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SCTM-103-53-51

EXPERIMENTAL PERFORMANCE CHARACTERISTICS OF A DUCTED WINDMILL

TM 103-53-51

R. C. Mayden

SANDIA SYSTEMATIC DECLASSIFICATION REVIEW	
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ABSTRACT

Performance characteristics of a ducted windmill were determined experimentally at Cornell Aeronautical Laboratory over a Mach number range of 0.2 to 0.884 and a rotational speed range of 6000 to 14,000 RPM. The wind tunnel data were used to calculate the windmill performance throughout the trajectory of a typical high altitude weapon release.

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SUMMARY

The power developed by several impeller-head-entrance duct configurations of the windmill was measured at Cornell Aeronautical Wind Tunnel over a Mach number range of 0.2 to 0.384. The rotational speed was varied from 6000 to 14,000 RPM. The optimum configuration consisted of the standard entrance duct and the fixed pitch impeller head with a blade angle of 60°. This impeller head is optimum only if used in conjunction with an eddy-current brake or paddle-blade centrifugal governor.

The optimum configuration developed 1.6 horsepower at the design RPM of 12,000 in air flow at 0.3 Mach number at a pressure level corresponding to 18,000 feet altitude. If a generator efficiency of 60% is assumed, the windmill would meet the 750 watt output design requirement at the above release conditions.

The agreement between the performance characteristics of the windmill as determined experimentally and as predicted from simple blade element theory is only fair at low Mach numbers. The simple blade element theory is inadequate in that it does not account for cascade effects (mutual interference of blades), the effect of aspect ratio, and the effect of compressibility on the lift and drag curves beyond the stall.

Application of the experimental performance data to a representative high altitude Mk-6 drop (45,000 feet release at M = 0.5) indicates that the maximum power that would be developed by the optimum configuration at design RPM at a burst altitude of 5000 feet is 21.6 horsepower. Hence, the paddle-blade or eddy current brake governor must be capable of absorbing a maximum of 21.6 horsepower or 9.5 ft-lbs of torque in order to regulate the system to 12,000 RPM.

RECOMMENDATIONS

1. The paddle-blade governor should be tested at high subsonic Mach numbers to ascertain its maximum torque-absorbing capabilities.

2. Shock starts should be conducted in a wind tunnel to determine the time required for the windmill to accelerate to 12,000 RPM.

3. Additional theoretical investigations should be made to correct the simple blade element theory for the effects of cascade, aspect ratio and compressibility in order to better correlate the existing experimental data. This would provide a combination theoretical-empirical method for future designs.

INTRODUCTION

The windmill generator is being developed for possible use on the Mk-5 or Mk-6 class of strategic weapons. The maximum Mach number of these weapons during drop is on the order of 0.95. Former aerodynamic performance data on the windmill (summarized in Reference 1) had been limited to low Mach numbers ($M \leq 0.4$) and a limited rotational speed range. This limitation was caused by the maximum of approximately one horsepower that could be absorbed by the eddy-current devices used in these former tests for measuring the power developed. In order to design a governing device and to predict the performance characteristics of the windmill during a typical drop, performance data was needed at high subsonic Mach numbers.

In particular, an impeller head with fixed pitch blades is being considered for use with a centrifugal paddle-blade governor or an eddy-current brake governor. The design requirements, of minimum time to accelerate to design RPM and the 750 watt generator output immediately after weapon release (high altitude, low Mach number release), dictate that the impeller blades be most efficient at release conditions. At lower altitudes during a drop (increased Mach number and density) a considerable excess of power is developed. Since this excess power or torque must be absorbed by a governing device, experimental performance data was needed over a large Mach number range to properly design a governor.

The purpose of this wind tunnel test was to determine quantitatively:

1. The power that would be developed by a fixed pitch impeller head during a representative drop.

2. The most efficient entrance duct.

3. The optimum blade angle for the fixed pitch head.

4. The effect of blade tip clearance and root chord - hub air gap on the efficiency of impeller heads.

This memo presents experimental aerodynamic performance data of several windmill configurations over a Mach number range of 0.2 to 0.384.

AERODYNAMIC NOMENCLATURE

AR	Aspect ratio, (for wings, AR = span^2/area), (for impeller blades, AR = $(r_t - r_r)/c$) , dimensionless
B	Number of blades, dimensionless
c	Blade chord, feet
c_w	Power coefficient, eqs. (2) and (4), dimensionless
C_D	Drag coefficient, $2D/\rho V_R^2 c(r_t - r_r)$, dimensionless
C_L	Lift coefficient, $2L/\rho V_R^2 c(r_t - r_r)$, dimensionless
d_r	Blade diameter at root chord, feet
d_t	Blade diameter at tip chord, feet
D	Drag of blade, pounds
1/J	Windmill advance ratio, eq. (3), dimensionless
n	Rotational velocity, revolutions/second
N	Rotational velocity, revolutions/minute
P	Power developed by impeller head, eq. (1), ft-lb/sec
Po	Wind tunnel total pressure, atmospheres
r_a	Average blade radius, $(r_r + r_t)/2$, feet
r_r	Blade radius at root chord, feet
r_t	Blade radius at tip chord, feet
V_d	Axial velocity in duct, ft/sec
V_R	Resultant Velocity at blades, $\left[V_d^2 + (2\pi r_a n)^2\right]^{1/2}$, ft/sec
V_{FS}	Free stream velocity, ft/sec
α	Angle of attack of blade element at r_a, eq. (6), degrees
βr	Blade angle at root chord, measured between axial velocity vector and blade section chord line, degrees

β_t Blade angle at tip chord, measured between axial velocity vector and blade section chord line, degrees

ρ_d Density in duct, slugs/ft^3

ρ_{FS} Free stream density, slugs/ft^3

ϕ Angle between plane of rotation and resultant velocity vector, eq. (5), degrees

DESCRIPTION OF TEST EQUIPMENT

A sketch of the windmill generator test setup is shown in Figure 1. The windmill duct was sting-mounted in the wind tunnel. The impeller head and spinner were mounted on the forward shaft extension of a water-cooled induction-type three phase model motor which was supported in the duct. The motor rating was 20 horsepower at 18,000 RPM. Before the tunnel tests, the motor was calibrated as a generator on a high speed dynamometer over a range of 6,000 to 14,000 RPM. During the tunnel tests the motor was used as a generator to measure the power developed by the impeller head. The rotational speed was measured with a tachometer built into the model motor.

Interchangeable entrance shrouds were used to vary the flow in the duct. Four static pressure probes and a flush orifice, located in annuli of equal areas upstream of the impeller, along with two total head probes were used for measuring the mass flow in the duct.

The blade dimensions of the two impeller heads are tabulated in Figure 1. The root chord blade angle of the fixed pitch head is 60°. The variable pitch head was tested at root chord blade angles of 50°, 60° and 70°.

TEST PROCEDURE

The five configurations tested were:

1. Standard nose shroud with fixed pitch head

2. Cylindrical nose shroud with fixed pitch head.

3,4,5. Standard nose shroud with variable pitch head, $\beta_r = 50°$, $\beta_r = 60°$, $\beta_r = 70°$

Each configuration was tested over the following tunnel Mach number, tunnel pressure and rotational speed range:

1. $M = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8$, and 0.884

2. $P_o = 0.5$ atmospheres for $M = 0.2$ to 0.8

   $P_o = 0.4$ atmospheres for $M = 0.884$

3. $N = 6, 7, 8, 9, 10, 11, 12, 13$, and 14×10^3 RPM.

For each configuration, the Mach number and pressure level of the tunnel was first adjusted. The rotational speed was set by loading up the generator. The RPM, generator load in watts, duct pressures and tunnel conditions were recorded for each point. The rotational speed was varied throughout the range at each Mach number level. The Mach number of 0.884 was the maximum obtainable in the tunnel for this particular series of tests.

EVALUATION OF DATA

Theory

By utilizing simple blade element theory (Ref. 1), the approximate power developed by a ducted windmill can be expressed as:

$$P = \frac{Bmnc}{2} (r_t^2 - r_r^2) \rho d V_d^2 \frac{C_L \sin \phi - C_D \cos \phi)}{\sin^2 \phi} \qquad (1)$$

The above expression is only approximate as it does not account for cascade effect (mutual interference of blades), the effect of tip losses and, or, the effective aspect ratio of the blades, the spanwise blade torque variation, the variation of density and velocity across the duct, and the effect of Mach number on lift and drag at angles of attack beyond the stall. Because of these limitations, the blade element theory is used merely as an indication of the way to properly interpret and apply the experimental wind tunnel data to drop conditions.

The power coefficient and advance ratio for the windmill can be defined as:

$$c_w = P/\rho_d V_d^3 d_t^2 \qquad (2)$$

$$I/J = nd_t / V_d \qquad (3)$$

Combining equations (1), (2) and (3) the power coefficient can be expressed as:

$$c_w = \frac{B \pi c (r_t^2 - r_r^2)}{2J\, d_t^3 \sin^2\phi} \left(C_L \sin\phi - C_D \cos\phi\right) \qquad (4)$$

where

$$\phi = \tan^{-1}\left[\frac{2V_d}{\pi(d_t + d_r)n}\right] = \tan^{-1}\left[\frac{2d_t\, J}{\pi(d_t + d_r)}\right] \qquad (5)$$

$$\alpha = \frac{(\beta_r + \beta_t)}{2} + \phi - 90^\circ \qquad (6)$$

Note that in the theoretical expression for the power coefficient (eq. 4), that the duct density and velocity terms have been eliminated. For any given blade angle, the power coefficient can be theoretically determined in terms of the advance ratio by use of equations (4), (5) and (6).

Experiment

Experimental values of the power coefficient and advance ratio were determined from eqs. (2) and (3) using the measured power developed, RPM, and duct density and velocity. The five measured duct static pressures and two duct total pressures were averaged, respectively, to determine the average density and velocity.

In order to use the experimentally-determined power coefficients for any drop condition, it is necessary to know the relation between the flow conditions in the duct to free stream conditions. The pertinent duct flow parameter from equation (2) is the density times the velocity cubed. Hence, the ratio of $(\rho_d V_d^3)$ to $(\rho_{FS} V_{FS}^3)$ was determined experimentally from measured pressures. The power that will be developed by the windmill during any phase of a typical drop can thus be calculated by using the experimentally-determined power coefficient-advance ratio plots and duct-flow parameter plots.

Data Accuracy

The error in determining the rotational speed of the windmill was on the order of 1/4 of 1%. The estimated error in determining the ratio of $(\rho_d V_d^3)$ to $(\rho_{FS} V_{FS}^3)$ varied from 6% at M = 0.2 to 3% at M = 0.80. No

accurate estimate of the error in measuring the power developed could be made. However, the uncertainty would increase as the generator loading decreased. An order of magnitude of the error is 2% at 5 KW and about 5% at 1 KW generator load.

DISCUSSION

General

Since a full-scale simulated windmill generator was tested, the resulting performance data should be directly applicable to drop conditions. The M = 0.2 test conditions correspond approximately to a pressure altitude of 18,000 feet. The M = 0.884 test conditions correspond approximately to a pressure altitude of 30,000 feet.

Power Developed

In figures 2a to 2e, the power developed by the five configurations tested is plotted versus rotational speed with free stream Mach number as the parameter. In general, the power developed increased with increasing Mach number, increasing RPM and decreasing blade angle. Examination of figure 2a indicates that the windmill develops 1.6 horsepower at design RPM at M = 0.3. This flow condition corresponds to a pressure altitude of approximately 18,000 feet. If a generator efficiency of 60% is assumed, the generator would meet the 750 watt output design requirement for these flow conditions.

Effect of Configuration Changes on Performance

The effect of entrance shrouds on the power developed by the fixed pitch impeller at design RPM is presented in Figure 3a. The same effect on the duct mass flow is presented in Figure 3b. The mass flow in the duct is slightly increased when the standard nose shroud is used. This flow increase is reflected in the slight increase in the power developed.

The effect of reducing the blade tip clearance and eliminating the air gap at the root chord-impeller hub juncture on the power developed at design RPM is presented in Figure 4a. The same effect on the duct mass flow is presented in Figure 4b. The fixed pitch head and the variable pitch head set at 60° root-chord blade angle were used in this comparison (for dimensions of each head, see Figure 1). The angle of attack of the midspan blade element, as determined from equations (5) and (6), is tabulated for each data point in Figure 4a. At M = 0.40, α is approximately 17°, which should be the angle of stall for these blade sections. Apparently, the blades of the fixed pitch

advance ratios were evaluated from equations (2) and (3). The theoretical power coefficients were calculated in terms of the advance ratio from simple blade element theory using equations (4), (5) and (6). The lift and drag data, which were used in the AR= 8 calculations, are presented in Figure 9. The theoretical calculations were made assuming effective blade aspect ratios of 8 and ∞.

A general understanding of the functioning of the windmill can be determined from examination of Figure 8. An advance ratio of zero must correspond to zero rotational speed and zero power or torque developed. This point corresponds to conditions at weapon release before the windmill starts to accelerate to speed. The angle of attack of the blades is the blade angle setting of the fixed pitch head. The windmill accelerates, the advance ratio increases, the angle of attack decreases and the power coefficient increases to a maximum near the maximum lift of the blades. For example, at a free stream Mach number of 0.3, the angle of attack decreases from 65.4° to approximately 10° as the rotational speed increases from 0 to 12,000 RPM. If the windmill is allowed to run freely (no generator load or governing device), it will seek the windmilling condition wherein no torque or power is developed and the rotational speed is the maximum obtainable. The windmilling speed of the optimum configuration is on the order of 50,000 RPM at a free stream Mach number of 0.95. Hence, it is imperative that a governing device be incorporated into the system to prevent the windmill from failing structurally as well as to control the output frequency of the alternator.

The experimental data taken at M = 0.3 and M = 0.4 agrees qualitatively with the theory calculated for blade aspect ratios of 8 and ∞. There is no method at present for calculating the effective aspect ratio of blade sections in rotational flow. The blade tip clearance and resulting tip losses due to spanwise flow should govern the magnitude of the aspect ratio. The large scatter of the data at M = 0.3 can be attributed to the large inaccuracies in measuring the power developed (small generator load) and the mass flow parameter (low dynamic pressures).

At higher free stream Mach numbers, the correlation of experimental data with the theory is poor. A possible explanation of this discrepancy is the unknown effects of compressibility on the lift and drag coefficients at angles of attack beyond the stall. Some data indicate that the lift coefficient increases with Mach number in this angle of attack region. This effect would increase the theoretical power coefficients for better correlation of the data.

The blade element theory falls down in that it does not account for the mutual interference of blades (cascade affect). Blades in cascade act as guide passages for turning the air which changes the resultant velocity

and lift and drag coefficients from that of a single airfoil used in blade element theory. Another unknown error in the blade element theory is the assumption that the torque loading on the midspan blade element is representative of the integrated torque loading along the blade span.

These effects on the blade element theory should be investigated theoretically at some future date to better correlate the experimental data and to better understand the aerodynamic aspects of windmill performance. However, even though the blade element theory does not correlate with the experimental data, it does indicate the correct method of interpreting the data. The experimental performance data presented in Figure 8 should be directly applicable to drop condition performance calculations.

Application of Performance Data to Drop Conditions

The power that would be developed by the optimum windmill configuration (if attached to the fin tip of a Mk-6 class weapon) during a representative high altitude drop is presented in Figure 10. The release Mach number and release altitude were 0.51 and 45,000 feet, respectively. It was assumed the windmill would accelerate to design RPM in 4 seconds and the governor would regulate the system at 12,000 RPM during the remainder of the drop. Calculations, using measured values of moment of inertia and torque developed, indicate the 4-second acceleration time is fairly realistic. Hence, four seconds after release the generator output would be 625 watts (assuming a 60% generator efficiency).

The power developed increases quite rapidly during the drop because of the increased density level and Mach number. If a burst altitude of 5,000 feet is assumed, the maximum power developed will be 21.6 horsepower. Thus, a paddle blade or eddy-current brake governor must be capable of absorbing 21.6 horsepower or 9.5 ft-lbs of torque in order to maintain a rotational speed of 12,000 RPM. For any given drop condition, the power that must be absorbed by the governor would depend upon the generator load.

The windmill performance during a drop can be calculated from the experimental performance data in the following manner:

1. The weapon velocity and density are known from trajectory data.
2. Determine the duct velocity from Figure 7.
3. Determine the power coefficient from the calculated advance ratio on Figure 8.
4. Determine $(\rho_d V_d^3) / (\rho_{FS} V_{FS}^3)$ from figure 6 and then calculate the power developed from equation (2).

In conclusion, the power developed by the windmill during a typical drop can be calculated with reasonable accuracy from the experimental performance data taken in the wind tunnel.

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REFERENCES

1. R. C. Maydew, Memo to G. E. Hansche, 5140, "Windmill Generator Performance—Theory and Experiment", Ref. Sym: 5141 (354) dated February 5, 1953. Confidential Restricted Data.

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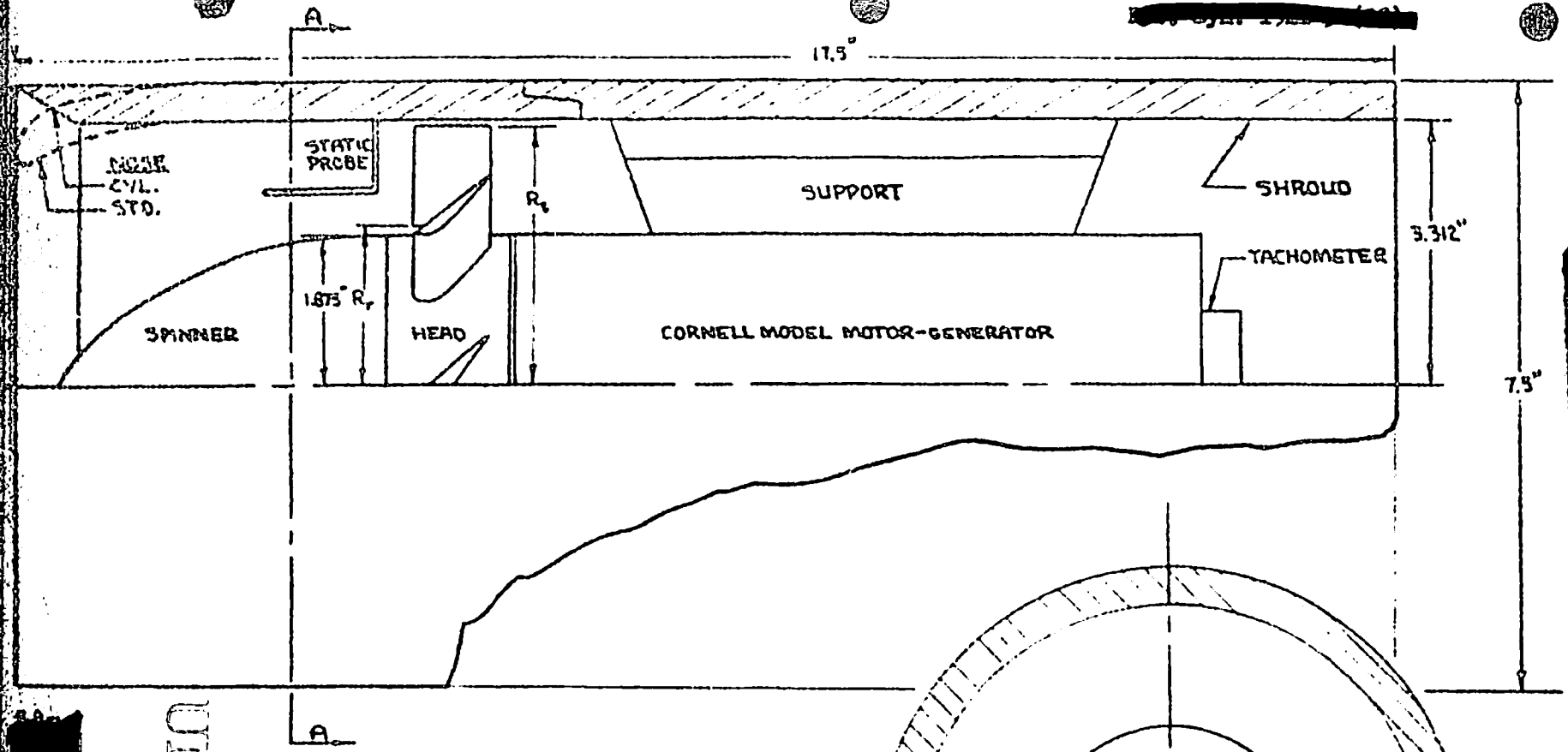

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IMPELLER HEADS
8 BLADES, 1" CHORD
CLARK-Y AIRFOIL SECTION
BLADE TWIST 7°45'/IN.

FIXED PITCH		VARIABLE PITCH
1.875"	R_r	2.000"
3.28"	R_t	3.25"

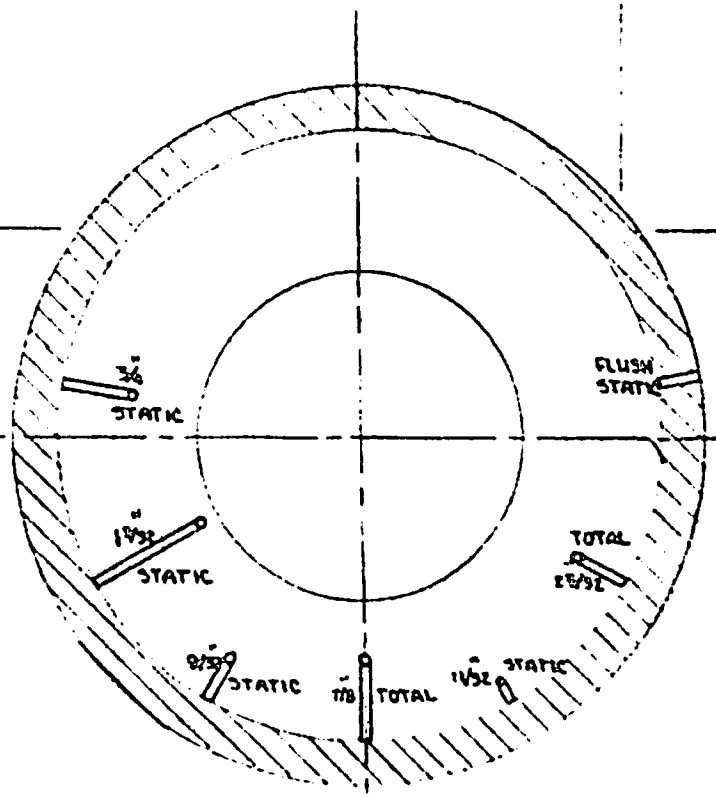

FIGURE 1-WINDMILL GENERATOR TEST APPARATUS

SECTION A-A
RADIAL LOCATION OF PRESSURE PROBES

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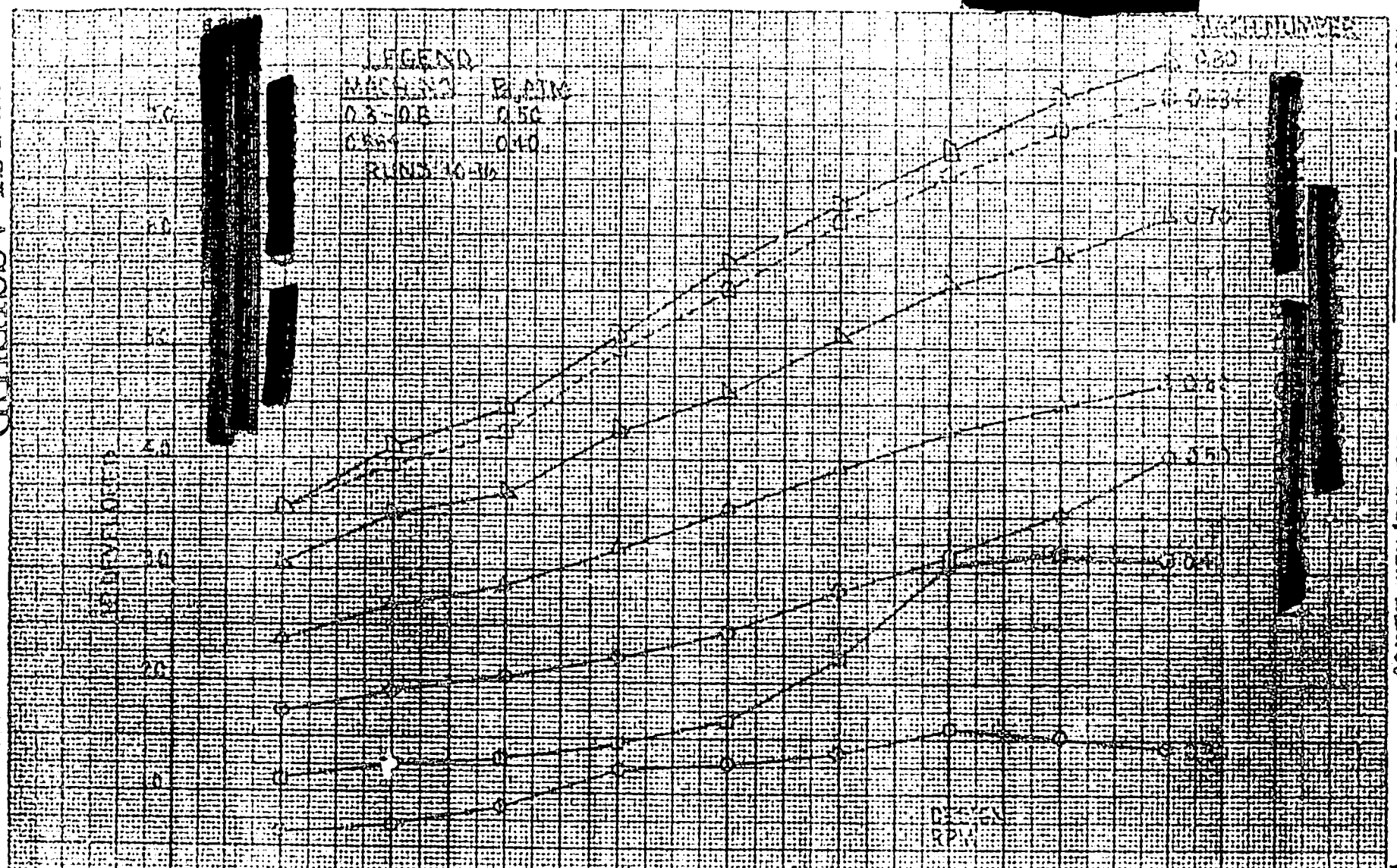

FIGURE 3. POWER DEVELOPED BY FIXED PITCH HEAD AND STANDARD NOSE SHROUD CONFIGURATION

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KEUFFEL & ESSER CO.
Millimeters, 5 mm lines accented, cm. lines heavy.

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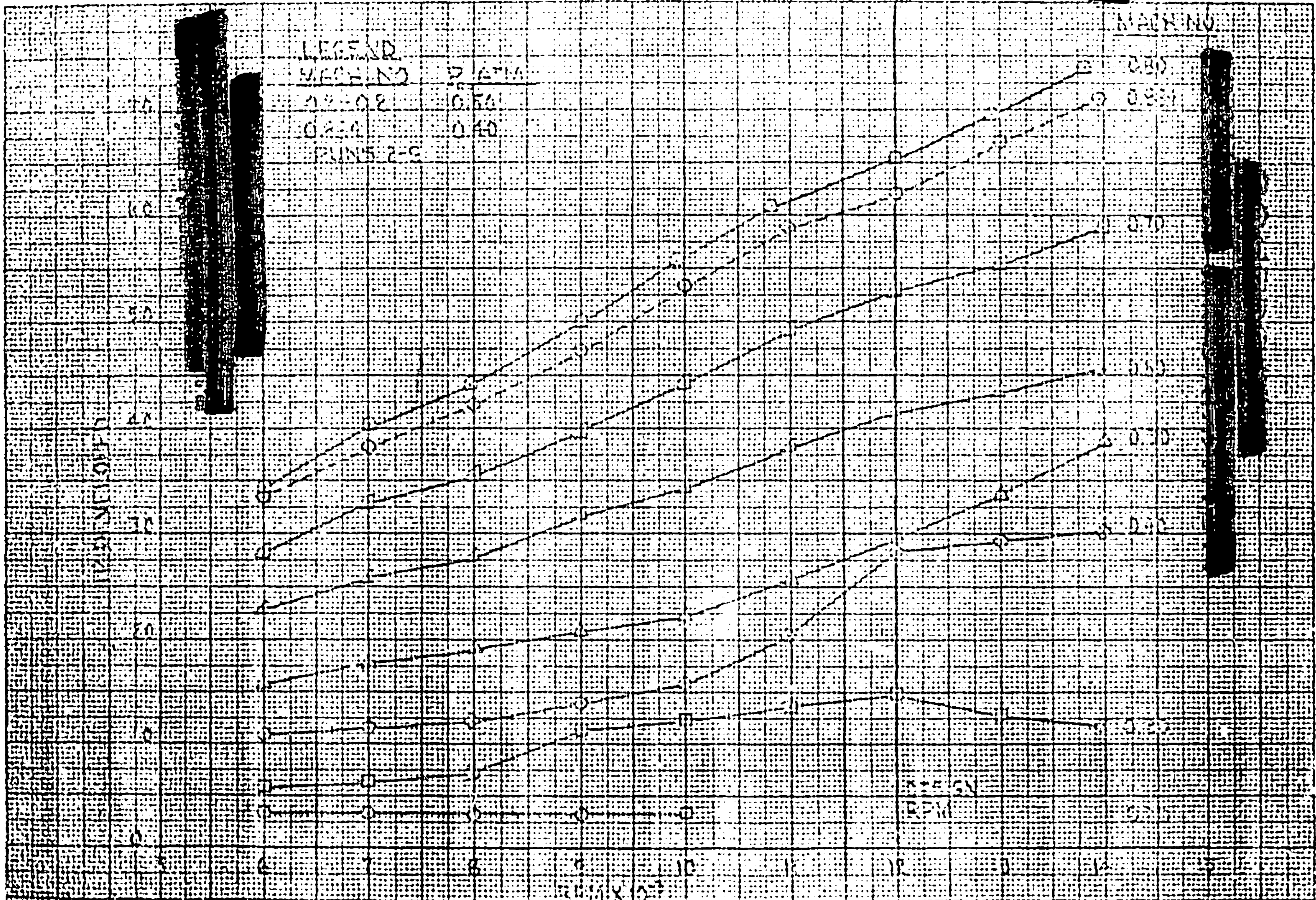

FIGURE [illegible] POWER DEVELOPED BY FIXED PITCH HEAD (= 50°) AND CYLINDRICAL NOSE SHROUD CONFIGURATION

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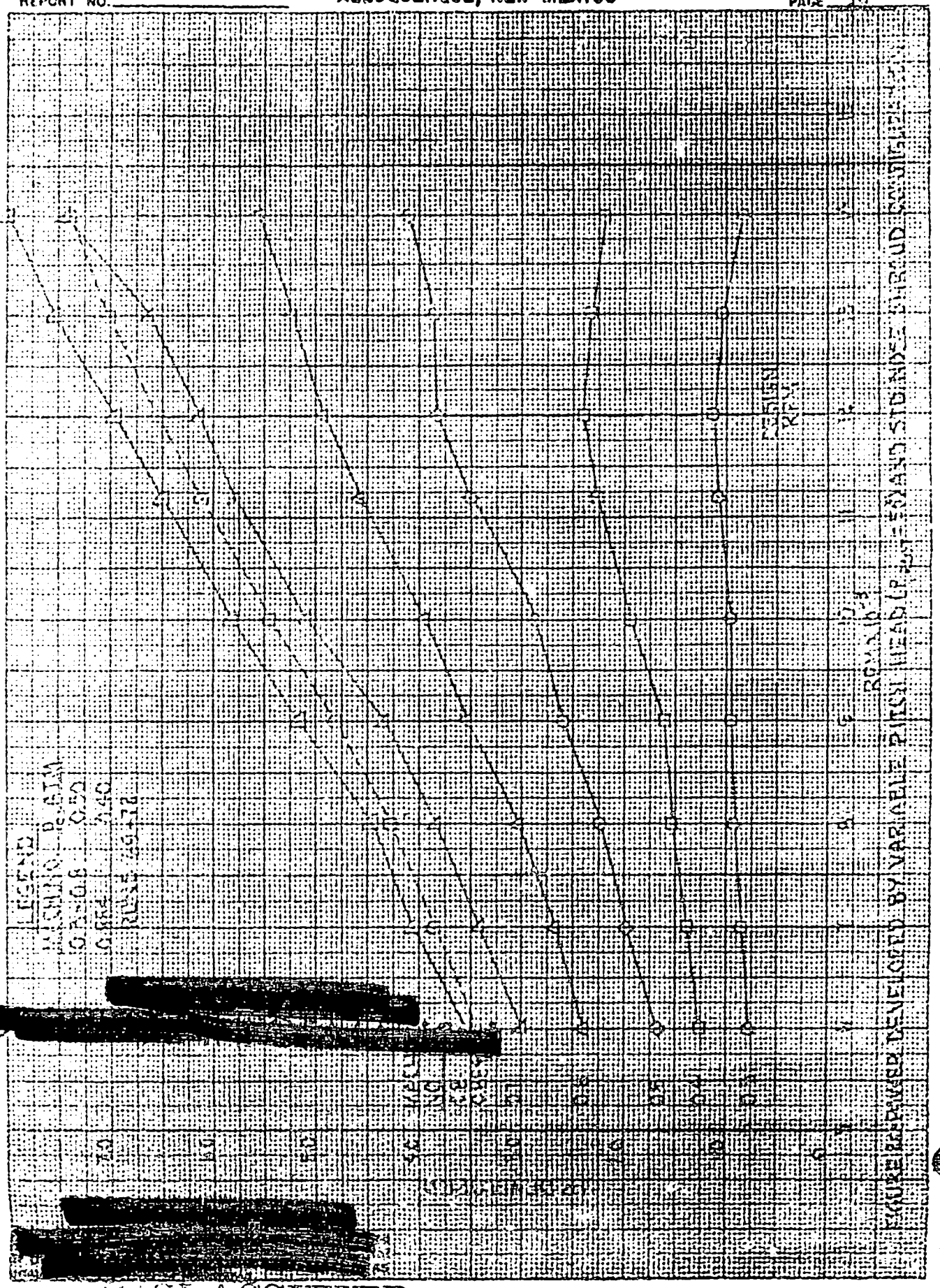

FIGURE 12 - POWER DEVELOPED BY VARIABLE PITCH HEAD (P_ATM = 50 AND STD NOSE SHROUD CONSIGLIERS)

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Millimeters, 5 mm. lines accented, cm. lines heavy

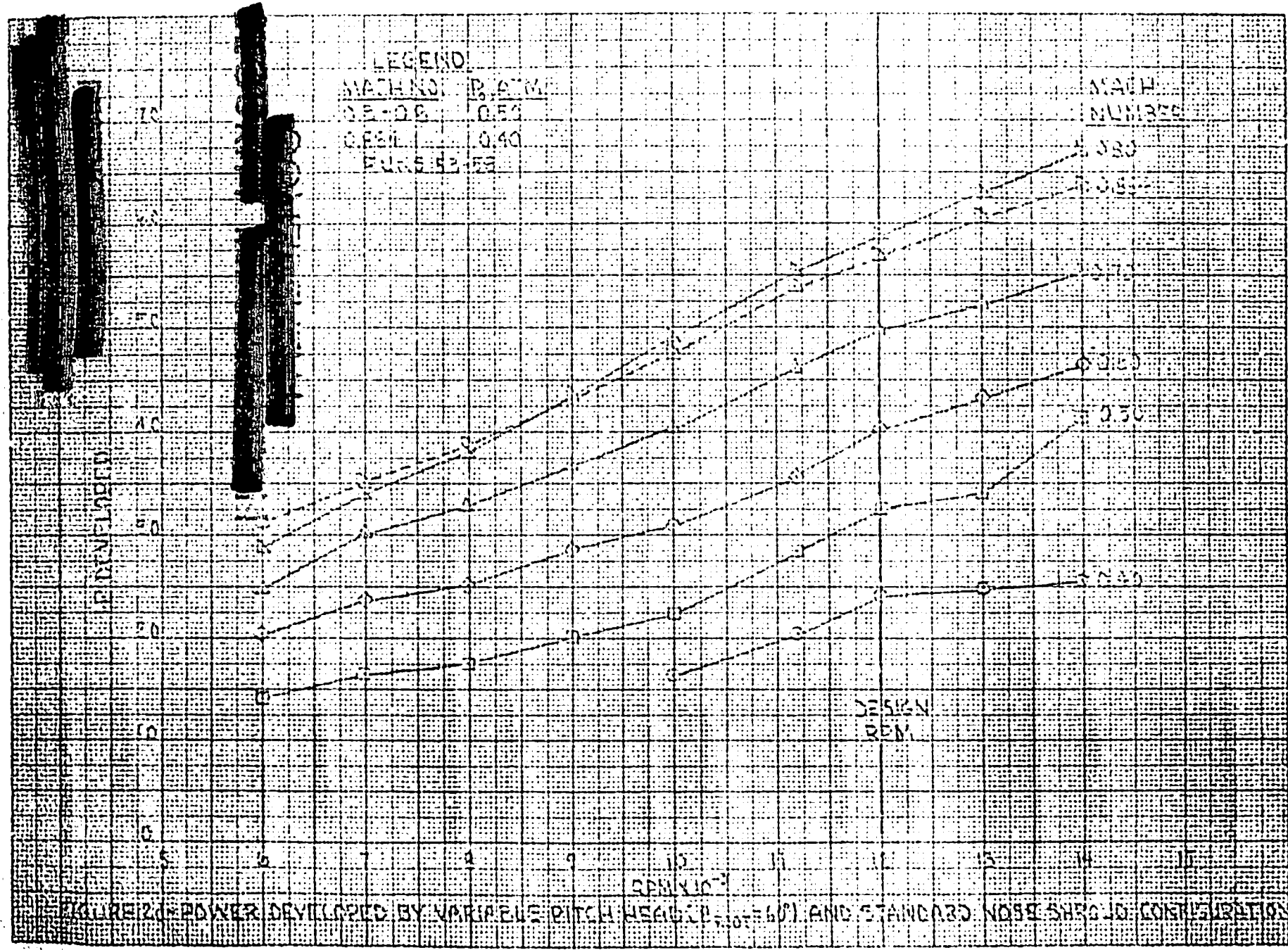
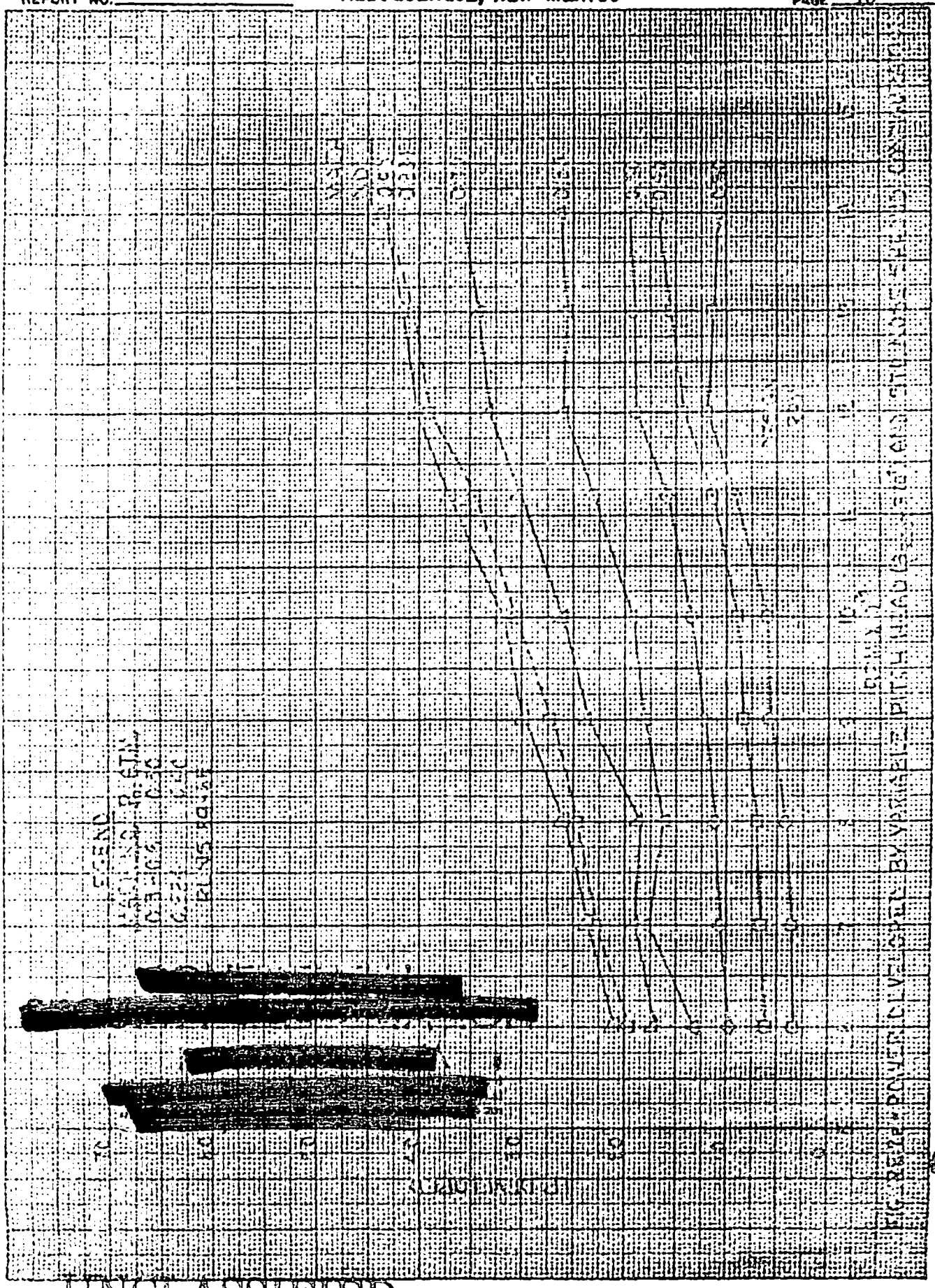


FIGURE 20 - POWER DEVELOPED BY VARIABLE PITCH HEAD (P_{TOT} = 60°) AND STANDARD NOSE SHROUD CONFIGURATION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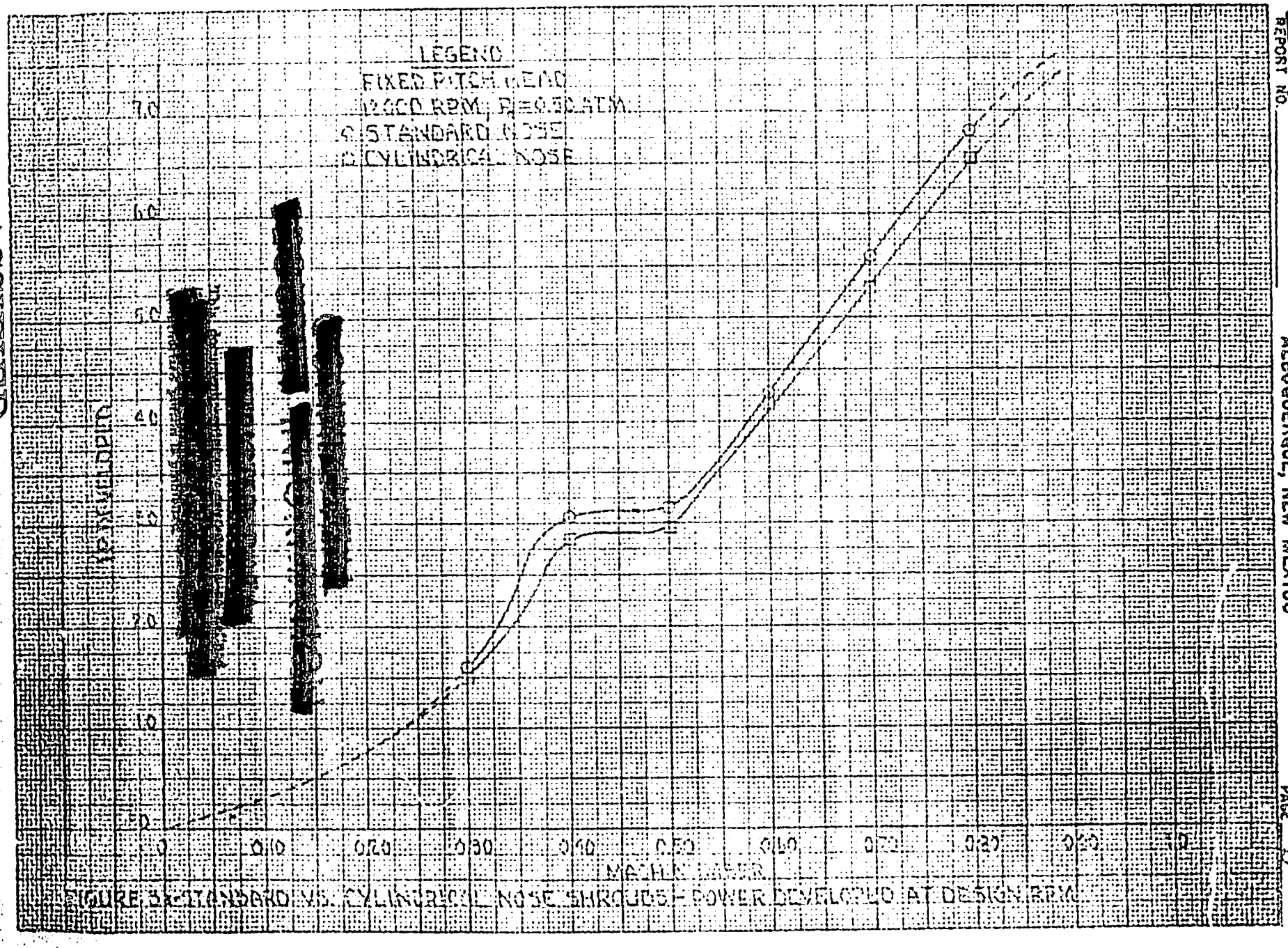

FIGURE 3x - STANDARD VS. CYLINDRICAL NOSE SHROUDS - POWER DEVELOPED AT DESIGN RPM

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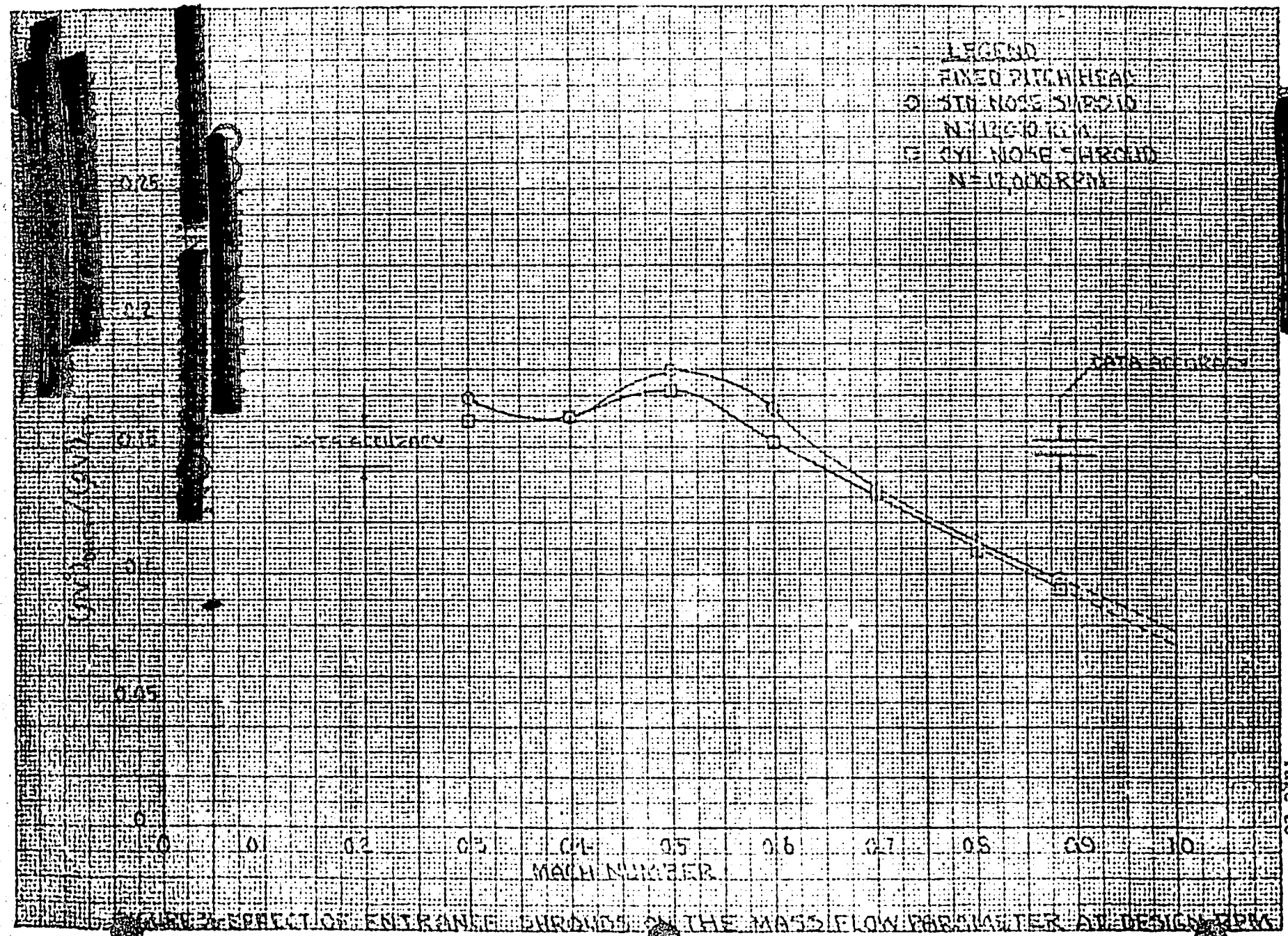

FIGURE 2. EFFECT OF ENTRANCE DIAMETER ON THE MASS FLOW PARAMETER AT DESIGN RPM

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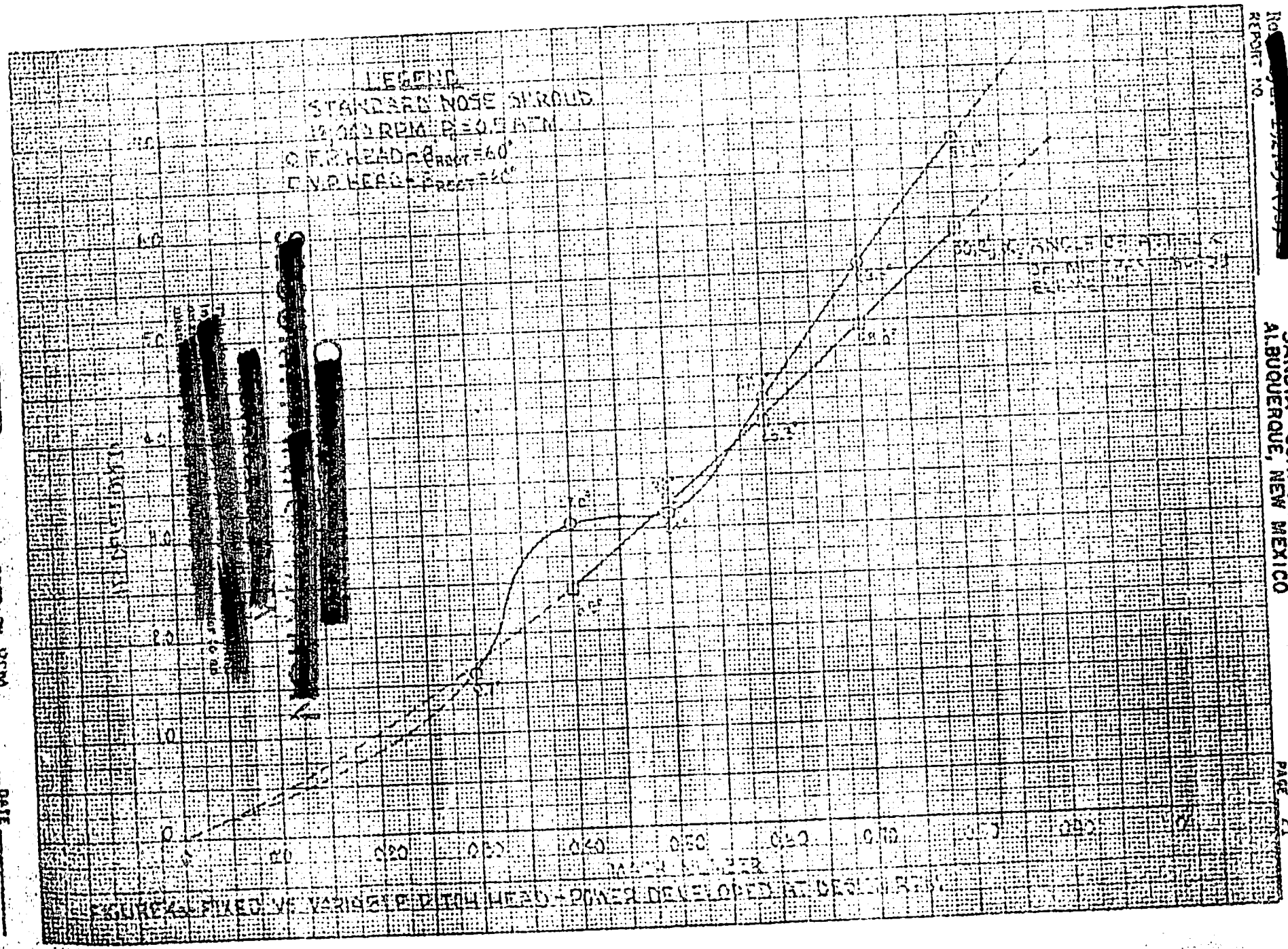
KEUFFEL & ESSER CO.
Millimeters, 1 mm. lines accented, cm. lines heavy
LEGEND
STANDARD NOSE SHROUD
14,000 RPM, P=0.5 ATM
O F.W. HEAD θ PROP=60°
□ V.P. HEAD θ PROP=60°
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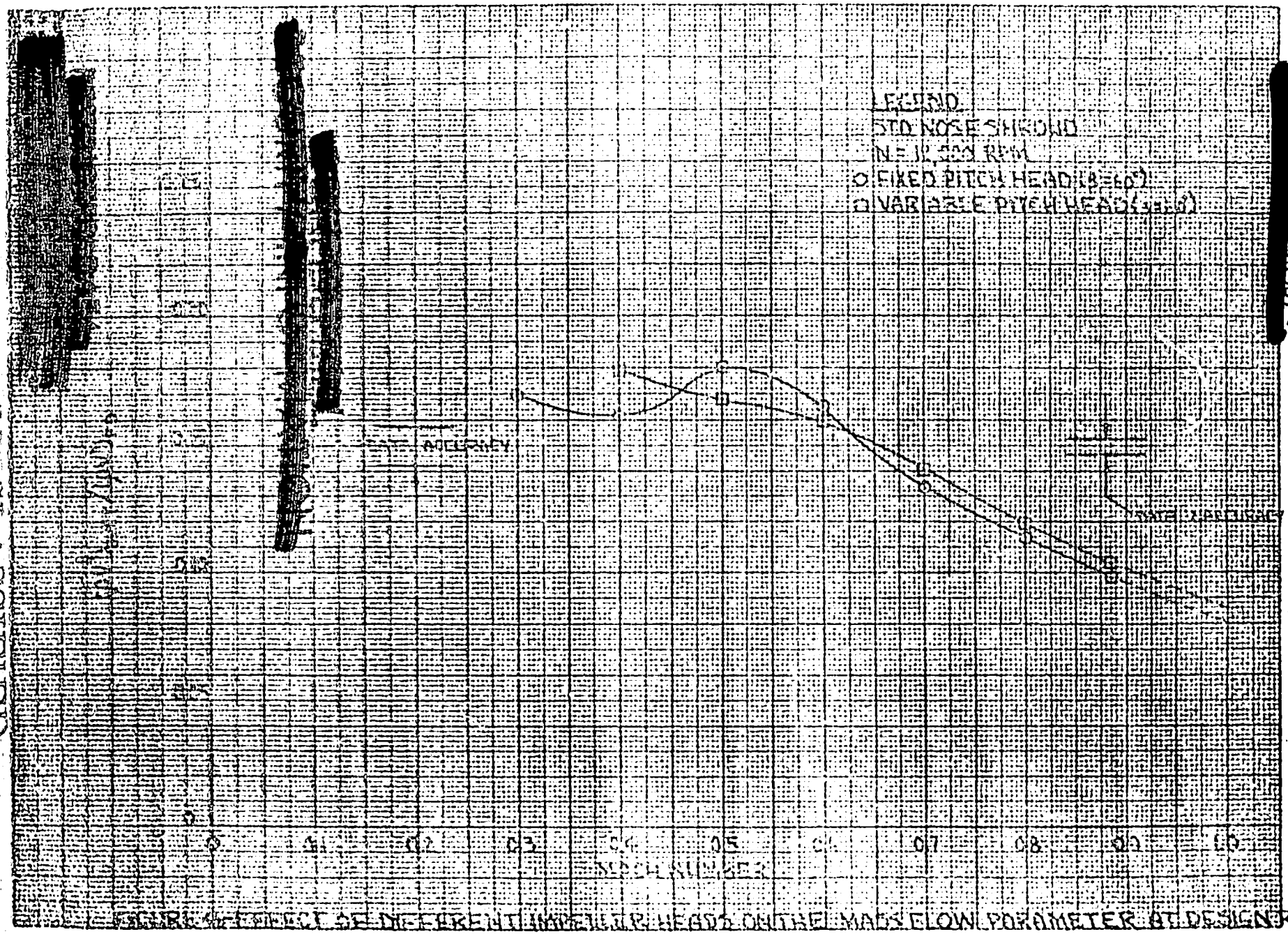
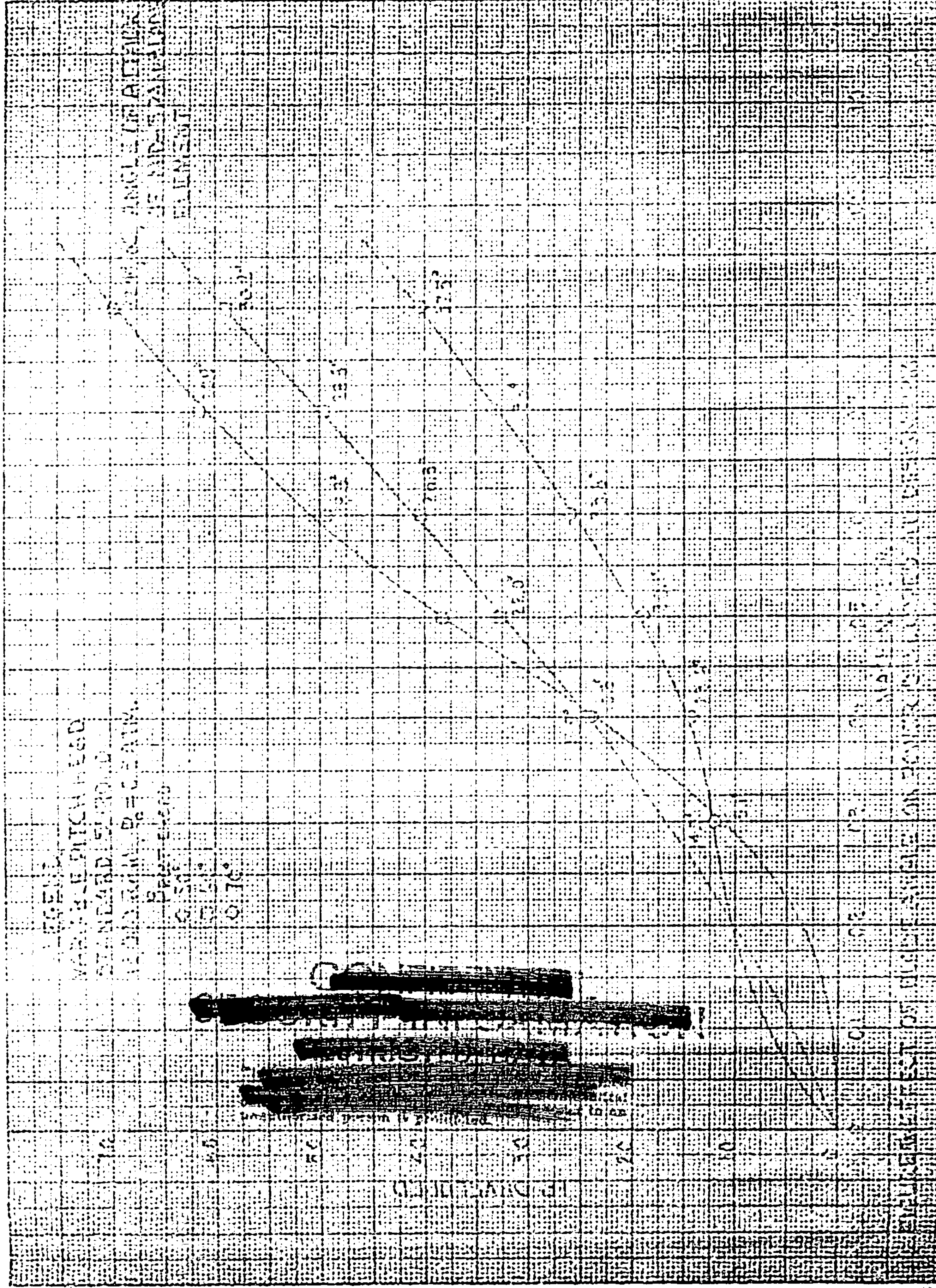


FIGURE 4 EFFECT OF DIFFERENT IMPELLER HEADS ON THE MASS FLOW PARAMETER AT DESIGN RPM



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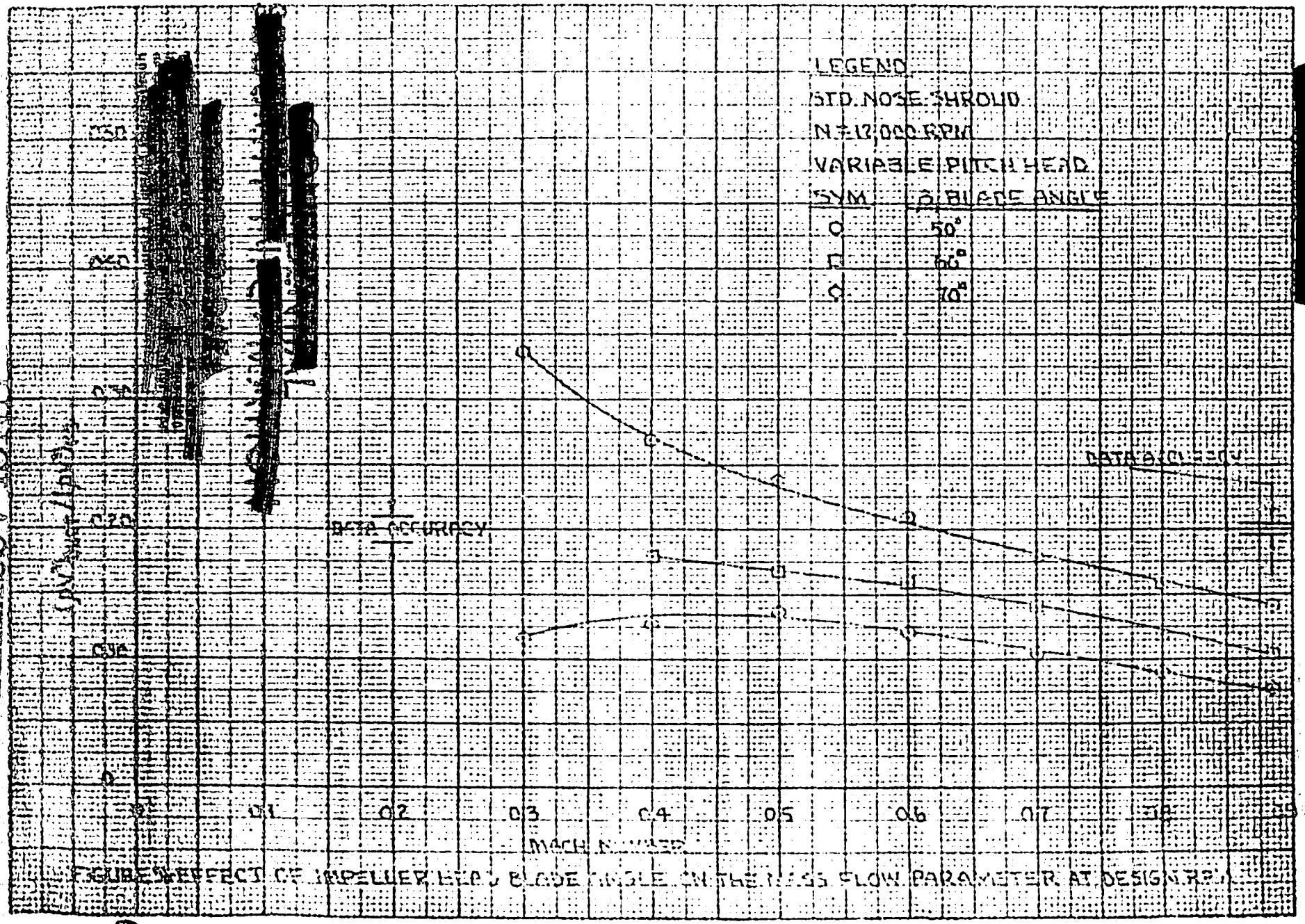

FIGURE 5 EFFECT OF IMPELLER HEAD BLADE ANGLE ON THE MASS FLOW PARAMETER AT DESIGN RPM

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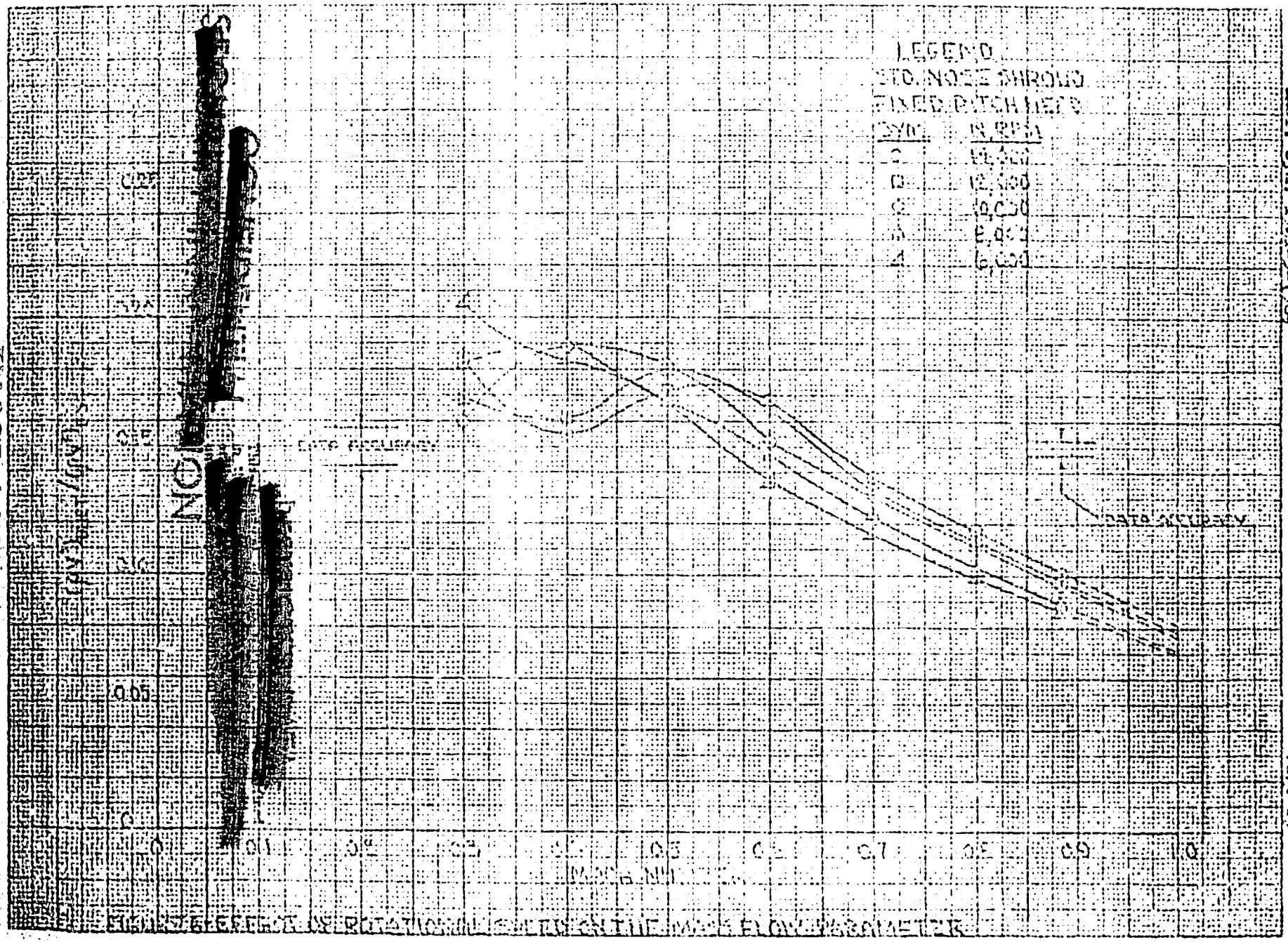

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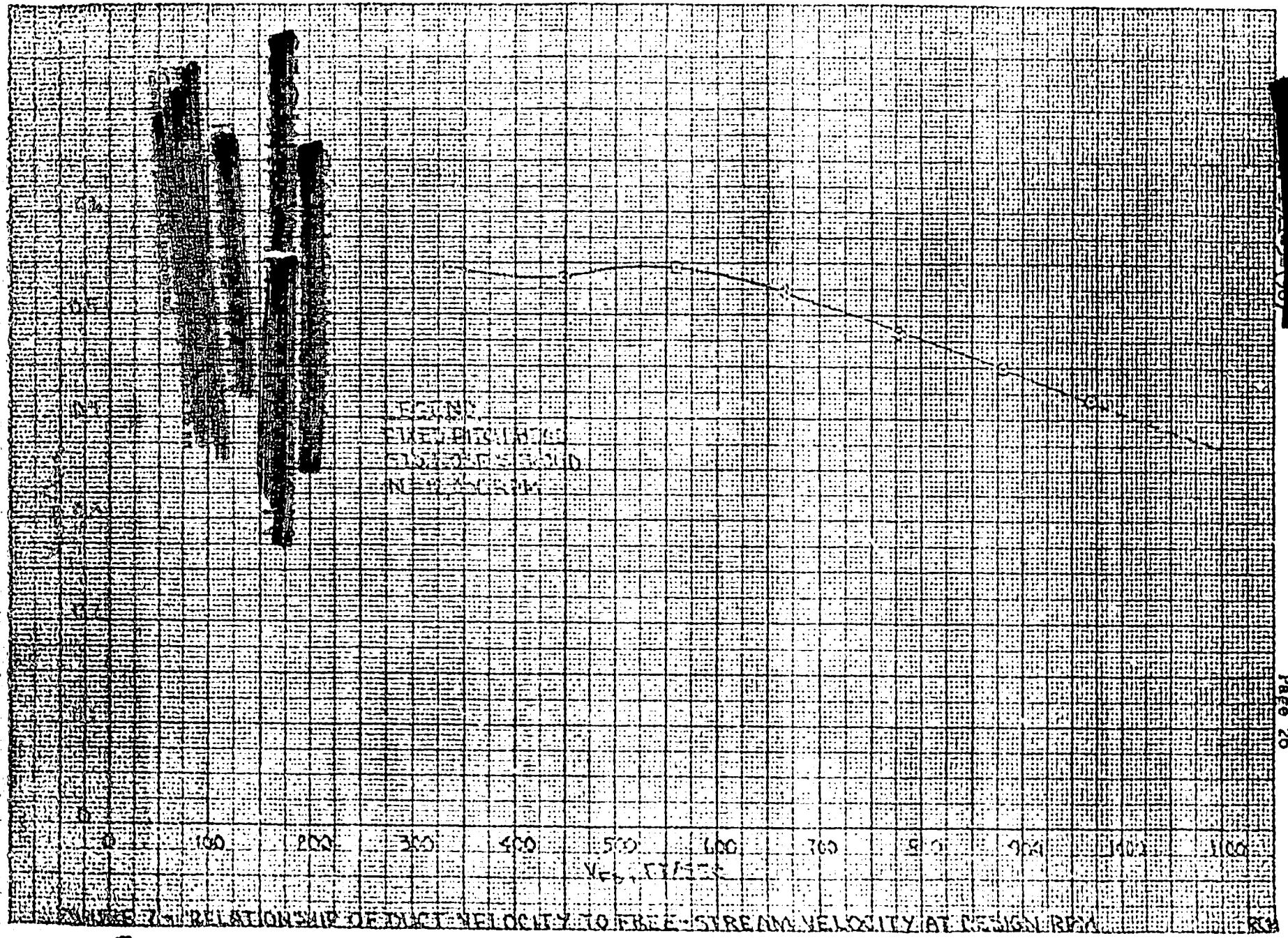

FIGURE 7 - RELATIONSHIP OF DUCT VELOCITY TO FREE-STREAM VELOCITY AT DESIGN RPM

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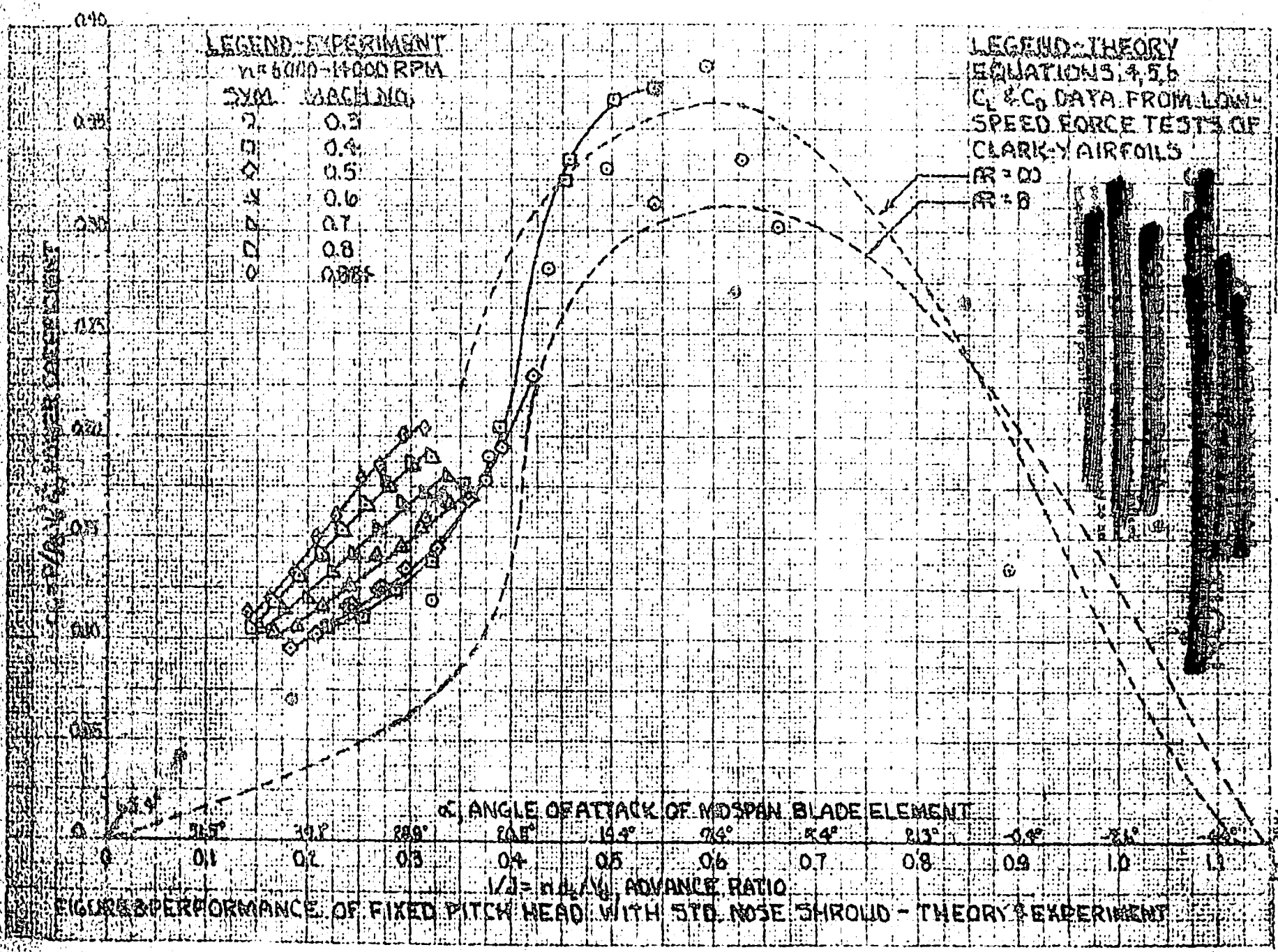

FIGURE 8 PERFORMANCE OF FIXED PITCH HEAD WITH STD. NOSE SHROUD - THEORY & EXPERIMENT

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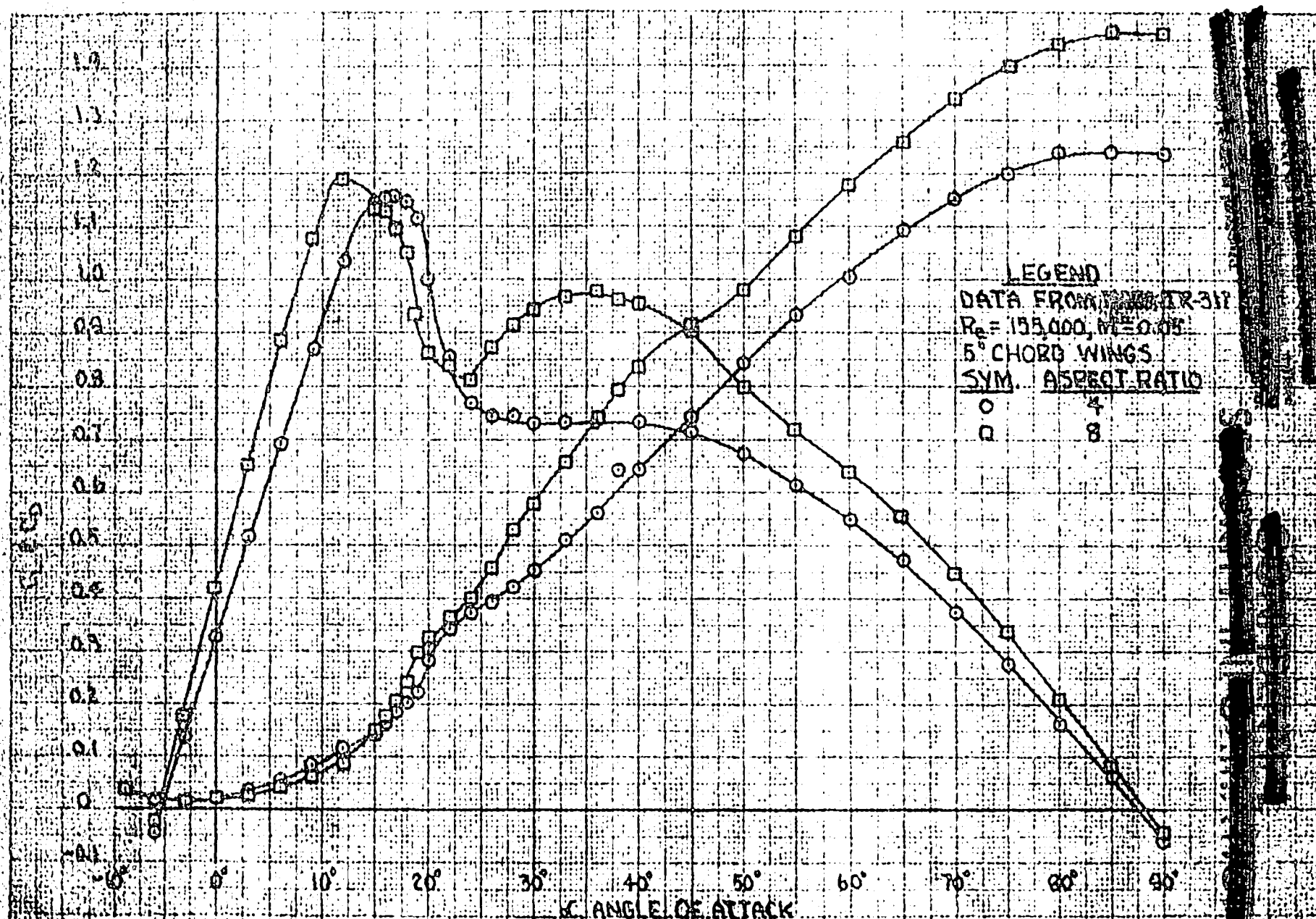

FIGURE 9- LIFT AND DRAG COEFFICIENTS OF CLARK-Y AIRFOIL

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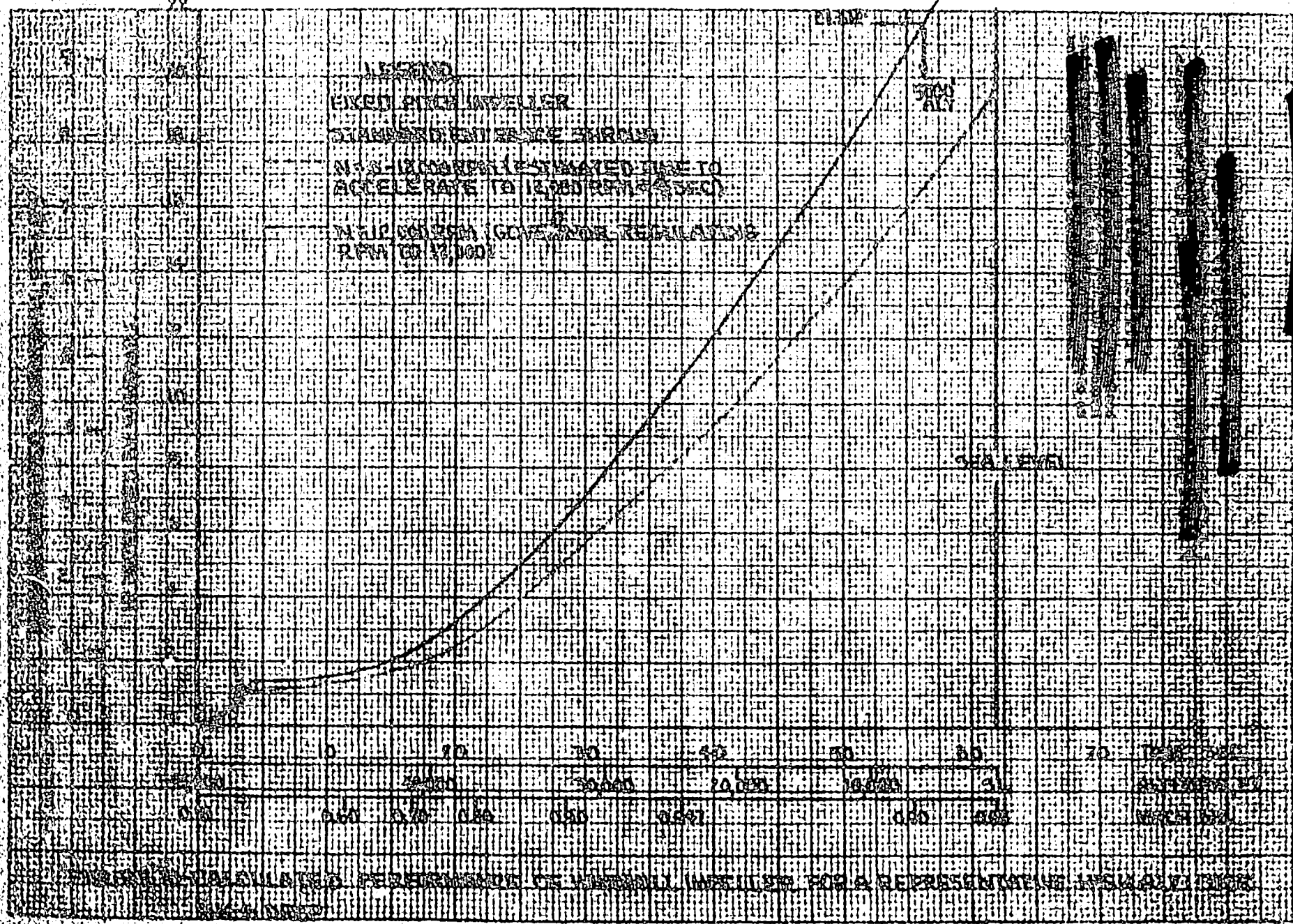

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