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MONTREAL

A ONE PORT SLAVE SMOKING MACHINE

PROJECT T-7050

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INTRODUCTION

A main objective of the Research Department is to help in developing smoking products which give maximum satisfaction with smoke of minimal biological activity. The industry is under pressure to reduce the tar and nicotine deliveries of cigarettes. Lowering tar deliveries is a valid objective, since this is one way of reducing the intake of biologically active material. However, recent evidence suggests that when the nicotine delivery (obtained by standard machine smoking) is lowered, then the smokers compensate for this, i.e. they adjust their habits to try and maintain their nicotine intake. Unfortunately, this will also increase the amount of tar they get. It was of vital importance, for product development, to confirm these compensating actions of smokers, and more particularly to measure the degree of success in compensation possibly to help in judging the extent of nicotine decrease which will be tolerated by smokers. To do this requires a means of determining the amount of nicotine (and tar) a smoker actually receives, with minimum interference in his enjoyment.

There is also evidence to suggest that the specific biological activity of the tar a smoker gets may be affected by the way in which he smokes. Currently, smoke for all bioassays is prepared by standard machine smoking, and there are reasons to think that the degree of activity of such smoke may be unrealistically high compared to that received by most smokers. Confirmation of this is important, and requires a means of obtaining smoke in ways which represent the range of patterns used by smokers. It is conceivable that products could be designed to persuade the smoker to obtain his nicotine in such a way as to reduce the activity of his tar. The background to the foregoing will be given in a separate report.

There are two realistic ways of estimating the amount of smoke received by smokers, (although neither can give information on the smoke inhaled).

1. From analysis of butts
2. By duplicating the subject's smoking

The butts of filter cigarettes can be collected while fresh, and the amount of smoke components (eg. tar, nicotine, phenols) on their filters can be measured. Knowing the filtration efficiency of the filters, the amount of smoke received by the smokers can be calculated. This technique has been used extensively by BAT Hamburg (1), Philip Morris (2) and others (3,4). It has the disadvantage that it assumes constant filtration efficiencies for all smoking patterns (including puff velocities). Also there is no way in which the condensate or vapour phase can be collected for biological or chemical assay.

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A ONE PORT SLAVE SMOKING MACHINE

ABSTRACT

This report describes the construction and calibration of a one port slave smoking machine, which will simultaneously reproduce a subject's smoking actions, so that the subject and the machine smoke matched cigarettes concurrently by the same puffing pattern with minimal interference in the subject's smoking pleasure.

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The second alternative is to duplicate the subject's smoking, by developing a machine which will simultaneously reproduce the subject's actions, and let the machine and the subject smoke matched cigarettes by the same pattern with minimal interference in the subject's smoking pleasure. This method had the disadvantage that cigarettes are not identical throughout their length, even when they are matched for weight and pressure drop. However, it does make it easier to assay the smoke in any desired way.

Such a machine has been developed in this Department, and has been given the name, Freiri Smoker, after its inventors, the authors. This report describes the machine, its standardization and mode of operation. A second report will describe a study of its use in measuring degrees of compensation for changes in available nicotine.

The machine has been developed over an extended period although the delays have mostly been due to supplier's problems in the performance of some of the machine's components. During the development, the machine has naturally undergone numerous changes.

Prerequisites for the Machine

The machine has to fulfil a series of prerequisites in its mode of operation.

1. It must smoke a cigarette in the same way that the human smokes. In the prototype machine, it was decided that the machine must be a slave, and smoke the cigarette simultaneously with the human subject. Later it could be converted to smoke by the pattern of the human, fed to it by magnetic tape, and at the same time could be modified to be a two, three or possible a four port machine.

2. As a slave, its operation must interfere as little as possible with the subject's normal smoking behaviour. Some inconvenience is unavoidable e.g.(a) his cigarette must be held in a cigarette holder to which a flexible tube is attached; (b) in the first instance, he has to sit in a particular part of the laboratory, and ignore a considerable amount of extraneous equipment and noise. This should be avoidable later. Tests have shown that after a number of runs, the smoker is accustomed to such circumstances. However, whereas other workers (5,6,7) have introduced a constriction and/or pitot head into the cigarette holder to give direct measurement of puff velocity (and hence puff volume), we wanted to avoid this, since (a) a constriction may interfere with the smoker's normal pattern for a given cigarette, (b) the degree of interference may depend on the type of puffs he takes, and (c) it may reduce the amount of smoke he would normally receive.

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3. The machine must reproduce the puffs and timing as accurately as possible, and must record puff durations, intervals and volumes accurately.

4. It must be easy to collect smoke.

5. The machine must be able to operate as a free smoker, i.e. the cigarette butt end must be open to the atmosphere in the intervals between puffs, as is normally the case in human smoking.

Principle of the Machine

The human smoker can be considered as a smoking machine, with the mouth and lungs acting as a source of vacuum, under the direction of very rapid nerve impulses. To duplicate the human's puffing, the changes in air pressure within the human's cigarette holder are converted into electrical signals. These are used to operate a rapid response valve, which in turn controls the air flow into a constant vacuum source. This controlled air flow in the slave smoker, which smokes the matching cigarette is a system which permits free smoking, the collection of smoke and the recording of puff parameters.

Capability

The machine gives excellent duplication of puffs with a wide range of profiles, with puff volumes of from 15 to 80 ml, puff velocities of from 800 to 1400 ml per minute, and puff durations of from 1 to more than 4 seconds. This applies for standard pressure drops of from 2.6 to 7 inches.

Construction and Operation

The construction of the slave smoker is rather complex, and its function is easier to understand if one refers to the block diagram shown in figure I. Table I shows a list of the components.

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Table 1 Components of the Freiri Smoker, and Auxillary Equipment

(The letters relate to the block diagram in Figure I, subscripts:
m = master, s = slave)

Am,As	Matched cigarettes
Bm,Bs	Teflon cigarette holders
Cm,Cs	Matched Sanborn transducers (Model 270, ex Hewlett-Packard)
Dm,Ds	Matched Sanborn transducer converters (Model 592-300, ex Hewlett-Packard)
E	Moseley 2 channel recorder (Model 7100B, ex Hewlett-Packard)
F	Valve Recorder and Controller (Model Electronic III - Sp. S111-2, ex Honeywell)
G	Pneumatic valve (Honeywell Series 1400 - Single Seated - Model 1405 Ultra-low flow), fitted with pneumatic valve positioner.
H	Vacuum pump (type DT/VT-1,5, ex Gebr. Becker G.m.b.H)
J	Surge tank
K	Artificial lip
L	Spiral Trap cooled in Dry Ice - Acetone
M	Flow restrictor (made from capillary)
N	Cambridge filter
O	Ultra-low pressure switch (Faircon, model PSF-100A or SRF-100A)
P	Time delay relay (Allen-Bradley, bulletin 849)
Q	Solenoid valves
	Air supply, at 20 and 50 psi (for operation of pneumatic valve but not shown)
R	Vacuum control valve

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A cigarette (Am) is held in a Teflon holder (Bm), fitted with a side arm, as shown in Figure 2. The side arm is connected through narrow-bore flexible tubing to one side of a pressure transducer (Cm), while the other side of the transducer is open to the atmosphere. Thus the electrical output of the transducer is being controlled by pressure changes occuring behind the cigarette as the human smokes. This electrical output is a pulsating signal, which is converted into D.C. by a converter (Dm) before being passed to the valve recorder and controller (F). Here the DC puff signals are recorded on a slow moving chart, giving the intervals between puffs accurately, and the signal is converted into an equivalent pneumatic 'signal' using compressed air to operate the pneumatic valve (G) to the commands of the human's puffing.

This valve (G) controls a vacuum source (derived from the pump (H) and surge tank (J)), as it smokes a matching slave cigarette (As) in its holder (Bs). During normal operation the side arm on the holder (Bs) is blocked off. Bs is held in an artificial lip, (K) designed in this Laboratory and shown in Figure 3, which operates in such a way as to draw the cigarette to the lip at the start of a puff and release it just after the puff is completed.

The smoke from the slave cigarette is collected just behind the lip K by any desired means, usually a cooled glass spiral trap (or sometimes a Cambridge filter). The puff parameters are determined by recording the flow rate through a capillary restrictor (M) (shown in Figure 4), which is inserted between the cold trap L and the pneumatic valve G. This is achieved by connecting a Tee on each side of the capillary to the corresponding arm of a second (matching) pressure transducer (shown as Cs, where the 2nd subscript represents position 1). The electrical output from Cs, equivalent to puff velocity, is fed via a converter (Ds_1) to one channel of a Moseley 2-channel recorder (E). Here the velocity profiles of the puffs are recorded, giving the puff durations and, after calibration, the puff volumes. The capillary (M) must be kept free of any smoke deposit which could alter its flow characteristics, and as an added precaution for this, a Cambridge filter (N) is inserted after the cold trap.

The lip (K) is actuated by the pressure changes behind the subject's master cigarette (Am), through an ultra-low pressure switch (O), a time-delay relay (P) and solenoid valves (Q). The time-delay relay (P) is necessary to compensate for the electrical, pneumatic and mechanical delays between the master signal and the slave response, by holding the cigarette in the lip for an extra 0.2 seconds to be sure the puff is completed.

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Selection of the Transducers

Originally we intended to determine puff volumes from profiles of pressure behind the cigarette relative to atmospheric pressure as did other workers (8), and obtained the transducers and recorder for this purpose following the recommendations of the supplier. However, while these transducers, in normal use, gave an electrical output which was linearly related to pressure change ΔP, this output was in pulse form, and could not be interfaced directly with the recorder, which required a d.c. signal. To overcome this, converters were obtained, but with these installed, the resulting d.c. output from the transducer-converter system was no longer linearly related to ΔP, but varied linearly with the square root of ΔP, as will be shown later. Thus peak heights of puff profiles obtained by recording the signals from this transducer-converter system do not correspond linearly to ΔP. The profiles in fact are very close replicates of true velocity profiles obtained when the transducer is measuring differential pressure across the capillary restrictor. There seems no reason why standard velocity transducers could not be used.

Selection of the Pneumatic Valve

The control valve for the slave smoker has to have a very fast response but also has to give fine control, suggesting a needle valve. A standard chemical engineering formula was used to calculate the required flow coefficient of the valve (9), by which the choice was governed. The maximum air flow through the valve (i.e. at full opening), anticipated for this application, was 40 ml per second.

The formula is shown below:

$$\text{Valve flow coefficient } C_V = \frac{Q}{1360} \quad \frac{(460 + T)\ G}{\Delta P\ (P_2)}$$

where: Q = maximum expected flow in standard cu.ft. per hour (SCFH) (40 ml/sec = 5.085 SCFH in our case)

T = room temperature in °F (70 in our case)

G = specific gravity, which is 1 for air

P_2 = pressure downstream of valve in psi (14 psi in our case)

ΔP = maximum pressure drop across the valve during opening in psi (calculated as about 1 p.s.i. in our case)

$$\therefore C_V = \frac{5.085}{1350} \quad \frac{(460 + 70)\ 1}{14 \times 1} = 0.023$$

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It was found that the Honeywell Ultra-low flow linear pneumatic valve, Model No. 1405, having a C_v of 0.025 and a full opening time response of 1 second, satisfied these requirements.

Operation of the Pneumatic Valve

Figure 5 shows the pneumatic system which operates the valve (a) controlling the action of the slave smoking. We said earlier that the highest air-flow to be expected in smoking was 40 ml per second, or 2400 ml/minute, and the valve was chosen so that when fully open, this flow rate could be achieved. The vacuum for drawing the puffs is regulated to give a pressure drop across the valve of about 1 p.s.i., using the bleed valve (b) provided.

The valve (a) has a fine needle (c) whose movement is controlled by changes in air pressure on either side of a Neoprene diaphragm (d). The 50 p.s.i. air line (e), stabilised through a surge tank (f), provides the driving force for rapid opening and closing of the valve. However, despite its speed, if it were the only controlling factor, it would have a tendency to overshoot the required openings and be too sluggish to respond to delicate commands.

The true control is achieved by a sort of power unit or servo-assistance using a 20 p.s.i. air line (g), again stabilised with a surge tank (h). The commanding electrical D.C. input to the Honeywell valve recorder-controller (j) is converted in a complex transducer-like manner into a controlled pneumatic pressure in the 'low' pressure line. It is this finely-controlled pressure, operating through a valve positioner (k) (selected to give maximum sensitivity) which gives such nimbleness to an otherwise clumsy 'giant' diaphragm, and hence gives the required duplication of the human's actions.

Calibration of the Valve

Details of the calibration are given in an Appendix. The valve controls are first adjusted such that pressures in the control line of 3, 9 and 15 lbs. correspond to the valve being fully closed, half open and fully open respectively. After checking that the two transducers are perfectly matched (i.e. give identical recorded profiles of the required size for a standard smoking machine puff), the slave smoking arrangement is set up as shown in Figure I, with the transducer being connected in position C_s2, and the Tee-joints of the capillary flowmeter being blocked off. A standard capillary (4.2 inch pressure drop) is secured in the slave holder (Bs), and the lip (K) is held in the sealed, smoking position. A precision voltage source is then connected to the valve recorder-controller (F). This is used to open the valve exactly half-way (i.e. by giving an air pressure of 9 lbs), and the vacuum is then

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adjusted using the bleed valve Q until the transducer reading on the Moseley recorder E is nearly halfway up the chart scale (45 chart units). The valve is closed, then reopened electrically in stages such that the controlling air-pressure increases in steps of one pound. In this way a calibration graph can be prepared of the recorded transducer response against the valve opening, as shown in figure 6. The valve is then ready for use in puff duplication, although its operation should be standardized daily at 3 pressures (6, 9 and 12 lbs) as outlined above.

Evaluation of the Duplication Characteristics of the Slave Smoker

Testing of the duplication characteristics of the slave smoker was achieved using capillaries, lengths of filter tow, or unlit cigarettes. The details of two such tests are now described.

1. Using controlled air flows on the master 'smoker'

Glass capillaries, or lengths of filter tow enclosed in snugly fitting glass tubes, matched for pressure drop, were secured in the cigarette holders (B,Bs). To the inlets of these, matched flow meters (ex. Fisher and Porter Co., Hatboro, Pa.) were attached. Tee pieces were inserted in the lines behind each holder, and to the side arms of the Tee pieces, matched water manometers were connected. In the slave side, the Tee-piece was fitted between the holder and the lip (K). An independently controllable vacuum source was used to replace the human smoker. The air flow through a capillary on the master side was increased in steps to test the ability of the machine to duplicate velocities and, for the sake of completeness, pressure changes. The air flows and pressure changes for the master and slave 'smokers' were recorded, together with the transducer response from position C_s2 on the slave side, in chart units. This testing was repeated for matched pairs of capillaries and also of filter tow sections, covering a range of standard pressure drops from 2.6 to 6.7 inches water. The results are given in Tables 2 and 3, and the duplication by the slave smoker is shown in Figures 7 and 8.

The overall duplication of velocities and pressure changes (ΔP) was not very good, although in general the capillaries gave better duplication than the tow sections, and some standard pressure drop 'restrictions' were better than others. Table 4 gives the correlation data for the various comparisons.

The accuracy, with which flowmeters and manometers can be read visually, leaves a lot to be desired and is a contributor to the errors seen in this test. However, there seems to be a bias towards an overresponse by the slave smoker under these "static, continuous puff" conditions, particularly at low velocities. The error may be caused by the atypical operation of the valve required under these tests, because other tests, with 'dynamic' human puffing on the master smoker, give excellent puff duplications.

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Table 4 Correlation Data for Duplication of Velocity and ΔP Using Controlled Air-Flows on the Master Smoker

	Equation for line of best fit	Standard Estimate of error Syx	Correlation Coefficient r
Velocity			
Capillaries	y = .885x + 85	109	0.92
Tows	y = .774x + 224	127	0.90
Overall	y = .82x + 163	122	0.90
ΔP			
Capillaries	y = .847x + 21.8	24.3	0.92
Tows	y = .804x + 30.7	27.2	0.83
Overall	y = .829x + 26	26.9	0.88

x = master, y = slave

The relationship between transducer response and pressure changes or velocities is interesting. The slave transducer (in position C_{s2} - Figure I) was responding to pressure changes in the slave holder (B_s). At the same time, the pressure changes ΔP_s were being read from the manometer. When the transducer response was plotted against ΔP_s, a curve was obtained, but a linear relationship was found between the response and $\sqrt{\Delta P_s}$, as shown in Figure 9, with the combined correlation data from the capillaries and tow sections being as follows: -

line of best fit: - y = .224x + 1.96 ----------------(i)

($y = \sqrt{\Delta P_s}$, x = transducer response)

standard estimate of error Syx = 0.547

correlation coefficienct r = 0.995

However, the velocity is known to be proportional to the square root of the pressure change in any flow system through a restriction (10). Thus considering the slave capillary or tow section as a restriction, then the velocity v through it will be given by: -

$$v = k\sqrt{\Delta P_s}, \quad \text{---------------------------------------(ii)}$$

where k is a constant for a given restriction.

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We can now relate the transducer response t and velocity v using equations (i) and (ii): -

$$t = \frac{1}{.224} \left(\frac{v}{k} - 1.96 \right) \text{ ---------------------(iii)}$$

Thus, for a given restriction, the transducer response obtained from this position (C_{s2}) is linearly related to the air velocity v, i.e. for a given standard pressure drop, the transducer is accurately recording velocity. If transducer response is plotted against velocity for the series of capillaries and tows, a series of straight lines should be obtained with a common intercept but with different slopes, the latter dependent on the value of k for each restriction.

Figures 10 and 11 show these plots of master velocity against slave transducer response. In fact the lines are not straight for the complete velocity range, probably because of incomplete linearity and reading inaccuracies of the flow-meter and the unusual mode of operation of the valve. The negative intercept on the t axis suggests that the valve would not respond at very low velocities. However the transducer itself appears to have a threshold signal requirement also, as shown by the negative intercept in equation (iii) which applies to measurements taken only on the slave side. In any event this minimum signal is not serious, since it would apply for velocities up to about 400 ml/minute i.e. in the worst case, a puff of around 14 ml taken over 2 seconds, which is highly unlikely. The small leading or tailing ripples on complex puffs would still be followed, since the velocities involved would still be higher than this.

To record true velocities, and hence true volumes, for conditions of changing standard pressure drop of the restriction (as in actual smoking), the transducer must respond to differential pressure across another fixed restriction, as in position C_{S1} (Figure I).

2. <u>Testing the Duplication using Human Puffs on the Master Smoker</u>

In a second test, matched pairs of capillaries and of filter tows (in the standard pressure drop range of 2.6 to 7 inches) were again used, but the standard flow-meters were replaced by soap bubble flow meters of 100 ml capacity. No pressure changes were measured. The side-arm of the slave holder (Bs) was blocked off, and the transducer was connected to the capillary flow-meter in position C_{s1}, so that velocity puff profiles from the slave smoker would be recorded on the Moseley recorder E. A virtually complete range of types of puff were drawn by humans on the master side, and the actual puff volumes of master and slave were recorded from the soap-bubble meters, together with the recorded profile area computed by the triangulation method. The results are shown in Table 5.

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The slave smoker gave excellent duplication of puffs, with the standard deviation of the slave puff volumes, from those of the human, being ±3.62% for puff volumes from 15 to 80 ml, puff durations from 1.0 to 4.6 seconds and 'average puff velocities' from 800 to 1400 ml per minute. The standard deviation of the slave puff volume (computed from the profile area) from the actual puff volume was ±4.70%. Linear relationships were observed between the various puff volumes, with the correlation coefficients being as follows:

	r
True puff volume, master v. true puff volume, slave	0.98
True puff volume, master v. computed puff volume, slave	0.99
True puff volume, slave v. computed puff volume, slave	0.99

Puff velocities, quoted in these results, were average velocities calculated as follows:

$$\text{Average puff velocity } v. = \frac{V \times 60}{d} \text{ ml/minute}$$

where V = puff volume (ml)

d = duration (seconds)

Additionally, many different types of puff profiles were tested, as typified by those shown below:

Considered as "virtually" symetrical — Shoulders — Double peaks — Distorted

The slave smoker reproduced even the most distorted peaks. For profiles which were "virtually symetrical", the slave puff volumes were within ±3% of those of the command puffs, while for very distorted profiles, the deviation tended to be larger (±6%). A significant improvement in the duplication of distorted puff volumes was seen when capillaries were replaced by matched unlit cigarettes, possibly due to smoother air-flow through the cigarettes. Better accuracy in peak area measurement can be achieved using a digital integrator (eg. Hewlett-Packard Model 3370A).

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Use of the Cold Trap with the Slave Smoker

The cold spiral trap (L, Figure I) did not interfere with puff profile areas (and hence with indirect puff volume measurements) when the trap was inserted in the line between the artificial lip K and the capillary flow meter M. Also it could not influence through contraction the actual puff volume taken on the slave cigarette, because the machine operates as a free-smoker.

Use of the Slave Smoker

In this report, the construction of the Freiri slave smoker has been described, and its duplicating performance has been demonstrated.

A second report will describe the first use of the slave smoker in studying smokers' compensation reactions to changes in cigarette smoke deliveries of nicotine.

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APPENDIX

CALIBRATION PROCEDURE FOR THE VALVE

The calibration of the valve is based on puffs whose ranges of volumes, velocities and durations are greater than those normally encountered. It was considered that an air flow of 1050 mls per minute through the valve at its half open position would be suitable to satisfy these demands.

Preparation of the Valve for Calibration

Cam no.2 is placed in the valve positioner housing as described in the valve manual specifications. The final cam position is adjusted by the lever arm (approx. at no.5 screw-support position) and the pneumatic spring control, in such a way that the vertex of the obtuse angle (approx. 130°) of the cam is firmly pressing against the pneumatic control positioner guide at the closed valve position. The pneumatic automatic reset and rate relays in the valve recorder are turned to the off position. The proportional band (gain) adjustment, which is used to control the conversion of the electrical input into the pneumatic output, is adjusted to almost full gain. The air and electrical supplies are now turned on.

Test of the Pneumatic Controller Function

The valve positioner indication knob is placed in the automatic position. The performance controller from the valve recorder is placed in the manual operation position. Output gauge and null indicator are adjusted, by the manual control adjuster and set point control knob, to read 3 lbs. air pressure on the output gauge, with the null indicator float in the mid-point gauge position. The gauges on the valve should now indicate air pressures on the valve diaphragm and positioner of 50, 3 and 0 pounds respectively. (If no zero reading on the upper gauge is obtained, a readustment to zero should be made using the pneumatic spring control, located in the positioner housing.) The valve is now opened manually using the manual control adjuster to insure that the valve operates properly. The closed, half-open and fully open positions, as indicated on the valve guide, must coincide with 3, 9 and 15 pounds of air pressure on the output gauge of the valve recorder. Readjustments with the lever-arm and the pneumatic spring control may be necessary to reach this valve performance.

Standardization of Transducers

The outputs of the two transducers are individually tested for equality before starting the valve standardization. A capillary with standard pressure drop of 4.2 inches is secured

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in a cigarette holder. The assembly is attached to one port of a BAT bellows smoking engine. The side arm of the cigarette holder is closed and a soap bubble flow meter is attached to the capillary inlet. The volume of the machine's puff is adjusted to 35 ml. The flow meter is disconnected and each transducer is connected in turn to the holder, so that the transducer response of each can be read from the Moseley recorder on its 1.00 volt scale, using a chart-speed of 0.5 inches per second. If necessary the transducers can be calibrated to deliver equal peak heights for the standard puff of 35 ml volume and 2 seconds duration. This puff will open the valve to 9 lbs. (midway) if the signal of the master transducer is connected to the valve recorder. (c.f. transducer manual).

Standardization of the Valve for Duplication

With reference to Figure 1, the slave smoker is assembled with the slave transducer in position CS2 and with the Tee's of the restrictor (M) closed. The standard capillary, in the slave holder (Bs) is inserted into the free smoker. The free smoker is held electrically in the smoking position (i.e. lips sealed). The valve, adjusted as described previously, is switched from manual to automatic control. A precision voltage source (e.g. a potentiometer) is connected to the valve recorder signal inlet, to permit electrical opening of the valve. Using this, the valve is now opened to exactly 9 pounds (midway) and the vacuum is adjusted by valve R to produce a transducer response of 45 chart units. This response should be stable and held for at least ten minutes. After this, the valve is closed, then reopened electronically one pound at a time to the fully opened position as indicated on the auto-manual transfer switch output gauge. The transducer response is recorded for each valve opening position for five minutes. A graph of the resulting transducer responses is prepared by plotting chart units against valve opening (figure 6). The potentiometer is now disconnected from the valve recorder and is replaced by the line from the master transducer C. Once the artificial lip has been freed, the valve is then fully calibrated. For daily standardizations, the valve should be checked only at 6, 9 and 12 lbs. as outlined above. Before use in duplication, the slave transducer is transferred back to position Cs, and the side arm of holder Bs is closed.

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Table 2 Duplication of Velocities and Pressure Changes (ΔP) by the Slave Smoker, for Matched Capillaries

Master		Slave			
Velocity ml/min	ΔP_m mm	Velocity ml/min	ΔP_s mm	Transducer Response	$\sqrt{\Delta P_s}$
Standard P.D. 3.3 inches					
580	50	355	30	14.0	5.48
630	54	430	36	16.5	6.00
670	60	530	46	20.0	6.78
760	72	630	60	24.5	7.75
850	80	740	72	29.0	8.49
950	90	870	86	33.0	9.27
1030	102	970	100	36.5	10.00
1140	118	1040	110	39.0	10.49
1250	132	1070	120	41.0	10.95
1420	156	1190	140	44.5	11.83
Standard P.D. 4.2 inches					
440	48	350	40	17.0	6.32
530	56	430	50	21.0	7.07
580	62	530	58	24.5	7.62
650	74	630	74	29.0	8.60
730	80	730	86	33.0	9.27
830	94	840	106	37.5	10.30
940	108	960	120	41.0	10.95
1030	126	1030	132	43.5	11.49
1090	138	1080	142	45.5	11.92
1310	174	1200	170	49.0	13.04
O.S.	228	1310	192	52.5	13.86
Standard P.D. 4.9 inches					
410	52	360	48	21.0	6.93
440	58	420	56	24.0	7.48
510	64	510	66	27.5	8.12
590	76	630	84	32.5	9.17
640	82	740	92	37.0	9.59
750	100	870	126	42.0	11.22
850	116	960	140	45.0	11.83
970	136	1030	146	47.5	12.08
1050	148	1070	168	49.0	12.96
1310	202	1190	198	53.0	14.07
O.S.	264	1310	224	56.0	14.97

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Table 2 (Cont'd)

Master		Slave			
Velocity ml/min	ΔP_m mm	Velocity ml/min	ΔP_s mm	Transducer Response	$\sqrt{\Delta P_s}$
Standard P.D. 4.7 inches					
420	50	290	38	18.0	6.16
480	58	420	54	23.0	7.35
550	66	540	66	27.5	8.12
630	76	640	82	32.5	9.06
680	82	740	96	36.0	9.80
750	98	860	116	40.5	10.77
880	114	960	130	43.0	11.40
990	134	1030	146	46.0	12.08
1070	148	1070	152	47.0	12.33
1310	192	1190	188	52.0	13.71
O.S.	254	1310	212	55.0	14.56
Standard P.D. 6.7 inches					
270	52	310	58	25.0	7.62
330	60	410	74	30.0	8.60
400	68	530	96	36.0	9.80
440	80	640	122	41.5	11.05
530	90	740	144	45.5	12.00
630	110	850	172	50.0	13.11
740	136	960	190	52.5	13.78
850	158	1030	210	55.0	14.49
980	186	1070	232	58.0	15.23
1220	257	1190	260	61.0	16.12
O.S.	418	1310	304	64.5	17.44

O.S. = off scale

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Table 3 Duplication of Velocities and Pressure Changes (ΔP) by the Slave Smoker, for Matched Filter Tow Rods

Master		Slave			
Velocity ml/min	ΔP_m mm	Velocity ml/min	ΔP_s mm	Transducer Response	$\sqrt{\Delta P_s}$
Standard P.D. 2.6 inches					
590	50	410	36	16.0	6.00
730	58	550	47	20.5	6.86
835	66	640	54	23.0	7.35
970	76	770	66	27.0	8.12
1030	80	840	70	28.5	8.37
1120	88	960	80	31.0	8.94
1190	96	1020	84	32.0	9.17
1320	106	1060	90	33.5	9.49
O.S.	128	1180	98	36.0	9.90
O.S.	144	1300	110	38.5	10.49
O.S.	188	1410	120	41.0	10.95
Standard P.D. 3.6 inches					
440	50	410	46	21.0	6.78
540	60	540	60	25.0	7.75
630	70	640	72	29.0	8.49
730	76	730	80	31.5	8.94
820	84	830	92	35.0	9.59
920	94	950	102	37.0	10.10
1030	106	1030	112	39.5	10.58
1070	118	1070	118	41.0	10.86
1180	140	1180	132	43.0	11.50
1410	176	1410	146	46.0	12.08
Standard P.D. 4.8 inches					
330	50	350	54	23.0	7.35
400	56	420	64	27.0	8.00
440	60	530	74	30.0	8.60
530	70	630	90	34.5	9.49
620	80	760	110	39.0	10.49
650	88	850	122	41.5	11.05
760	100	960	136	44.0	11.66
890	118	1030	148	46.0	12.17
960	126	1070	154	47.0	12.41
1190	158	1190	174	50.0	13.34
~1490	206	1310	190	52.5	13.78
O.S.	268	1420	210	55.0	14.49

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Table 3 (cont'd)

Master		Slave			
Velocity ml/min	ΔP_m mm	Velocity ml/min	ΔP_s mm	Transducer Response	$\sqrt{\Delta P_s}$
Standard P.D. 5.7 inches					
270	48	330	56	24.5	7.48
330	56	440	72	29.5	8.49
380	62	530	86	33.0	9.27
440	72	630	100	37.0	10.00
530	84	740	120	41.0	10.95
620	94	870	138	45.0	11.75
740	114	960	144	47.5	12.00
870	134	1040	168	49.0	12.96
960	144	1070	174	50.0	13.19
1180	186	1180	192	53.0	13.86
~1400	240	1310	214	55.0	14.63
O.S.	312	1420	230	57.5	15.17
Standard P.D. 6.6. inches					
230	48	290	58	25.0	7.62
290	56	420	78	31.5	8.83
330	62	530	96	35.5	9.80
410	74	630	118	40.5	10.86
470	84	740	140	45.0	11.83
540	96	850	158	48.0	12.57
670	118	960	176	50.5	13.27
820	142	1040	192	52.5	13.86
850	148	1070	198	53.5	14.07
1130	198	1180	220	56.0	14.83
O.S.	281	1310	248	59.0	15.75
O.S.	390	1420	270	61.0	16.43

O.S. = off scale

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Table 5 Standardization of Slave Smoker using Puff Volumes

Puff Volume (ml)			Peak Height H cm	Peak Width W cm at H/2	Peak Area	Puff Duration sec.	Average Velocity ml/min
Master	Slave	From Peak Area					
Capillaries, Standard P.D. 3.3 inches							
40.0	38.4	38.0	12.6	2.37	14.9	2.4	960
41.6	40.0	38.6	14.3	2.12	15.2	2.2	1091
27.8	27.0	26.6	16.0	1.2	9.6	1.3	1080
37.8	38.0	37.7	17.2	1.72	14.8	2.0	1140
52.6	51.0	51.9	12.6	3.4	21.4	3.2	956
28.0	26.0	25.5	19.2	0.95	9.1	1.4	1115
* 73.8	73.0	71.9	14.2, 9.3	2.6, 2.65	30.7	4.9	894
38.2	37.0	37.1	16.6	1.75	14.5	2.0	1110
43.6	42.0	45.7	12.3	3.0	18.5	2.9	869
40.0	38.2	38.2	15.8	1.9	15.0	2.0	1146
47.8	47.0	49.8	14.0	2.92	20.4	2.8	1007
41.6	40.6	41.8	14.1	2.37	16.7	2.4	1015
Capillaries, Standard P.D. 4.2 inches							
36.2	36.6	37.3	13.6	2.15	14.62	2.2	999
40.4	41.0	42.0	14.9	2.25	16.8	2.4	1025
46.2	45.4	45.1	17.2	2.12	18.2	2.4	1135
*	78.2	75.0	13.0, 15.7	2.1, 2.3	31.7	4.6	1020
45.0	45.8	45.1	15.2	2.4	18.2	2.5	1099
16.8	16.0	20.0	16.6	0.8	6.6	1.1	873
23.6	23.4	24.0	15.0	1.12	8.4	1.6	878
38.6	37.0	36.0	17.9	1.58	14.1	2.0	1110
48.2	50.0	51.5	15.5	2.75	21.3	2.8	1071
57.0	55.4	55.4	18.4	2.5	23.0	2.6	1278
47.8	46.0	46.5	18.0	2.1	18.9	2.4	1150
52.4	54.0	53.5	15.5	2.85	22.1	3.0	1080
Capillaries, Standard P.D. 4.7 inches							
45.0	46.0	45.1	15.9	2.3	18.3	2.5	1104
48.2	48.6	49.0	17.4	2.3	20.0	2.6	1122
23.6	24.0	24.0	16.2	1.05	8.5	1.5	960
46.2	45.0	45.0	19.1	1.9	18.1	2.2	1227
35.0	35.8	35.5	17.0	1.62	13.8	2.0	1074
46.4	48.0	47.0	16.1	2.38	19.2	2.5	1152
62.2	63.2	66.0	19.2	2.92	28.0	3.1	1223
57.4	58.0	61.0	18.6	2.75	25.6	3.0	1100
28.8	29.8	30.5	15.3	1.5	11.5	1.8	1010
47.6	47.2	47.5	16.6	2.33	19.3	2.6	1089
70.4	76.0	72.0	16.3	3.75	30.6	4.2	1086
41.4	42.0	41.0	16.4	2.0	16.4	2.2	1145
40.0	40.6	40.3	15.6	2.05	16.0	2.3	1059

* Double peak

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Table 5 (cont'd)

Puff Volume (ml)			Peak Height H cm	Peak Width W cm at H/2	Peak Area	Puff Duration sec.	Average Velocity ml/min
Master	Slave	From Peak Area					
Capillaries, Standard P.D. 4.9 inches							
41.4	41.8	42.0	16.8	2.0	16.8	2.4	1045
30.4	31.0	31.0	16.3	1.42	11.6	1.8	1033
40.0	41.0	40.0	15.5	2.05	15.9	2.5	984
45.4	47.6	47.0	12.4	3.1	19.2	3.1	921
43.0	42.2	42.2	18.3	1.85	16.9	2.3	1109
22.0	21.4	23.5	10.5	0.9	8.3	1.4	917
62.8	61.0	65.0	21.8	2.55	27.7	3.0	1220
49.2	48.0	49.0	19.5	2.05	20.0	2.4	1220
40.4	40.4	40.0	18.3	1.73	15.8	2.2	1102
* 56.0	55.6	48.5	18.5,15.5	1.3,1.0	19.8	3.2	1043
41.4	42.4	41.0	16.4	2.0	16.4	2.4	1060
35.2	35.4	35.0	17.0	1.6	13.6	2.0	1062
Capillaries, Standard P.D. 6.7 inches							
41.4	43.0	43.0	18.6	1.85	17.2	2.4	1075
35.8	37.6	36.0	16.8	1.68	14.1	2.2	1025
42.0	42.8	42.5	20.7	1.65	17.1	2.2	1167
47.0	46.0	45.5	20.4	1.8	18.4	2.4	1150
41.0	43.0	42.0	17.1	1.95	16.7	2.4	1075
35.8	35.2	33.5	21.4	1.2	12.8	2.0	1056
41.2	43.2	44.0	18.6	1.9	17.7	2.4	1080
56.4	55.4	55.0	21.2	2.15	22.8	2.6	1278
23.0	20.6	23.0	20.0	0.8	8.0	1.5	824
51.0	51.6	52.0	21.5	2.0	21.5	2.6	1191
41.8	44.0	43.5	19.1	1.82	17.4	2.4	1100
44.0	44.0	43.0	16.9	2.05	17.3	2.6	1015
36.0	37.6	37.0	16.1	1.8	14.5	2.2	1025
66.8	69.0	71.5	21.7	2.8	30.4	3.5	1183
Filter Tow, Standard P.D. 2.6 inches							
41.0	40.0	41.0	15.5	2.1	16.3	2.3	1043
33.0	32.0	34.0	14.6	1.8	13.1	1.9	1011
60.0	58.0	55.5	17.3	2.65	22.9	2.7	1290
23.4	22.0	23.5	14.9	1.1	8.2	1.3	1015
48.0	48.0	50.5	16.1	2.5	20.9	2.6	1108
45.0	44.8	45.0	16.3	2.22	18.1	2.3	1169
49.6	48.6	47.0	17.0	2.25	19.1	2.3	1268
60.0	60.4	60.0	18.5	2.72	25.2	2.8	1294
27.4	26.6	26.5	17.1	1.14	9.7	1.5	1064
49.2	48.0	49.0	17.4	2.3	20.0	2.4	1200
34.0	33.4	32.5	18.0	1.38	12.4	1.6	1253
45.0	45.0	46.0	15.6	2.4	18.7	2.4	1125
* 68.8	71.0	68.0	13.5 , 4.0	3.85, 1.35	28.7	4.3	991

* Double peak

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Table 5 (cont'd)

Puff Volume (ml)			Peak Height H cm	Peak Width W cm at H/2	Peak Area	Puff Duration sec.	Average Velocity ml/min
Master	Slave	From Peak Area					
Filter Tow, Standard P.D. 2.9 inches							
49.6	48.0	49.0	13.3	3.0	20.0	2.9	993
51.4	50.0	50.0	16.0	2.55	20.4	2.6	1154
* 72.6	69.4	68.5	15.6,4.6	3.4,1.1	29.1	3.8	1096
24.8	24.0	27.0	21.0	0.95	10.0	1.3	1108
43.0	42.4	42.5	17.0	2.0	17.0	2.2	1151
54.0	52.6	51.5	16.3	2.6	21.1	2.6	1214
37.8	39.0	37.0	20.7	1.4	14.5	1.7	1376
58.0	55.8	53.5	17.1	2.6	22.2	3.0	1116
65.2	63.0	69.0	19.5	3.0	29.3	3.1	1219
51.0	49.0	44.0	18.1	1.95	17.6	2.5	1176
47.8	50.0	50.5	14.1	2.95	20.8	2.9	1034
32.4	33.0	32.5	13.3	1.87	12.4	1.9	1042
Filter Tow, Standard P.D. 4.3 inches							
52.4	52.4	52.5	14.9	2.9	21.6	2.8	1123
37.0	35.4	35.0	18.0	1.5	13.5	1.8	1180
53.6	52.0	53.8	17.8	2.5	22.3	2.6	1200
36.0	34.0	33.0	19.0	1.32	12.5	1.9	1074
48.2	50.4	50.0	16.3	2.52	20.5	2.6	1163
37.0	38.0	38.0	15.9	1.9	15.1	2.2	1036
29.6	28.4	28.5	17.5	1.2	10.5	1.6	1065
36.2	35.4	34.5	17.0	1.57	13.3	1.9	1118
77.0	81.0	79.5	15.9	4.3	34.2	4.6	1057
47.0	49.0	48.5	15.1	2.62	19.8	2.6	1131
25.2	23.4	23.0	18.5	0.85	7.9	1.3	1080
30.0	31.2	31.0	14.8	1.6	11.8	1.7	1101
27.6	29.0	30.0	14.4	1.58	11.4	1.8	966
30.0	29.0	29.0	16.4	1.3	10.7	1.6	1088
Filter Tow, Standard P.D. 5.1 inches							
42.6	44.2	43.0	16.4	2.1	17.3	2.4	1105
42.6	43.0	41.0	17.3	1.9	16.4	2.3	1122
30.4	29.8	29.5	17.4	1.25	10.9	1.8	993
21.8	20.2	24.0	18.6	0.9	8.4	1.2	1010
51.2	52.6	53.8	17.8	2.5	22.3	2.6	1214
50.2	52.0	51.0	17.6	2.4	21.1	2.5	1248
65.2	67.0	69.0	18.2	3.22	29.3	3.3	1218
41.0	39.2	38.0	18.8	1.6	15.0	2.0	1176
72.4	74.2	76.9	18.9	3.5	33.1	3.6	1237
30.2	32.0	32.0	16.0	1.52	12.2	1.8	1067
52.0	54.0	51.0	16.2	2.7	21.9	2.8	1157
24.2	22.0	24.5	19.2	0.9	8.6	1.4	943

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Table 5 (cont'd)

Puff Volume (ml)			Peak Height H cm	Peak Width W cm at H/2	Peak Area	Puff Duration sec.	Average Velocity ml/min
Master	Slave	From Peak Area					
Filter Tow, Standard P.D. 5.9 inches							
43.0	44.6	43.0	17.2	2.0	17.2	2.4	1115
56.0	57.0	59.5	18.5	2.68	24.8	2.8	1221
28.0	29.2	28.0	17.2	1.2	10.3	1.6	1095
51.2	53.4	53.0	17.2	2.55	21.9	2.6	1232
30.4	32.0	31.0	16.5	1.4	11.6	1.8	1067
57.2	59.0	58.6	17.2	2.85	24.5	3.2	1106
49.2	51.0	49.0	16.0	2.5	20.0	2.7	1133
41.6	40.0	38.5	20.3	1.48	15.0	1.9	1263
39.0	38.0	37.5	18.8	1.55	14.6	2.0	1140
48.0	48.0	48.5	19.9	2.0	19.9	2.4	1200
63.6	65.4	66.0	18.9	2.95	27.9	3.0	1308
46.6	47.0	46.5	19.1	1.98	18.9	2.4	1175
28.4	28.0	31.5	21.8	1.1	12.0	1.4	1200
29.8	29.0	29.5	17.3	1.28	11.1	1.6	1088
Filter Tow, Standard P.D. 7.0 inches							
44.0	45.0	44.0	15.5	2.3	17.8	2.6	1038
43.2	44.8	44.0	21.2	1.67	17.7	2.2	1222
62.4	64.0	65.5	21.9	2.48	27.2	2.8	1371
29.8	28.0	27.0	21.7	0.9	9.8	1.5	1120
47.2	48.2	46.5	21.0	1.8	18.9	2.4	1205
31.2	32.0	31.5	20.2	1.18	11.9	1.7	1129
52.0	53.0	50.5	19.8	2.2	21.8	2.6	1223
63.2	67.0	71.5	21.8	2.8	30.5	3.4	1182
36.2	38.0	37.0	19.3	1.5	14.3	2.1	1086
32.0	31.4	30.5	17.6	1.3	11.4	1.9	992
25.0	27.0	27.0	19.3	1.02	9.8	1.6	1012
33.6	34.0	31.8	18.4	1.3	12.0	1.8	1133

* Double peak

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FIGURE: 1 – SLAVE SMOKER.

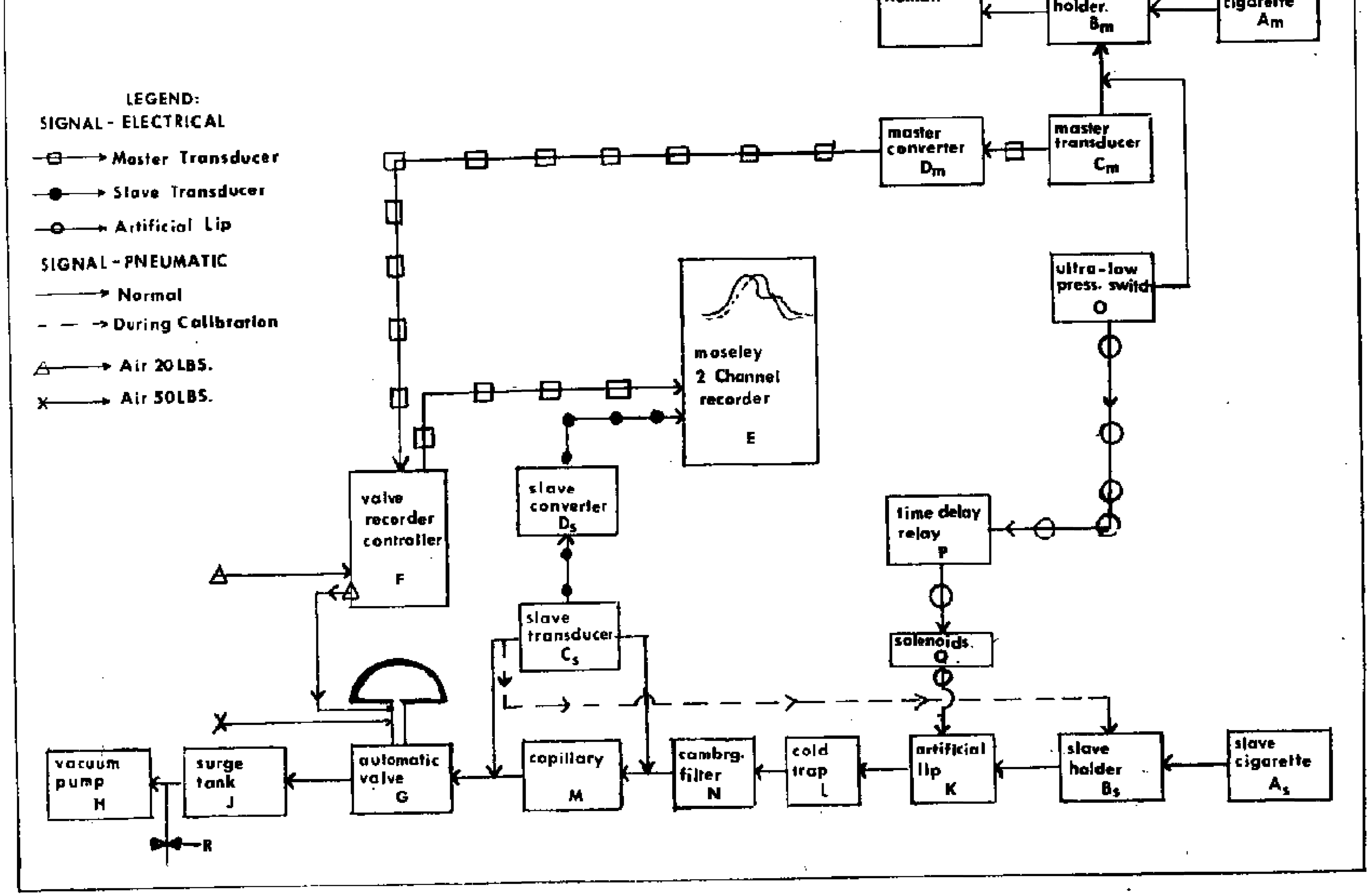

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Fig.: 2 Cigarette Holder

Material Teflon

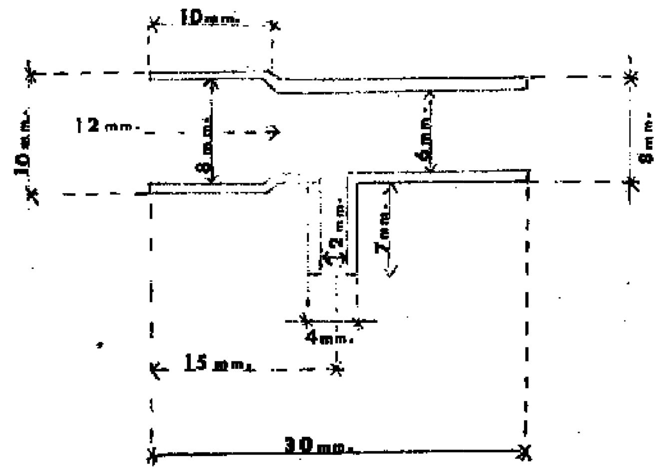

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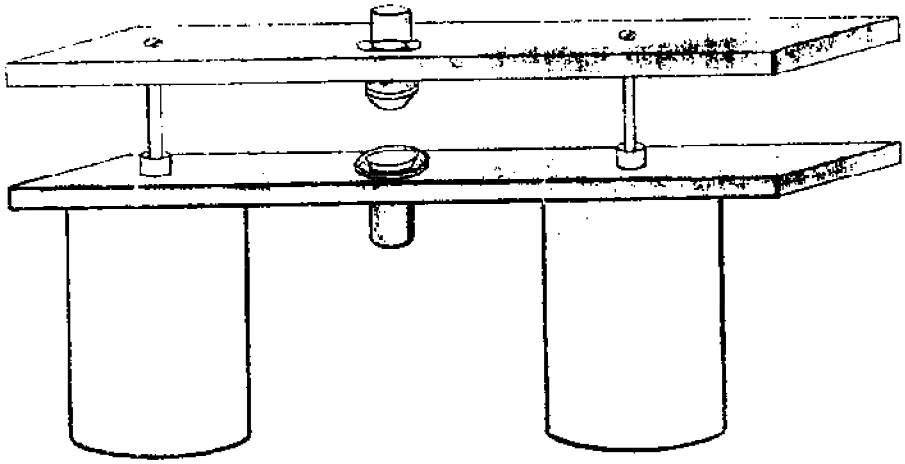
FIGURE: 3 ARTIFICIAL LIP.



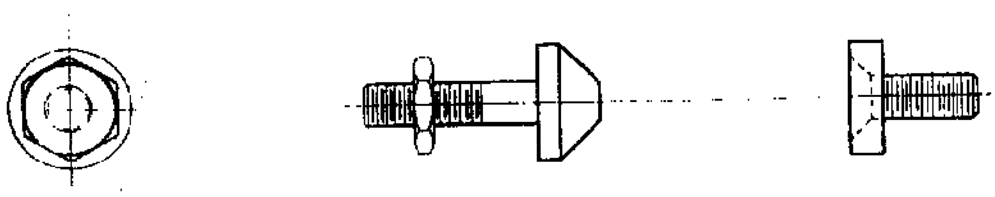


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Fig. :4 Capillary Arrangement To Use Transducer

As Flow Meter.

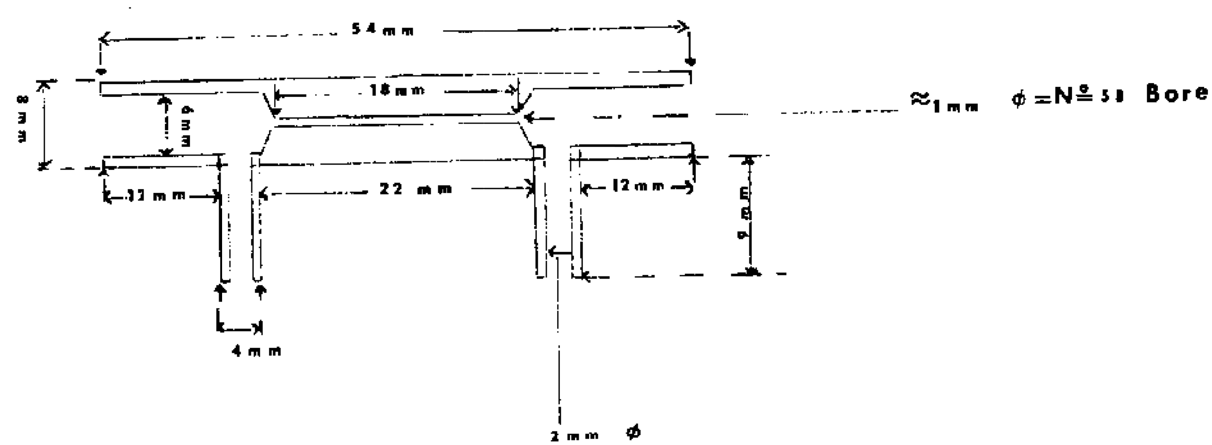

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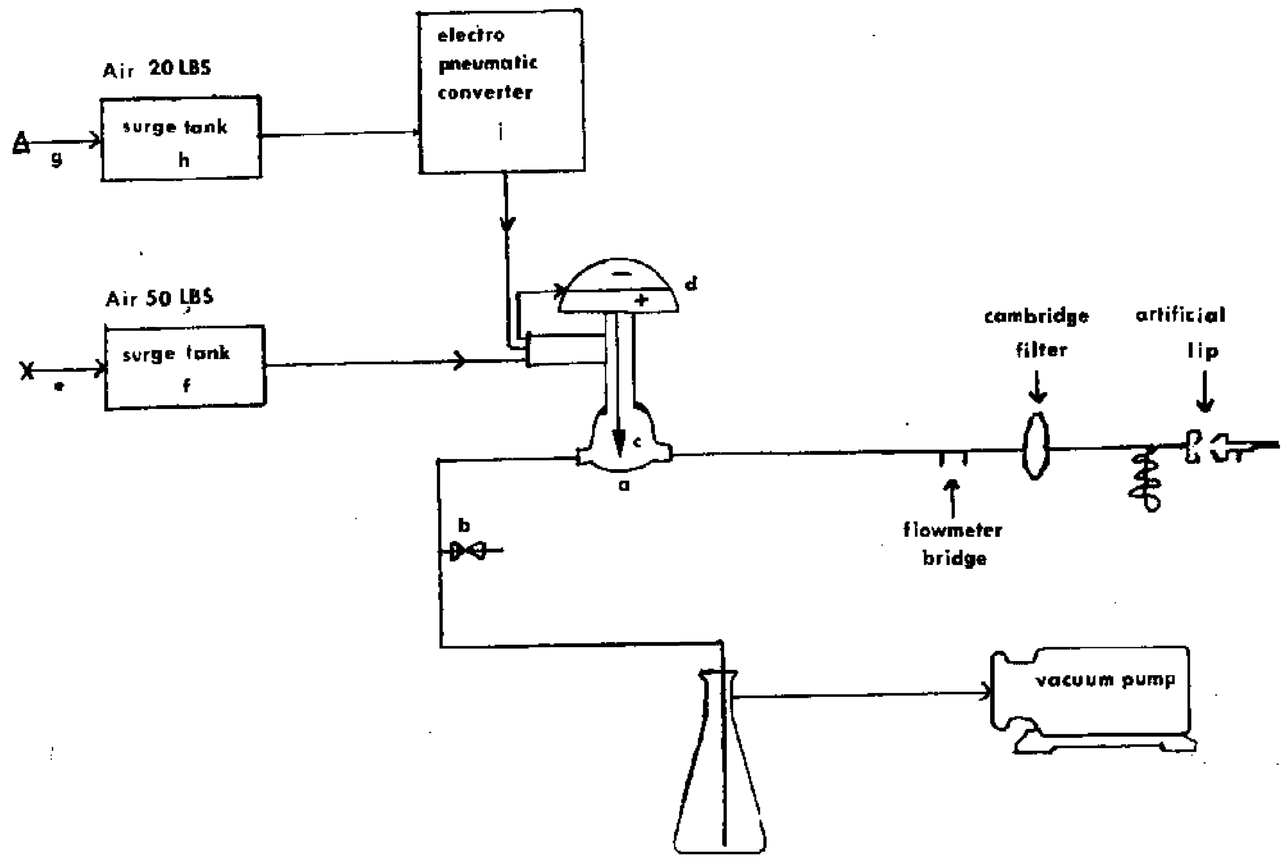
FIGURE: 5 PNEUMATIC SCHEMATIC.



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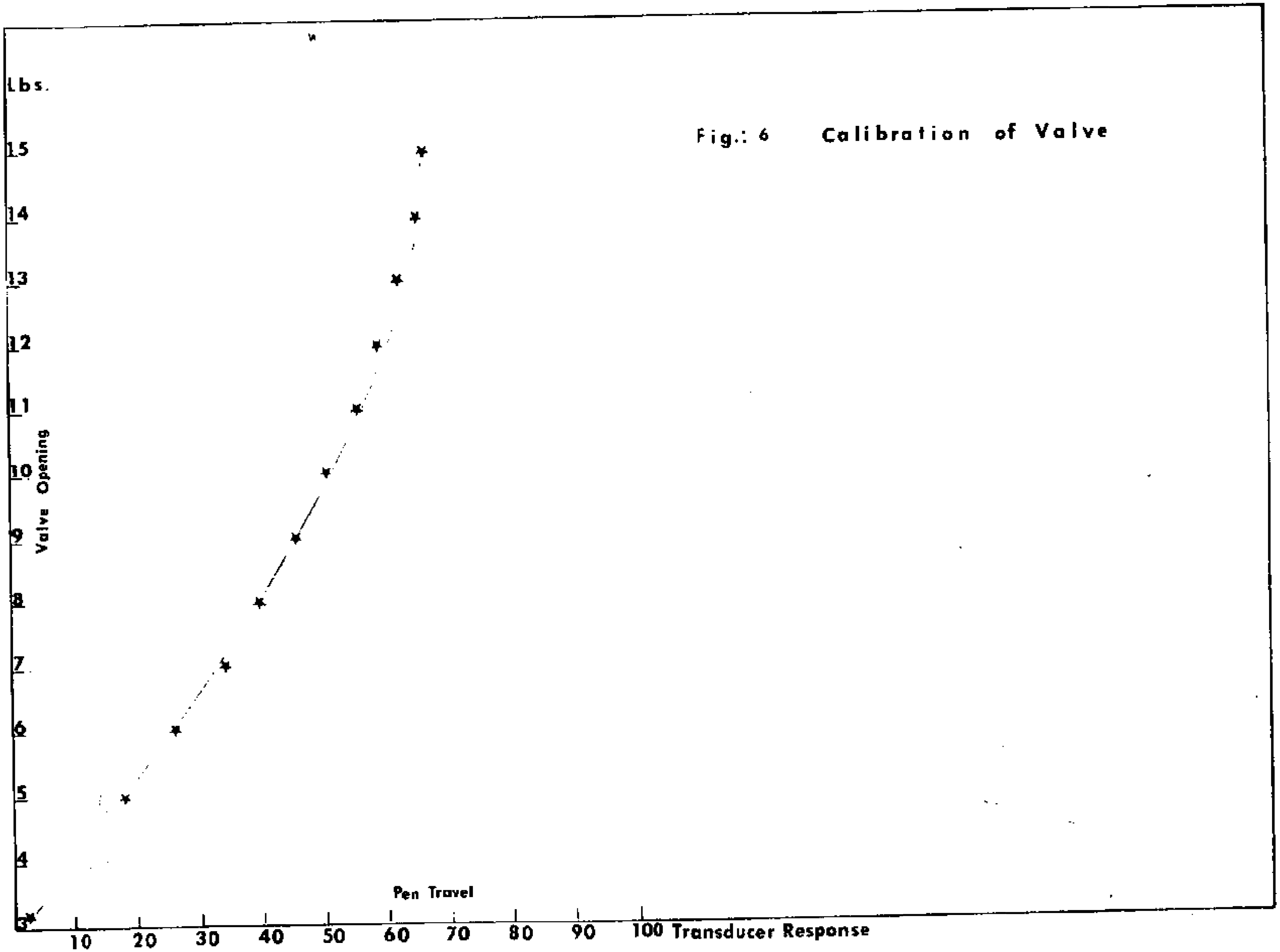

Fig.: 6 Calibration of Valve

FIGURE: 7 DUPLICATION OF VELOCITIES USING CONTINUOUS AIR FLOWS ON THE MASTER SMOKER.

[VELOCITIES - CAPILLARIES, TOWS]

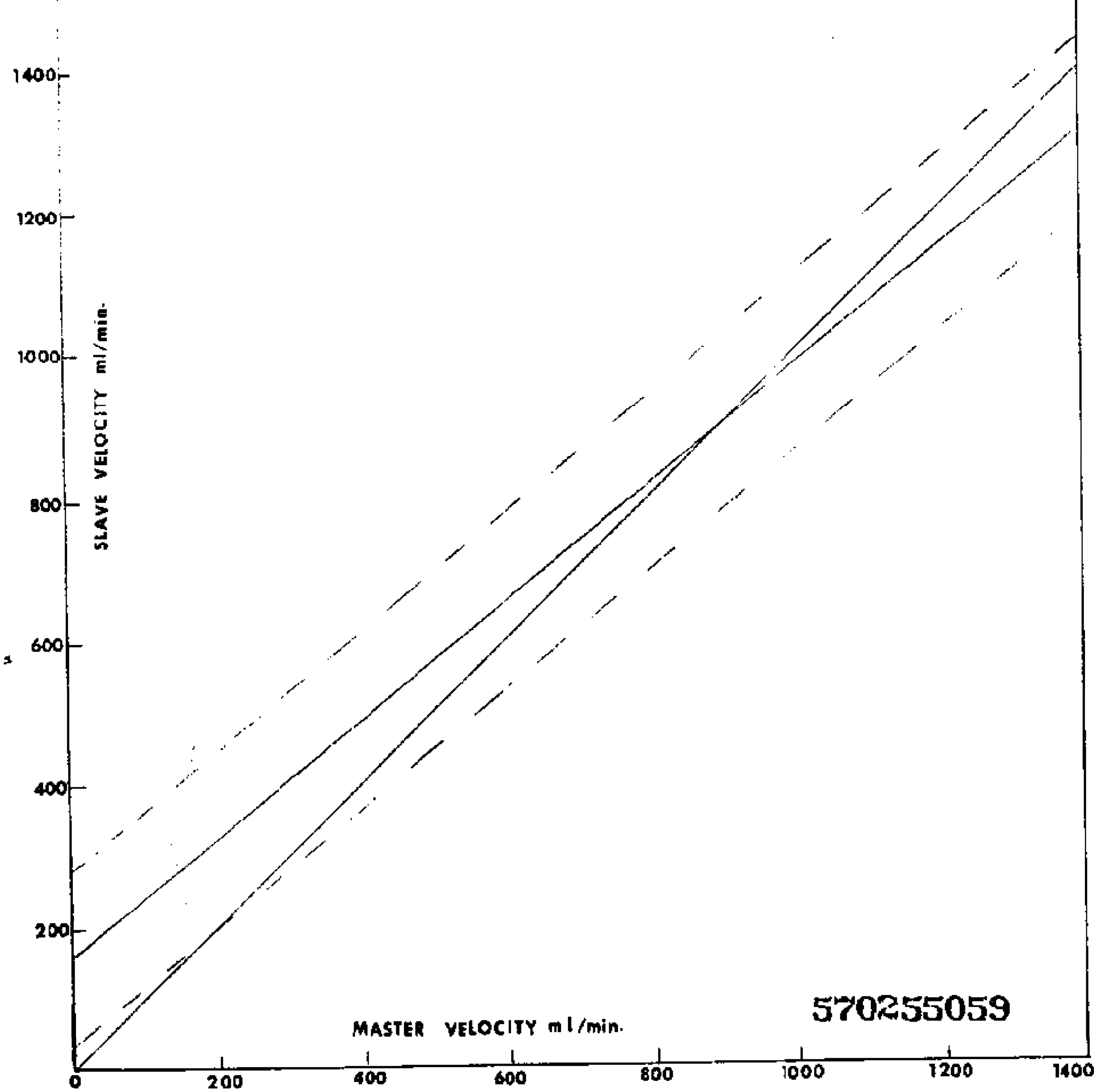

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FIGURE: 8 DUPLICATION OF PRESSURE CHANGES BEHIND RESRICTIONS [ΔP] USING CONTINUOUS AIR FLOWS ON THE MASTER SMOKER.

[ΔP-CAPILLARIES, TOWS]

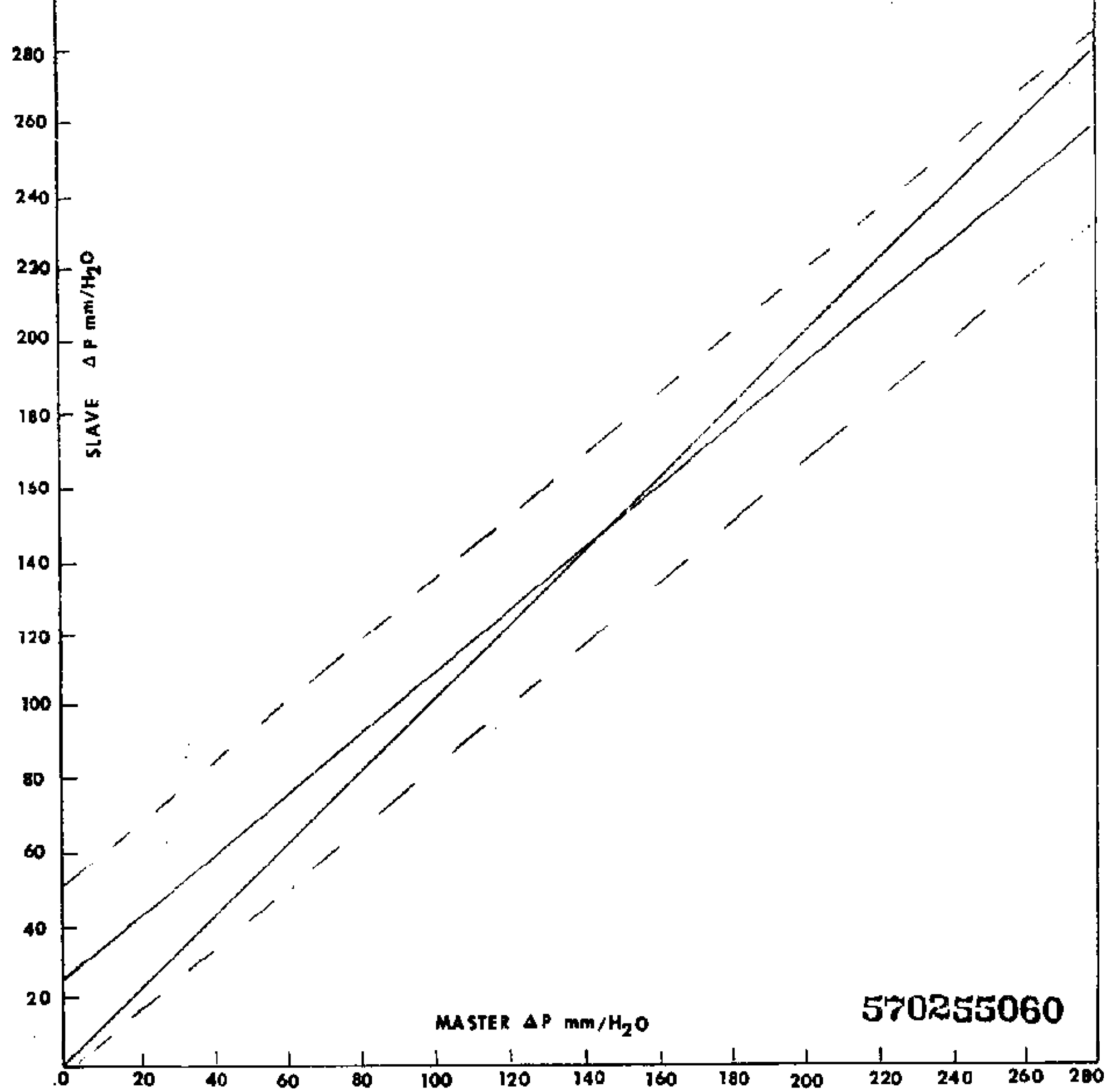

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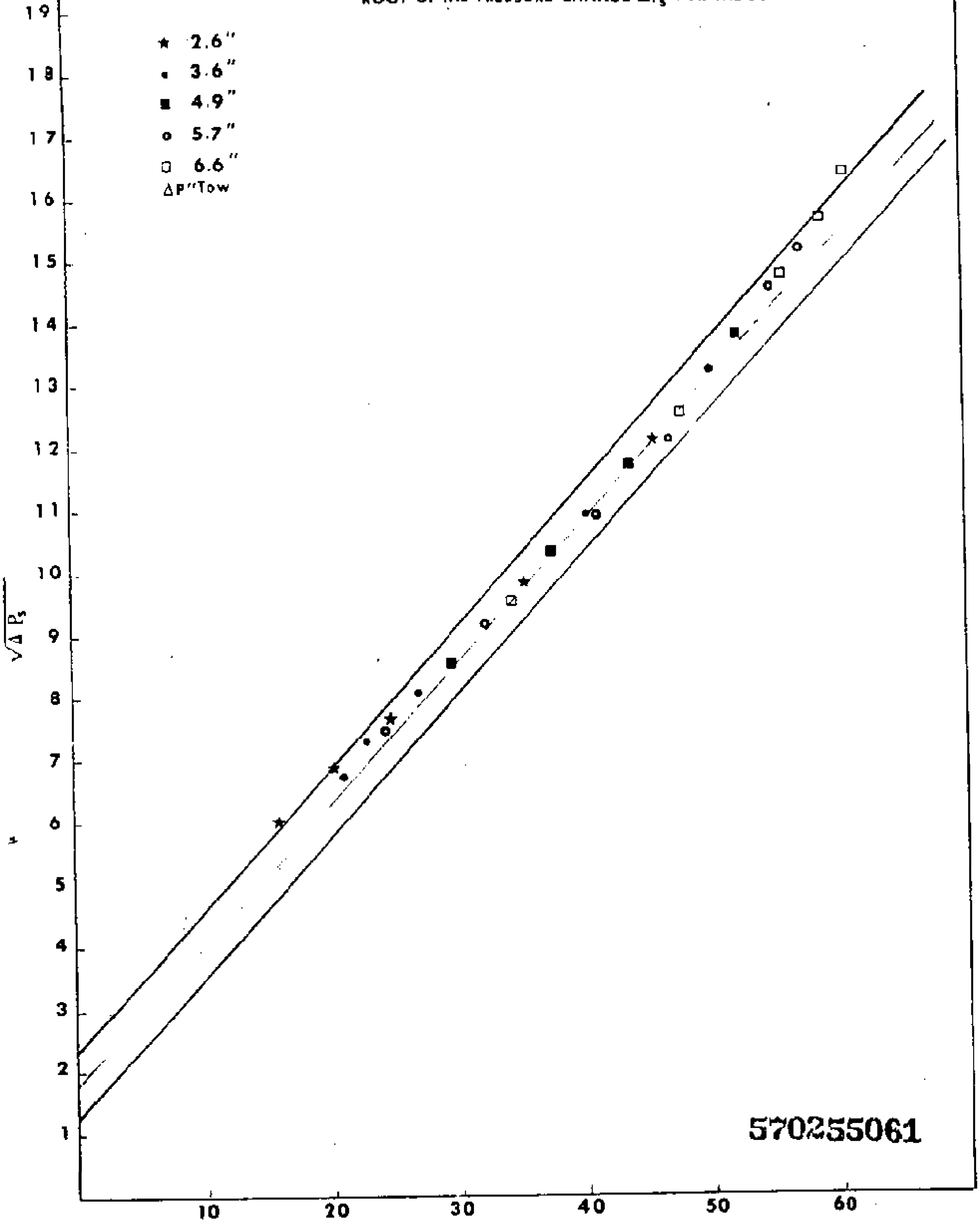
FIG.: 9 RELATIONSHIP BETWEEN THE TRANSDUCER RESPONSE t_s AND SQUARE ROOT OF THE PRESSURE CHANGE ΔP_s FOR THE SLAVE SMOKER.



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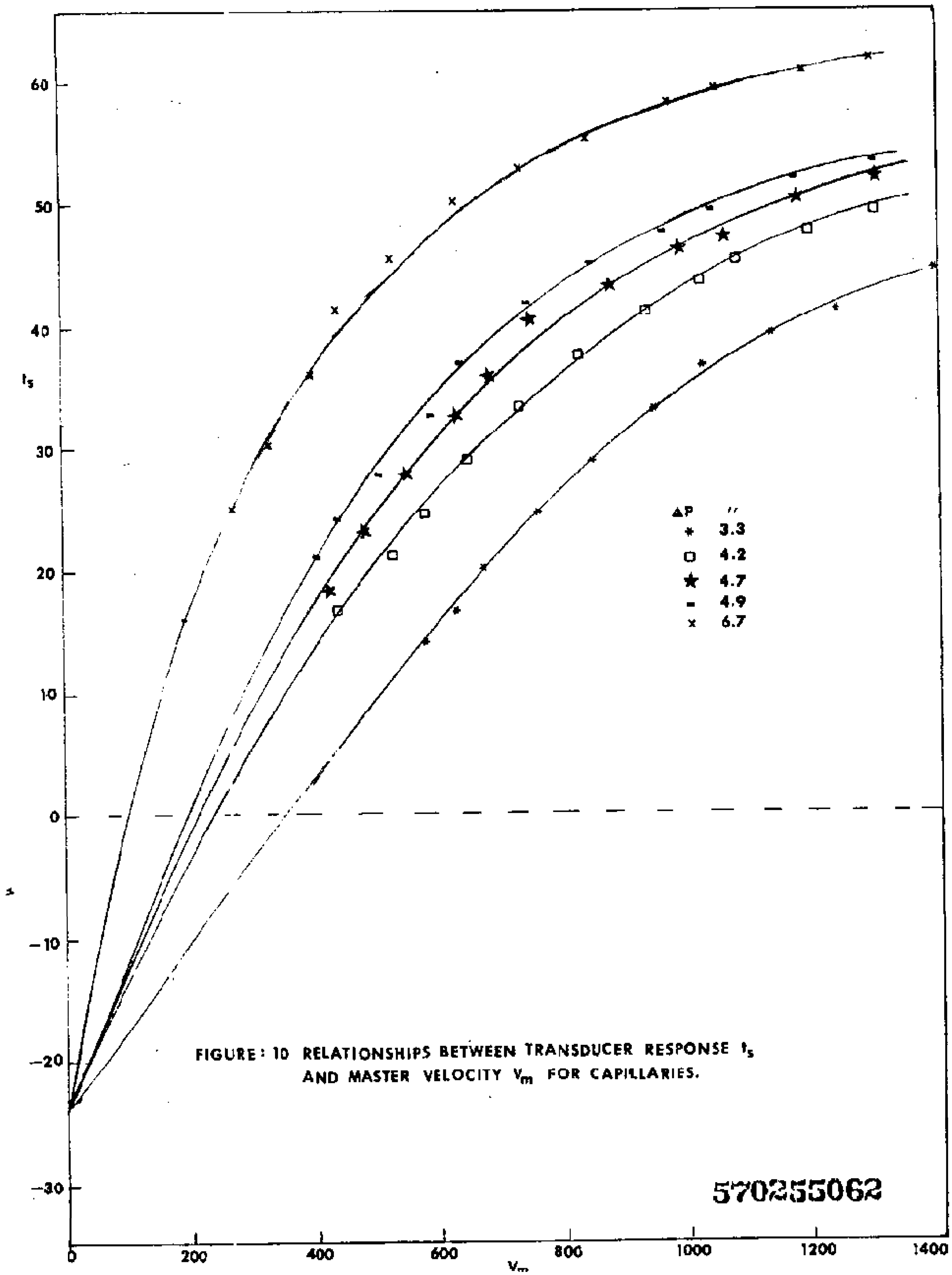

FIGURE: 10 RELATIONSHIPS BETWEEN TRANSDUCER RESPONSE t_s AND MASTER VELOCITY V_m FOR CAPILLARIES.

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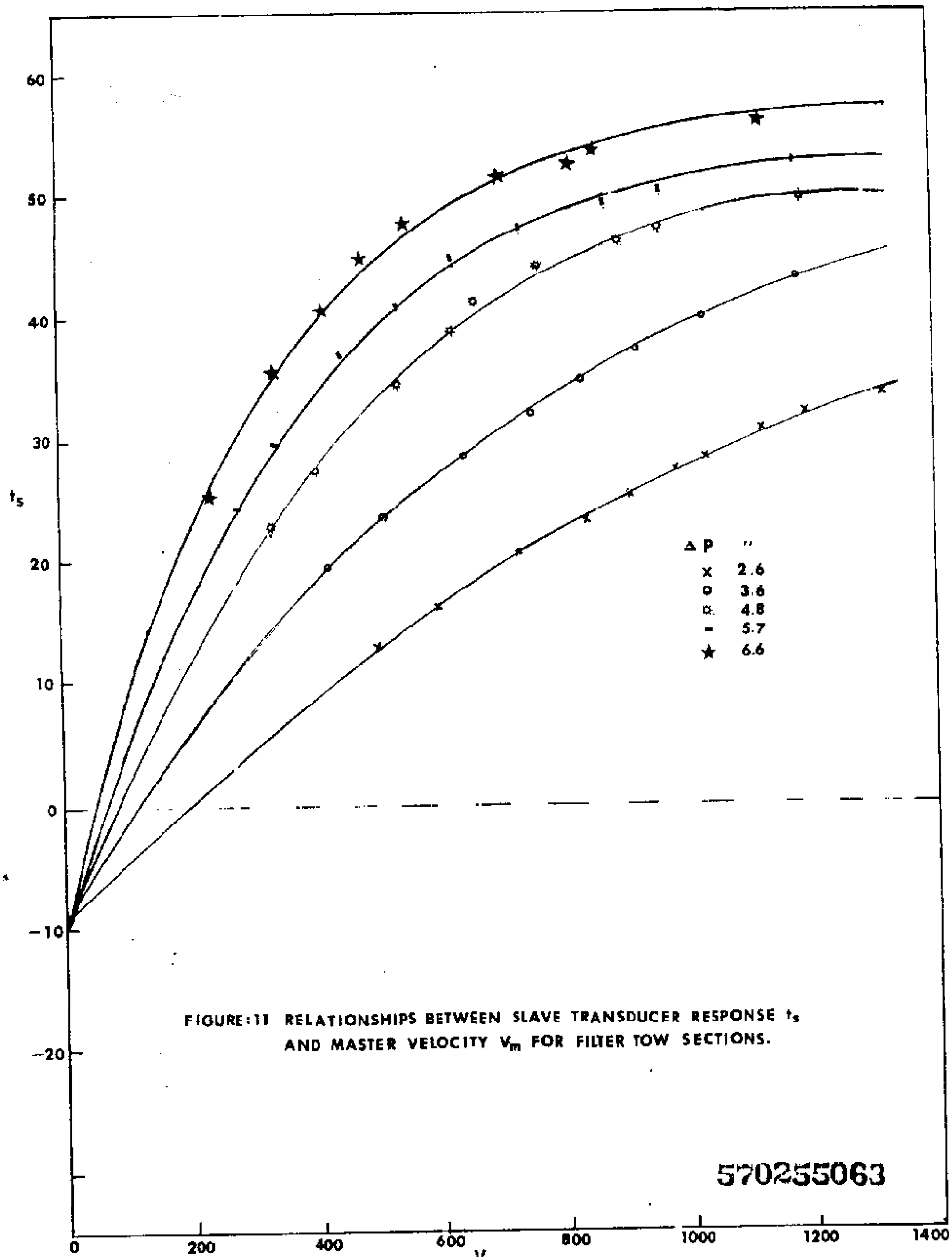

FIGURE: 11 RELATIONSHIPS BETWEEN SLAVE TRANSDUCER RESPONSE t_s AND MASTER VELOCITY V_m FOR FILTER TOW SECTIONS.

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DATE DUE

MR 1 '73			
~~AUG 2 '78~~			
SEP 1 '78			

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Res. Lab. Rep. 139 #16
Imperial Tobacco Products, Ltd.
A ONE PORT SLAVE SMOKING MACHINE
E. R. Freiesleben and A. Riel
Proj. T-7050 July 20, 1972

DATE DUE	BORROWER'S NAME	ROOM NUMBER
1-2-73	3/2/73 Kennedy Fusion	4/3/73 Room
3/4/73	Kennedy JUL	6 '73
JUL 3 '74 MAY 2 '74		
SEP 5 '74	Fisher	OCT 9 '74
JUN 15 '76	McGSNER JUN	15 '76
JUL	SEP 11 '78	

DEMCO 32-298

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