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BRL

TECHNICAL NOTE No. 1038

The Flight Mechanics Of Spinning Shell At Large Angles Of Initial Yaw (U)

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BALLISTIC RESEARCH LABORATORIES

TECHNICAL NOTE NO. 1038

AUGUST 1955

THE FLIGHT MECHANICS OF SPINNING SHELL AT LARGE ANGLES OF INITIAL YAW (U)

C. L. Poor

This Note is essentially the same as the paper presented at the Tripartite Conference in Canada, October 1954.

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INTRODUCTION

The advent of supersonic flight, and the increasing certainty that supersonic speeds will be routine for both fighter and bomber aircraft within the next few years, have brought the problem of describing the motion of bullets launched with large initial yaw from a difficult low priority research investigation to an equally difficult problem of the utmost current engineering importance.

The practical problem can be simply stated - to describe the trajectories of bullets fired from aircraft with sufficient accuracy to permit the design of adequate fire control equipment. The trajectory data must be available to the fire control designer about two years before the equipment is to be ready. The airplanes are not available, so the predictions must be based on model tests and ground firings, for the most part.

In this paper we discuss the steps being taken at the Ballistic Research Laboratories to attempt to obtain the basic information needed to predict the paths of bullets launched cross-wind from aircraft whose speeds will be comparable to that of the bullets. The general plan of the research is described, together with some of the preliminary results, and some novel experimental techniques are reported.

FLIGHT CONDITIONS TO BE EXPECTED

Aircraft currently under development, to be armed with machine guns now undergoing test, are expected to fly at Mach numbers of the order of 2 and at altitudes of the order of 60,000 ft. Ammunition designed for these guns yields muzzle velocities of approximately 3,000 ft/sec. Figure 1 shows the initial yaw of the bullet as function of the gun angles off the airplane center line for a typical World War II bomber, and for a Mach No. 2 bomber, typical of the performance expected in the immediate future. The increasing severity of the launch conditions with the future airplane is what makes the problem. Figure 2 gives the aerodynamicist's view of the problem; it shows the initial yaw as function

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of bullet Mach No. for the 30mm shell T306E10, for flight conditions specified by the U. S. Air Force.

With initial yaws as large as shown, there is no reason to believe that calculations based on the linearized theory of motion of shell (Ref. 1, 2, 3) should be adequate. Although the experimental firings of Simon and Sterne, (Ref. 2) gave a gratifying agreement with the predictions of linear theory, these firings in 1942 were conducted at an air speed of some 270 mph. The more recent firings off the rocket sled at the U. S. Naval Ordnance Test Station, Inyokern, (Ref. 4) are markedly at variance with the predictions of the linearized theory. Here the sled velocity was about 1,100 ft/sec, giving substantial initial yaws.

THE SOURCES OF AERODYNAMIC DATA ON SHELL

The principal sources of accurate aerodynamic data on shell are free flight aerodynamic ranges using the spark photography techniques developed during World War II by Charters at BRL, and supersonic wind tunnels. Both techniques have limitations which affect their application to the problem at hand.

The free flight ranges have been developed into instruments of great precision, capable of yielding the path of the center of gravity of shell to an accuracy of about 0.01 inch, with timing accuracy of about one millionth of a second. From the photographs, the attitude of the shell can be determined within about 3 minutes of arc. With this sort of accuracy, it is possible to determine the drag of a bullet with about three significant figures, and to get two significant figure accuracy on the normal force coefficient by measuring the amplitude of the swerving motion, which amplitude is of the order of one caliber. However, this accuracy depends on a curve-fitting process - the motion of the shell is assumed to be that predicted by the linearized theory. If the aerodynamic force system is significantly non-linear, even though a good fit may be obtained with the assumed linear force system, the forces themselves may be grossly in error. This error shows up through a dependence of the results on initial conditions, as a scatter

[redacted]

in the results, not predictable from round to round. Due to the reduction procedures which must be used to obtain high precision, the ranges are blind to non-linearities.

Thus, unless the correct initial conditions are used, the range data say nothing about the trajectories to be expected with high initial yaws. For small yaws, where the linear theory may be expected to hold, they are by far the most accurate measuring device available to the exterior ballistician, but for the present problem the inability to launch shell with large initial yaw and zero yawing velocity makes them essentially useless by themselves.

The wind tunnel, on the other hand, is not bothered by non-linearities. Data have been available for many years on the variation of lift, drag, and pitching moment on bodies of revolution, through a range of angle of incidence large enough to exhibit large non-linear effects. The first static tests on the aerodynamics of shell at large yaw made in the BRL supersonic wind tunnel were carried out in 1947 (Ref. 5, 6). Walchner, at Gottingen, (Ref. 7) had carried out systematic measurements on the lift, drag, and moment characteristics of shell during World War II, although he covered a relatively limited range of angles of attack and Reynolds' No.

Until recently, however, little progress had been made in the development of techniques for the measurement of dynamic properties like the damping in pitch, and relatively little effort had been expended on measurement of the Magnus force and moment, the forces due to spin.

Data of the sort which has been available from the ranges and wind tunnels are shown in Figures 3 through 9. These are the results of recent measurements on the 30mm shell T306E10, whose outline is shown in the spark photograph, Figure 10.

AN ATTACK ON THE LARGE YAW PROBLEM

In principal, at least, it should always be possible to compute the motion of a rigid body through the air, given the initial conditions, and given enough information about the aerodynamic force system to compute the instantaneous linear and angular accelerations. Thus, with large scale electronic computers to do the computing for us, the problem reduces to an aerodynamic one - the specification of the force system. This force system could be expected to depend on the following quantities, representative of the instantaneous condition of flight: Mach number, Air Density, Yaw Angle, Rate of Change of Yaw Angle, Axial Spin, Yawing Acceleration, Transverse Acceleration, Axial Acceleration.

Since an eight parameter non-linear specification of each of the six quantities required to establish the instantaneous force system seems to suggest a lifetime of experimentation, and since we can't measure some of the proposed dependences anyhow, we look for a simplified representation, which we hope will prove sufficient. The simplifications are based in part on reasonably good experimental grounds, and in part on theoretical estimates of the relative magnitudes involved. The simplified force system we are assuming can be represented as follows:

$$
\begin{aligned}
\text{Lift} &= f_1(\mathrm{Ma},\ \mathrm{Re},\ \delta)\rho V^2 \\
\text{Drag} &= f_2(\mathrm{Ma},\ \mathrm{Re},\ \delta)\rho V^2 \\
\text{Pitching Moment} &= f_3(\mathrm{Ma},\ \mathrm{Re},\ \delta)\rho V^2 \\
\text{Damping Moment} &= f_4(\mathrm{Ma},\ \mathrm{Re},\ \delta)\rho V\dot{\delta} \\
\text{Damping Force} &= f_5(\mathrm{Ma},\ \mathrm{Re},\ \delta)\rho V\dot{\delta} \\
\text{Magnus Force} &= f_6(\mathrm{Ma},\ \mathrm{Re},\ \delta,\ \nu)\rho V^2 \\
\text{Magnus Moment} &= f_7(\mathrm{Ma},\ \mathrm{Re},\ \delta,\ \nu)\rho V^2 \\
\text{Axial Torque} &= f_8(\mathrm{Ma},\ \mathrm{Re},\ \nu)\rho V^2
\end{aligned}
$$

Where ρ = Air Density $\dot{\delta}$ = Yawing Velocity

V = Velocity ν = Dimensionless Spin

δ = Yaw Angle   Ma = Mach No.

Re = Reynolds' No.

The assumption that the lift, drag, and pitching moments do not depend on spin is based on limited wind tunnel experiments on models with turbulent boundary layers. Happily, we have not been able to measure any effect of spin on these components, so, at least the dependence is small enough so that it can be neglected for the moment. Neglect of dependence of any of the force or moment components on linear or angular accelerations appears permissible, since these accelerations are in general very small, and since estimates based on linear aerodynamic theory suggest the associated aerodynamic forces can safely be neglected. Neglect of Magnus forces and moments depending on the angular velocity normal to the shell axis is on rather shaky ground - the crude estimates we have made suggest these forces and moments should be small compared to the pitching moment and lift, and small compared to the Magnus force and moment in most cases. In any event, we have never been able to detect the effects of such forces and moments in the spark photography range experiments, and we cannot at this time measure them in the wind tunnel. Thus we will neglect them unless forced to include them by failure to predict correct trajectories with the present force and moment system.

If we can accept this force system as adequate, we should be able to define it completely using the wind tunnel, using rotating models for Magnus force and moment determination, and non-rotating oscillating models to measure the damping in pitch.

Once the force system is specified for the range of conditions expected in flight, yaw histories and trajectories will be computed using large-scale electronic computers available at BRL. Some of these trajectories, with initial conditions appropriate to airplane launch conditions, will make up the firing tables. Others will be used to test the assumptions about the force system.

To test our assumptions we plan to use the spark photography ranges. In the ranges we cannot get large initial yaws, but we can easily obtain large initial yawing velocities by well-known techniques. The yaw histories, jump, and swerving motions will be different from those corresponding to the airplane case, but we will have large amplitude yawing motions, and great accuracy of experimental trajectory determination. If the force system assumed is inadequate, the inadequacy should be revealed by comparison between the computed motions for the range initial conditions, and the measured motions. Additional checks are planned by firings from the Inyokern track, where we should be able to get test trajectories with the correct initial conditions but limited to sea level densities. As a final check, some very limited firings from a specially instrumented fighter airplane are contemplated, with correct initial conditions at operational altitudes.

WIND TUNNEL TECHNIQUES FOR MAGNUS MOMENT AND DAMPING IN PITCH

Personnel of the Supersonic Wind Tunnels Branch of the BRL's Exterior Ballistics Laboratory have developed what appear to be adequate techniques for the measurement of the Magnus force and moment on spinning shell models, and of the damping in pitch for non-spinning models. While no reports have as yet been published on this work, due to the very preliminary nature of the results, it seems worthwhile to make some mention of the techniques and exhibit preliminary results at this meeting.

The spinning model tests involve the use of a shell model driven by an air turbine, at speeds up to 40,000 rpm or higher, mounted on a 4-component strain gage balance. Figure 11 is a sketch of a typical installation, and Figure 12 shows a representative Magnus moment curve. Good results depend on very steady air flow in the wind tunnel, and great care in avoiding interactions in the balance system.

The damping in pitch measurements have been made using special struts supporting the model at the desired center of rotation by crossed flexure hinges, allowing one rotational degree of freedom, as shown in Figure 13. The inherent static instability of the model is overcome by proper choice of flexure stiffness, and the decay of small amplitude pitching oscillations induced by a remotely controlled tripping device is observed by recording the signal output from calibrated strain gages mounted on the flexures. Typical results are shown in Figure 14. With this technique accuracy of the order $\pm 10\%$ in the damping coefficient is obtainable, provided the tunnel flow is very steady, and provided very accurate measurements of the damping due to the flexures under load are available.

[redacted]

SUMMARY

The work at the Ballistic Research Laboratories on large yaw characteristics of shell has been shown to depend heavily on wind tunnel measurements and machine computations. Checks are to be obtained with free flight experiments. The program has advanced past the preliminary technique development stage, and systematic measurements on two shell are now underway. No final trajectory checks have as yet been made.

C. L. POOR

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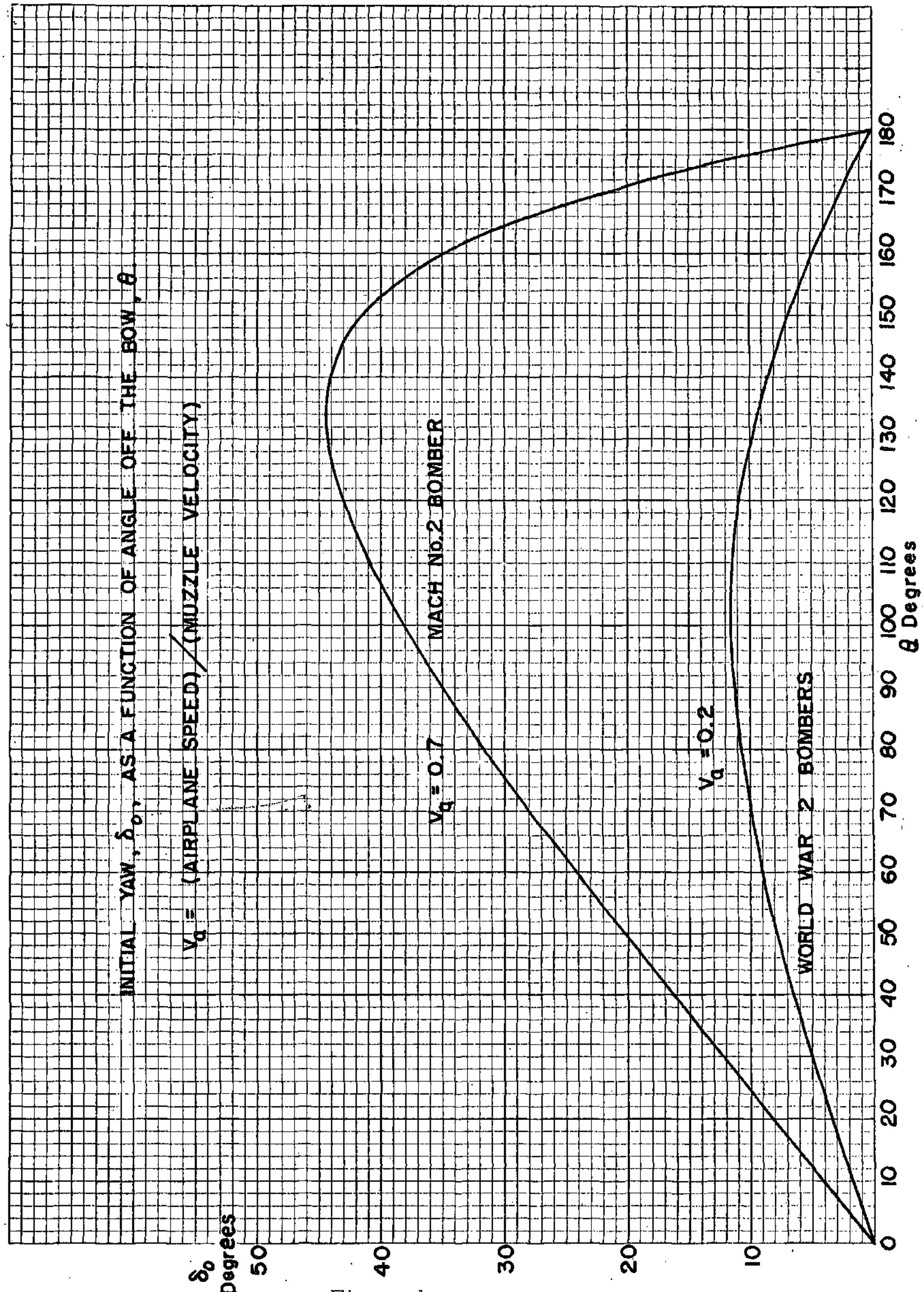

Figure 1

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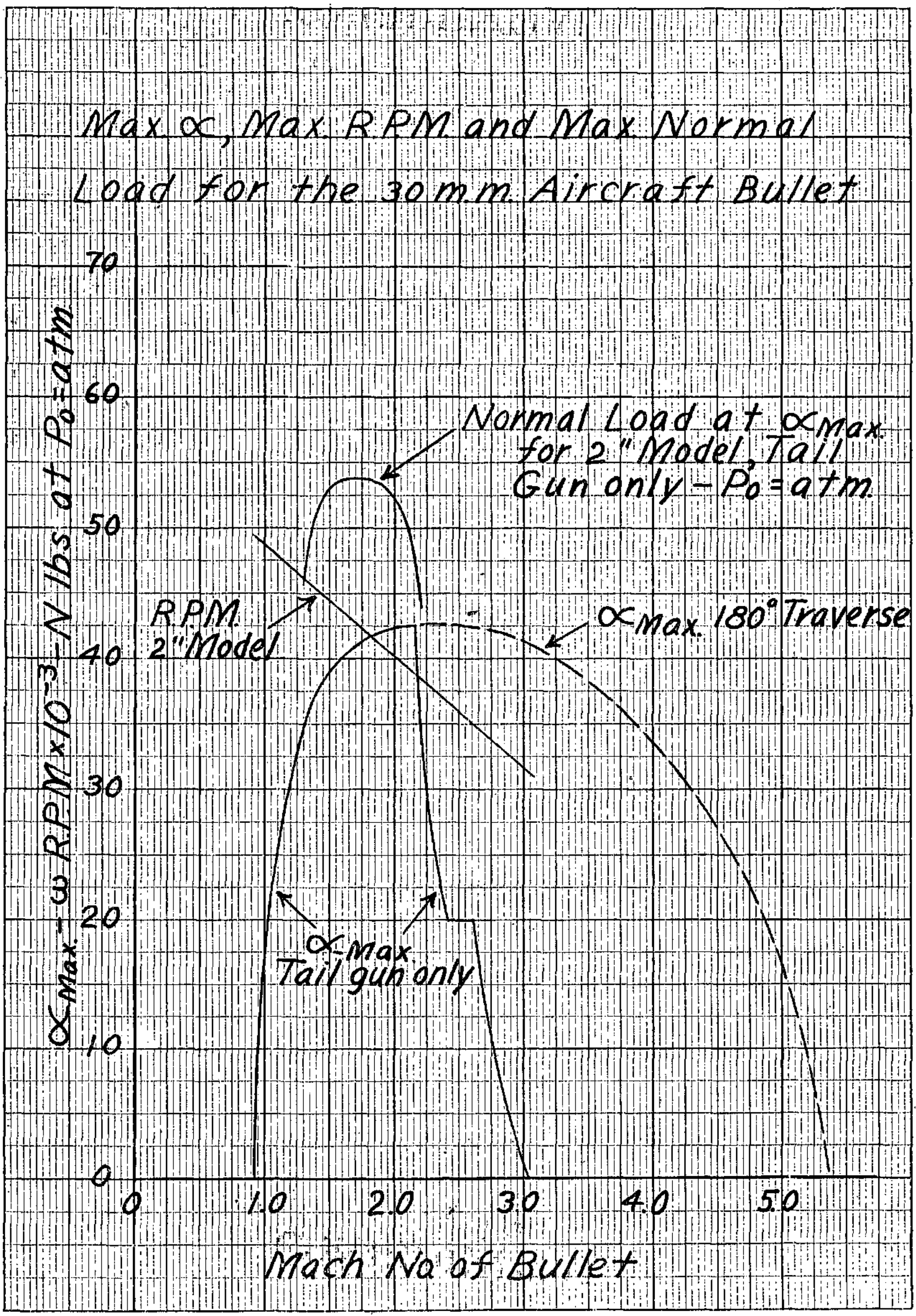
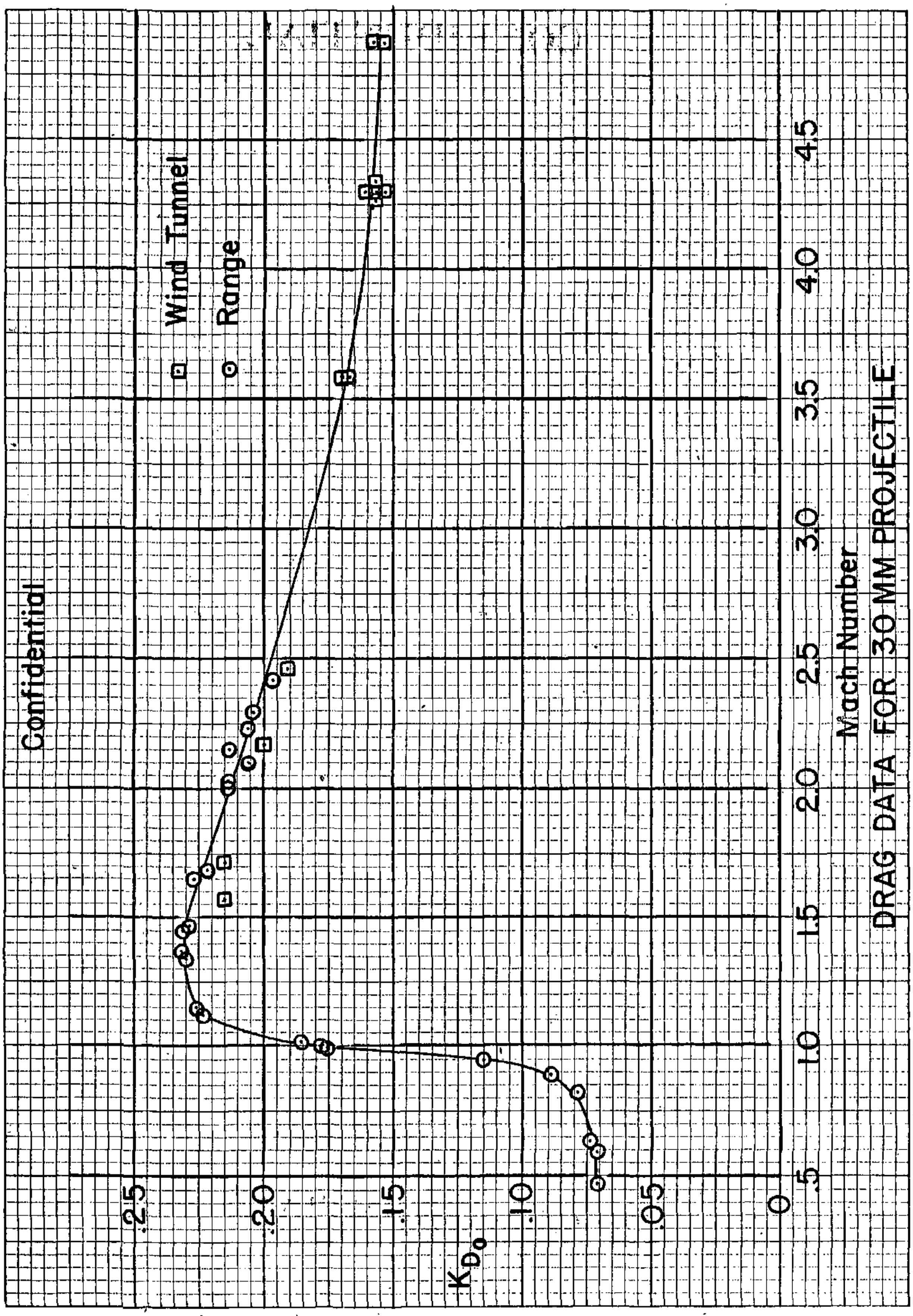


Max ∝, Max RPM and Max Normal
Load for the 30mm Aircraft Bullet
∝Max. - ω RPM×10⁻³ - N lbs at P₀=atm
70
60
50
40
30
20
10
0
0
1.0
2.0
3.0
4.0
5.0
Mach No of Bullet
Normal Load at ∝max.
for 2" Model, Tail
Gun only - P₀=atm.
R.P.M.
2" Model
∝Max. 180° Traverse
∝ Max.
Tail gun only

Figure 2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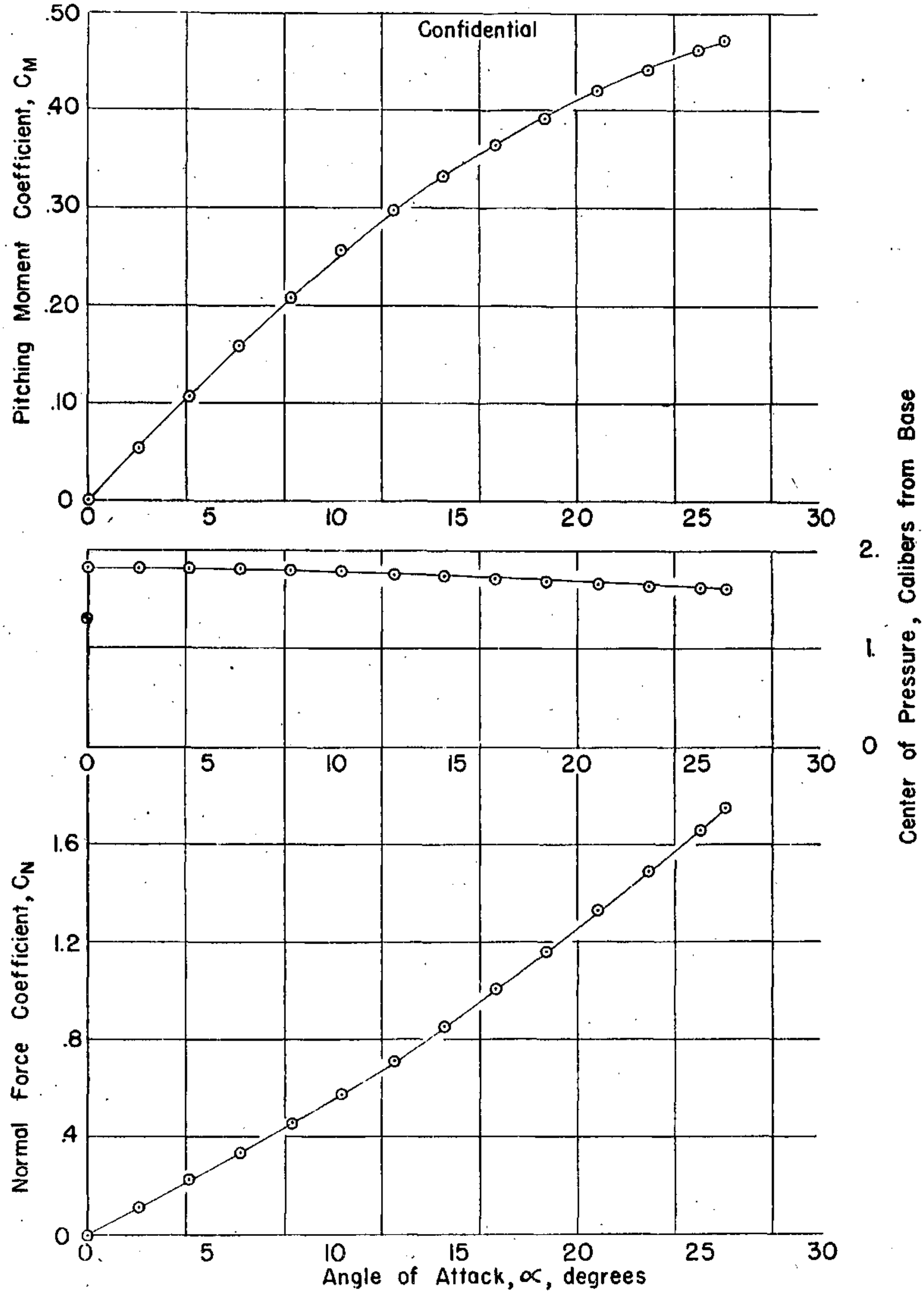
Wind Tunnel
Range
K_{D_0}
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Mach Number
0
.5
1.0
1.5
2.0
2.5
DRAG DATA FOR 30 MM PROJECTILE

Figure 3



PITCH DATA FOR 30 MM PROJECTILE

Ma = 2.00 Figure 4 Re = $.62 \times 10^6$

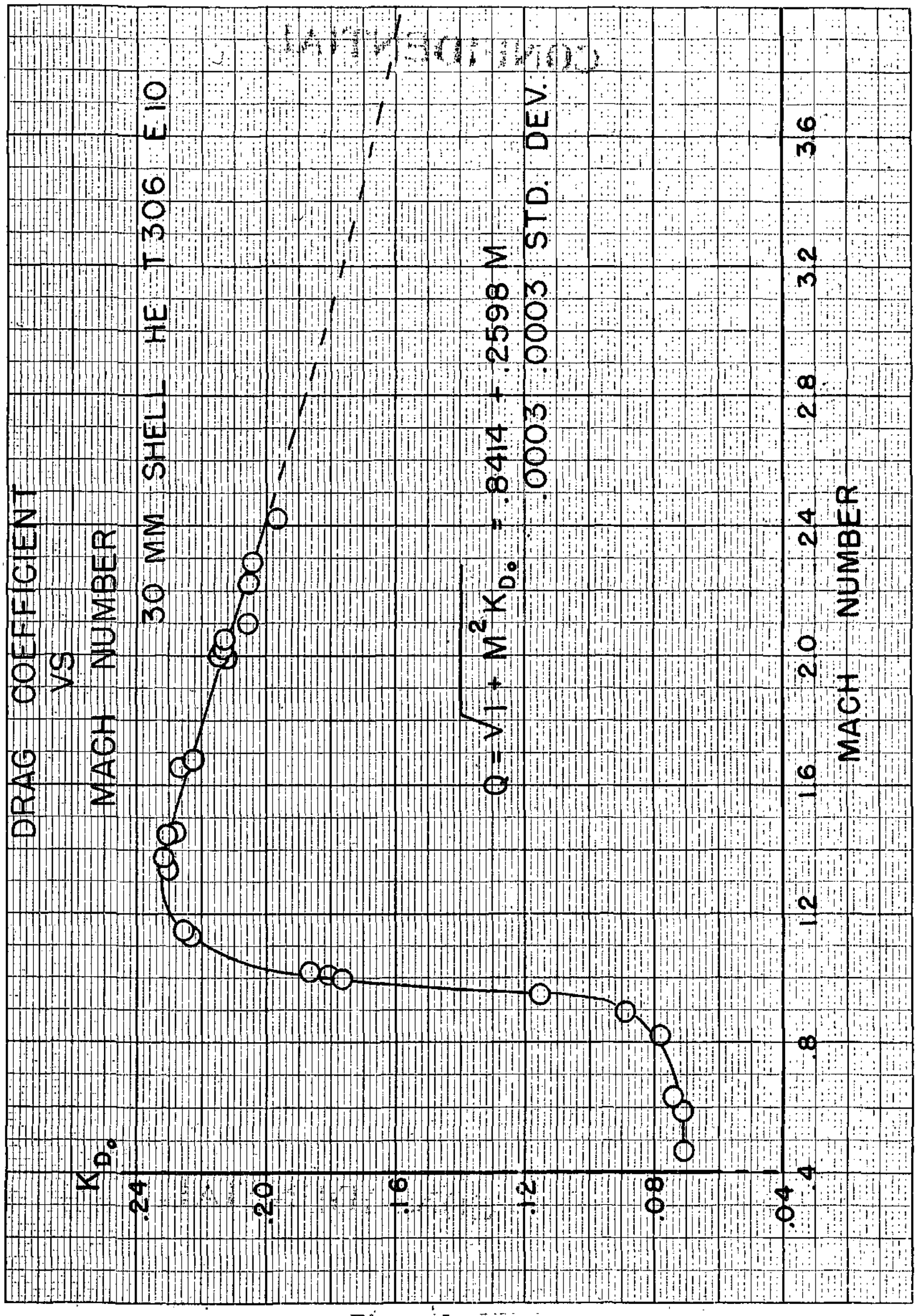

DRAG COEFFICIENT
VS
MACH NUMBER
30 MM SHELL HE T306 E10
$Q = \sqrt{1 + M^2 K_{D_0}} = .8414 + .2598\,M$
.0003 .0003 STD. DEV.
K_{D_0}
.24
.20
.16
.12
.08
.04
.4
.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
MACH NUMBER

Figure 5

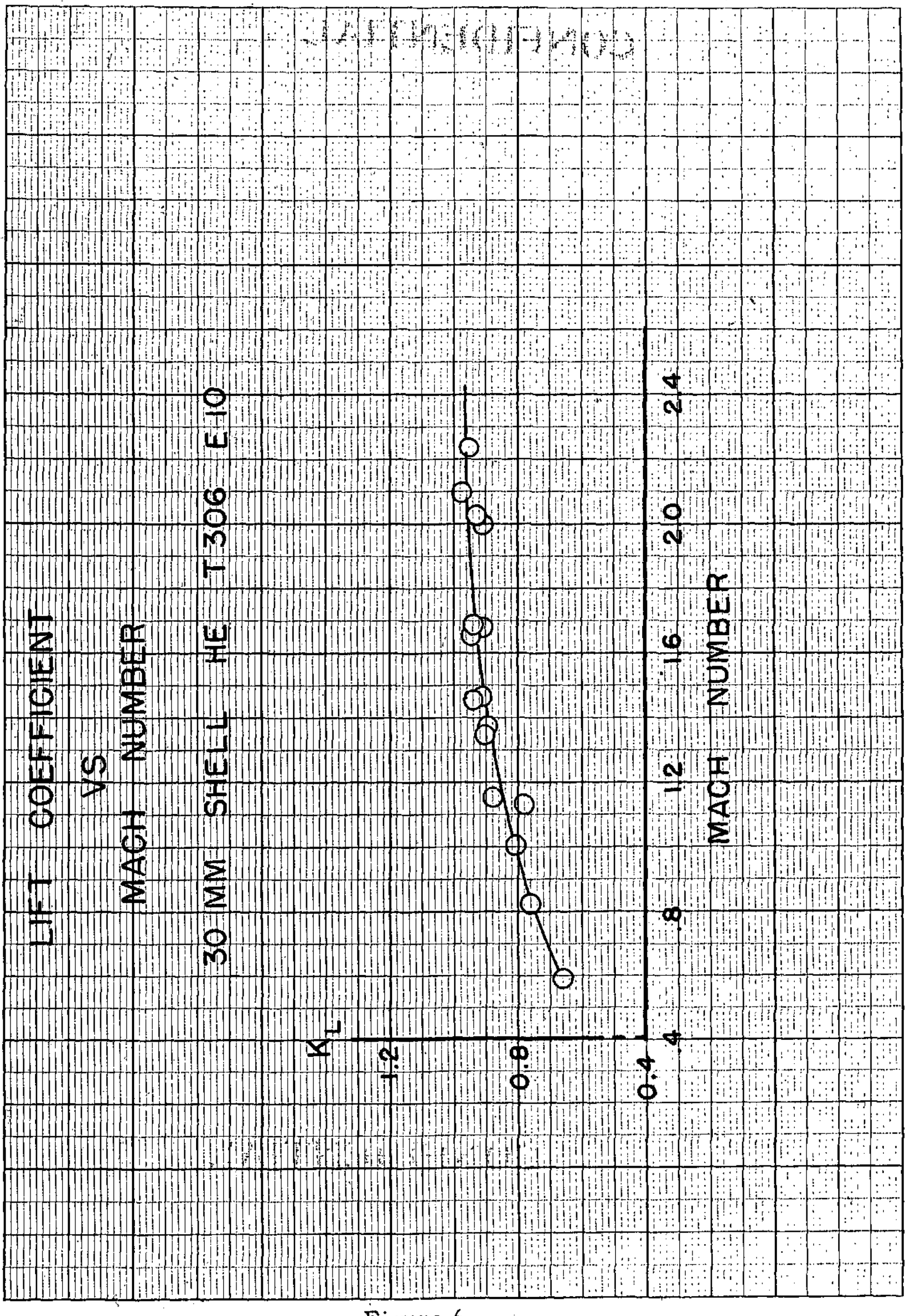

LIFT COEFFICIENT
VS
MACH NUMBER
30 MM SHELL HE T 306 E 10
K_L
1.2
0.8
0.4
4
8
1.2
1.6
2.0
2.4
MACH NUMBER

Figure 6

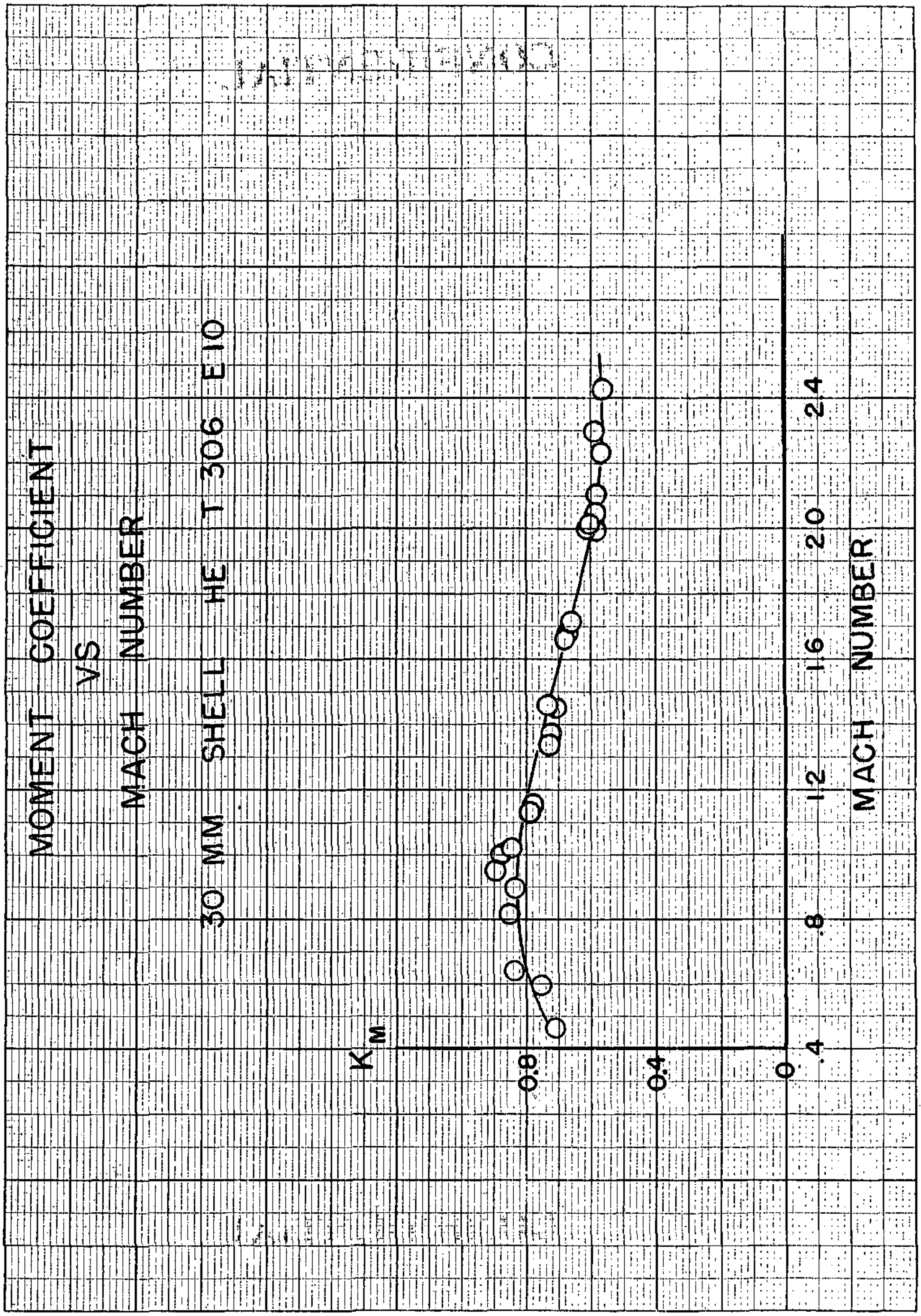

MOMENT COEFFICIENT
VS
MACH NUMBER
30 MM SHELL HE T 306 E10
K_M
0.8
0.4
0
.4
.8
1.2
1.6
2.0
2.4
MACH NUMBER

Figure 7

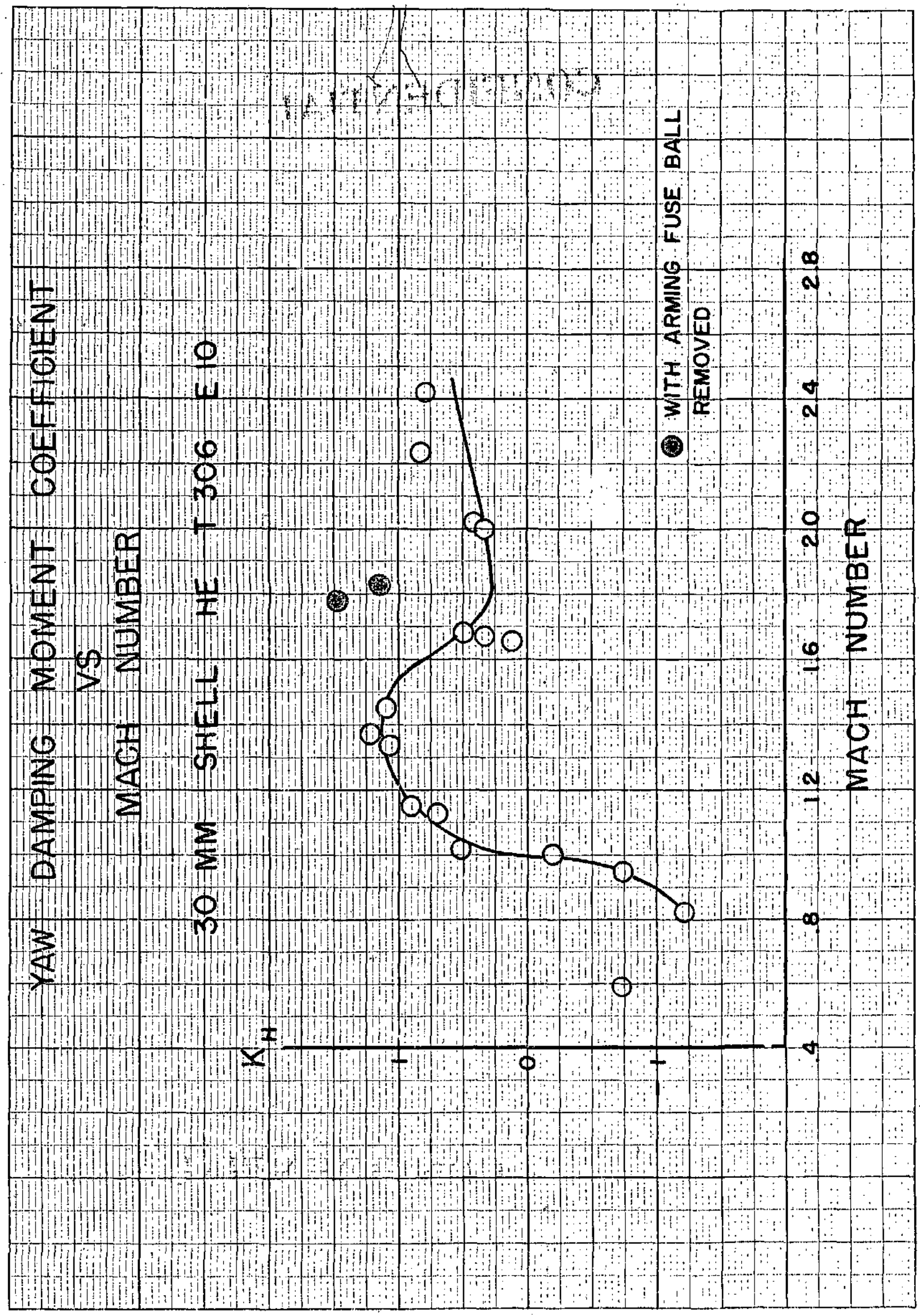

YAW DAMPING MOMENT COEFFICIENT
VS
MACH NUMBER
30 MM SHELL HE T 306 E 10
WITH ARMING FUSE BALL
REMOVED
K_H
1
0
-1
.4
.8
1.2
1.6
2.0
2.4
2.8
MACH NUMBER

Figure 8

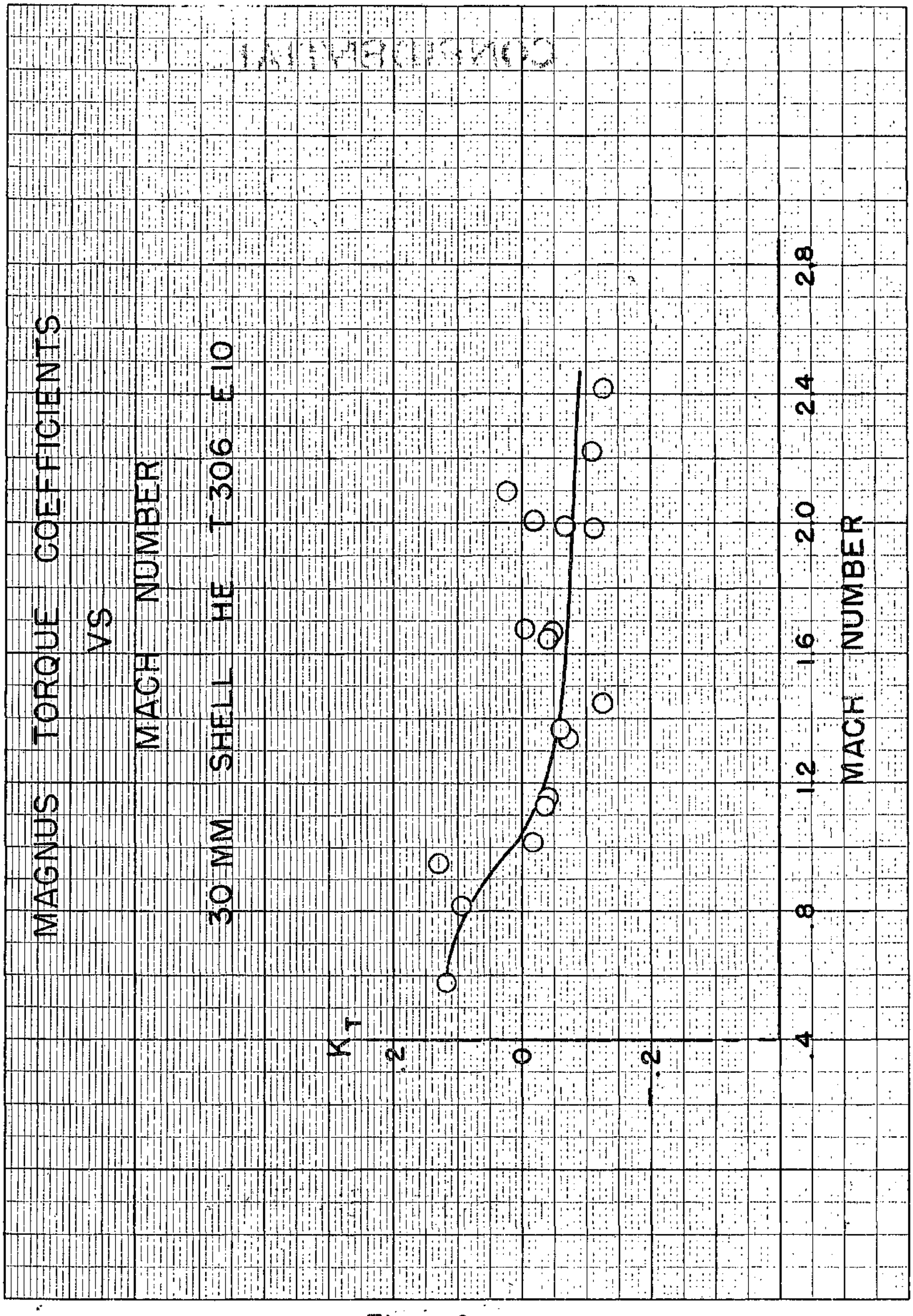
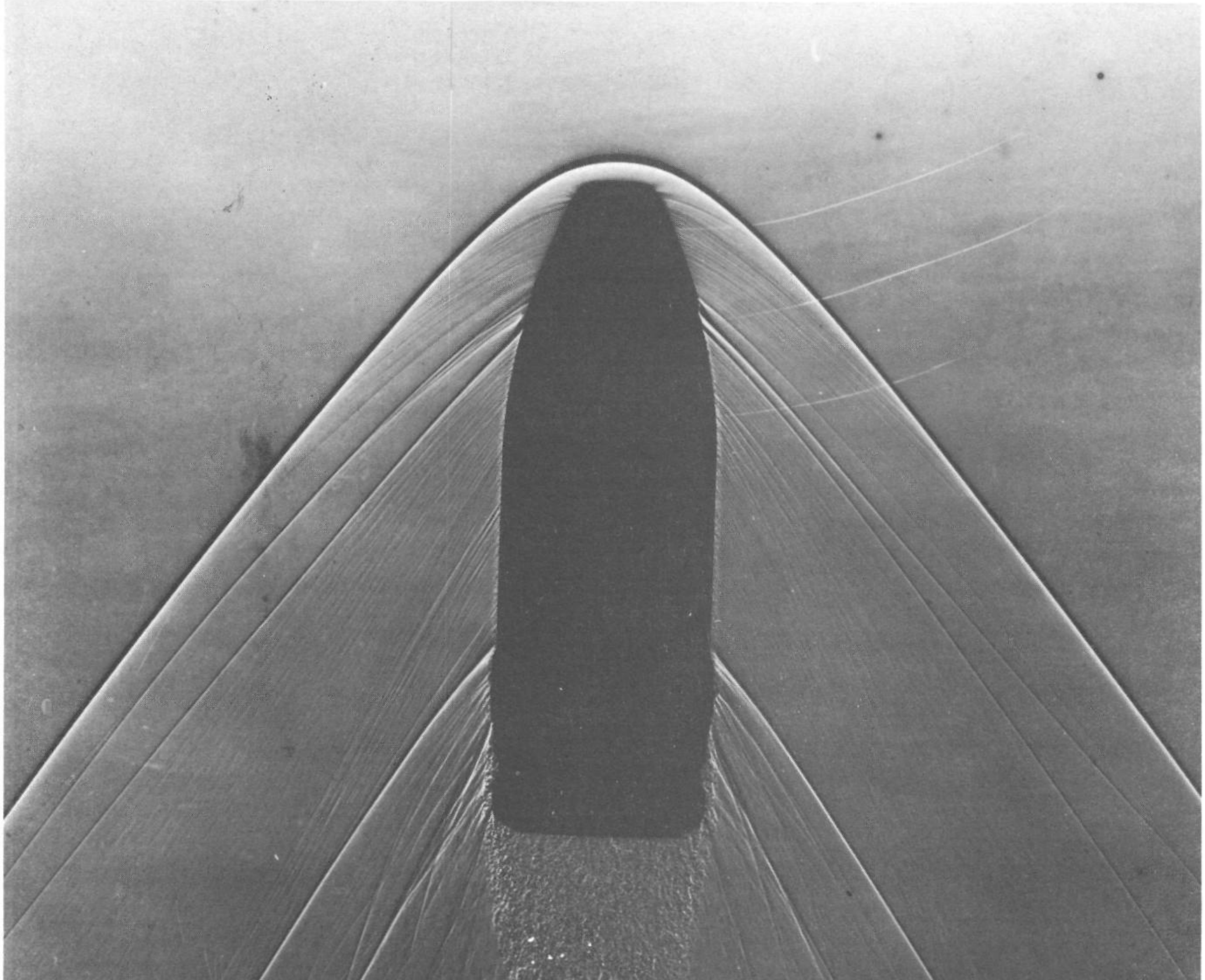
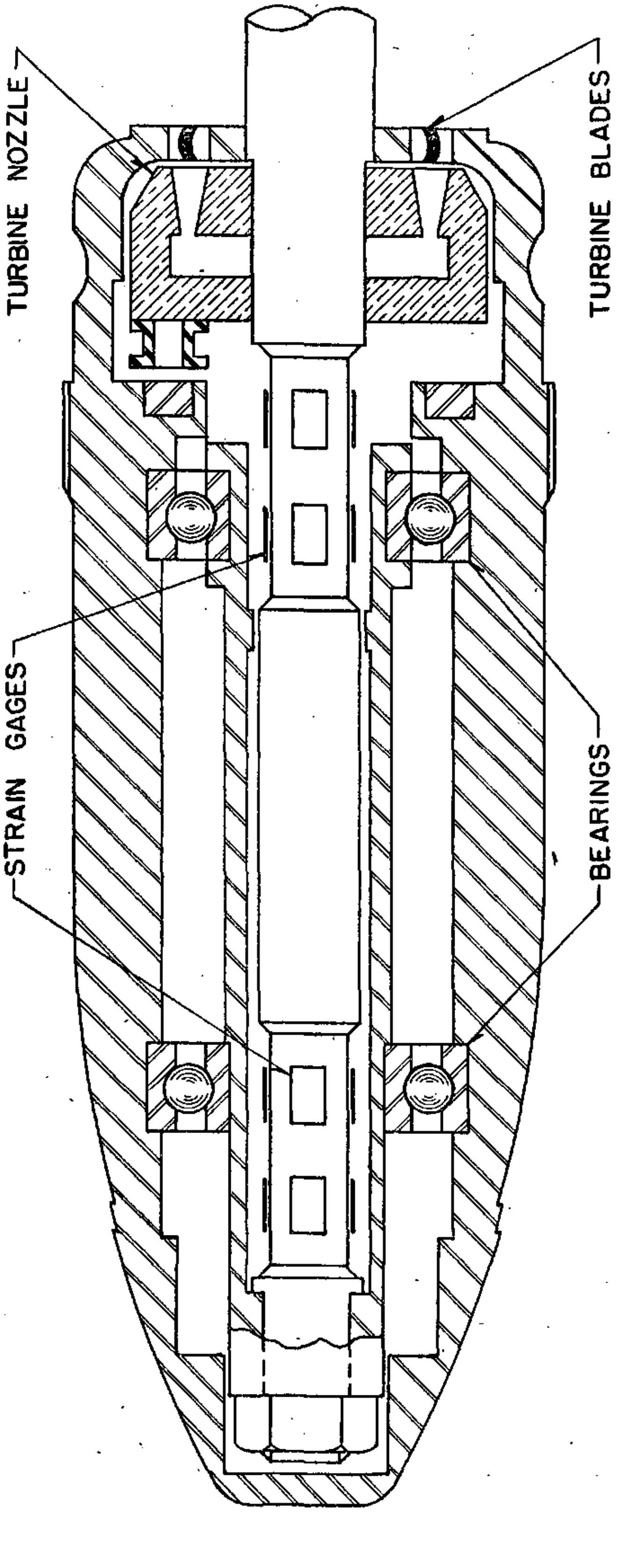

MAGNUS TORQUE COEFFICIENTS
VS
MACH NUMBER
30 MM SHELL HE T 306 E 10
K_T
.2
0
.2
.4
.8
1.2
1.6
2.0
2.4
2.8
MACH NUMBER

Figure 9





WIND TUNNEL MAGNUS INSTRUMENTATION

Figure 11

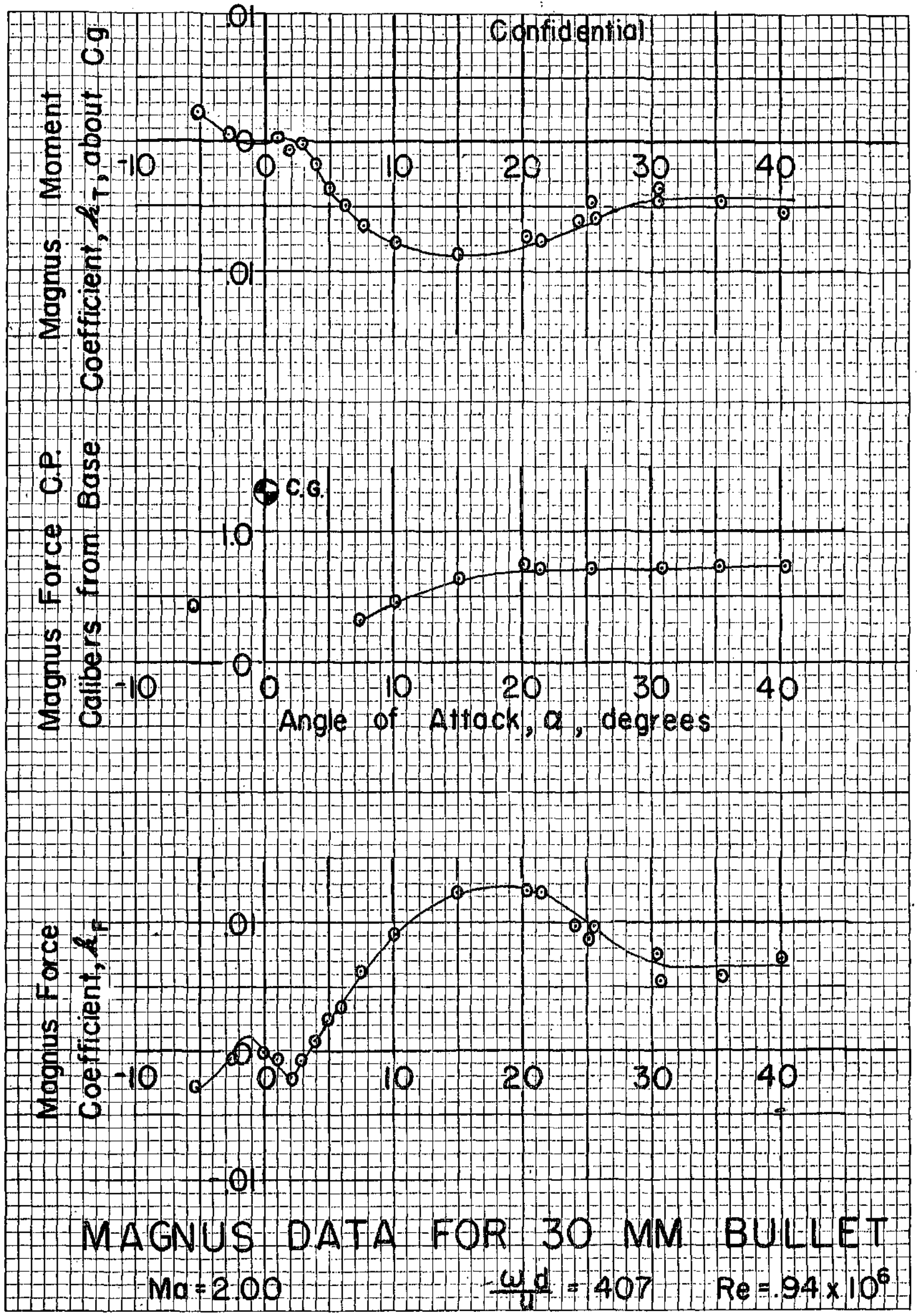
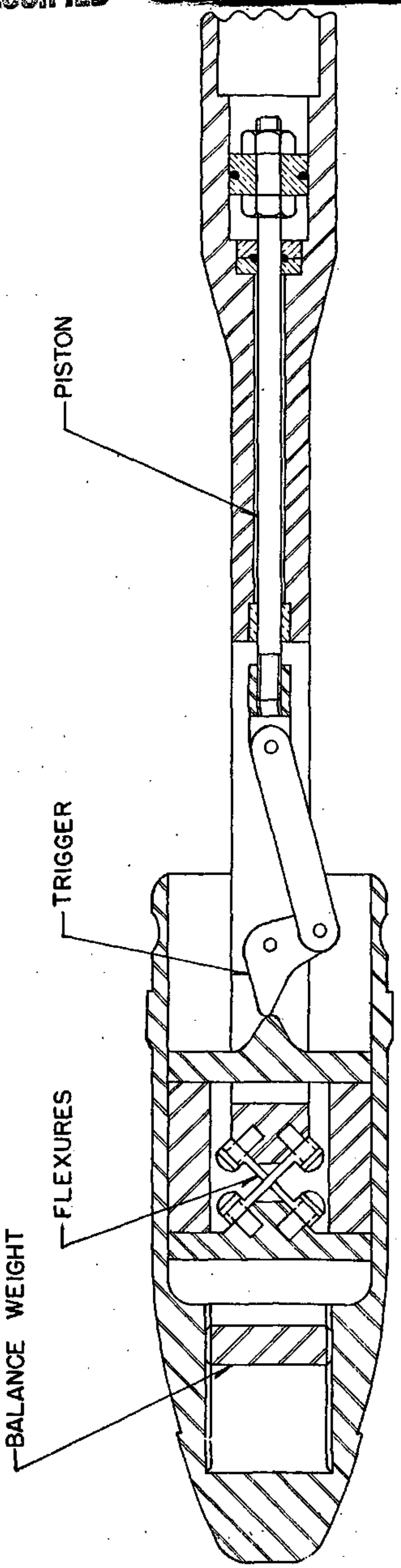

Confidential
Magnus Moment Coefficient, k_T, about Cg
.01
-.01
-10
0
10
20
30
40
Magnus Force C.P. Calibers from Base
C.G.
1.0
0
Angle of Attack, α, degrees
Magnus Force Coefficient, k_F
MAGNUS DATA FOR 30 MM BULLET
Ma = 2.00
$\frac{\omega d}{u}$ = .407
Re = .94 x 10^6

Figure 12



DAMPING IN PITCH MODEL

Figure 13

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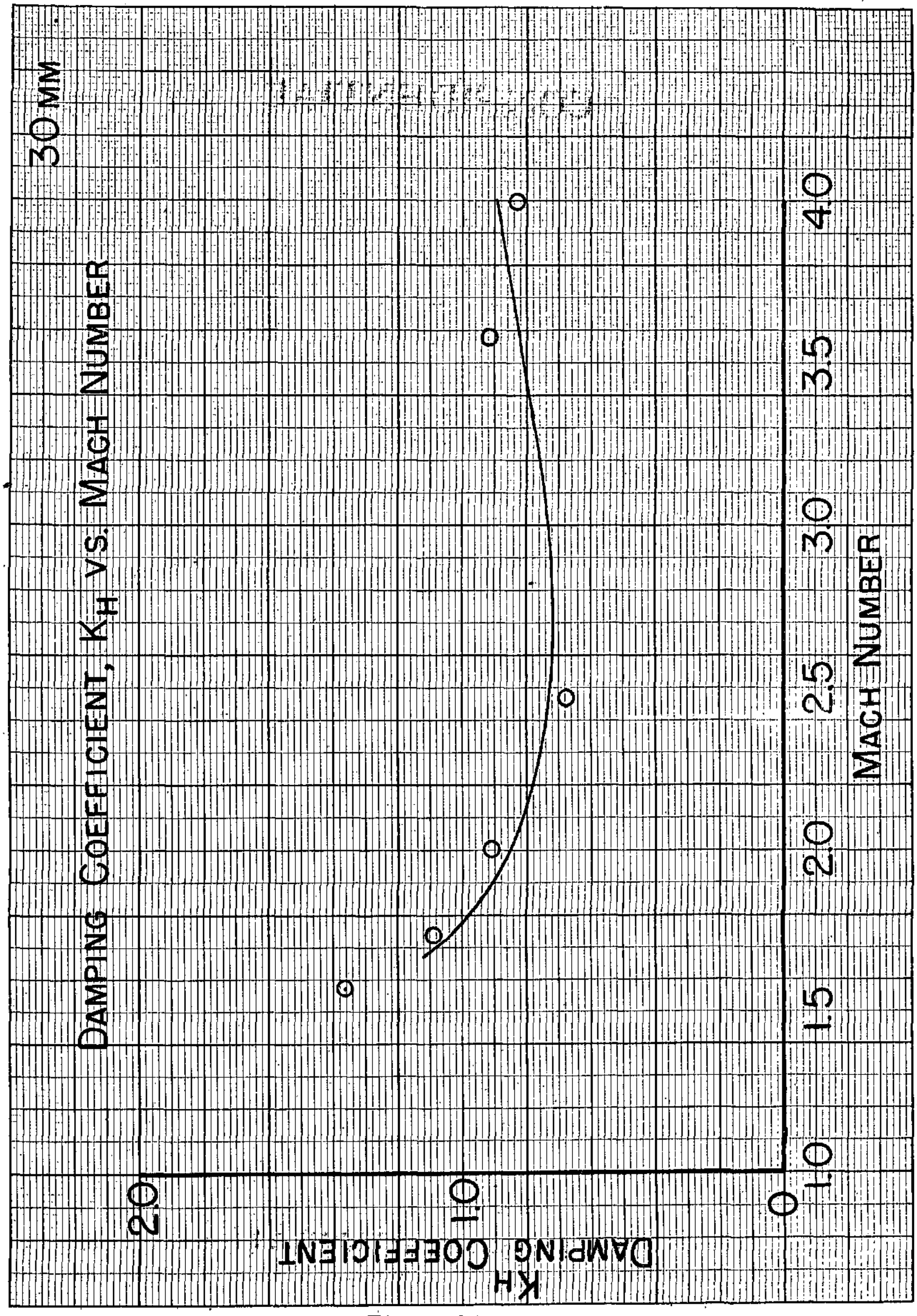

Figure 14

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