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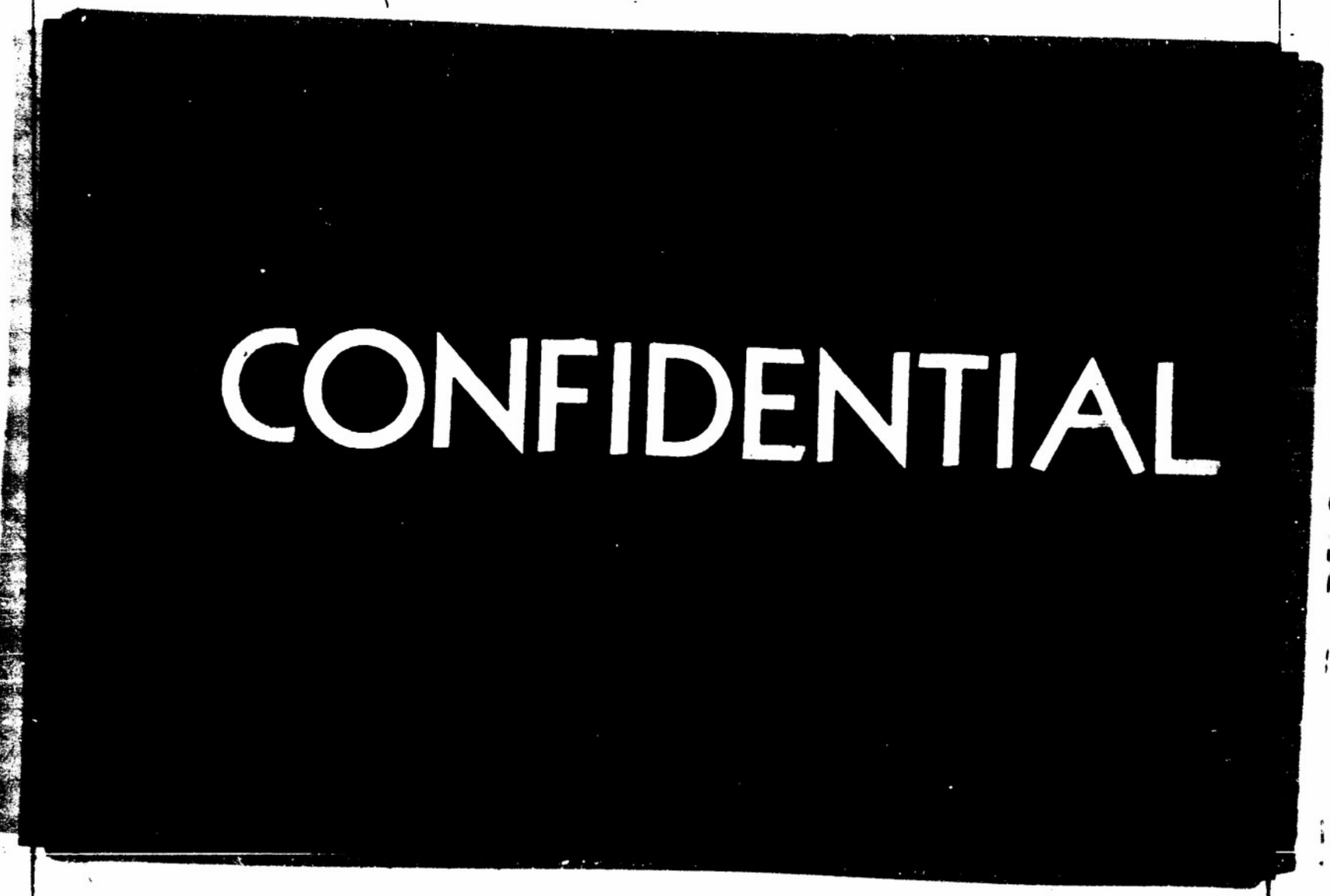
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Performance of a Rotary Wing Air Brake in Supersonic Flow

29301
(Item)

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R-58300

May '47 Confid U.S. Eng. 29 photos, diagrs, graphs

A one-fifth scale model of a "Retochute" rotary-wing air brake has been tested at M = 1.73 in a supersonic wind tunnel. The object of the test was to observe and measure the performance of a rotary wing air brake under supersonic flow conditions. The information obtained has been applied to calculate vertical trajectories of missiles equipped with such brakes when the descent is started at 100 miles and at 570 miles, respectively, above sea level. Tests indicate that the rotary wing air brake initiates and maintains its rotation at M = 1.73. Peak decelerations of 3.9 "g" and 40.0 "g" respectively are predicted and occur between 100,000 and 200,000 ft.

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Guided Missiles (1) Retorchutes (83282)
Auxiliary Equipment (7)

Air Documents Division, T-2
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ATI No. 29301

Report No. 55200

PROJECT HERMES

Subject

PERFORMANCE OF A ROTARY WING AIR BRAKE IN SUPERSONIC FLOW

BY

GENERAL ENGINEERING AND CONSULTING LABORATORY

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Report No. 55260

GENERAL ELECTRIC COMPANY

Schenectady, N. Y.

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Date May 18, 1947

Title PERFORMANCE OF A ROTARY WING AIR BRAKE IN SUPERSONIC FLOW.

By

General Engineering and Consulting Laboratory
(Department)

Schenectady, New York
(Location)

For PROJECT HERMES (TU1-200) Contract No. W-30-115 Ord 1768 Department U. S. Army Ordnance

Work directed by I. B. Benson

Tests made by V.J.Wattenberger, W.Curry, V.Corbo, General Electric Company R.Jackson, H.Gardinier, J.W.Kamper, J.Clark, H.N.Harmon of Consolidated Aircraft Corp.

Report prepared by I. B. Benson (Name, typewritten) I. B. Benson (Signature) 5-26-1948 (Date)

Report countersigned by J. K. Salisbury (Name, typewritten) J. K. Salisbury (Signature) 5-26-1948 (Date)

This report includes 16 pages, ... charts, ... curves, ... drawings 9 diagrams, ... oscillograms, and 3 photographs; whose serial numbers are:

Diagram Nos. P-9611214 - P-9611215 and K-9102723 thru K-9102729

Photograph Nos. Photographs from Consolidated Vultee Aircraft Corp. not General Electric Company files.

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They were subdivided into two programs, depending on the degree of luck to be encountered: Program Minimum was to be merely an observation of whether or not the rotor will begin to revolve, fan out and sustain its autorotation at M = 1.73. Program Maximum would add to this the measurements of drag, rotor rpm, coning angle, air conditions at the throat and other quantities necessary for the calculation of C_D.

Results exceeded our expectations. Not only were both programs fulfilled, but additional runs and measurements were made at Mach = 0.13 and 0.38. This permitted the calibration of the rotor, which afforded a tie-in with the subsonic data obtained previously by other methods (see Chap. 6.41 in G.E. T.R. 55230 (Reference 14).

APPARATUS

The test setup included (1) the model, (2) a pneumatic thrust measuring system (3) Strobotac and Audio Signal Generator for RPM measurements, (4) motion picture cameras and miscellaneous accessories.

The model, shown in Figures 1 and 5 consisted of a three bladed head assembly, rotating freely on a thrust strut. The blades were free to flap, but were tied together to maintain equal flapping angles. A conical cast-iron skirt was provided on the aft portion of the revolving head, as a brake, to prevent its rotation when desired. To release the brake it was necessary to inflate the internal thrust bellows, thereby disengaging the two conical surfaces. A vacuum pump was connected to the bellows to engage the brake at low speeds, while at high air speeds enough drag was produced by the head to keep the brake engaged.

The "pneumatic thrust measuring system" utilized the bellows described above to oppose the drag force of the rotor. To measure the rotor drag, the bellows was inflated by a controlled nitrogen pressure until it engaged an electrical contact, thereby lighting a pilot light, as shown in Figure 4. Readings of the pressure regulating valve were previously calibrated against the actual axial force on the bellows.

The Strobotac was used to measure rotor RPM at low air speeds. At high speeds an audio oscillator had to be used; its frequency was matched with that of the rotor pitch and divided by 3 to yield actual rotor speed, since there were 3 blades.

TEST PROCEDURE

Test procedure of a single run consisted of the following sequence:

1. The model was installed in the tunnel on the mounting strut; electrical and pneumatic lines were checked for proper functioning.

2. With nitrogen valve closed and vacuum pump turned on, the tunnel was started and brought to the desired speed.

3. Vacuum pump was shut off; nitrogen valve was quickly opened until the pilot light indicated equilibrium between thrust and drag. Regulator pressure reading was then recorded.

4. Rotor RPM was measured and recorded.

5. Motion picture camera made visual records of the tests, No Schlieren photographs were taken. The model was installed outside and downstream of the optical field of the Schlieren apparatus to minimize possible damage to the tunnel in the event of centrifugal failure of the rotor.

   Three runs were made.

TEST NOTES AND COMMENTS

A complete account of the sequence of events during the tests is recorded in the author's Laboratory Notebook, No. 50831, pp. 46-50. It can be summarized as follows:

Practice runs were made at M = 0.13 and 0.38 chiefly to train the test personnel in operating the apparatus and taking the measurements.

Finally, full flow was turned on. Two motion picture cameras were positioned to record the passage of the normal shock, which is usually accompanied by a severe shaking of the model. Rotation of the rotor head was prevented by engaging the brake band; the blades remained free to flap about their flap hinges. Fortunately, normal shock passed very smoothly, the blades never even having left their droop stops. Only one camera recorded this event.

As the flow reached full M = 1.73, the brake band was gradually released by applying nitrogen pressure to the thrust bellows. The blades began to revolve instantly, fanning out to full disc diameter within about 1 second after the brake was released. Some rubbing nevertheless persisted in the brake, as the cast-iron band soon was seen to become red hot. Ultimately it must have melted off, judging by the sudden increase of the rotor rpm and by the disappearance of the red glow in the brake region. These events were very well recorded on the motion picture film. Meanwhile, rotor thrust was measured by increasing nitrogen pressure in the bellows until the latter engaged the front pilot light contact. Pressure in the bellows indicated 75 p.s.i. From the bellows calibration curve thrust was determined to be 47.0 lbs. The rotor was whining with a loud pitch tone, which was later matched by an audio oscillator, measuring 710 cycles per second. This corresponded to 14,200 rpm (the conversion factor is 20, not 60, because there are 3 blades).

Temperature failure of the rotor bearing, which indeed was imminent, terminated this test after about 2 minutes of operation at full flow. The model broke off from its support and disappeared in the diffuser section. Unfortunately, neither camera was operating at that moment. When the tunnel was shut down and broken pieces were recovered, the occurence of intense heat in the main bearing was clearly evidenced by the deep blue color of the races, as well as by

distorted shapes of the balls. The brake band, with its friction surfaces molten away, confirmed the inferences made about the brake heating during the test.

Nevertheless, the test was considered a success, inasmuch as all the contemplated measurements were duly made and recorded. The rotor withstood an equivalent loading of "52 g", which was far above the maximum loading computed for the normal descent from 100 miles (see Table II). Some pitting was observed on the upper blade surfaces, probably caused by collision with solid particles or ice. Stagnation temperature rise did not produce any visible marks on the blade surfaces.

THEORY

Subsonic theory of operation of a rotochute rotor in vertical descent was satisfactorily worked out, and it is reported on pp. 14-18 of the Reference 14. It was difficult, if not impossible, to extend this theory to supersonic conditions, since both C_L and C_D of the blade vary spanwise within wide limits due to large velocity gradients. Moreover, the effective airfoil chord and its angle of attack also vary considerably with the coning angle.

No attempt therefore was made here to reconcile the experiment with the theory now held valid for the subsonic operation. As a matter of first order approximation, it was assumed that the high C_D at $M = 1.0$ at the blade tips in supersonic flow would hold down rotor rpm and thus would not permit the centrifugal force to expand the coning angle beyond the Mach cone. Mach cone angle μ is of course, related to Mach number, M by the relation:

$$\frac{1}{M} = \text{Sin}^{-1} \mu$$

Substituting 1.73 for M, we find:

$$\mu = 35.3^{\circ}$$

Inasmuch as within this cone the blades would operate entirely in the subsonic regime, it was not unreasonable to assume a normal subsonic inflow velocity pattern and to use a subsonic C_D determined previously in Reference 14 and shown in Figure 6.

The latter, of course, is referred to the actual projected disc area.

Thus, estimated rotor drag under wind tunnel conditions would be:

$$D_r = C_{D_r} A \rho \frac{V^2}{2}$$

Where

C_{Dr} = rotor drag coefficient (as defined hereby)

A = projected disc area sq. ft.

ρ = tunnel air density, slugs per cu. ft.

V = axial velocity, ft. per sec.

The magnitude of the Drag Coefficient depends upon the blade pitch angle as seen in Figure 6.

Bearing in mind that the "delta-three" hinge shown in Figure 9 reduces the effective blade pitch as the blades flap toward the axis, it may seem that at 35.3° the effective pitch angle is -4.8. From Figure 6, C_D is found to be 0.25.

The projected disc area at 35.3° cone half-angle is:

$$A = A_o \text{ Sin}^2$$

$$= \frac{\pi \times 13.422^2}{4} \text{ Sin}^2 35.3^\circ$$

$$= 0.330 \text{ sq. ft.}$$

Tunnel air density was 1.03×10^{-3} slugs per cu. ft. and V at M = 1.0 was 964 ft. per second. Thus,

$$D = 0.25 \times 0.330 \times 1.03 \times 10^{-3} \times \frac{964^2}{2}$$

$$= 39.4 \text{ lbs.}$$

Additional drag is produced by the body of the retriever model itself. References 18 and 19 furnished the figure of 0.50 for C_D for geometric bodies closely approximating that of the rotochute model. With that, the body drag was calculated to be 6.1 lbs. Thus total tentative drag figure used in preliminary calculations was:

Total D = 45.5 lbs.

Needless to say, these were only rough figures, used mostly for proportioning and stress analysis of the test equipment.

Nevertheless, in light of the actual measured figure of thrust of 47.0 lbs., we feel that the above approximations served the useful purpose in determining at least the correct order of magnitude of the thrust.

The surprising circumstance, which still remains to be analyzed quantitatively, is the fact that the blades opened beyond the Mach cone and maintained nearly 80° angle with the axis of rotation. A velocity vector diagram constructed for this coning angle in Figure 10 shows that if there were no shock formation, the resultant velocity at the blade tip would form an angle of incidence of 62° with the blade airfoil. This angle further increases nearer the rotor hub. While the airfoil would not be stalled in the true sense of the word, still it appears hardly conceivable that the large drag exerted on the airfoil at such angle could be balanced out by only 1° negative pitch, i. e. that the resultant force vector would be axial, without any tangential component tending to retard the rotation. A possible explanation may lie in the formation of revolving detached bow shocks just ahead of the blades, which permitted them to operate in fully or partly subsonic mode. Much more analytical effort than has yet been attempted here would be required to work out a rigorous theory for this condition.

EVALUATION OF C_D: FROM TEST RESULTS

The drag coefficient is readily calculated from:

$$C_{Dr} = \frac{D_r}{A} \left(\frac{1}{\rho V^2} \right)$$

Where: D_r = rotor drag, lbs.

A = projected disc area, sq. ft.

ρ = air density, slugs per cu. ft.

V = axial velocity, ft. per sec.

All quantities in the right hand side of the equation were observed and measured during the tests.

Table I shows the values of C_{Dr} as well as of the other pertinent quantities measured in the wind tunnel.

TABLE I

WIND TUNNEL TEST RESULTS

AIR VELOCITY	AIR DENSITY	AIR TEMP.	ROTOR SPEED	ROTOR DRAG	C_D	DISC LOADING	ACCEL.
ft/sec.	sl/ft^3	deg.R	RPM	lbs.	--	lbs/ft^2	"g"
150	2.30×10^{-3}	540	650	2.5	0.10	2.55	2.8
430	2.14×10^{-3}	550	1800	21.9	0.11	22.4	24.2
1672	1.03×10^{-3}	378	14200	47.0	0.03	48.0	52.0

The right-hand column of Table I reveals the severe punishment the model had to withstand during the tests. While the normal disc loading of a rotochute brake is 0.93 lbs. per sq. ft., this wind-tunnel test imposed as much as 48.0, owing mostly to a relatively high air density in the tunnel. As it will be shown later, when descending from 100 miles in rarefied atmosphere, only 3.9 "g" deceleration is expected to occur, although the missile would reach Mach number of nearly 4.

Two corrections were applied to the values of C_D to bring them in line with those measured previously on full size rotors as shown in Figure 6. The latter were confirmed by the actual drop tests and were considered reliable.

First, for reasons of simplicity and strength in the model, the automatic pitch control was left out in the supersonic model. Therefore the blades operated with a pitch considerably below the optimum value of 1.2 degrees. The wind tunnel model had 0° pitch at 0° coning angle, by design. Taking into account 8° delta-three angle and about 10° coning angle during the test, actual blade pitch was:

$$0^\circ - (8 \frac{10}{90}) = -0.9^\circ$$

From Figure 6, it may be seen that at that pitch angle C_D was only 0.75. Therefore, with the proper adjustment of pitch, a full scale model would have a C_D:

$$\frac{C_D \quad 1.2}{C_D - 0.9} \times C_{D_r} = \frac{1.6}{0.75} \times .0332 = 0.071$$

The second correction was made to account for the scale effects, wall effects, Reynolds Number, variations of the blade planform, solidity, surface roughness, etc. Since no instrumentation was on hand to measure these effects individually, it would be quite impossible to account for them properly had it not been for the subsonic runs in the tunnel. Although admittedly not too accurate, they nevertheless furnished the necessary order of magnitude of the subsonic C_{D_r} of the model, which then served as a best available beachmark to make a lump adjustment for the above effects between the model and the full scale rotor. Since the coning angle in both subsonic runs was again nearly 10°, the tie-in was made again at -0.9^o pitch angle. Therefore, the correction factor becomes:

$$\frac{(C_D)_{fs}}{(C_D)_m} = \frac{0.75}{0.105}$$

where subscripts "fs" and "m" signify "full scale" and "model" respectively.

Thus, the final figure of the supersonic C_{D_r} for the full scale rotor is obtained:

$$(C_D)_{fs} = \frac{0.75}{0.105} \times 0.071$$

$$= 0.507 \quad \text{(at M 1.73)}$$

HIGH ALTITUDE TRAJECTORIES

Braking trajectories were calculated for full size rotochutes, weighing 32 lbs (hence m = 1.0 slug). Initial altitudes presently reached by V-2 rockets were taken as starting points, as well as still higher altitudes contemplated for two-stage firings, as in the "Bumper" project. The fundamental equation of motion of free fall descents formed the basic trajectory relation:

$$\frac{d^2h}{dt^2} = \left[g - \frac{C_D A}{2m} \sigma \rho_o \left(\frac{dh}{dt}\right)^2 \right] dt$$

where h = altitude, ft.

g = acceleration of gravity, 32 ft per sec^2 .

C_D = drag coefficient.

A = disc area, sq. ft.

m = mass of the missile, slugs.

ρ_o = air density at sea level, 2.39×10^{-3} slugs per cu. ft.

σ = density ratio at altitude h.

t = time, sec.

A fully analytical solution of this equation appeared to be too laborious, so a step-by-step intergration was resorted to with some minor simplifications. Rewriting this equation for finite increments, it becomes:

$$\Delta V = \left[g - \frac{(C_D A \rho_o)}{(2m)} \sigma V^2 \right] \Delta t$$

supplemented with: $\Delta h = (V + \Delta V)\ \Delta t$

where $V_o = 0$ at $t = 0$

The variation of the density ratio with altitude was rationalized with approximate relations, after Prof. Gutenberg (Reference 16):

$$\sigma = \ell^{-4.20 \times 10^{-5} h} \quad \text{- for } 0 < h < 1.6 \times 10^5$$

$$\sigma = 0.153 \ell^{-3.07 \times 10^{-5} h} \quad \text{- for } 1.6 \times 10^5 < h < 3 \times 10^6$$

Also, C_D was no longer constant, but was assumed to maintain the values:

$C_D = 0.51$ for $1.0 < M < 5.0$

$C_D = 1.6$ for $0 < M < 1.0$

The time intervals were judiciously varied from 100 seconds, when the fall was essentially in vacuum, to 1 second, when the decelerations obtained were the greatest.

The trajectories were plotted in Figures 7 and 8. Once a steady-state descent has been established at about 100,000 feet, the equation of motion may be solved analytically, since it is then in the general form:

$$\frac{d\,h}{d\,t} \cdot e^{(k\,h/2)} = K^{\frac{1}{2}}$$

then

$$\int_{h_1}^{o} e^{k\,h/2}\,dh = \int_{o}^{t} K^{\frac{1}{2}}\,dt$$

and

$$t = \frac{2}{KM^{\frac{1}{2}}}\,(1 - 2^{kh_1})$$

where $h_1 = 10^5$ and K and M are derived constants of the equation.

No specific skin temperature calculations were made to accompany these trajectories, for it appeared from the comparison with data in previously published reports (References 7, 15, and 17), that with proper design precautions, blade skin temperature would never reach the destructive range. In particular, a step-by-step calculation of skin temperatures for descents from 3×10^6 feet was carried out in Reference 15. It is directly applicable to our analysis of the 3×10^6 ft. trajectory, which is worse of the two cases; using a method of simple interpolation, the maximum theoretical skin temperature predicted by Reference 15 is computed to be 900°F occuring at 427 seconds after the release.

It should be noted that the "braking constant" of the rotochute is:

$$\frac{C_D A}{W} = 0.65 \text{ supersonically and}$$
$$= 1.7 \text{ subsonically.}$$

The most effective brake analyzed in Reference 15 had a braking constant of only 0.12; (corresponding to $C_D A = 35$ ft^2. and $W = 290$ lbs.) the brake was assumed to have 0.060" thick J-1 magnesium alloy skin. Rotochute blades are normally covered with 0.050" thick "Fiberglas" glass cloth, molded to the porous core with the "Permafil" binder. The stress carrying steel spar is in the center of the cellular core. Since the temperature rise and decline last only 30 seconds, it is quite improbable that the spars could be destructively affected.

These were the reasons why no special calculations of skin temperatures were undertaken in this analysis.

Essential quantities of the rotochute braking trajectories are tabulated in Table II.

TABLE II

BRAKING TRAJECTORY DATA

Descent From	Time to Descend	Maximum Velocity	Maximum Deceleration	Maximum Skin Temperature	Altitude at Max. Velocity	Altitude at Maximum Deceleration	Gliding Radius
ft.	sec.	ft/sec.	"g"	deg R	ft.	ft.	Miles
3×10^6	2300	13,116	40	900°*	300,000	165,000	50
0.5×10^6	1990	3,680	3.9	---	200,000	160,000	50

Note * From Reference 15.

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With an angle of glide of about 15°, the rotochute may reach any point on the ground within 72 miles radius, in calm air. Optimum forward indicated air speed to maintain this angle of glide is 45 mph. However, greater forward velocities may be obtained at the expense of increased sinking speeds. To account for that, a safe figure of 50 miles for "radius of action" was chosen. With the pitch governor in operation the rotochute lands with a terminal sinking speed of 22 feet per second at sea level; the final impact is largely absorbed when the pointed nose enters the ground.

CONCLUSION

This is the last in the series of reports devoted to the rotary wing brake, developed by the Laboratory under the Contract W-30-115 Ord-1768. It is earnestly hoped that this device will prove its usefulness to the guided-missile programs, wherever successful recovery techniques may reduce the costs, or speed up to the pace of missile developments.

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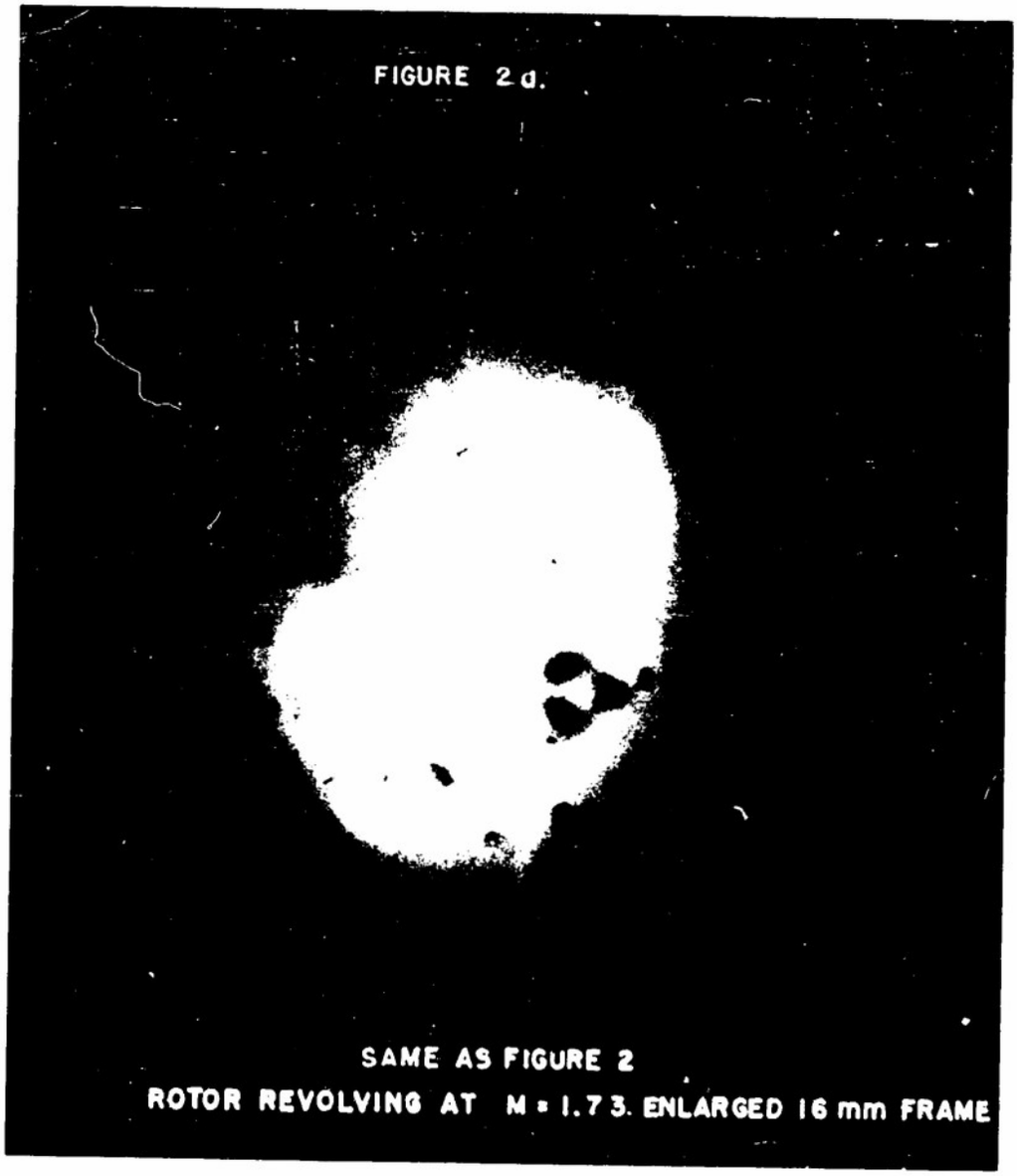
* By mistake "Project Meteor" was cited instead of "Project Hermes" on the original title page of this report.

FIG. 1 ROTOCHUTE MODEL IN THE TEST SECTION OF LONE STAR WIND TUNNEL

FIG. 2 SUPERSONIC MODEL MOUNTED IN THE WIND TUNNEL THROAT AT LONE STAR LABORATORY

FIGURE 2d.



SAME AS FIGURE 2
ROTOR REVOLVING AT M = 1.73. ENLARGED 16 mm FRAME

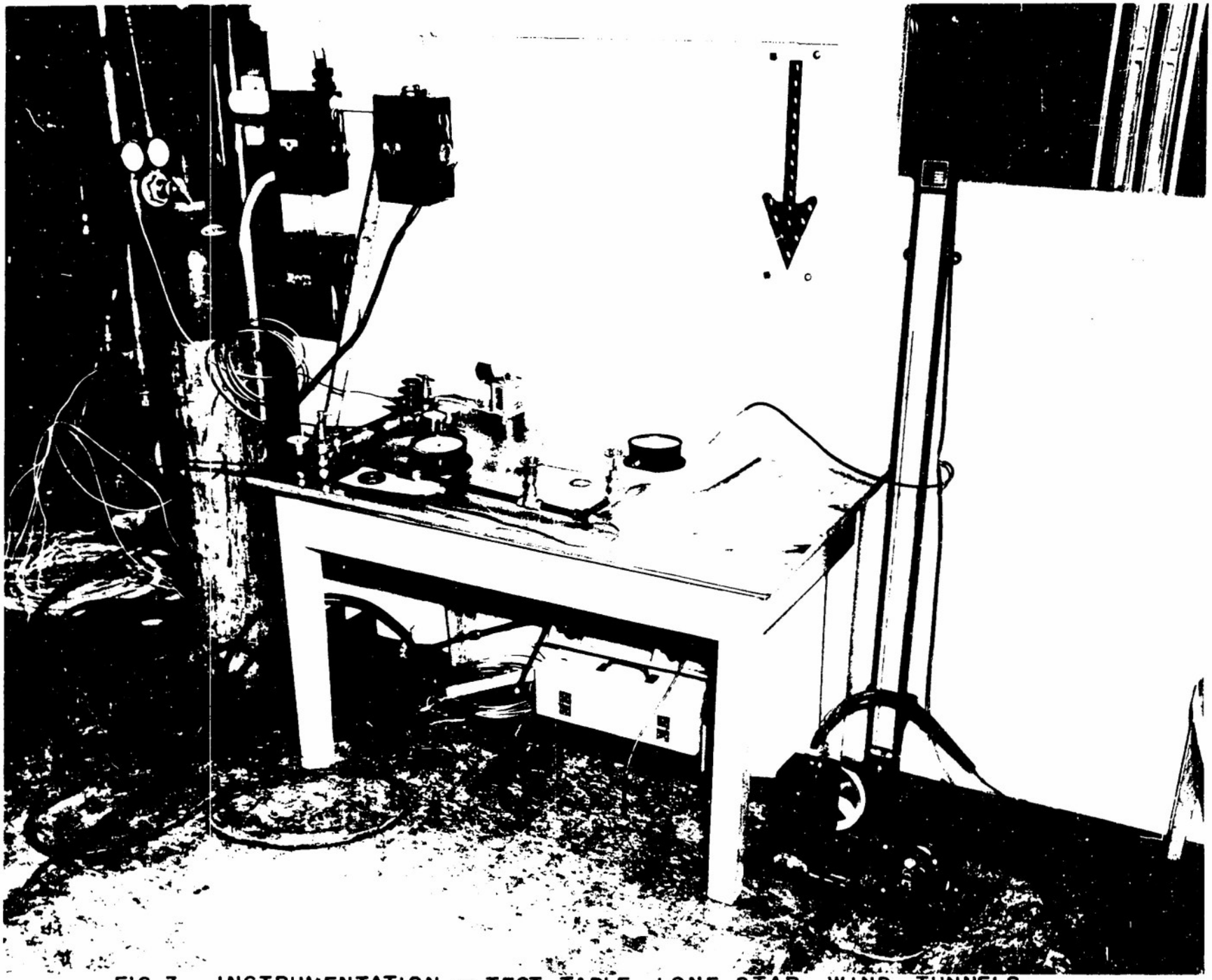


FIG. 3 INSTRUMENTATION — TEST TABLE. LONE STAR WIND TUNNELS

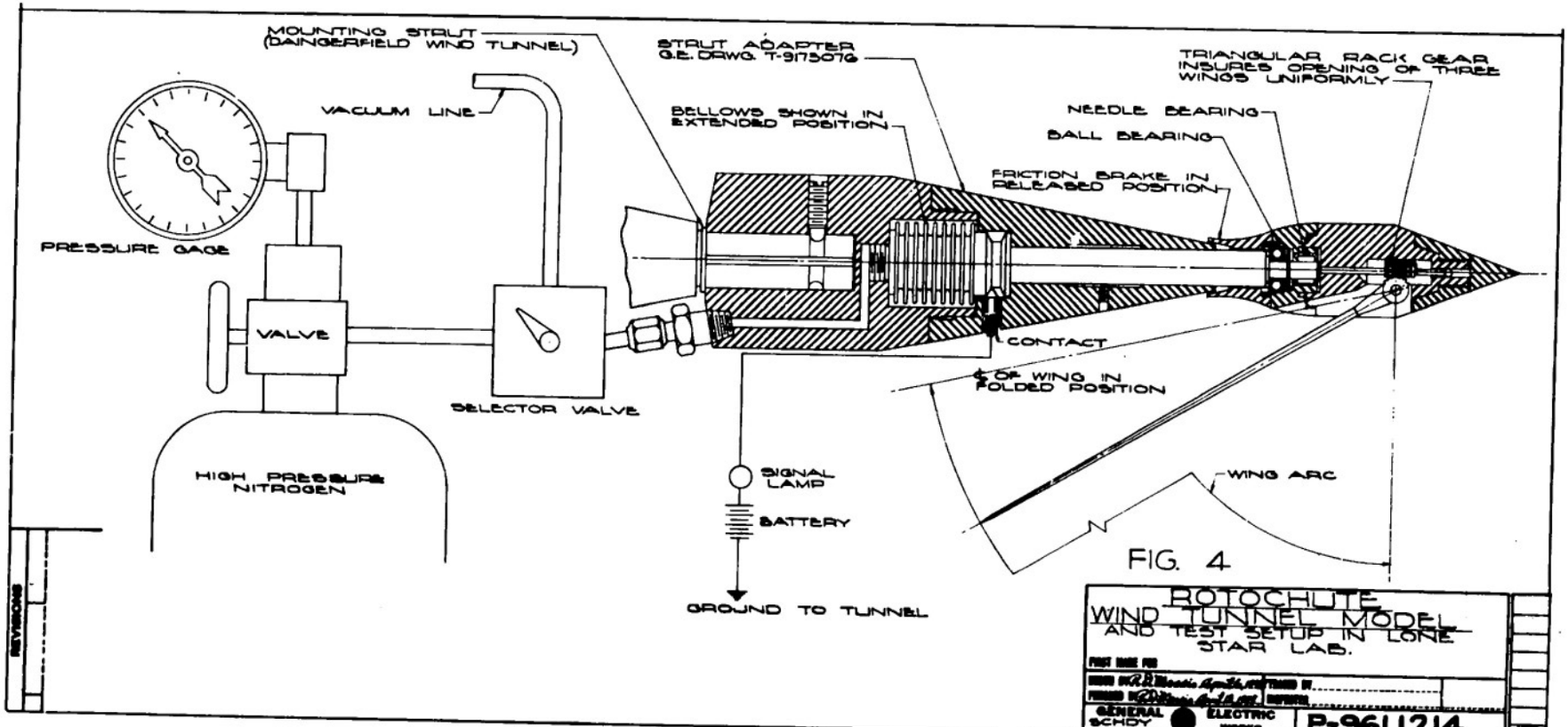


FIG. 4

ROTOCHUTE WIND TUNNEL MODEL AND TEST SETUP IN LONE STAR LAB.

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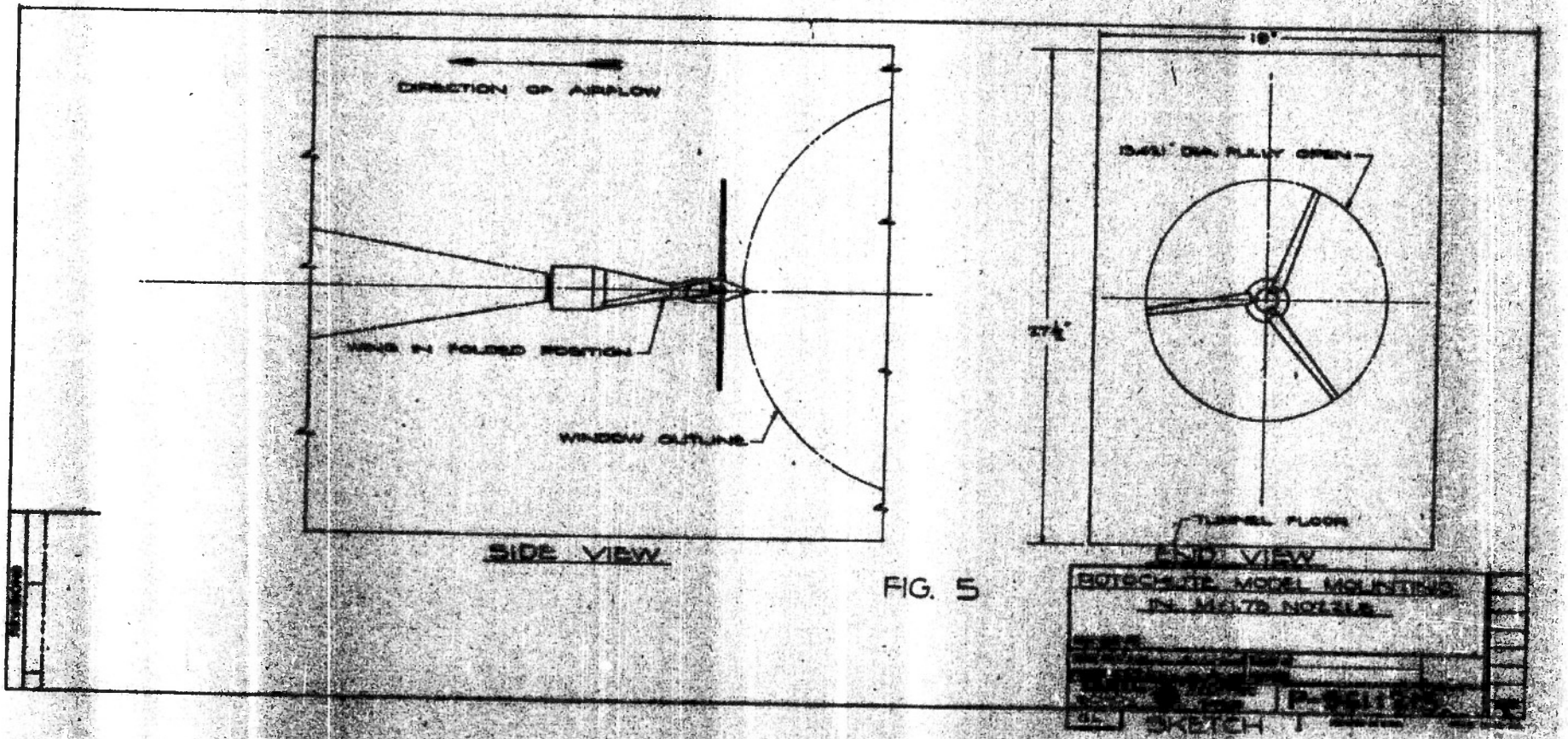
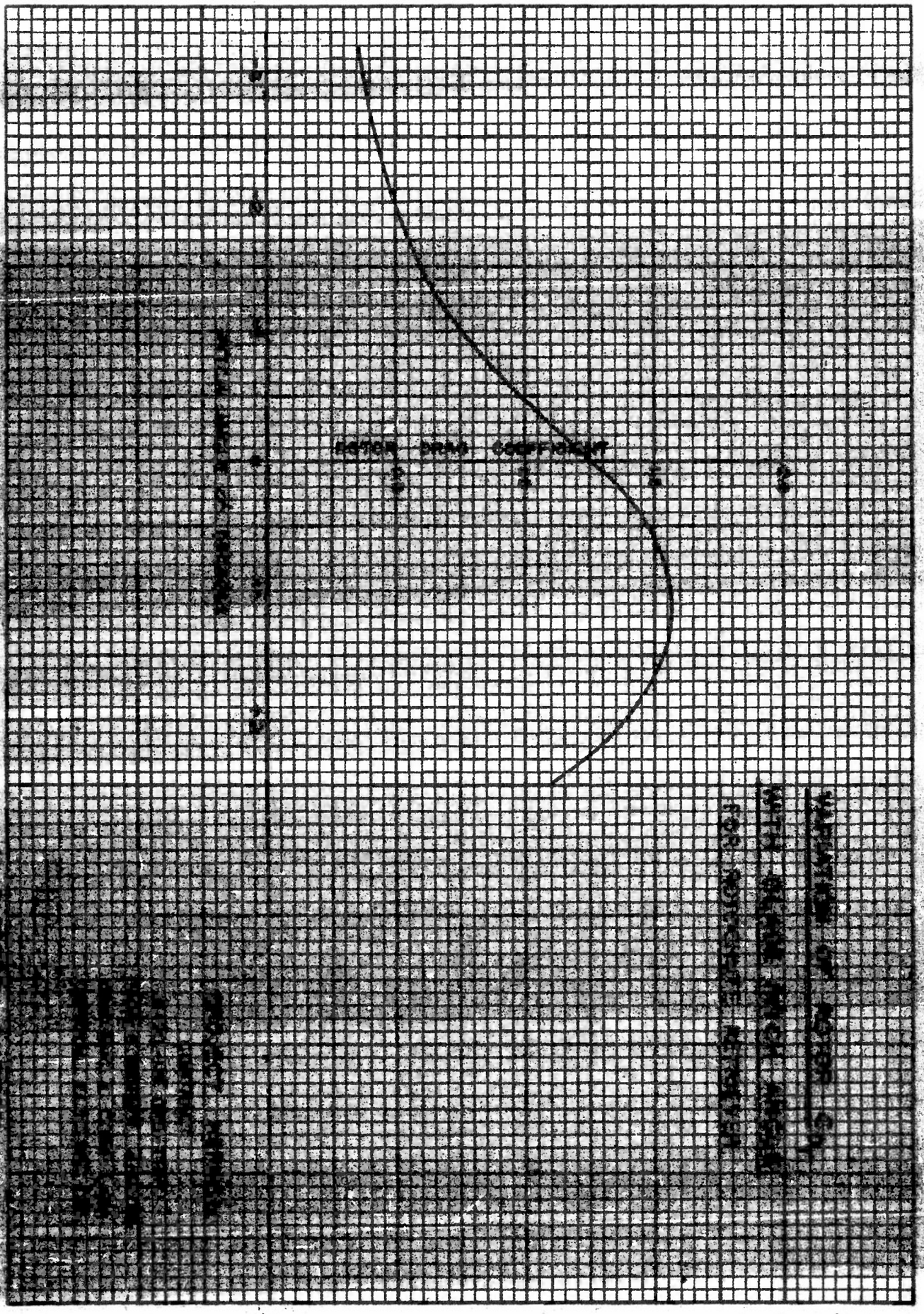

DIRECTION OF AIRFLOW
WING IN FOLDED POSITION
WINDOW OUTLINE
SIDE VIEW
10"
END VIEW

FIG. 5



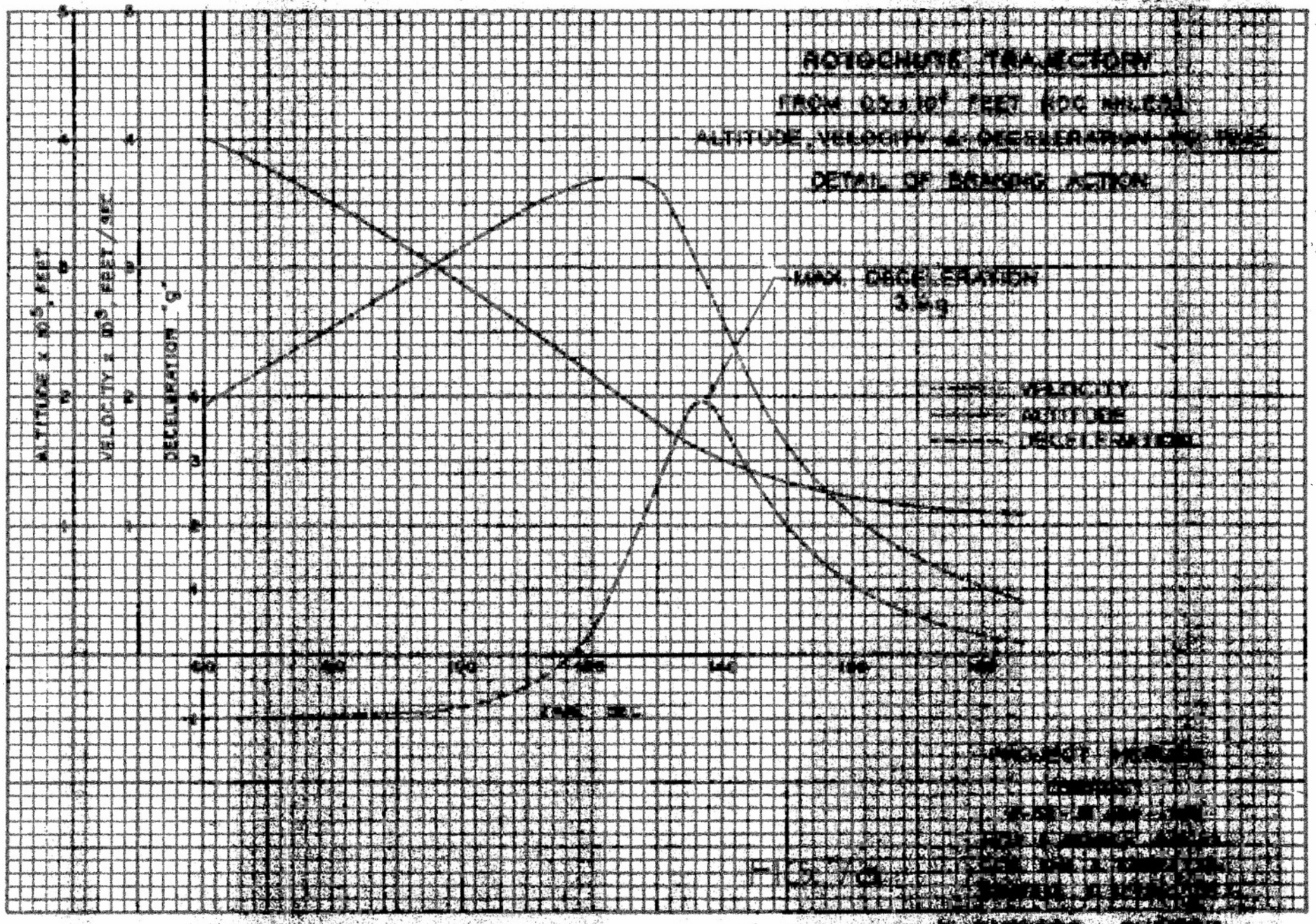
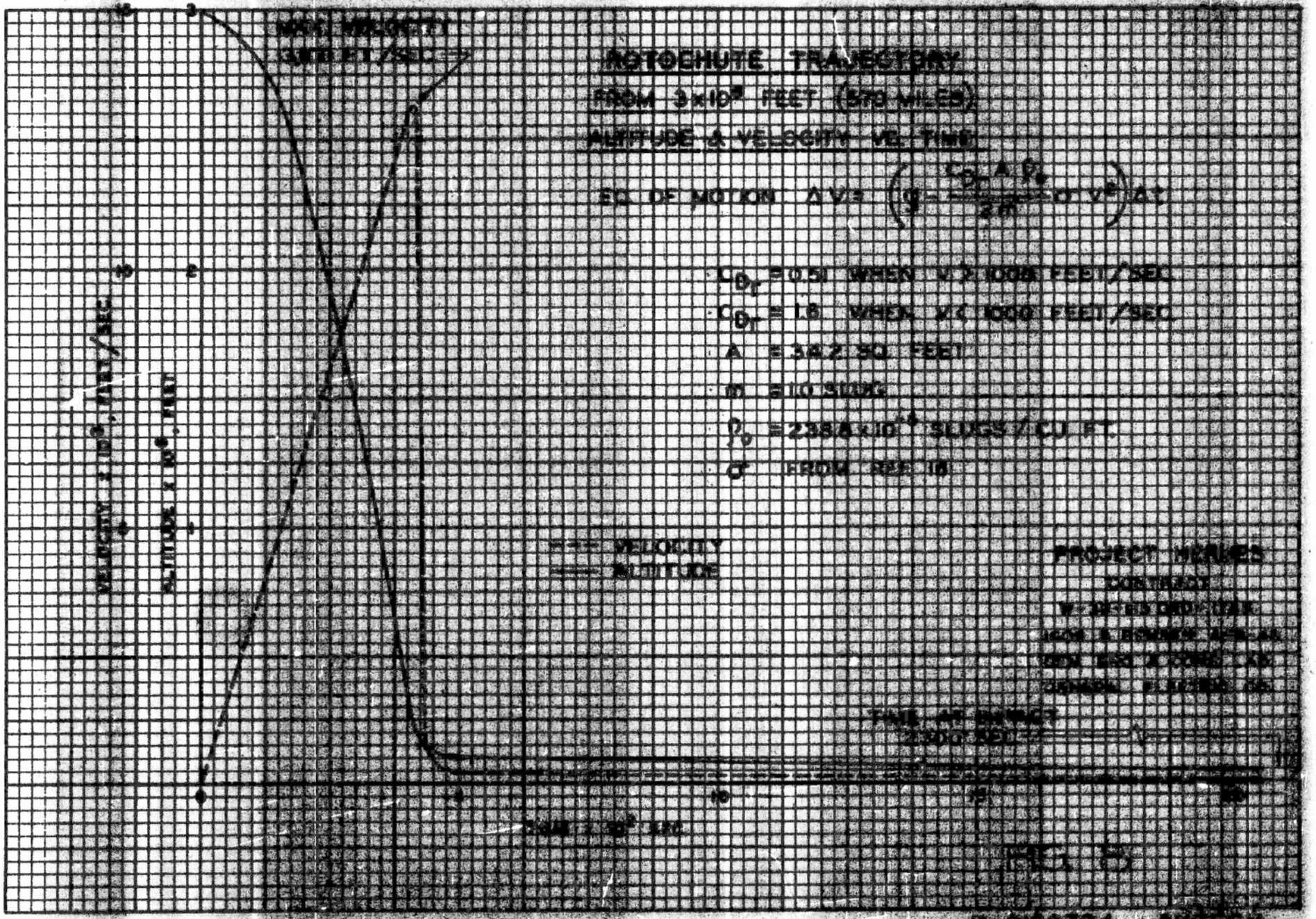
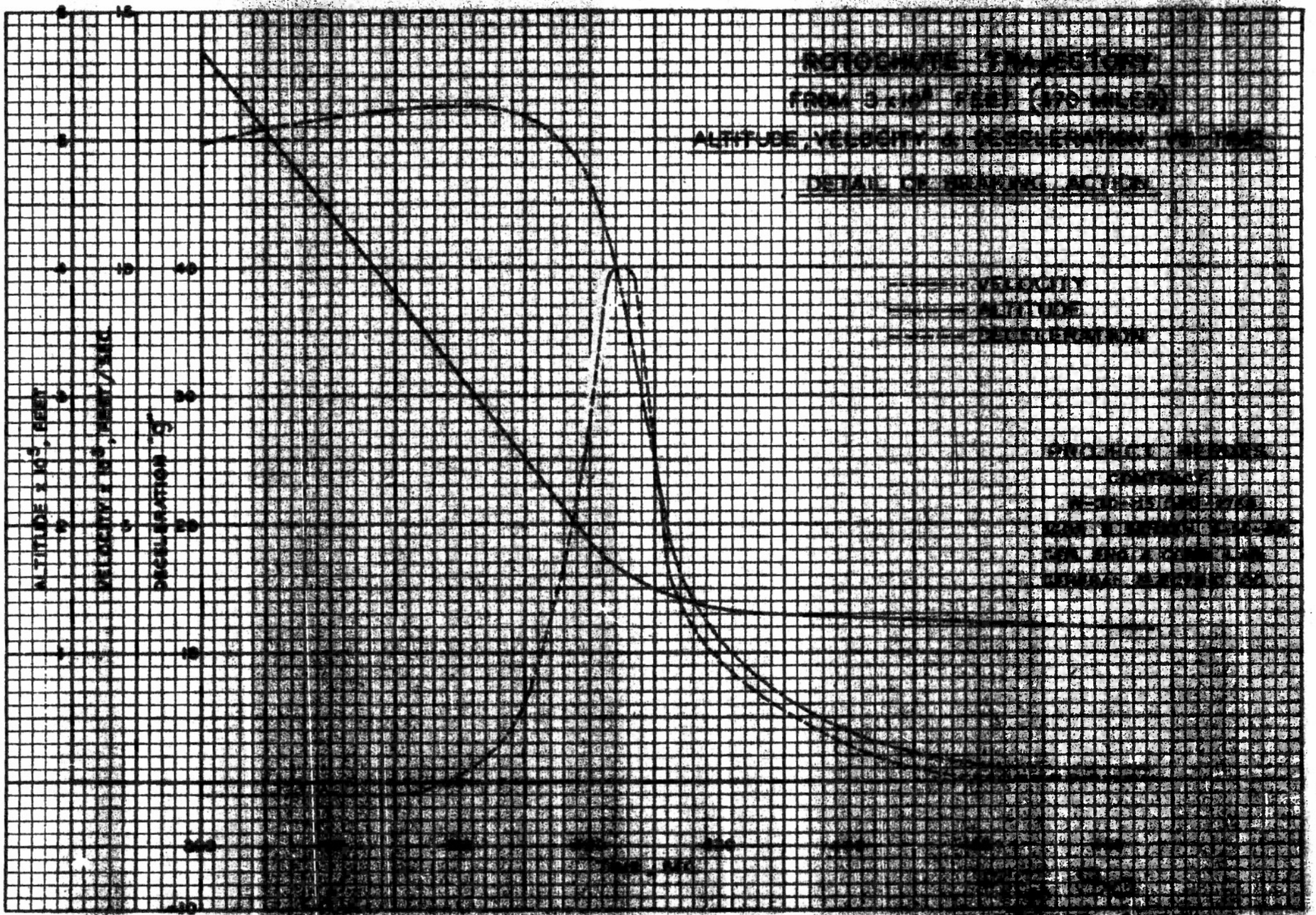

ROTOCHUTE TRAJECTORY
DETAIL OF BRAKING ACTION
MAX. DECELERATION
VELOCITY
ALTITUDE
DECELERATION
ALTITUDE x 10^3, FEET
VELOCITY x 10^3, FEET/SEC
DECELERATION "g"
TIME, SEC.

FIG. 7a

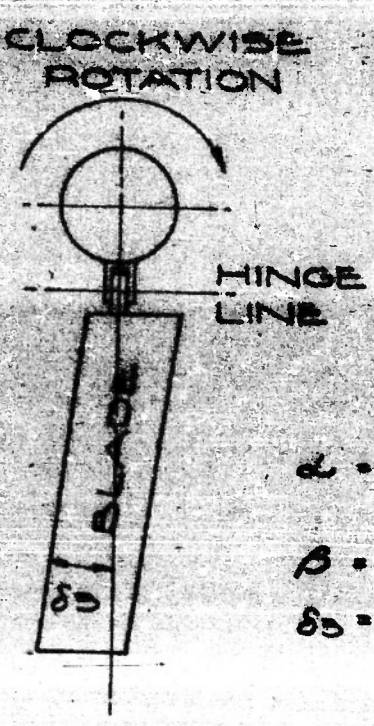
R-55260


MAX. VELOCITY
3,970 FT./SEC.
ALTITUDE & VELOCITY VS. TIME
FROM 3×10⁵ FEET (378 MILES)
EQ. OF MOTION
C_{D_f} = 0.51 WHEN V ≥ 1000 FEET/SEC
C_{D_f} = 1.8 WHEN V < 1000 FEET/SEC
A = 342 SQ. FEET
m = 110 SLUGS
ρ_0 = 2.378 × 10⁻³ SLUGS / CU. FT.
σ FROM REF. 18
VELOCITY
ALTITUDE
PROJECT MERCURY
TIME AT IMPACT
2300 SEC
R-102724

R-55260


ALTITUDE x 10⁻⁴, FEET
VELOCITY x 10⁻³, FEET/SEC
DECELERATION, g's
VELOCITY
ALTITUDE
DECELERATION

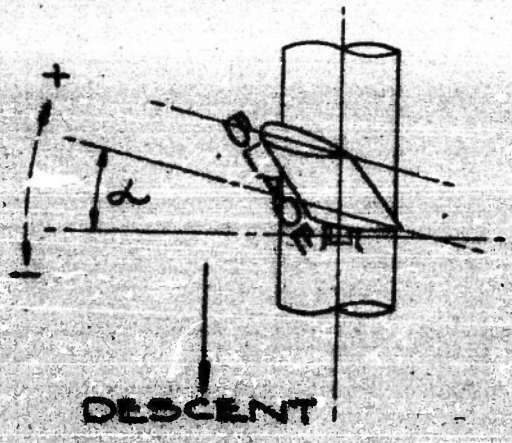
R55260 THIRD ANGLE PROJECTION K-9102729



α = PITCH ANGLE - MEASURED WHEN $\beta = 0$.

β = CONING ANGLE

δ_3 = FORWARD SWEEP ANGLE - MEASURED WHEN $\beta = 0$.



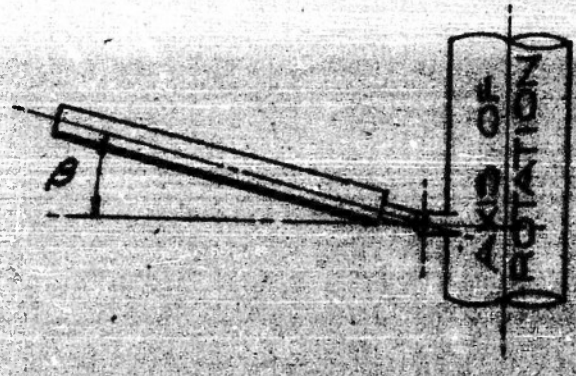


FIG. 9

BLADE IN OPEN POSITION

DRAWN BY R.D. Morris April 21, 1961 INSPECTED BY

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R55260 THIRD ANGLE PROJECTION

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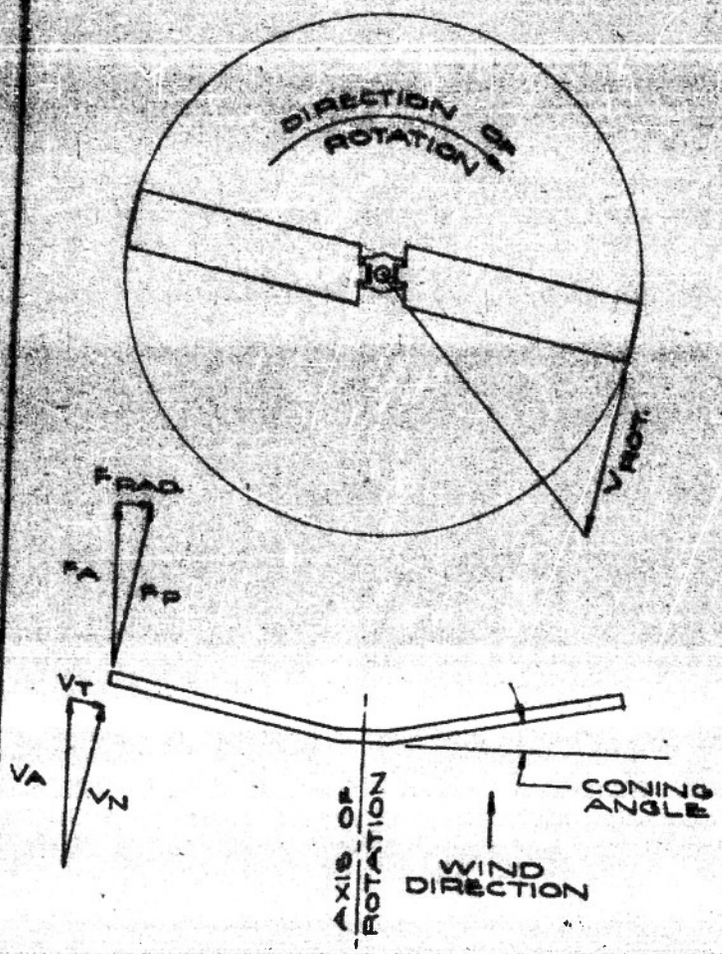

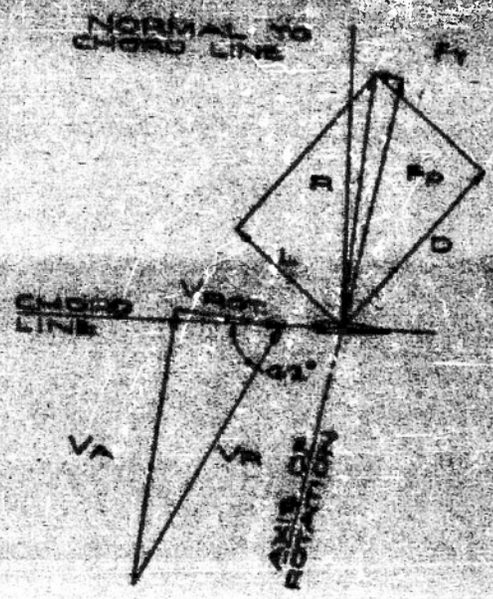

FORCES ON TIP OF BLADE

FIG. 10

V_A = AXIAL VELOCITY, 1672 FT. PER SEC.
V_T = TANGENTIAL VELOCITY, 820 FT. PER SEC.
V_R = RESULTANT VELOCITY, 1860 FT. PER SEC.
L = LIFT
D = DRAG
R = RESULTANT OF L AND D FORCES
F_T = COMPONENT OF R WHICH CONTRIBUTES TO ROTATION.
F_P = COMPONENT OF R WHICH IS IN PLANE OF ROTATION
F_A = COMPONENT OF F_P WHICH IS PARALLEL TO AXIS. THIS FORCE TENDS TO DECELERATE ROTOCHUTE WHEN DROPPED.
F_{RAD} = RADIAL COMPONENT OF F_P.

AUTOROTATION VELOCITY DIAGRAM AT M = 1.73

DRAWN BY [signature] April 21, 1948 INSPECTED BY

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