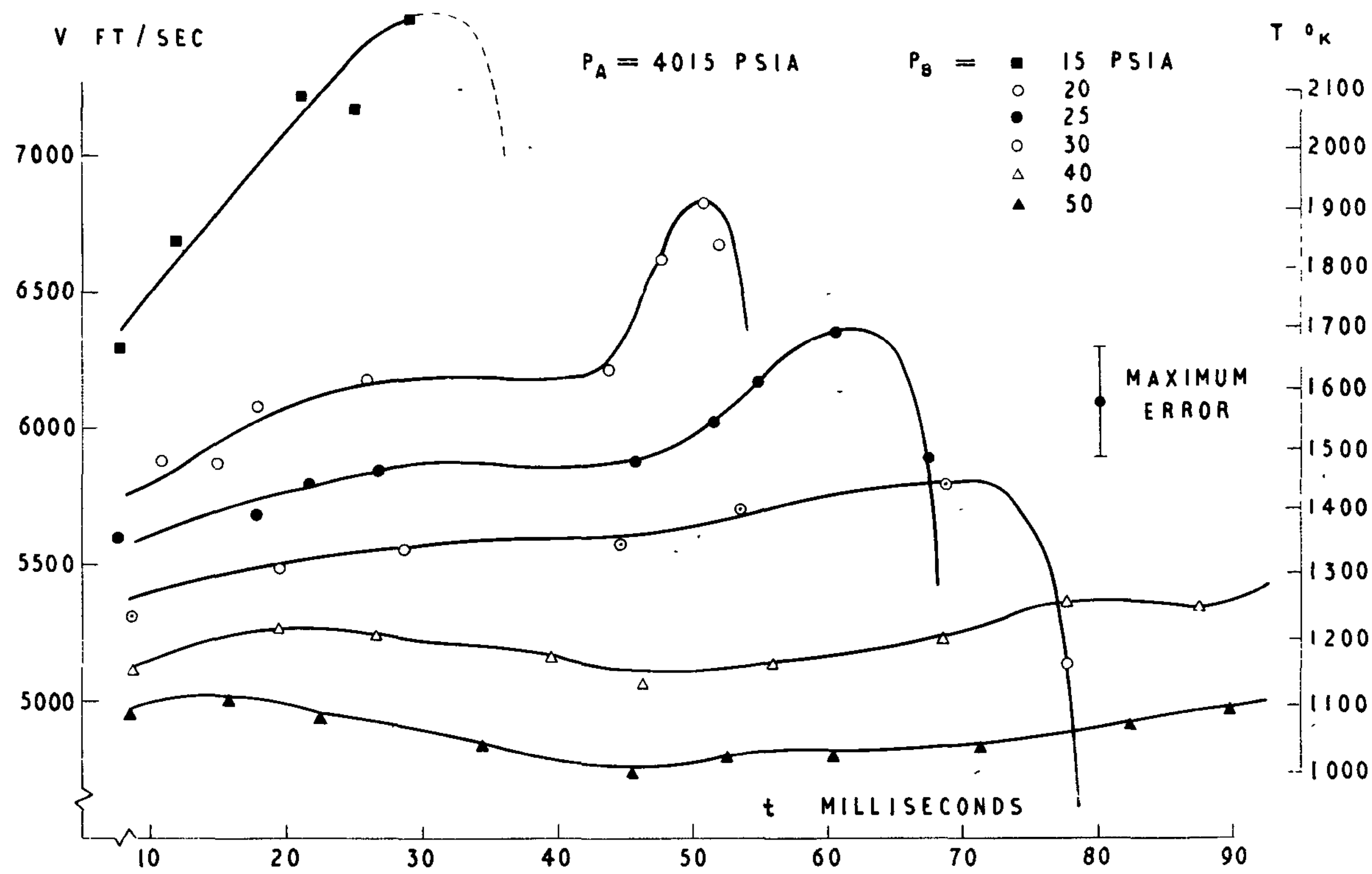

FIG. 8 M = 12·9 : WORKING GAS AIR

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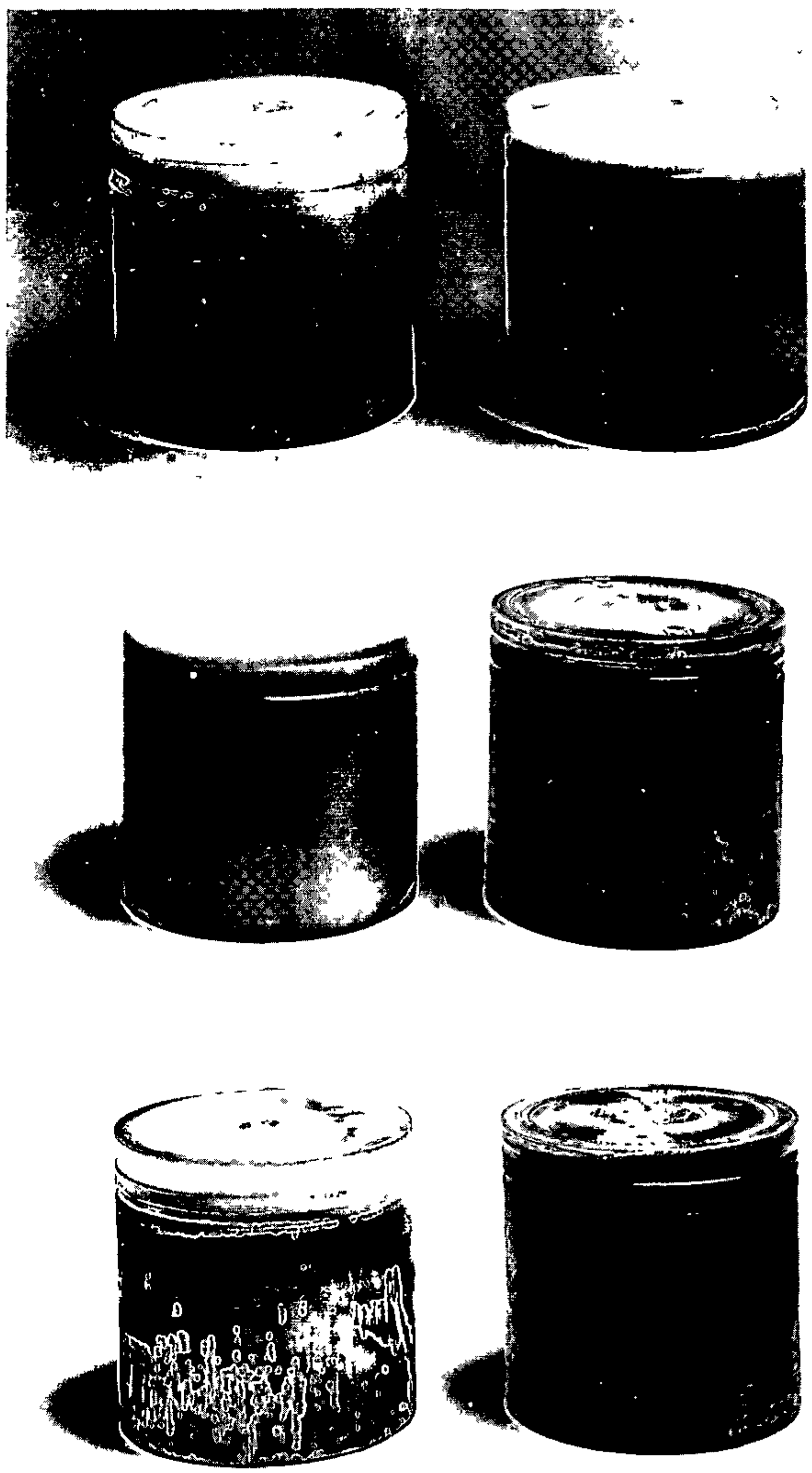

FIG. 9 NYLON PISTONS AFTER SIMILAR RUNS WITH NITROGEN AND AIR

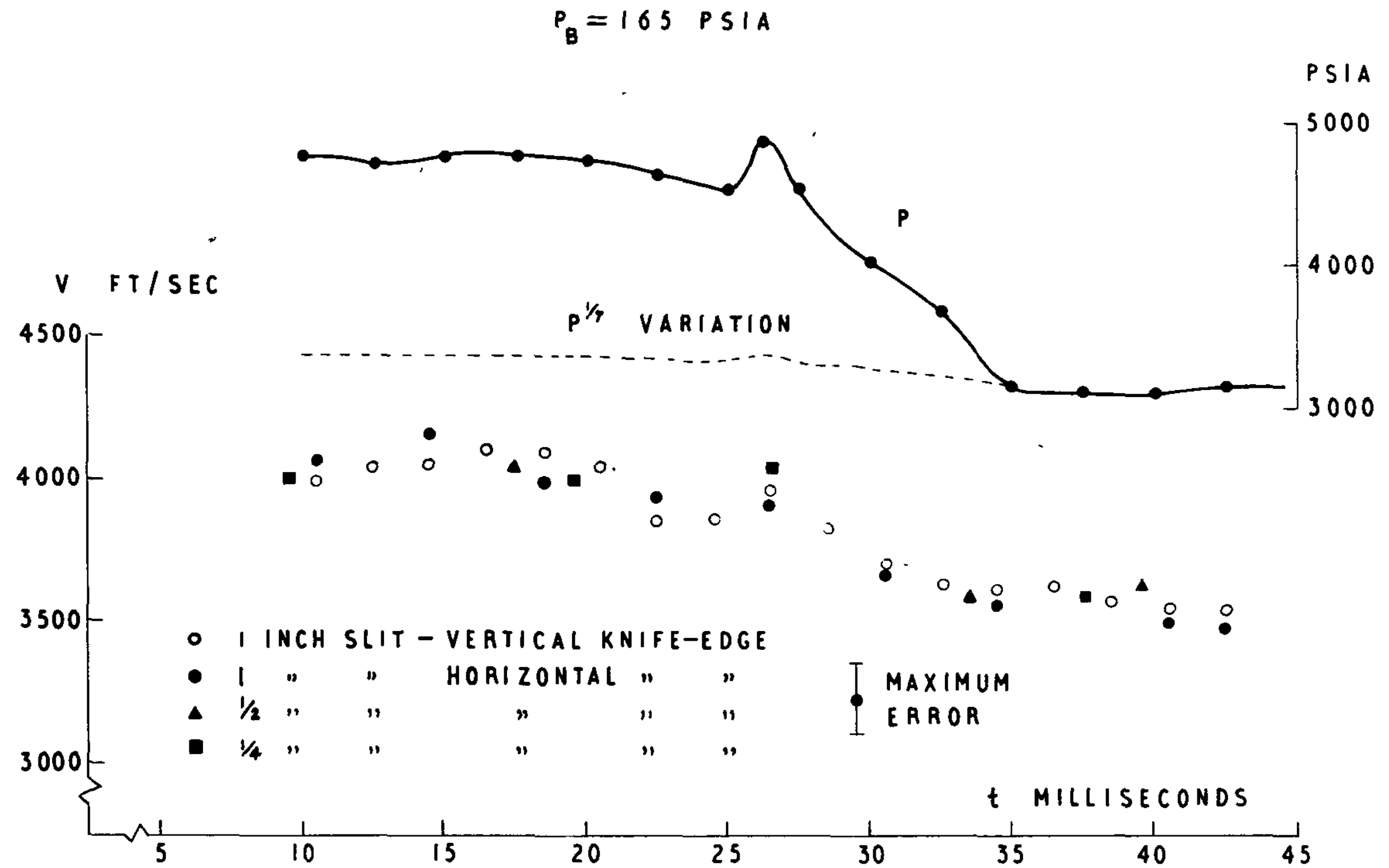

FIG. 10 M = 8 4 : WORKING GAS AIR

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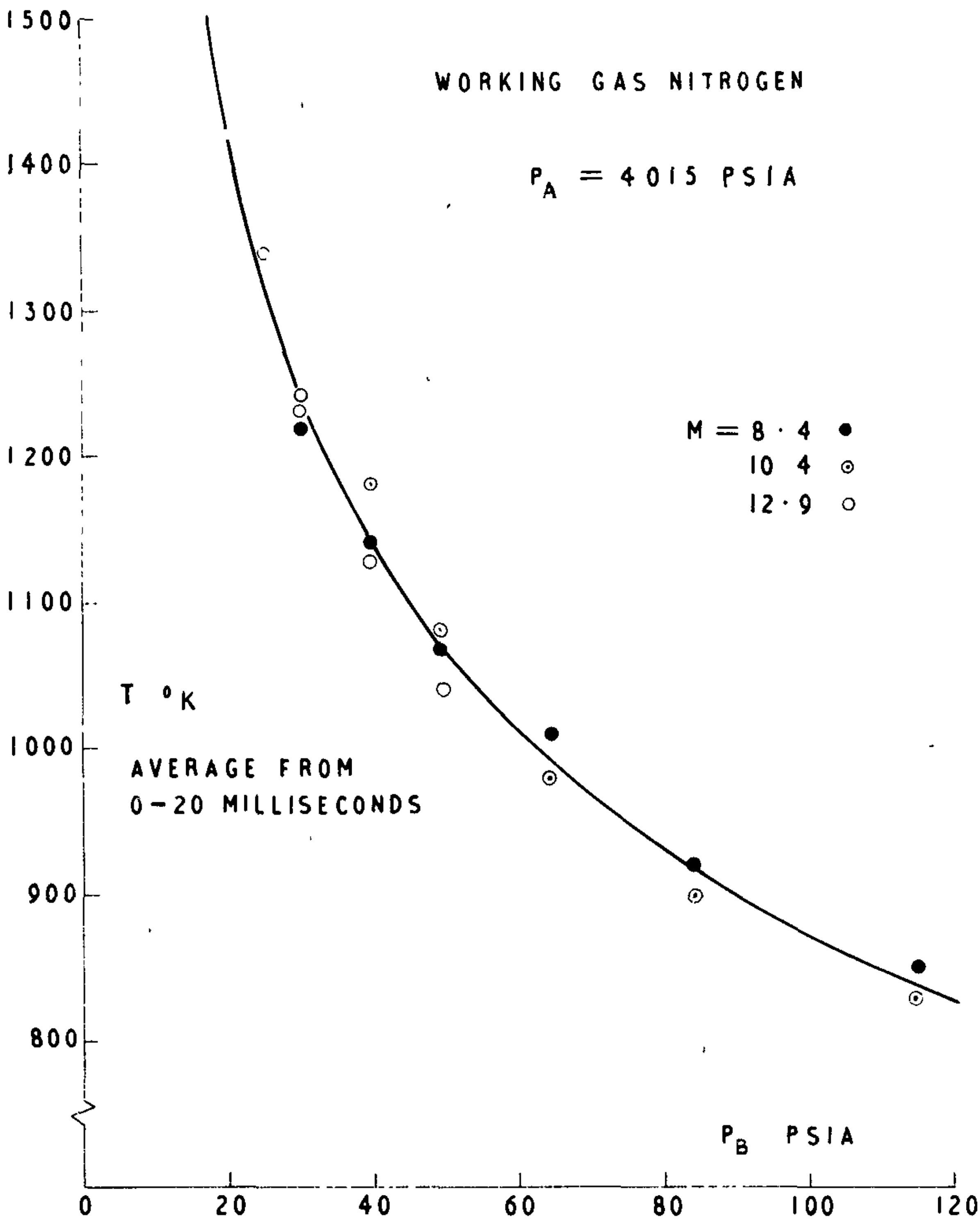

FIG. 11 STAGNATION TEMPERATURE CALIBRATION CURVE FOR R.A.R.D.E. HYPERSONIC GUN TUNNEL

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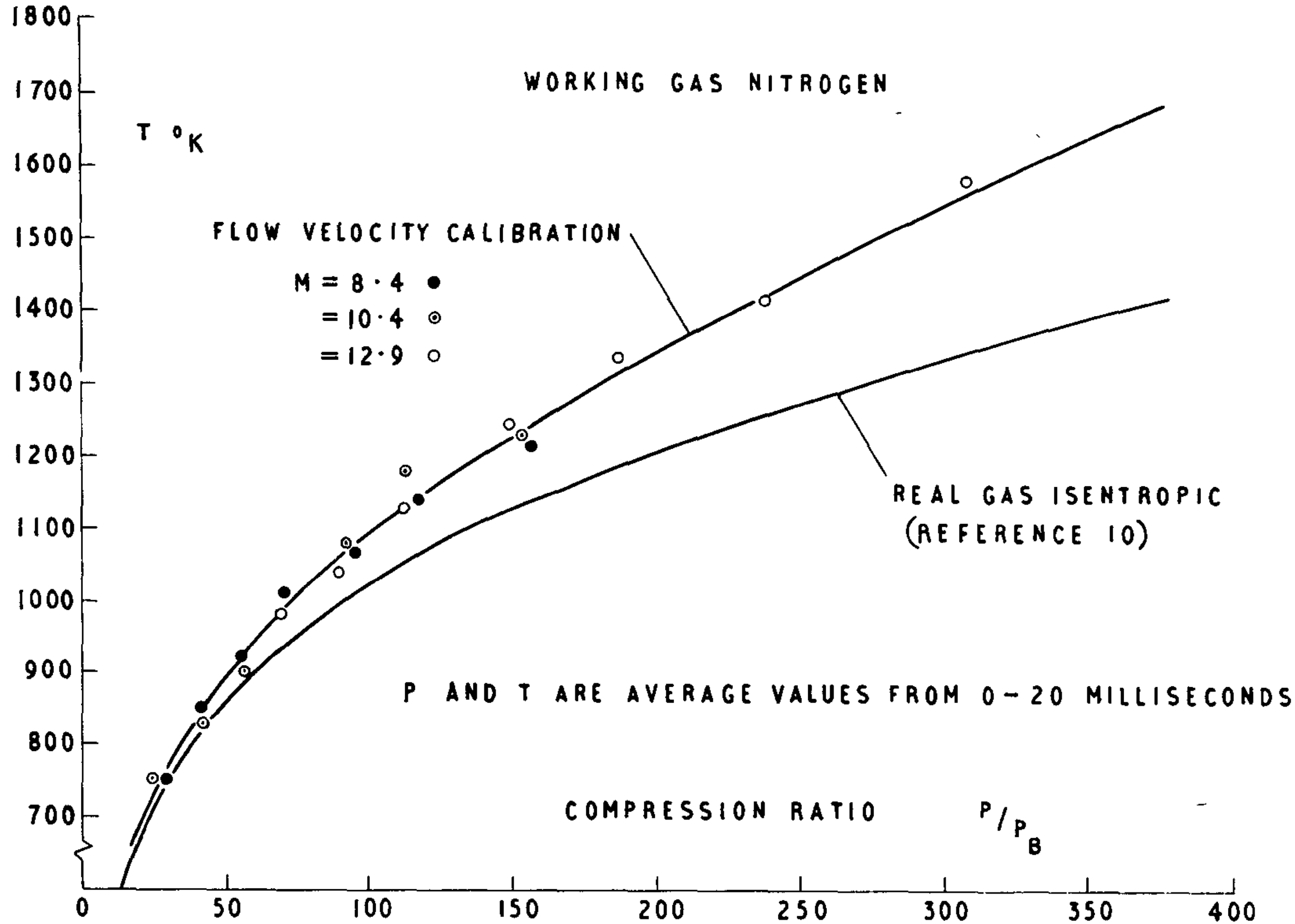

FIG. 12 STAGNATION TEMPERATURE AND COMPRESSION RATIO

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