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FEASIBILITY OF USING A ROTOCHUTE IN RETARDING A 10,000-POUND WEAPON

INVENTORIED 6-28-57

W. B. Pepper - 5141

INVENTORIED MAY 12 1958 BY ORG. 2743

ABSTRACT

The application of a four-bladed governing rotochute to laydown from high altitude of a 10,000-pound weapon is considered. The possibility of achieving 50 feet per second impact velocity by using a blade pitch change near the ground to produce a "flare-out" is considered.

Preliminary analysis indicates that the system is feasible and should not require the application of power to the rotor during flare-out.

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SUMMARY

Division 5141 is investigating the feasibility of using a rotochute for laydown of Class A and B weapons. A four-bladed governing rotochute design with telescoping blades based on experience gained from a rotochute study contract with Kaman Aircraft Corporation, Bloomfield, Connecticut, is considered. The chief hope in using a rotochute for this application is the use of blade pitch change near the ground resulting in a "flare-out." Drag coefficients of 4.0 to 8.0 based on disk area may be obtained during flare-out, which is to be compared with the maximum value of 1.2 for steady-state operation of conventional parachutes or rotochutes.

This preliminary analysis has indicated that sufficient kinetic energy can be extracted from the potential energy of fall and stored in rotational inertia to produce a velocity decrement from 228 ft/sec down to 50 ft/sec. Conventional rotochute operation (that is, before flare-out) will accomplish deceleration from the Mach number of 0.9 release speed down to 228 ft/sec. It does not appear necessary to apply power to the rotor during flare-out.

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SYMBOLS

C_D = Drag coefficient = $\frac{D}{qS}$

S = Drag reference area (ft^2)
(S = 12.6 with rotochute stored, S = 177 with rotochute open)

D = Drag force (lb)

q = Dynamic pressure (lb/ft^2)

W = Weapon weight (lb)

ρ = Air density (.002378 $slugs/ft^3$ at sea level and .0020 at 5000 feet)

V_v = Vehicle velocity (ft/sec) (negative when climbing)

K.E. = Kinetic energy (ft-lb)

m = Weapon mass (slugs)

P.E. = Potential energy (ft-lb)

h = Altitude (ft)

I = Moment of inertia of rotor about its axis of rotation ($slug\text{-}ft^2$)

ω = Angular velocity (rad/sec)

M = Mach number

$\bar{F}$ = Average thrust coefficient based on u

$\bar{f}$ = Average thrust coefficient based on V_v

T = Rotor thrust parallel to axis of rotation (lb)
(positive in direction of rotor advance)

R = Rotor radius (ft)

u = Resultant mean velocity through rotor disc (ft/sec) (positive up)

U_o = Thrust velocity (ft/sec)

g = Acceleration of gravity (ft/sec^2)

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FEASIBILITY OF USING A ROTOCHUTE IN RETARDING A 10,000-POUND WEAPON

INTRODUCTION

Mr. Gunner Scholer, 1821, from Livermore visited Sandia Corporation on December 10, 1956 and discussed with the author the possibility of using a rotochute for laydown of Class A and B weapons. The warhead is 120 inches long and must fit within the B-47 bomb bay which is 145 inches long, so that the retardation system must fit within a 2-foot length and the weapon base diameter of about 4 feet. Mr. Scholer suggested that the use of a rotochute might provide the desired impact velocity of 50 feet per second or less if the blade pitch could be changed near the ground to produce a "flare-out" such as helicopters use in landing.

Reference 1 requests a theoretical study of such a rotochute application. This memorandum will present the preliminary analysis to date.

Reference 2 is a parallel study being made by Sandia Corporation, Division 5141, to investigate the feasibility of using parachutes for laydown of Class A and B weapons.

PROPOSED CONFIGURATION

The largest rotor diameter that will fit into the limited storage space available appears to be a four-bladed, telescoping rotor with 15 feet maximum diameter. Figure 1 illustrates the configuration. The blades are assumed to be made of a heavy steel skin construction in order to withstand the high centrifugal accelerations expected and to produce a high rotational inertia. Two of the blades that are opposite each other would be folded one on top of the other. Double hinges could be used to allow flat folding and conserve space. The other two blades would also be folded one on top of the other at right angles to the first two blades. The blade attachment fittings are schematic only since provision for blade pitch-governing and pitch change during flare-out would be a matter for detailed mechanical design.

A preliminary weight estimate indicates that the rotochute proposed in Fig. 1 would weigh 1000 pounds.

NORMAL WORKING STATE OF ROTOCHUTE

The weapon is intended to be released at an approximate altitude of 40,000 feet at a speed of Mach 0.6 to 0.9. The weapon should free-fall as far as possible to decrease the weapon vulnerability. The rotochute will probably have to be opened at about 20,000 or 30,000 feet altitude in order to decelerate the weapon sufficiently to insure that the rotochute reaches the step condition where the drag coefficient is 1.2. When the weapon is about 100 feet from the ground, an altitude-sensing device initiates a blade pitch change producing a "flare-out."

Trajectories are being calculated to determine the characteristics of the normal working state of a governing rotochute during the upper portion of the trajectory. Table 1 lists the trajectories and gives results of the calculations. All trajectories were calculated using the standard NACA atmosphere, and rotochute opening was assumed to be instantaneous for this general parametric study. Actual opening time should be about 1 to 2 seconds. The drag shown in Fig. 2 that was assumed

for the weapon with the rotochute undeployed is the experimental curve for the Mk 15 weapon which is similar in shape to the weapon shape shown in Fig. 1. The drag curves assumed for the rotochute are shown in Fig. 3. Curve (1) is extrapolated to high Mach number from the experimental drag of a four-bladed governing rotochute with a solidity of 0.13 (Ref. 3). Since the rotor presently being considered has a solidity of 0.237, as shown in Fig. 1, the drag curve (2) shown in Fig. 3 was estimated. The rotochute governing system could be designed to produce curves (4) and (5) if such variations are found to be necessary.

Table I presents the results from 12 trajectories. As discussed in the next section, a velocity of 228 ft/sec is desired about 300 feet above the ground. Trajectory (10) results in 223 ft/sec with the rotochute opening delayed to 20,000 feet altitude. Rotochute opening cannot be delayed to lower altitudes since the velocity becomes larger than the desired 228 ft/sec. It is of interest to note that the maximum deceleration for trajectory (10) is 3.42 g's, which is desirable for the present laydown application.

ENERGY REQUIREMENTS OF ROTOCHUTE FLARE-OUT

After the rotochute has progressed through the normal working state of windmill brake and is operating in the step condition (turbulent windmill brake), the vehicle will assume, at the best, a terminal velocity condition based on a drag coefficient of 1.2. For terminal velocity the weight equals the drag,

$$W = D = C_D \, 1/2 \, \rho \, V_v^2 \, S \tag{1}$$

$$V_v = \sqrt{\frac{2W}{C_D \, \rho \, S}} = \sqrt{\frac{2(11,000)}{1.2(.002378)(177)}} \tag{2}$$

$$V_v = 209 \text{ ft/sec (sea level density)}$$

$$V_v = 228 \text{ ft/sec (5000 ft above sea level)} .$$

If the 5000-foot ground level is considered the worst case and an impact velocity of 50 ft/sec is desired, the flare-out must provide a velocity decrement of 178 ft/sec.

The kinetic energy equivalent to the necessary velocity decrement can be found by,

$$\begin{aligned} K.E. &= 1/2 \, m \, \Delta\left(V_v^2\right) \\ &= 1/2 \, \frac{11,000}{32.2} \left[(228)^2 - (50)^2\right] = 8.45 \times 10^6 \text{ ft-lb} \end{aligned} \tag{3}$$

As a point of interest the potential energy of altitude can be equated to the needed kinetic energy and the equivalent altitude of vehicle fall can be found.

$$\begin{aligned} P.E. &= W \, \Delta h = 8.45 \times 10^6 \\ \Delta h &= \frac{8.45 \times 10^6}{11,000} = 770 \text{ ft.} \end{aligned} \tag{4}$$

It is evident that sufficient potential energy is available in a very short distance of fall to supply the necessary energy to achieve 50 ft/sec impact velocity. In reality the potential energy of fall would be converted and stored as rotational kinetic energy at maybe 10 per cent efficiency during the normal operating stage of the upper rotochute trajectory. The potential energy of fall must be converted by the rotochute into kinetic energy of rotation if the energy is to be made available for use during the flare-out. It is hoped that no power to the rotor will be required except this energy stored in rotational inertia. As an example, the rotor shown in Fig. 1 has an inertia about its axis of rotation of

$$I = 323 \text{ slug-ft}^2 .$$

The kinetic energy of rotation is,

$$K.E._R = 1/2\ I\ \Delta(\omega^2) \quad . \tag{5}$$

This can be equated to the desired kinetic energy of translation needed to decrease the vehicle velocity from 228 ft/sec to 50 ft/sec, assuming 100 per cent efficient conversion and that the final rotor speed is zero

$$1/2\ I\ \Delta(\omega^2) = 8.45 \times 10^6$$

$$\omega = \sqrt{\frac{2(8.45 \times 10^6)}{323}} = \sqrt{5.24 \times 10^4} = 229 \text{ rad/sec} \tag{6}$$

$$= \frac{228}{2\pi}(60) = 2190 \text{ rpm} \quad .$$

A preliminary structural analysis of the rotor shown in Fig. 1 indicates that the rotor could possibly be designed to withstand 2190 rpm. The desired rotor speed can be achieved before flare-out by proper adjustment of a governing rotochute. The efficiency of energy conversion during flare-out (vortex ring state of rotochute operation) is not known at the present time. A contract is presently being negotiated by Sandia Corporation with Kaman Aircraft Corporation to study theoretically and experimentally the flare-out stage of rotochute operation (Ref. 4). Work will begin March 1, 1957 and will be completed by July 1, 1957.

The present study of a 10,000-pound weapon indicates that all of the performance available from the proposed rotochute shown in Fig. 1 must be used in order to achieve a 50 ft/sec impact velocity; therefore, it is evident that the same size rotochute could not be used for a Class A weapon weighing 15,000 pounds. The retardation system storage space would have to be larger in diameter. The rotor diameter would have to be 18.5 feet so the body diameter would have to be about 60 inches.

ROTOR THEORY

During the high altitude portion of the rotochute trajectory the rotor is operating in the windmill brake state, as shown by Sketch (c) in Fig. 4. The rotor theory and Fig. 4 may be found in Refs. 5 to 8. As the rotor forward velocity decreases down to about 0.2 Mach number the rotochute governor will allow the rotor to enter the "step condition" or turbulent "windmill" brake state of operation where the rotor drag coefficient approaches 1.2. Sketch (d) in Fig. 4 illustrates

the flow stream line pattern through the disk during this stage. During the final portion of the trajectory where flare-out is to be used, the rotor will be operating in the "vortex ring" and "transition vortex ring" states of operation shown in Fig. 4 as Sketches (e) and (f). The two general theories of airscrew operation, which are the momentum theory and vortex theory, break down for conditions (d), (e) and (f) so that an empirical treatment must be used.

The two parameters used in Fig. 4 are defined as,

$$\bar{F} = \frac{T}{2\pi\rho R^2 u^2} \tag{7}$$

$$\bar{f} = \frac{T}{2\pi\rho R^2 V_v^2} \tag{8}$$

where,

T = rotor thrust (lb) (positive in direction of advance)

R = rotor radius (ft)

ρ = air density (slugs/ft^3)

V_v = vertical component of true airspeed of rotor (ft/sec) (negative when climbing)

u = resultant mean velocity through rotor disc (positive up)

$\bar{F}$ = average thrust coefficient based on u

$\bar{f}$ = average thrust coefficient based on V_v

Lock developed a more convenient method of presentation than Fig. 4 by introducing dimensionless velocity ratios,

$$\frac{V_v}{U_o} = \frac{V_v}{\sqrt{\frac{T}{2\rho A}}} = \sqrt{\frac{1}{\bar{f}}} \tag{9}$$

$$\frac{u}{U_o} = \frac{u}{\sqrt{\frac{T}{2\rho A}}} = \sqrt{\frac{1}{\bar{F}}} \tag{10}$$

where,

$$U_o = \sqrt{\frac{T}{2\rho S}} \text{ thrust velocity (ft/sec)}$$

$$S = \pi R^2 \text{ rotor disc area (ft}^2\text{)} . \tag{11}$$

Figure 5 is a plot of the dimensionless velocity ratios. The solid curve is Glauert's empirical curve transcribed from Fig. 4. The letters denote the different

states of aircrew operation and are defined in Fig. 4. Figure 5 is taken from Fig. 1.1.2.6 of Ref. A-1.* Experimental measurements of Lock and Hafner substantiate Glauert's curve and make possible the estimation of rotor performance in the vortex ring state where momentum theory and vortex theory cannot be used.

APPLICATION OF THEORY TO ROTOCHUTE FLARE-OUT

The flare-out stage is desired to provide a deceleration from 228 fps down to 50 fps,

$$dV = 228 - 50 = 178 \text{ ft/sec.}$$

Using Newton's first law and assuming the deceleration should take place in 3 seconds, the required average rotor thrust is,

$$F = ma = \frac{W}{g}\frac{dV}{dt} = \frac{11,000}{32.2}\frac{(178)}{3} = 20,200 \text{ lb.}$$

The initial thrust velocity term is,

$$U_o = \sqrt{\frac{T}{2\rho S}} = \sqrt{\frac{-20,200}{2(.002)\pi(7.5)^2}} = -169 \text{ ft/sec.}$$

At the beginning of flare-out the dimensionless descent velocity parameter is,

$$\frac{V_v}{U_o} = \frac{228}{-169} = -1.35 \quad .$$

Using Glauert's curve in Fig. 5,

$$\frac{u}{U_o} = .10$$

$$u = .10\ (-169) = -16.9 \text{ ft/sec.}$$

The resultant mean velocity through the rotor (u) is therefore downward from the assumed sign convention.

As a method of rotor performance comparison the drag coefficient based on rotor disc area may be found,

$$C_D = \frac{D}{qS} = \frac{-T}{1/2\ \rho V_v^2 \pi R^2} \quad . \qquad (12)$$

*There was a mistake discovered in Fig. 1.1.2.6 in that the quantities D/U_o and V/U_o representing the two axes should be interchanged to be correct and agree with other references.

From equation 8,

$$T = \bar{f}\, 2\pi \rho R^2 V_v^2$$

and substituting in equation 12,

$$C_D = \frac{-\bar{f}\, 2\pi \rho R^2 V_v^2}{1/2\, \rho V_v^2\, \pi R^2} = -4\, \bar{f}\,. \qquad (13)$$

Using equation 9,

$$\bar{f} = \frac{1}{\left(\frac{V_v}{U_o}\right)^2} = \frac{1}{(1.35)^2} = -.55\,. \qquad (14)$$

Substituting the value from 14 in 13,

$$C_D = -4\,(-.55) = 2.2\,.$$

As V_v decreases in value, the drag coefficient increases, when U_o (and therefore the rotor drag) are held constant. The initial power required, which will be supplied by deceleration of the rotor, is assuming 100 per cent efficiency

$$P = T\,u = -20{,}200\,(-16.9)$$

$$= 342{,}000\ \frac{\text{ft-lb}}{\text{sec}}\,.$$

The energy of rotation stored in the rotor, which is assumed to be rotating at 2190 rpm, is,

$$K.E._R = 8{,}450{,}000 \text{ ft-lb.}$$

Therefore, at the rate of power extraction during the initial part of flare-out (that is 342,000 ft-lb/sec) the rotor could continue rotating for 24.7 seconds. The time assumed for flare-out was 3 seconds so the application appears feasible.

CONCLUSIONS

A preliminary study of the application of a rotochute using a blade pitch change near impact has brought the following points to light:

1. Sufficient kinetic energy can be extracted from the potential energy of fall and stored in rotational inertia to produce a velocity decrement from 228 ft/sec down to 50 ft/sec.

2. Theoretical trajectories have been computed to determine the required rotochute performance to achieve 228 ft/sec before flare-out.

3. It does not appear that power applied to the rotor during flare-out will be necessary.

W. B. PEPPER - 5141

Case No. 669.02
January 31, 1957

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TABLE I

THEORETICAL ROTOCHUTE TRAJECTORY RESULTS FOR 11,000-POUND WEAPON RELEASED AT 40,000 FEET ALTITUDE

Trajectory	1	2	3	4	5	6	7	8	9	10	11	12
Rotochute drag curve used	(1)	(1)	(2)	(1)	(1)	(4)	(4)	(4)	(5)	(5)	(5)	(5)
Release Mach No.	.9	.6	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
Rotochute opening altitude (ft)	40,000	40,000	40,000	30,000	20,000	20,000	30,000	40,000	30,000	20,000	10,000	5,000
Velocity at 300 ft above ground (ft/sec)	480	482	382	481	484	302	245	239	219	223	360	600
Drop time (sec)	78.1	77.5	89.5	74.5	69	74	80.8	88.0	92.1	80.0	63.7	58.8
Angle from vertical at 300 ft above ground (degrees)	3.0	2.8	1.3	5.0	7.7	4.0	2.3	1.0	0.8	1.7	10.5	16.5
Horizontal range (ft)	24,400	17,400	20,600	32,800	39,200	34,800	31,500	22,700	30,700	34,000	36,200	36,800
Max. drag deceleration (g's)	1.2	1.2	1.15	1.47	2.36	2.67	1.54	1.43	2.1	3.42	4.94	5.5

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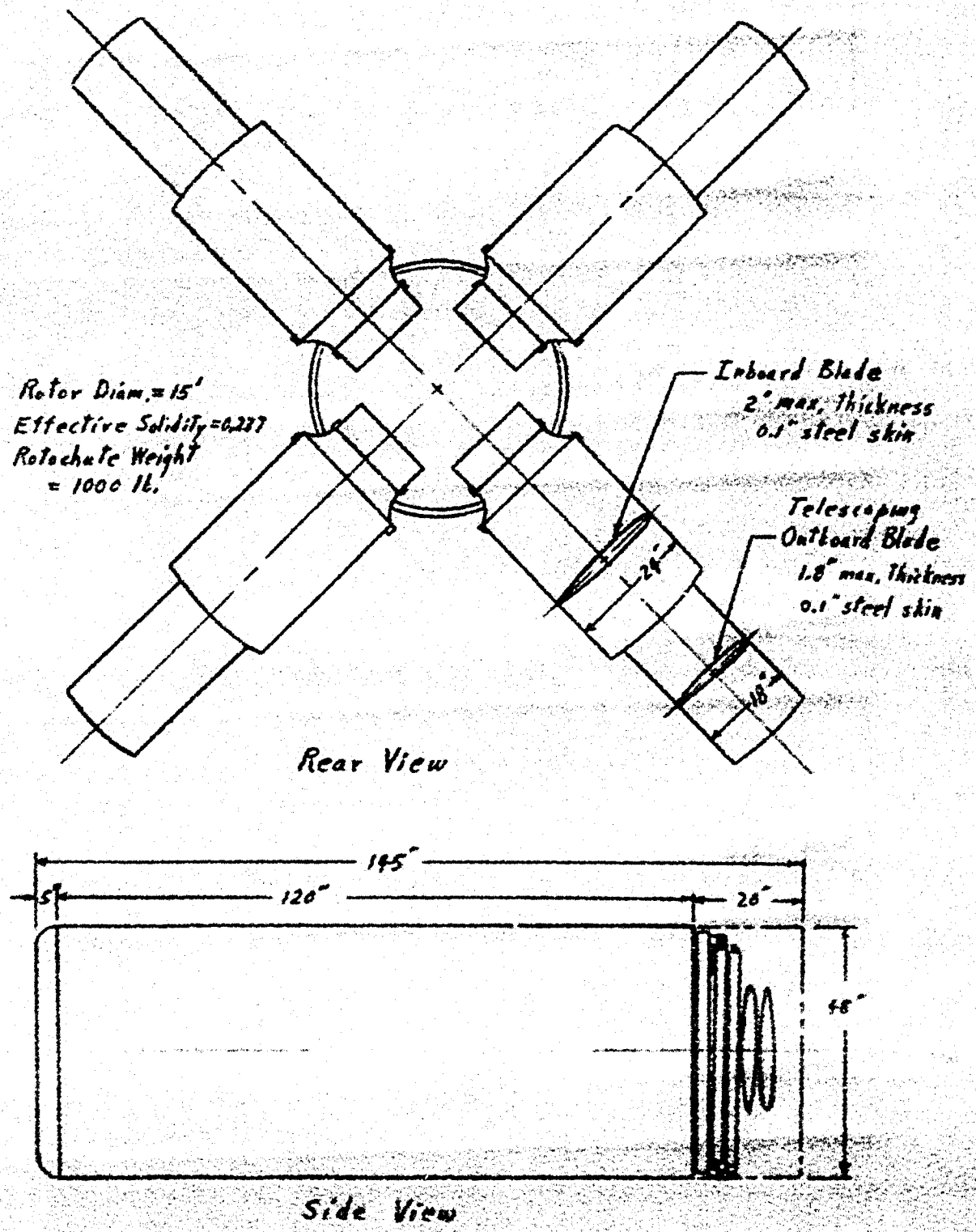

Figure-1. Rotochute for 10,000 lb. Vehicle.

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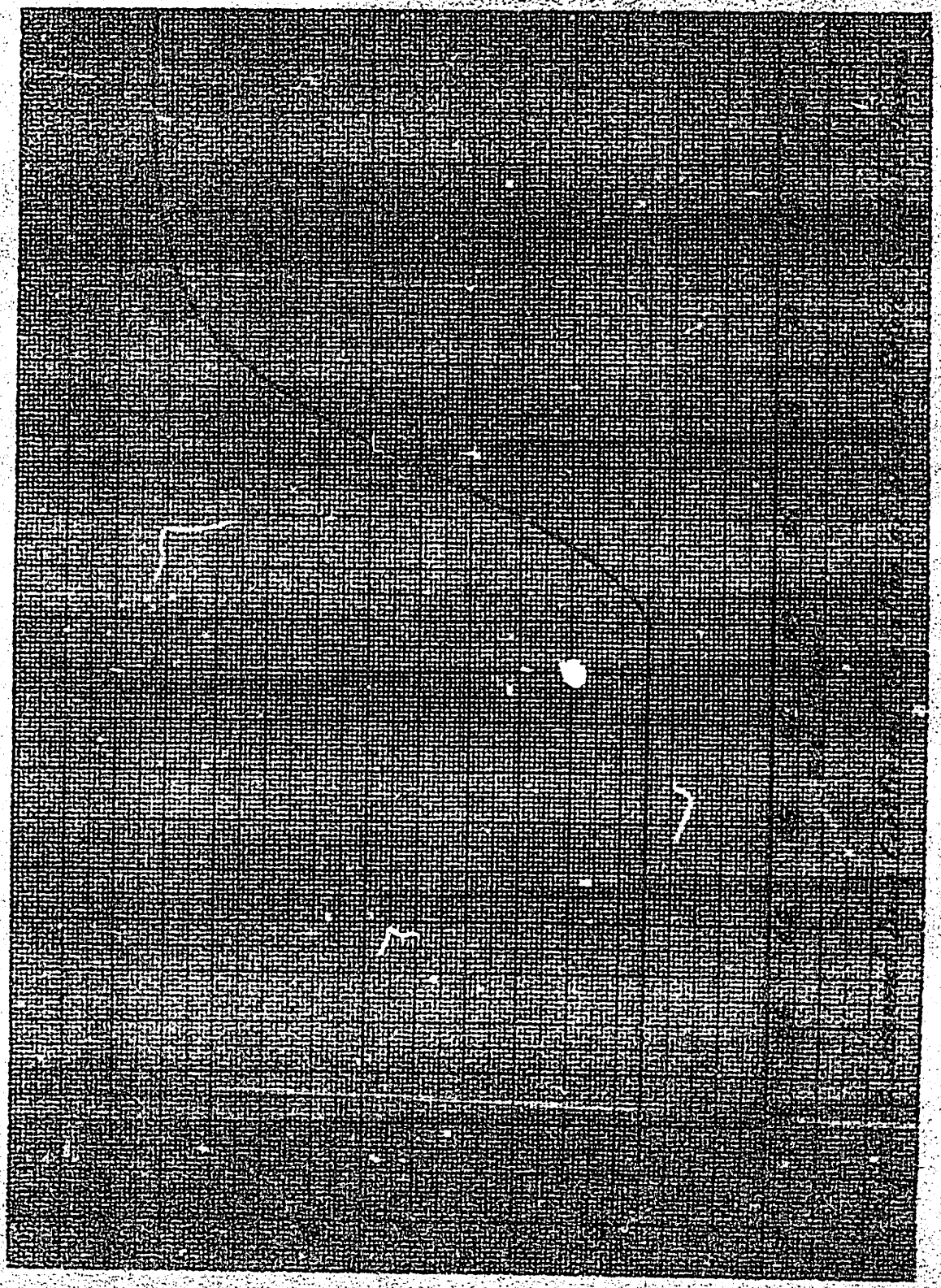

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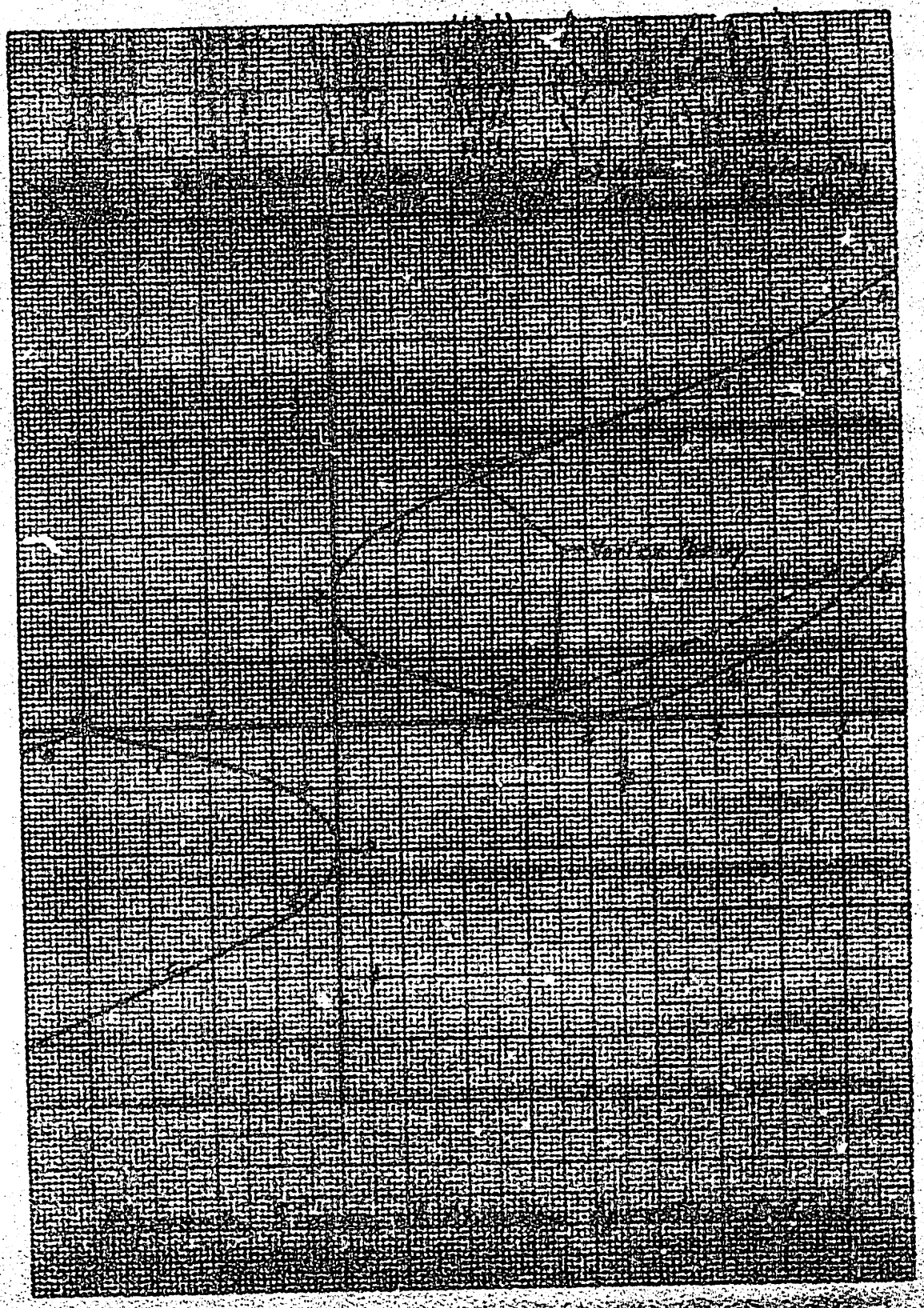
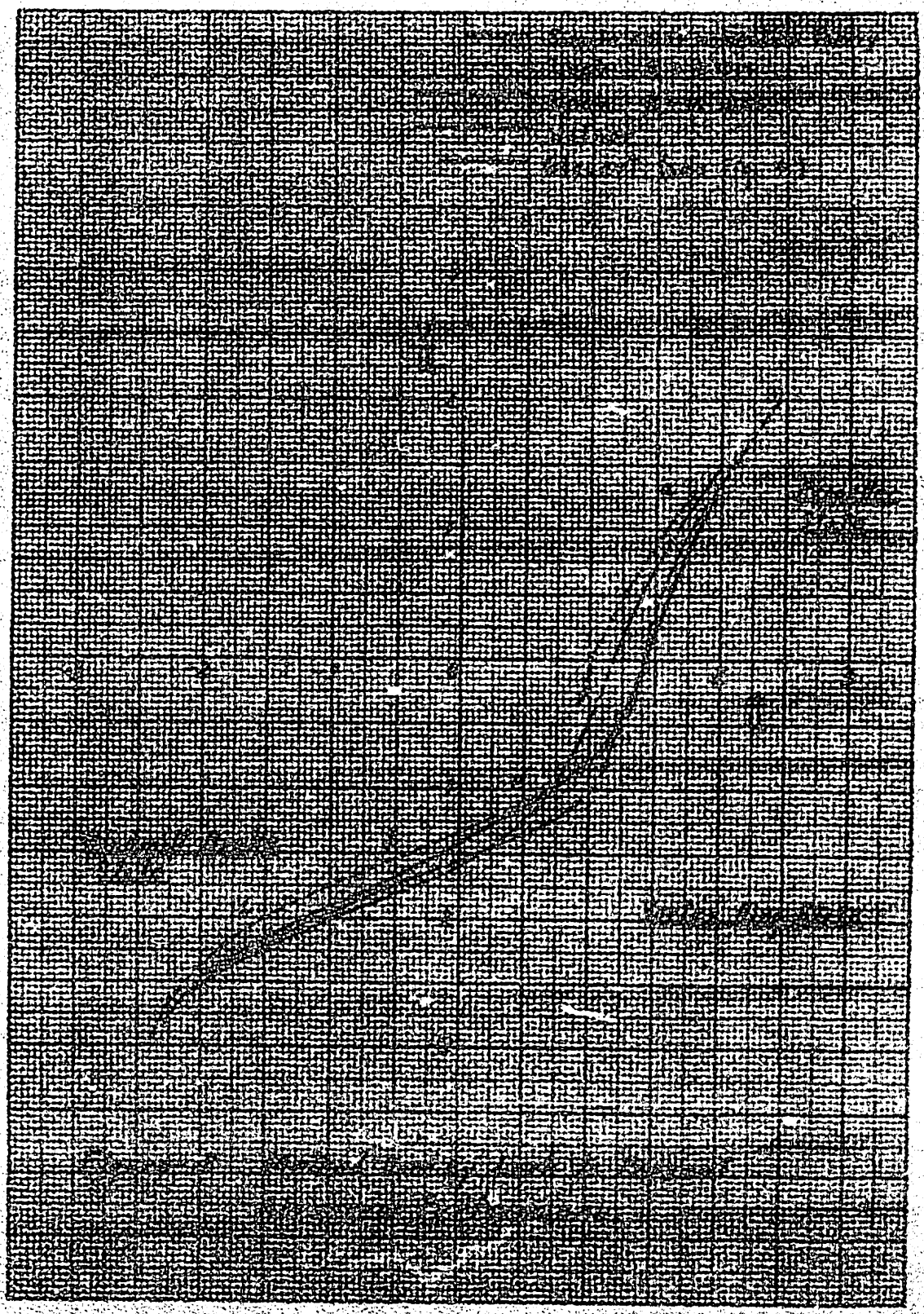
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