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MC DONNELL AIRCRAFT CORP., ST. LOUIS, MO. (REPORT 2050)

GROUND TOW AND LOW ALTITUDE AUTOROTATION TEST RESULTS OF THE XH-20 HELICOPTER

GEORGE W. KALLAL 26 MARCH 51 66PP PHOTOS, TABLES, DIAGR, GRAPHS

USAF CONTR. NO. AF-33(038)-9845

HELICOPTERS - AUTOROTATION
HELICOPTERS - PERFORMANCE
H-20

ROTATING WING AIRCRAFT(34)
AERODYNAMICS AND
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MCDONNELL *Aircraft Corporation*
 ST. LOUIS 3, MISSOURI

GROUND TOW AND LOW ALTITUDE
 AUTOROTATION TEST RESULTS OF
 THE XH-20 HELICOPTER

SUBMITTED UNDER Contract AF 33 (038)-9845

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1. SUMMARY

The McDonnell Aircraft Corporation presents the results of ground tow and low altitude autorotation tests for various configurations of the Model XH-20 helicopter in accordance with Item 2 of Contract AF 33 (038)-9845, P. R. 97219, E. O. No. 582-164 (SR-1). The report contains performance curves and data for simulated autorotative flight tests made by towing the rig-mounted helicopter on the ground in addition to performance curves for actual low altitude autorotative flights. The simulated autorotative flight performance data show the variation of rotor thrust coefficient with tip speed ratio and rotor angles from which are derived the rates of descent for the Model XH-20 helicopter. A comparison between the rates of descent as determined by the simulated autorotation tests and through theoretical calculations show that for low forward velocities and high rotor angles there is excellent agreement; and for high forward velocities and low rotor angles, a difference of only 7 per cent exists.

In addition to the preliminary or simulated flight tests, approximately 75 actual autorotative flights from altitudes below 320 feet are reported. They include a number of vertical descents from hovering at 60-70 feet. Due to the somewhat undesirable characteristics of the landing gear and the limited availability of the runways upon which to land,

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spot landings without forward roll were necessary. This resulted in a variation of flight technique which frequently nullified any stabilizing RPM effect expected from the higher test altitudes. Despite the adverse flight restrictions, tests were performed satisfactorily and show conclusively that the relatively high rates of descent and steep glide angles associated with the present configuration result in no undue difficulty in flaring out and landing gently on a desired spot. The pilot suffered no discomfort during the high rates of descent after preliminary familiarization. Tests results, in addition to pilots' reports, indicate that a steady state rate of descent is closely approached at approximately 450 RPM with a blade pitch of one degree or at 400-420 RPM with a blade pitch of zero degrees. However, it was considered desirable to discontinue the autorotative flight tests because of inadequate landing gear which affected pilot technique, relatively low rotor speed which indicated small pull-up margins of safety, and resulting high stress level which adversely affected the fatigue life of the rotor. The speed of the rotor prior to flare-out decreased in most cases to approximately 30 RPM less than the RPM estimated to provide a desired margin of safety in the form of kinetic energy in case of pilot error.

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2. INTRODUCTION

The McDonnell Aircraft Corporation presents the test results on the autorotation characteristics of the XH-20 helicopter in accordance with Item 2 of Contract AF 33 (038)-9845, P. R. 97219, E. O. No. 582-164 (SR-1).

A brief historical review of all preliminary autorotation tests and studies conducted by the contractor serves as a background for the more advanced autorotational data which is presented in this report. The history concerns the simulated autorotative flight tests made by mounting the flyable test stand on a truck and operating on a local highway, and by mounting the test stand behind the prop wash of a Navy JD-1 airplane. In addition to the tests are the studies that were made of pull-ups from power-off vertical descents and of the potential of helicopters to make safe autorotative descents.

The body of this report, however, concerns the more advanced testing of the XH-20 helicopter which is obtained by testing through two methods. In the first method, autorotative performance data is obtained without endangering the pilot nor subjecting the helicopter to possible damage through a series of simulated autorotative flight tests made on the ground in which the helicopter, mounted on a test rig, is towed by a truck

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on the airport runways. A second method, that for obtaining final results, is through a series of actual autorotative flights in which the helicopter makes power-off descents from altitudes.

In the simulated ground tow tests, three rotors of 20 foot diameter are tested to determine the effect of ram jet drag and the change in solidity on autorotation. The original data from these tests on which the performance data is based was reduced to a non-dimensional form and plotted as test points in Figures 6 through 9, 12 through 15, and 18 through 21, but was not included herein because of bulk. The performance data presented includes the relationship between rotor angles of attack, blade pitch, rotor tip speed ratio, rotor thrust coefficient, horizontal velocity and the rate of descent of the XH-20 helicopter. The resulting data is compared to the theoretical calculations of Reference 7.7 and an attempt is made to explain the reasons for the few discrepancies that were found to exist.

After ground tow tests and theoretical studies indicated that safe autorotative landings could be made with the 20 foot diameter rotor of .0531 solidity, a series of actual autorotative flights incorporating this rotor are made from low level altitudes with the XH-20 helicopter. To acquaint himself with the characteristics of the helicopter in autorotative flight, the pilot made power-off practice vertical descents

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from hovering at very low altitudes before proceeding with any autorotation flight with initial forward speed. After the period of familiarization, the pilot gradually increased altitude by increments unless a major change in the helicopter configuration compelled the process to be reestablished. The usual flight test technique is to attain a desired altitude and forward speed and then simultaneously turn off the fuel and decrease the collective pitch to a minimum to begin a power-off descent. Before contact with the ground, flare-out is initiated by an increase in collective pitch to the magnitude necessary to arrest the descent but not to cause ballooning. Throughout the flight regime, a motion picture camera focused on the photopanel records on film the fuel pressure, airspeed, altitude, rotor speed and collective pitch, the results of which are presented graphically in Figures 24-30 for seven representative actual autorotative flight tests.

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3. HISTORY

Simulated autorotative flight tests at McDonnell Aircraft Corporation were conducted as early as July 1947, the results of which were promulgated in Reference 7.1. In the preliminary tests of the rotor alone, prior to the development of gasoline burning ram jets, the flyable test stand was mounted on a small pick-up truck and adjusted to a glide angle which resulted in the highest RPM for various airspeeds and pitch settings. Operations were conducted on a local four-lane highway. Results of the tests and preliminary calculations indicated that satisfactory autorotation was possible with a rotor employing ram jets.

After the development of suitable gasoline burning ram jets, a second series of autorotative tests were made employing the ram jets on the same 18 foot diameter rotor of 6.22 inch chord as used in the initial tests. In view of the high costs involved to obtain data through full scale wind tunnel tests, a much less expensive method was employed. Simulated wind tunnel tests were made utilizing the prop wash from a Navy JD-1 aircraft. The test stand was located approximately 120 feet behind the engine propellers. To simplify the supporting rig, the helicopter (flyable test stand) was blown at backward

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with the rudder removed as in Figure 1. With landing gear wheels removed, the front shocks were mounted on hinges to permit testing at various rotor angles. Two rotors of 18 foot diameter were tested; the first with a blade chord length of 6.22 inches and the second with a chord length of 8.22 inches. The second rotor was made after the tests of the first rotor indicated the need for a rotor of greater solidity. Results of both rotor tests are contained in Reference 7.9.

Meanwhile, autorotative landing studies were also performed using the work of D. L. L. Fitzwilliams (Reference 7.6) as a guide to the theoretical considerations which were limited to pull-ups from pure vertical descent through the use of only collective pitch control. The studies concerned the time increment available for a pull-up and the altitude from which a safe landing could be made by the use of the energy available, i.e., rotor kinetic energy. Two approaches were considered in these studies; the first was a rough approximation of the time and the altitude for a safe power-off descent from an initial hovering flight condition; the second was a calculation of the vertical descent characteristics and a reduction of the equilibrium vertical rate of descent by use of collective pitch control for the initial conditions of 50 feet per second rate of descent at 500 feet per second tip speed. Details of both methods appear in Reference 7.2.

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Another study made was a comparison between autorotational landing potential of tip jet helicopters and conventional helicopters. An autorotational landing potential of a helicopter was expressed as the ratio of the kinetic energies available to arrest the steady state autorotation rate of descent to the kinetic energy of descent. The potential or capacity of the helicopter to make a safe autorotative landing increased with this ratio. The available energies that can be employed to arrest the steady state rate of descent are three in number; the usable kinetic energy of the rotor by collective pitch control, the kinetic energy of the horizontal component of the glide path velocity by cyclic pitch control, and the energy absorption capacity of the landing gear. Only the first two were considered in the determination of the landing potential of the helicopter and are discussed at length in Reference 7.3.

These preliminary tests and theoretical studies led to the selection of the test configurations employed in the ground tow tests, and serve as a background for the actual autorotative flight tests by the XH-20 helicopter. The results of both the simulated and actual autorotative flight tests are reported in the following pages.

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4. NOTATIONS AND SYMBOLS

- Ω Rotor angular velocity, radians per second
 R Blade radius, feet
 V Resultant flight path velocity, feet per second
 V_h Horizontal component of flight velocity, feet per second
 V_v Rate of descent, feet per second

μ Rotor tip speed ratio, $\frac{V \cos \alpha}{\Omega R}$

σ Rotor solidity ratio, $\frac{b c}{\pi R}$

γ Resultant glide angle

ρ Air mass density, slugs per cubic foot

W Gross weight, pounds

T Rotor thrust

C_T Rotor thrust coefficient, $\frac{T}{\rho \pi R^2 (\Omega R)^2}$

$C_{T/\sigma}$ Aerodynamic blade loading

C_{D_j} Cold jet drag coefficient, $\frac{\text{jet drag}}{\rho/2 \pi R^2 (\Omega R)^2}$

$\left[\frac{D}{L} \right]$ Equivalent drag-lift ratio

$\left[\frac{D}{L} \right]_R$ Rotor equivalent drag-lift ratio $\left[\frac{D}{L} \right]_o + \left[\frac{D}{L} \right]_j$

$\left[\frac{D}{L} \right]_o$ Profile equivalent drag-lift ratio

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$\left(\frac{D}{L}\right)_i$ Induced equivalent drag-lift ratio
 $\left(\frac{D}{L}\right)_j$ Jet unit equivalent drag-lift ratio
 $\left(\frac{D}{L}\right)_p$ Fuselage parasite equivalent drag-lift ratio
 $\left(\frac{D}{L}\right)_G$ Glide or rate of descent equivalent
drag-lift ratio

D Equivalent drag, pounds
 α Angle of attack of plane perpendicular to control axis
 f_s Fuselage flat plate area, $[C_D = 1.0]$, square feet

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5. AUTOROTATIVE GROUND TOW TESTS

5.1 Apparatus And Instrumentation

A prerequisite of the simulated autorotative flight tests was that the helicopter operate at various attitudes of flight and at various flight velocities. Therefore, an apparatus consisting of a test rig was constructed to carry the helicopter at pre-selected attitudes of flight and a tow truck was used to provide the flight velocity. A photograph of the tow test equipment is presented in Figure 2.

Instrumentation consists of a Heiland 8" recording oscillograph which records blade pitch, rotor speed, towing air speed and thrust and drag forces. Both the anemometer and the oscillograph used to record towing speeds are mounted on the truck as in Figure 2. Rotor lift and drag forces are measured by means of strain gauge instrumentation - the strain gauges being mounted at the rotor hub as in Figure 3.

5.2 Test Configurations

A series of simulated autorotation flight tests employing three configurations are conducted to determine quantitatively the effect of ram jet drag and solidity on

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autorotative performance. All three configurations utilize a 20 foot diameter rotor and are the following:

- (a) Rotor of .0435 solidity - no ram jets
- (b) Rotor of .0435 solidity and ram jets
- (c) Rotor of .0531 solidity and ram jets

5.3 Test Procedure

The test procedures employed with each of the three configurations are identical. However, prior to testing the rotor without ram jets, a weight of 3.70 pounds is fastened to each rotor blade tip to prevent the bending moment imposed on the blade from exceeding its maximum allowable value. A fairing is installed over the rotor tip weights to maintain drag values in accordance with the airfoil section for the blades. The test rig, with the helicopter at a pre-determined rotor angle, is then towed behind the truck to various pre-selected velocities until the rotor speed becomes constant, at which time the corresponding autorotational data is recorded. This procedure is repeated for other blade pitches and rotor angles.

The procedure for testing the rotor with ram jets is identical to that without ram jets except for large rotor angles. At large rotor angles, due to the weight of the ram jet engines,

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blade chordwise deflections result in excessive vibration at low rotor speeds. Consequently, it became necessary to attain a speed of approximately 650 RPM under ram jet power with the rotor in a horizontal plane before tilting to the desired rotor angle prior to towing. After the test rig is accelerated to the desired velocity, the fuel to the ram jet engines is shut off and rotor speed allowed to decrease to a constant RPM as governed by the forward velocity of the test rig. In all ground tow testing, the cyclic control stick is fixed in position after the rotor has passed through its critical vibration frequency. Rotor angles of attack selected for testing the rotor without ram jets are 23, 34, 44 and 48 degrees; and with ram jets, 23, 34, 44 and 53 degrees. Each rotor angle is tested with collective pitch settings of 0, ± 2 , and ± 4 degrees. In plotting the results, a wide scatter of test points indicate that many tests for each blade pitch angle would be required before a mean value could be established.

5.4 Experimental Results

5.4.1 Data Analysis

A sample of the recorded data showing traces of magnitudes of thrust, drag, airspeed, collective pitch and rotor speed with their respective conversion factors obtained

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by calibration of the oscillograph appear in Figure 4. This original test data, being bulky in size, is omitted from the report but has been reduced to a nondimensional form, i.e., rotor thrust coefficient (C_T) and tip speed ratio (μ) for a given rotor angle and blade pitch angle. For tests of the rotor without ram jet engines, Figures 6, 7, 8 and 9 show the variation of the rotor thrust coefficient with tip speed ratio. Figures 12, 13, 14 and 15 give the variations for tests of rotors with ram jet engines while Figures 18, 19, 20 and 21 are for a rotor of higher solidity with the same ram jets.

For a helicopter (XH-20) of 550 pounds gross weight, values of thrust coefficient (C_T) are calculated for tip speeds of 350, 400, 450 and 500 feet per second and the corresponding autorotative values of tip speed ratio (μ) are obtained from the nondimensional test curves for various glide angles. Neglecting fuselage parasite drag, the horizontal and vertical components of simulated autorotative flight velocities are obtained as $V \cos \gamma$ and $V \sin \gamma$ respectively in accordance with Reference 7.7 and appear in Tables 1, 2, 3, 4, 5 and 6. The final plot of V_v vs V_h for each configuration is obtained by this procedure which may be summarized by the following steps:

- (a) Assume a gross weight and range of tip speed (ΩR) and rotor angle α .

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- (b) Calculate rotor thrust coefficients for the above assumptions.
- (c) For a given C_T and rotor angle α , read the tip speed ratio μ from the C_T vs μ graph.
- (d) Knowing μ and ΩR and α , calculate V_v and V_h .

$$V_h = \mu \Omega R = V \cos \gamma$$

$$V_v = V_h \tan \alpha = V \sin \gamma$$

Figures 11, 17 and 23 present the results of the above steps as dimensional plots of the variation of rate of descent with horizontal velocity for various tip speeds. In addition, theoretical data is plotted on these graphs for comparative purposes. Results of this comparison are discussed in Section 5.5.

5.4.2 Experimental Test Results

There is considerable difference in the advance ratio range of the performance curves of thrust coefficient with tip speed ratio and rotor angle for the 20 foot diameter rotor, with and without ram jets. This difference is reflected in their respective rates of descent. As anticipated, the rotor without ram jets results in the lowest rate of descent of the three configurations tested - it having the lowest equivalent

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drag-lift ratio $\left(\frac{D}{L}\right)$ by virtue of no ram jet drag. However, the rotor of highest solidity, which should have given a lower rate of descent according to theory, actually resulted in rates of descent higher than the rotor of lower solidity - both rotors employing identical ram jets. This discrepancy may be explained by the increase in profile drag of the blade due to the manner by which the chord length was increased from 8.22 to 10.22 inches.

Test results show that incongruities exist in the rate of descent for a helicopter employing a rotor without ram jets flying with a forward speed of less than 27 ft/sec. and with a rotor tip speed of 350 ft/sec. Rates of descent with tip speeds in excess of 350 ft/sec. result in a congruent family of curves as in Figure 11.

A considerably higher rate of descent for a comparable horizontal velocity occurs with the addition of ram jet engines to the rotor. The corresponding rates of descent can be compared by inspecting Figures 11 and 17 which show that the test curves differ completely in that for a given rotor angle the curves inflect upward as in Figure 11 and deflect downward as in Figure 17.

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For a ram jet operated rotor of increased solidity, the rate of descent for a given horizontal velocity is even greater, although contrary to the prediction by theory. In comparing Figures 17 and 23, it can be seen that at high horizontal velocities and at rotor angles of 23 degrees the curves differ in slope. With the high solidity rotor, Figure 23 indicates that no appreciable change in rate of descent occurs at a horizontal velocity in excess of 50 MPH, which is to be expected since the influence of fuselage parasite drag is excluded by the test method. For the rotor of decreased solidity, test results of Figure 17 indicate that an increase in horizontal velocity will result in a decrease in the rate of descent.

Since steady state rate of descent is only approached, and since no actual autorotative flights were made at a forward velocity greater than 30 MPH, no attempt was made to compare the results of ground tow tests with those of actual flight tests.

5.5 Test Data Comparison With Theory

5.5.1 Theoretical Analysis

The rate of descent of each of the three rotor configurations found experimentally can be evaluated by a comparison to the rate of descent calculated theoretically.

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Therefore, the same gross weight of 550 pounds as used in determining the rotor thrust coefficient in the simulated autorotative flight tests is used in the theoretical calculations. The ram jet drag coefficient (C_{Dj}), based on rotor disc area, used in the analysis is .000122 which is representative of the ram jets used in the experimental tow tests. Values of drag-lift ratio for the ram jets $\left(\frac{D}{L}\right)_j$ are calculated from the equation given in Reference 7.7,

$$\left(\frac{D}{L}\right)_j = \frac{bD}{T} \left[\frac{1}{\mu} + \frac{3\mu}{2} \right]$$

Drag-lift ratio for the rotor $\left(\frac{D}{L}\right)_R$ for the various thrust coefficient-solidity ratios $\frac{C_T}{\sigma}$ are obtained from Reference 7.7. The two values are added as in Tables 2, 3 and 6 to obtain the theoretical rotor glide angle from which the rate of descent is determined. The equations used in brief are as follows:

$$\left(\frac{D}{L}\right)_G = \tan \gamma$$

$$\left(\frac{D}{L}\right)_G = \left(\frac{D}{L}\right)_o + \left(\frac{D}{L}\right)_i + \left(\frac{D}{L}\right)_p + b \left(\frac{D}{L}\right)_j$$

= Profile + Induced + Parasite + Jet

$$\tan \gamma = \left(\frac{D}{L}\right)_o + \frac{C_{T \text{ AUTO}}}{2 \mu^2} + \frac{f_s}{\pi R^2} \frac{\mu^2}{2 C_{T \text{ AUTO}}} + \frac{bD}{T} \left[\frac{1}{\mu} + \frac{3\mu}{2} \right]$$

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As the fuselage parasite drag did not influence the rate of descent determined experimentally in that only forces on the rotor are measured, the parasite drag-lift ratio $\left(\frac{D}{L}\right)_p$ of the fuselage of the above equation is omitted in the theoretical calculations.

5.5.2 Comparison of Test Results With Theory

The variation of rate of descent with horizontal velocity and tip speed from simulated autorotative flight tests of a 20 foot diameter rotor without ram jets is plotted and compared, in Figure 11, to results obtained from theory. The two curves compare excellently particularly at low forward velocities for all tip speeds and at high rotor angles, if the extended theoretical curves as indicated by the dotted lines are assumed as being correct. At horizontal velocities above approximately 35 MPH, theoretical calculations are optimistic compared with test results indicating that the profile drag for the test rotor blade is greater than average. The identical rotor, to which ram jets are added, produces a more harmonious agreement between test and theory, as seen in Figure 17, where the maximum difference between them is 7 per cent for any rotor speed at 40 MPH forward velocity. The discrepancies that exist between test and theoretical rates of descent at low rotor

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angles and comparatively high forward speeds can be justified on the basis of ground effect, instrument error, erroneous assumptions as to profile drag coefficient and data analysis. From Figure 6 it is evident that at a rotor angle of approximately 23 degrees, the mean height of the rotor disc is only .70 rotor diameter above the ground which is within the range of ground effect.

Autorotative performance test data for the ram jet operated rotor of .0531 solidity is obtained by the same methods as in the previous two series of tests. Results with this rotor are similar to those of the other two configurations except that excellent agreement between test results and theoretical calculations are obtained for rates of descent at tip speeds below 500 ft/sec. and rotor angles of 34 degrees and above. At 50 MPH forward velocity, maximum discrepancy between test results and theory is 7 per cent and that occurring at 500 RPM rotor speed. The discrepancy can be attributed to the poorly constructed rotor blades resulting in high profile drags at high tip speeds.

An increase in rotor solidity from .0435 to .0531 (chord length 8.22 to 10.00 inches) result in little change in rate of descent at rotor tip speeds below 450 ft/sec. and rotor angles greater than 34 degrees. From an aerodynamic standpoint,

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the rework of the blade to 10.00 inches is considered unsatisfactory. Correct solidity is obtained but at the expense of cleanliness of design. For reasons of economy, the rotor with blade chord length of 8.22 inches was increased to 10.00 inches simply by riveting an extension to the trailing edge. At that time, it was believed that, although the contour of the blade left much to be desired, the effect on autorotation by the reworked blade would be within the accuracy of the ground tow tests.

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6. LOW ALTITUDE AUTOROTATIVE FLIGHT TESTS

6.1 Apparatus And Instrumentation

After preliminary ground tow tests and theoretical studies indicated that safe autorotative landings could be made with the 20 foot diameter rotor, it was decided to perform and record a series of actual autorotative flights from low altitudes. In addition to the normal instrumentation carried by the helicopter, consisting of an altimeter, tachometer, airspeed indicator and fuel pressure gauge, two sliding indicators (one to measure collective pitch angles and the other to indicate cyclic pitch position with respect to the fuselage) were added as in Figure 5. In order to record the necessary data, a motion picture camera focused on the instrument panel is mounted above the head of the pilot. A switch, located on the cyclic control stick and operated by the pilot, controls the operation of the camera. Both the camera and instrument panel were rigidly mounted to the helicopter frame after several flight tests indicated the need for eliminating excessive vibration. Except for lag and natural frequency of oscillation within the tachometer, the instrumentation is considered satisfactory.

Rotor configuration (C) of Section 5.2, identical to that used in ground tow tests, is employed for all actual autorotative flights.

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6.2 Test Procedure

To familiarize himself with the characteristics of the helicopter in autorotative pull-ups, the pilot made practice power-off, vertical descents from hovering from approximately 60-70 feet altitude with the XH-20 helicopter before undertaking any autorotative flight with initial forward speed. After the period of familiarization, the pilot increased altitude by increments of approximately 20 feet, unless a major change in the helicopter configuration compelled the process to be reestablished.

The usual autorotation flight technique employed in testing the XH-20 helicopter is the following. After attaining sufficient rotational speed for hovering, the pilot takes off, ascends to the desired altitude and flies with a forward velocity of approximately 25 MPH. Having approximately 650 RPM rotor speed and approximately 5 degrees collective pitch, the fuel to the ram jets is shut off. Immediately after the fuel pressure drops to zero pressure, indicating that the ram jets are inoperative, the collective blade pitch is decreased to a minimum and the rotor allowed to decelerate in power-off descent. According to the traces, flare-out is initiated at approximately 50 feet above the ground when collective pitch is increased

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rapidly to a degree which halts the vertical descent, but at the same time does not cause the helicopter to balloon. The pilot maintains, however, that he began flare-out at approximately one-half the indicated height.

6.3 Experimental Results

6.3.1 Data Analysis

Experimental results of autorotative flight tests of the Model XH-20 helicopter appear in Figures 24 through 30 inclusive on which are plotted a variation of RPM, collective blade pitch, altitude, fuel pressure and indicated airspeed (obtained from photo panel data) with respect to time measured in camera frames. As the time required for the autorotative flights is of short duration and almost impossible to read accurately on the clock, the camera frames are counted, and, knowing the camera speed, the elapsed time is easily determined. Every twentieth frame is read and plotted. Autorotation, as noted in Figures 24-30, lies between zero fuel pressure and the point at which the collective blade pitch is increased from its minimum value.

It is of interest to note from the same figures that when entering into autorotation, the direction of airflow through the rotor changes from downward to upward resulting in a change

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in pressure beneath the rotor that causes a recorded erroneous increase of altitude of approximately 20 to 40 feet. For a more accurate altitude curve these points were ignored. Figure 25 indicates that the altimeter is affected by inertia forces and/or ground effect inasmuch as sub-ground level altitudes are recorded. With the influence of ground effect, setting the altimeter to indicate correct altitudes under all phases of flight becomes almost an impossibility.

Assuming that the instruments are read accurately from the camera film, the tachometer, altimeter and airspeed indicator each have an inherent frequency of oscillation as denoted by the test points in Figures 24-30. However, the curves are constructed through the mean test points and represents the actual condition that exists.

It is apparent from the curves that the instrument most affected by sudden changes in flight or vibration and most erratic in amplitudes of oscillation is the magnetic tachometer which replaced the unsatisfactory chronometric tachometer. Despite its shortcomings, performance of the magnetic tachometer is considered satisfactory.

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6.4 Discussion

Of the 75 autorotative power-off descents performed, some of which were discussed in References 7.4 and 7.5, seven flights considered most representative are plotted in Figures 24-30 inclusive. They show a rate of descent ranging from 30 ft/sec. to 48 ft/sec., the former with 1 degree collective pitch setting during autorotation and the latter with 0 degrees collective pitch. To obtain the design maximum of 11 degrees collective pitch for flare-out and pull-up, more autorotative flights are made with collective pitch at 1 degree than with 0 degrees. However, as the rotor speed appears to be approaching stabilization at approximately 450 RPM, with more than sufficient energy remaining for flare-out, the collective pitch angle is reduced from 1 degree to 0 degrees.

A comparison of Figures 29 and 30 with 24-28 will demonstrate that the slope of the RPM curve for zero degrees collective pitch is not as steep as with one degree, prior to flare-out. With zero degrees collective pitch in autorotation, stabilization appears to occur at approximately 400-420 RPM. However, prior to flight testing, 450 RPM was estimated as the minimum rotor speed necessary for flare-out and to provide a margin of safety in the advent of pilot error. For lack of more concrete knowledge, therefore, a rotor speed of 400-420 RPM

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must be considered marginal. In all 75 autorotative flights, however, not one descent was made in which the landing gear was forced to cushion the landing. Due to the somewhat undesirable characteristics of the landing gear, the autorotative landings were to be made without any appreciable forward roll. Combined with limited runways upon which to land unless the wind direction paralleled the runways, a variation of flight technique was required so that in many cases when descents were made from the higher altitudes tested, collective pitch was also applied at a higher altitude, resulting in a rotor deceleration period of the same length as those of the lower altitude flights.

The inadequate landing gear which affected pilot technique, the relatively low rotor speed which indicated small pull-up margins of safety, and the lack of knowledge as to the stress level in the blades during these tests made further autorotative flight testing undesirable with the present configuration. Excluding the ram jet, to improve the autorotative characteristics, the following three modifications are recommended; the rotor blades be constructed to a known and desired contour for low profile drag, the fuselage be redesigned for low parasite drag, and the landing gear be made more suitable for ground maneuvers. These modifications, when incorporated, should result in a satisfactory configuration for autorotation.

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7. REFERENCES

- 7.1 Ballauer, A. C., Progress Report 11, Ram Jet Helicopter Rotor Development. 15 August 1947.
- 7.2 Ballauer, A. C., Progress Report 33, Ram Jet Helicopter Rotor Development. MAC Engineering Report 1273, 15 June 1949.
- 7.3 Ballauer, A. C., Progress Report 41, Ram Jet Helicopter Rotor Development. MAC Engineering Report 1572, 15 February 1950.
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- 7.5 Ballauer, A. C., Progress Report 47, Ram Jet Helicopter Rotor Development. MAC Engineering Report 1793, 15 August 1950.
- 7.6 Fitzwilliams, D. L. L., "Engine-Off Landings", Flight Magazine, 13 November 1947.
- 7.7 Heck, Alan, Charts For Estimating The Autorotative Performance Of Jet Rotors. MAC Engineering Report 1079, 18 March 1949.

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7.8 Heck, Alan, Effect of Design Parameter Variation On
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Helicopters. MAC Report 1691, 15 May 1950.

7.9 Toney, E., Progress Report 29, Ram Jet Helicopter Rotor
Development. MAC Engineering Report 1081,
14 February 1949.

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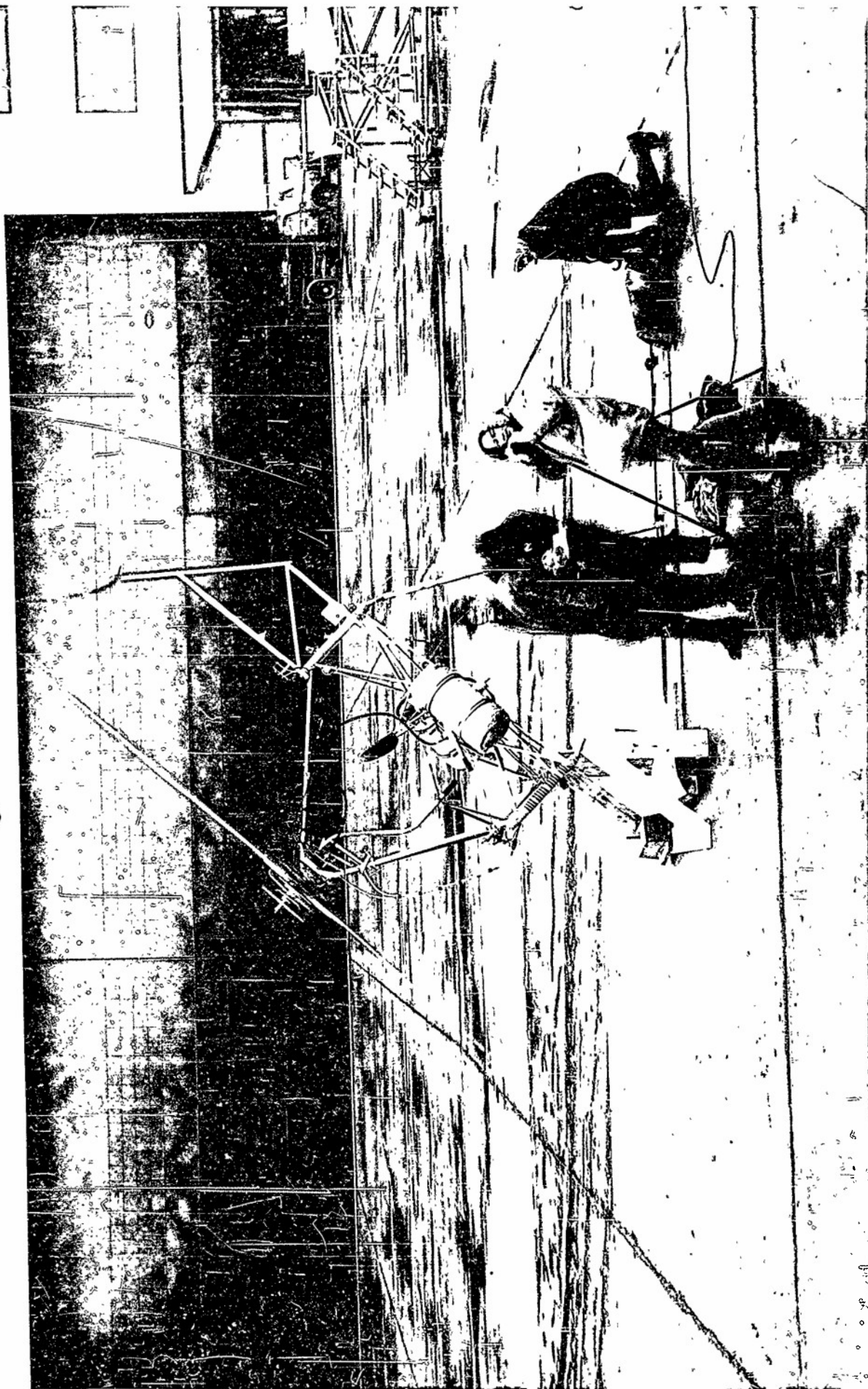
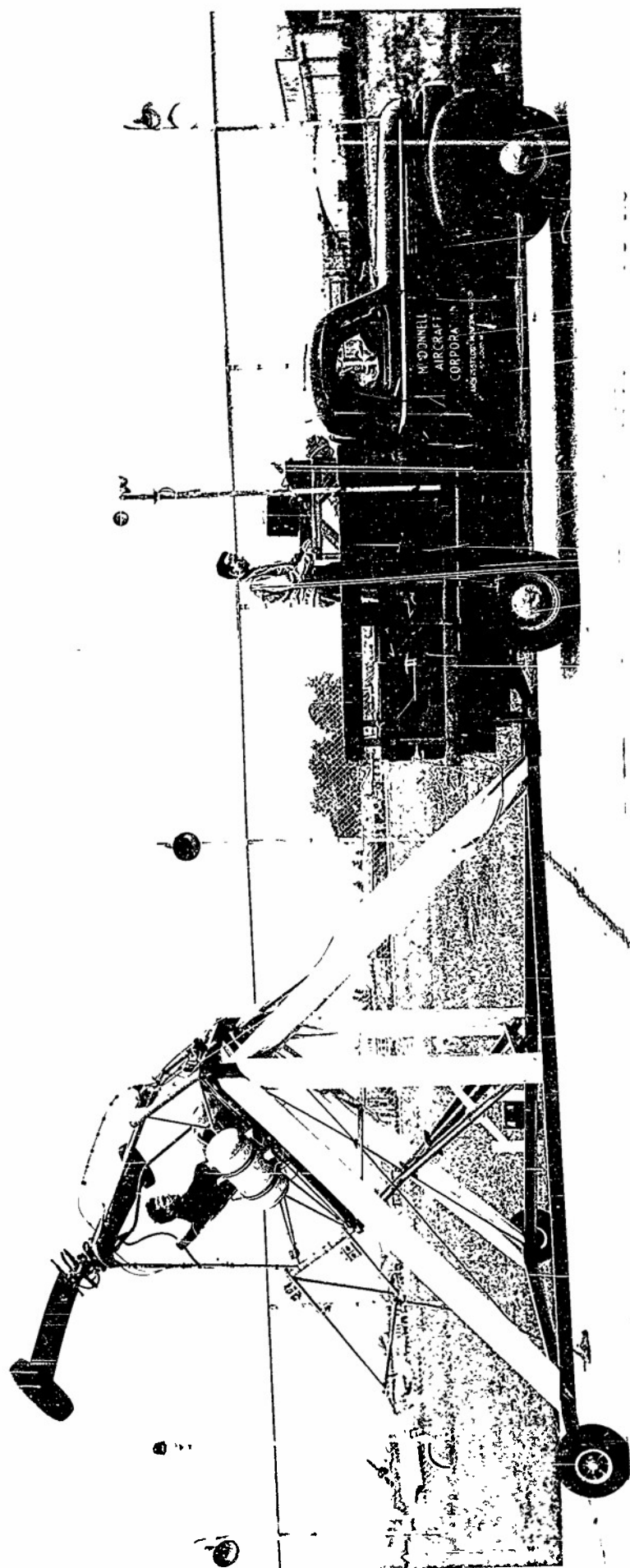


Figure 1
D4H-12312

HELICOPTER IN PROP WASH OF NAVY JD-1

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FLYABLE TEST STAND MOUNTED IN RIG
WITH TRUCK IN TOWING POSITION

Figure 2
D4H-15179

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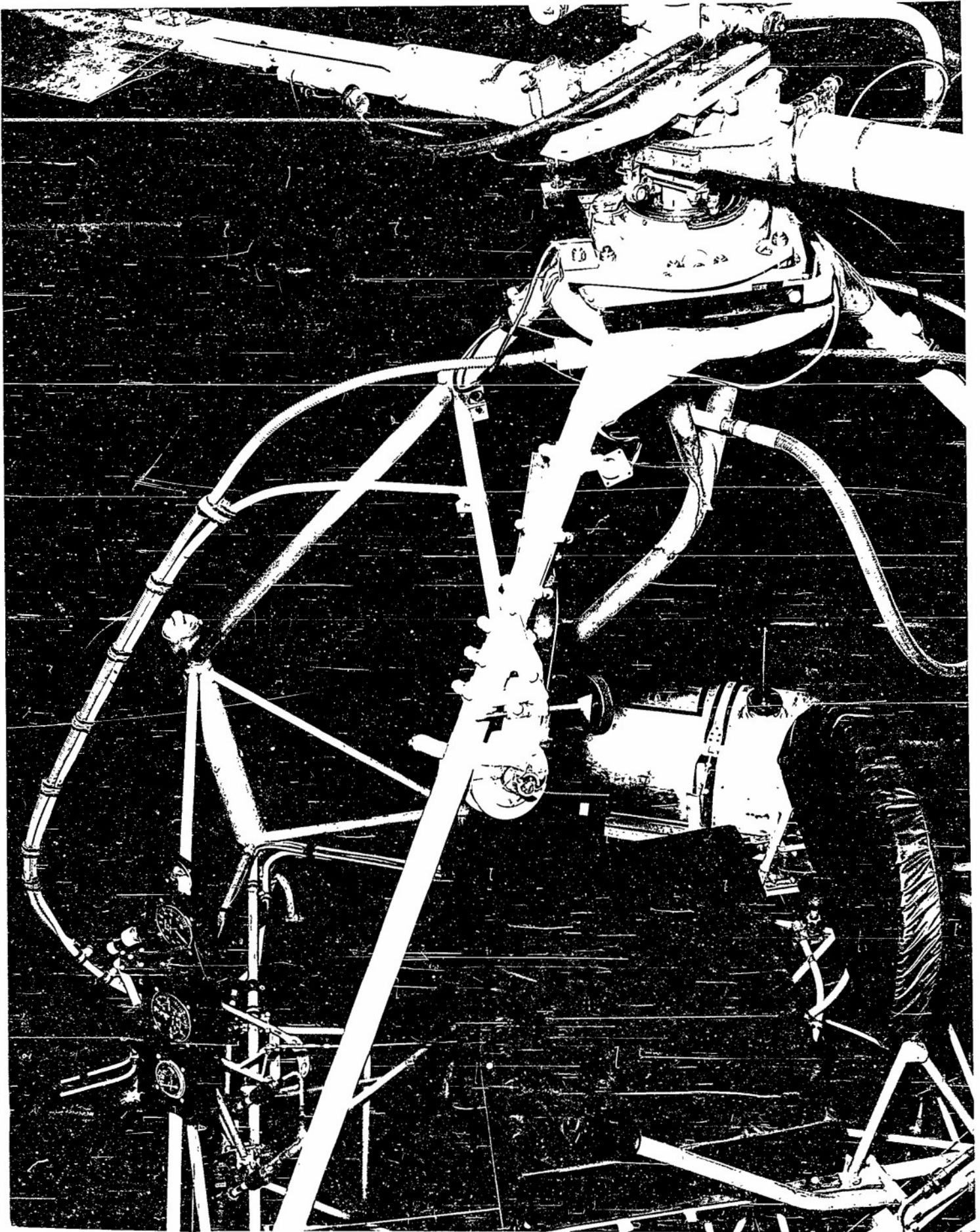


Figure 3 FLYABLE TEST STAND STRAIN GAUGE INSTRUMENTATION Report 2050
D4H-14765

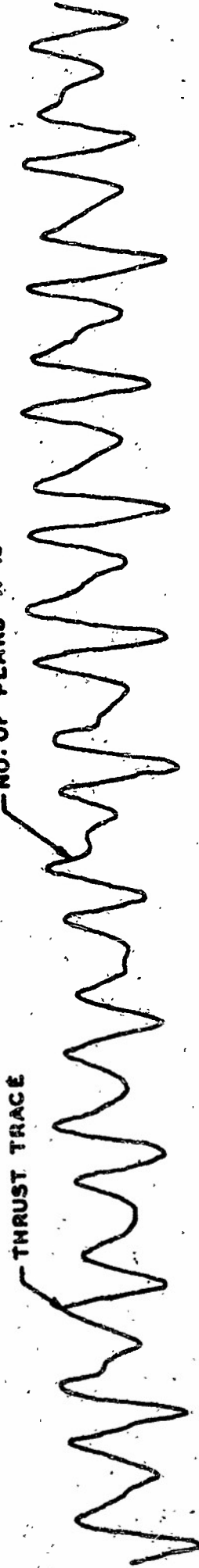
TYPICAL TRACE FOR AUTOROTATION DATA FOR 20 FT. DIA. ROTOR WITH NO. 26
AND 27 JETS AT APPROXIMATELY 45° ROTOR ANGLE OF ATTACK.

NO. OF PEAKS X 1.49 = AIRSPEED IN M.P.H.



NO. OF PEAKS X 15 = R.P.M.

THRUST TRACE



DRAG TRACE



0 DRAG (60#/INCH)

0 THRUST (430#/INCH)

0° PITCH (REF.)

+4° PITCH

1 SECOND

FIGURE 4

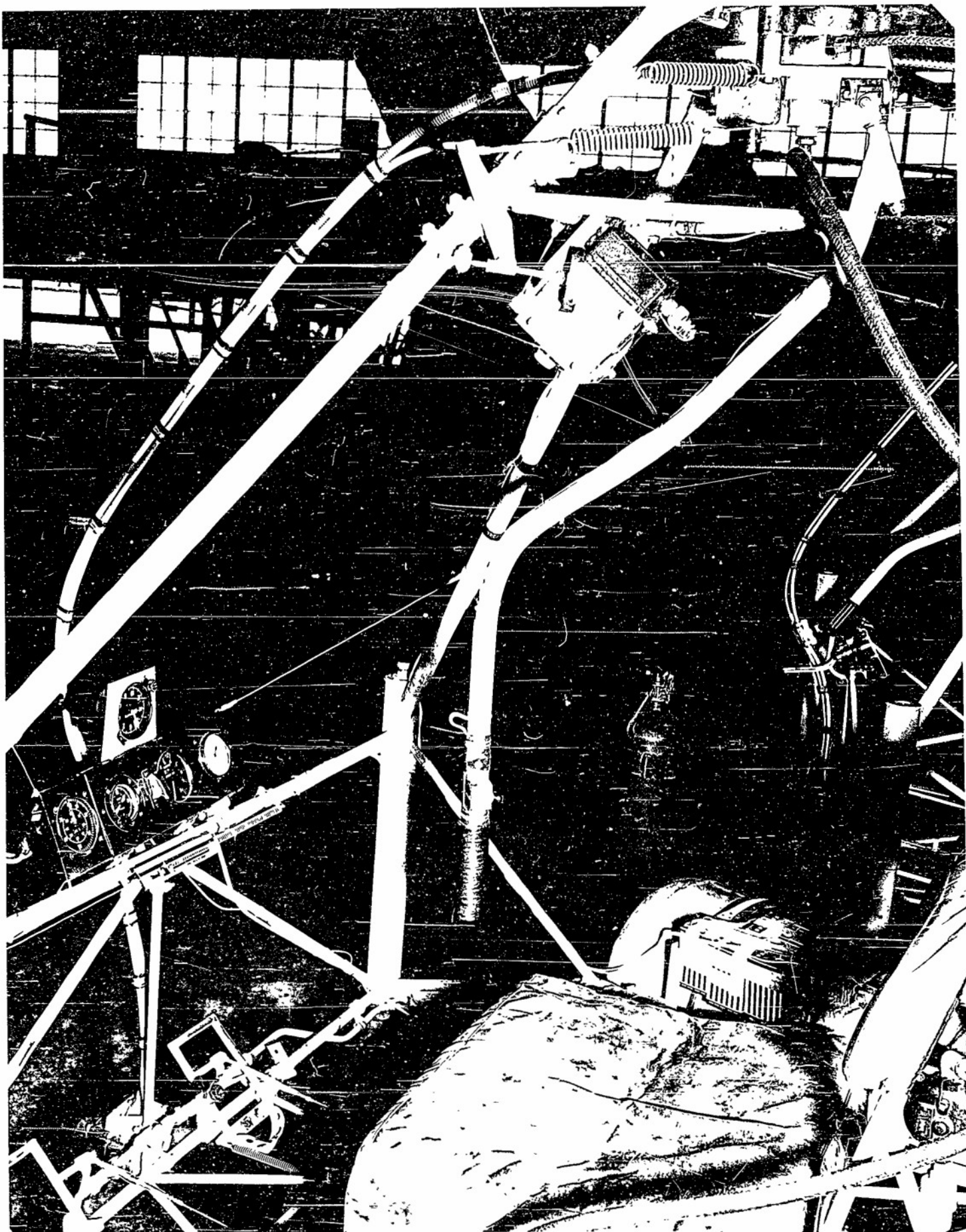


Figure 5 CAMERA INSTALLATION FOR
D4H-14326 LOW ALTITUDE AUTOROTATION FLIGHT TESTS Report 2050

FIGURE 6

MODEL XH-20 ROTOR

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

ROTOR ANGLE = 23°

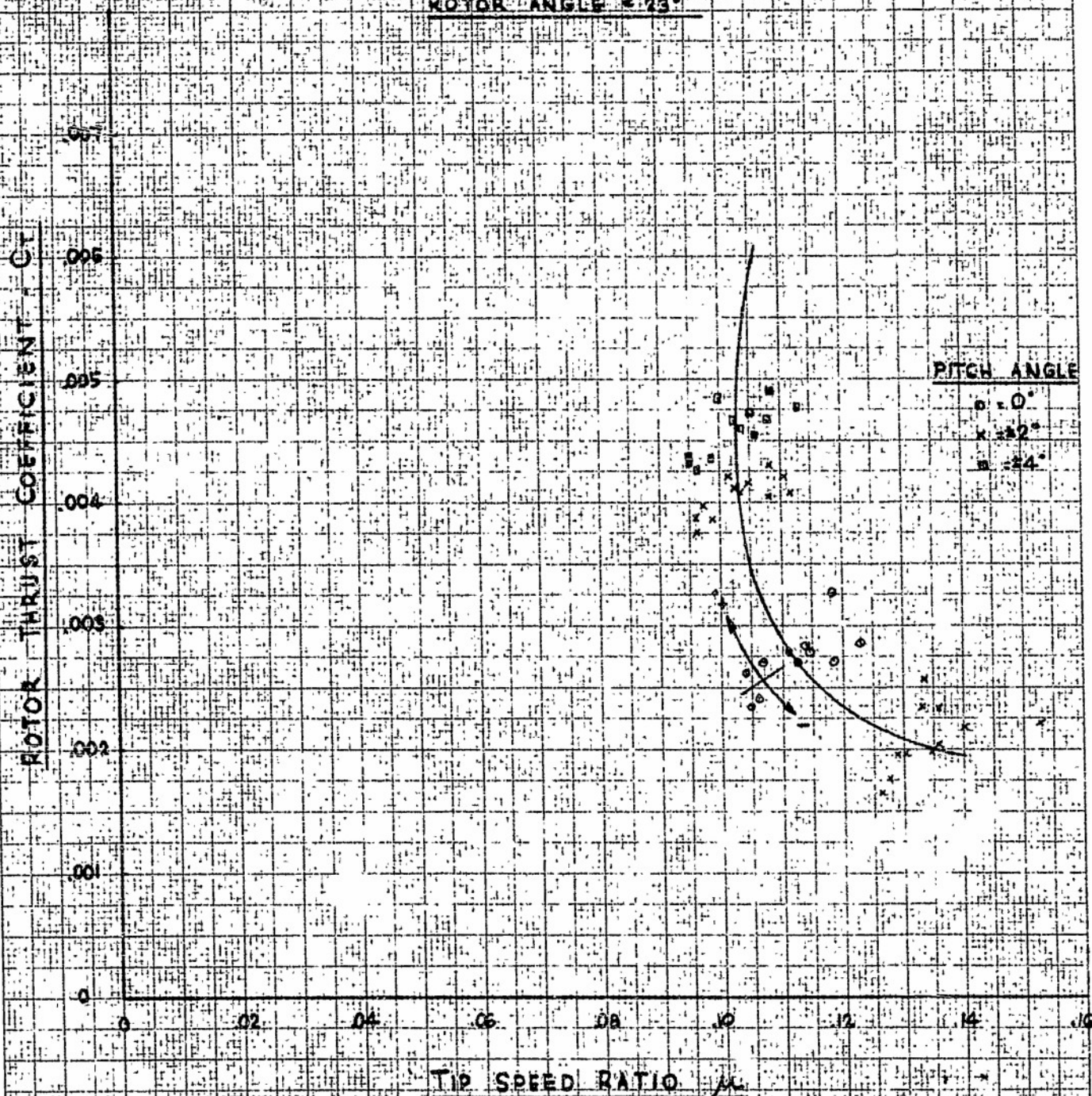


FIGURE 7

MODEL XH-2 ROTOR

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

ROTOR ANGLE = 34°

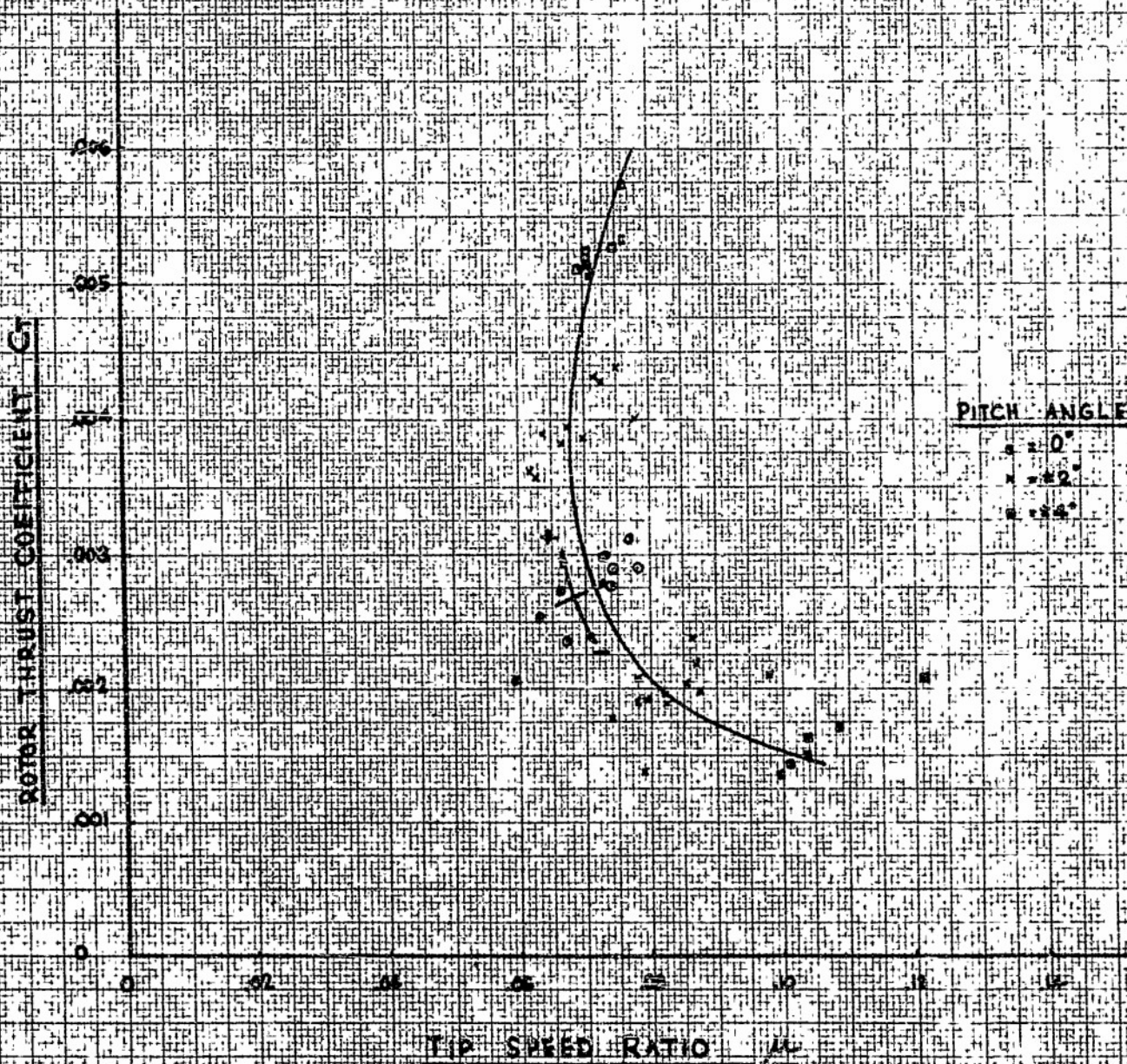


FIGURE 8

MODEL XE-20 ROTOR

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.0435

ROTOR ANGLE = 43°

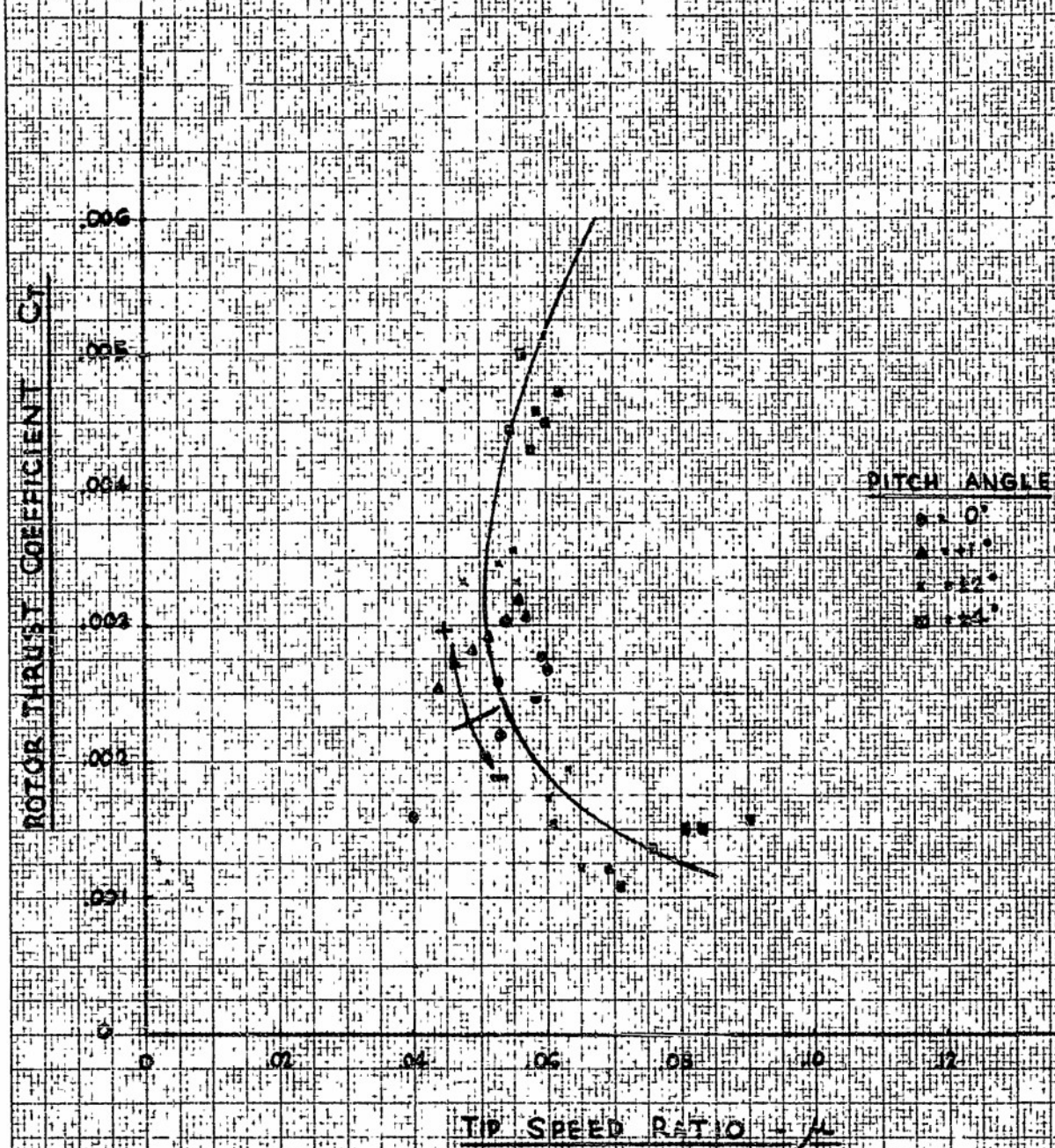


FIGURE 9

MODEL 14-20 ROTOR

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = .0435

ROTOR ANGLE = 4.9°

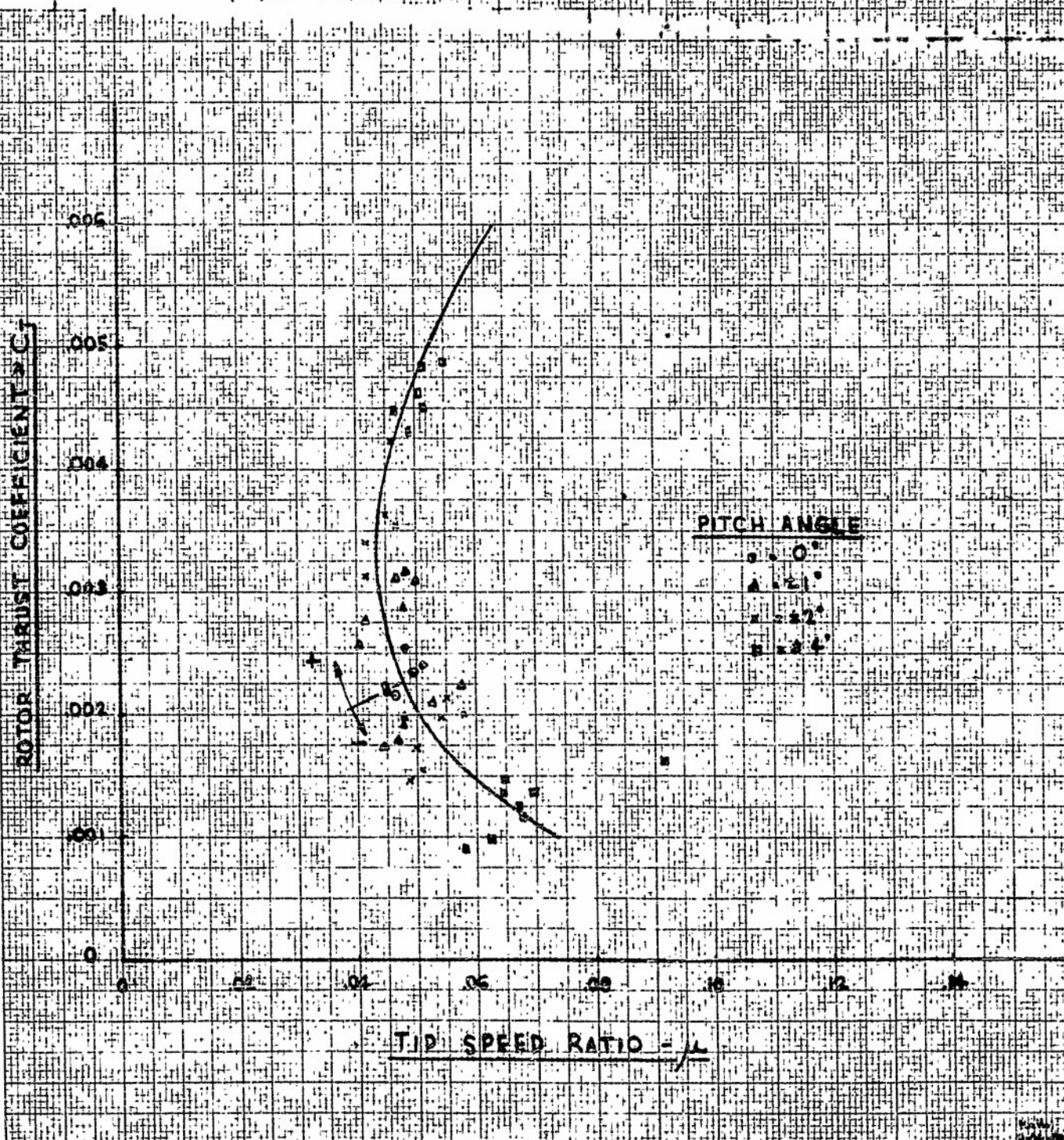


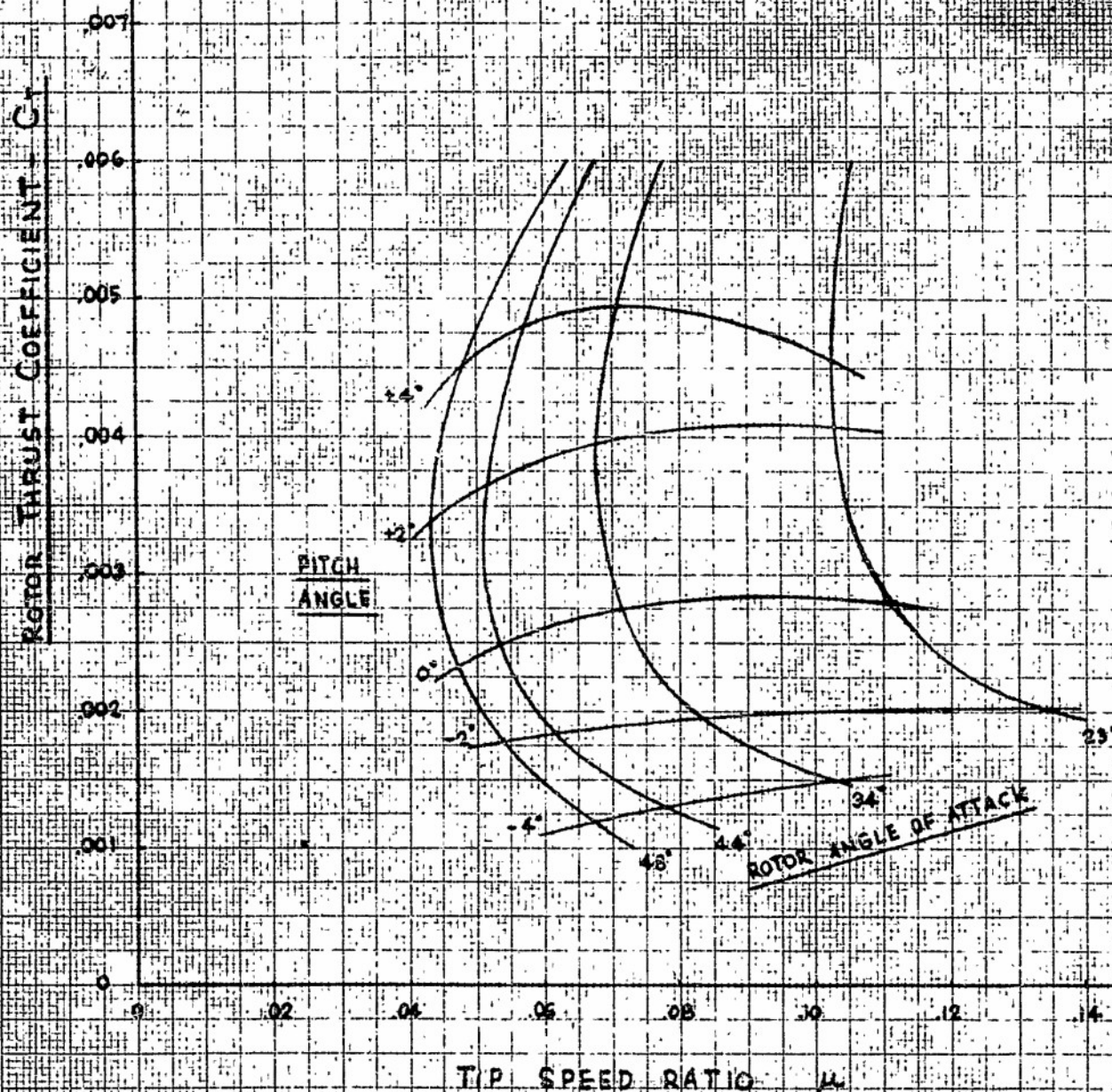
FIGURE 10

MODEL XH-20 ROTOR

VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO AND ROTOR ANGLE

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435



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MODEL _____

TABLE 1

Test Dimensional Plot for Rate of Descent

Gross Weight = 550 pounds

Rotor Diameter = 20 feet

Rotor Solidity = .0435

TEST					
γ	ΩR	350	400	450	500
	C_T	.00601	.00461	.00364	.00295
23°	μ	.106	.1025	.104	.1092
	V_h	37.8	41.0	46.6	54.6
	V_v	16.0	17.4	19.8	23.2
34°	μ	.0775	.069	.0675	.070
	V_h	27.15	27.6	30.4	35.0
	V_v	18.3	18.6	20.5	23.6
44°	μ	.0675	.056	.0515	.051
	V_h	23.6	22.4	23.2	25.5
	V_v	22.8	21.6	22.6	24.6
48°	μ	.0635	.0488	.0438	.044
	V_h	22.23	19.5	19.7	22.0
	V_v	24.6	21.6	22.0	24.4

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TABLE 2

Theoretical Dimensional Plot for Rate of Descent

Gross Weight 550 pounds

Rotor Diameter 20 feet

Rotor Solidity .0435

Theory					
μ	ΩR	350	400	450	500
.10	$\left[\frac{D}{L}\right]_R = \tan \gamma$	.438	.369	.338	.323
	V_h	35.0	40.0	45.0	50.
	V_v	15.33	14.76	15.21	16.15
.15	$\left[\frac{D}{L}\right]_R = \tan \gamma$	.229	.198	.188	.188
	V_h	52.50	60.0	67.5	75.0
	V_v	12.02	11.88	12.69	14.20
.20	$\left[\frac{D}{L}\right]_R = \tan \gamma$	.151	.135	.130	.135
	V_h	70.0	80.0	90.0	100.0
	V_v	10.57	10.80	11.70	13.50
.25	$\left[\frac{D}{L}\right]_R = \tan \gamma$	.111	.103	.101	.105
	V_h	87.50	100.0	112.5	125.0
	V_v	9.71	10.30	11.36	13.12

FIGURE 11

MODEL XH-20 ROTOR

VARIATION OF RATE OF DESCENT WITH
HORIZONTAL VELOCITY AND TIP SPEED

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.0435

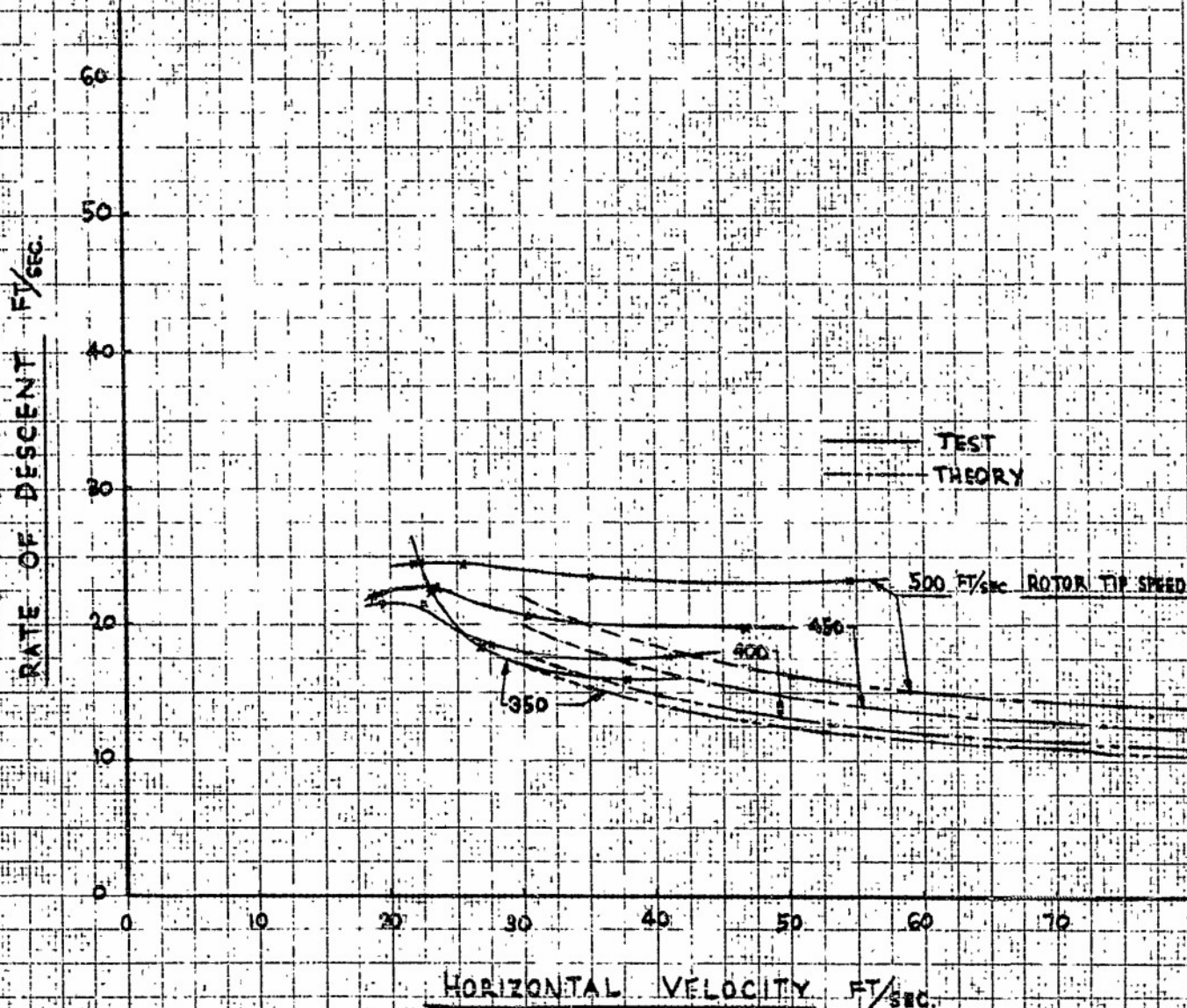


FIGURE 12

MODEL X28 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS * 6 & * 27 (MOD. EXIT * 2)

ROTOR ANGLE = 23°

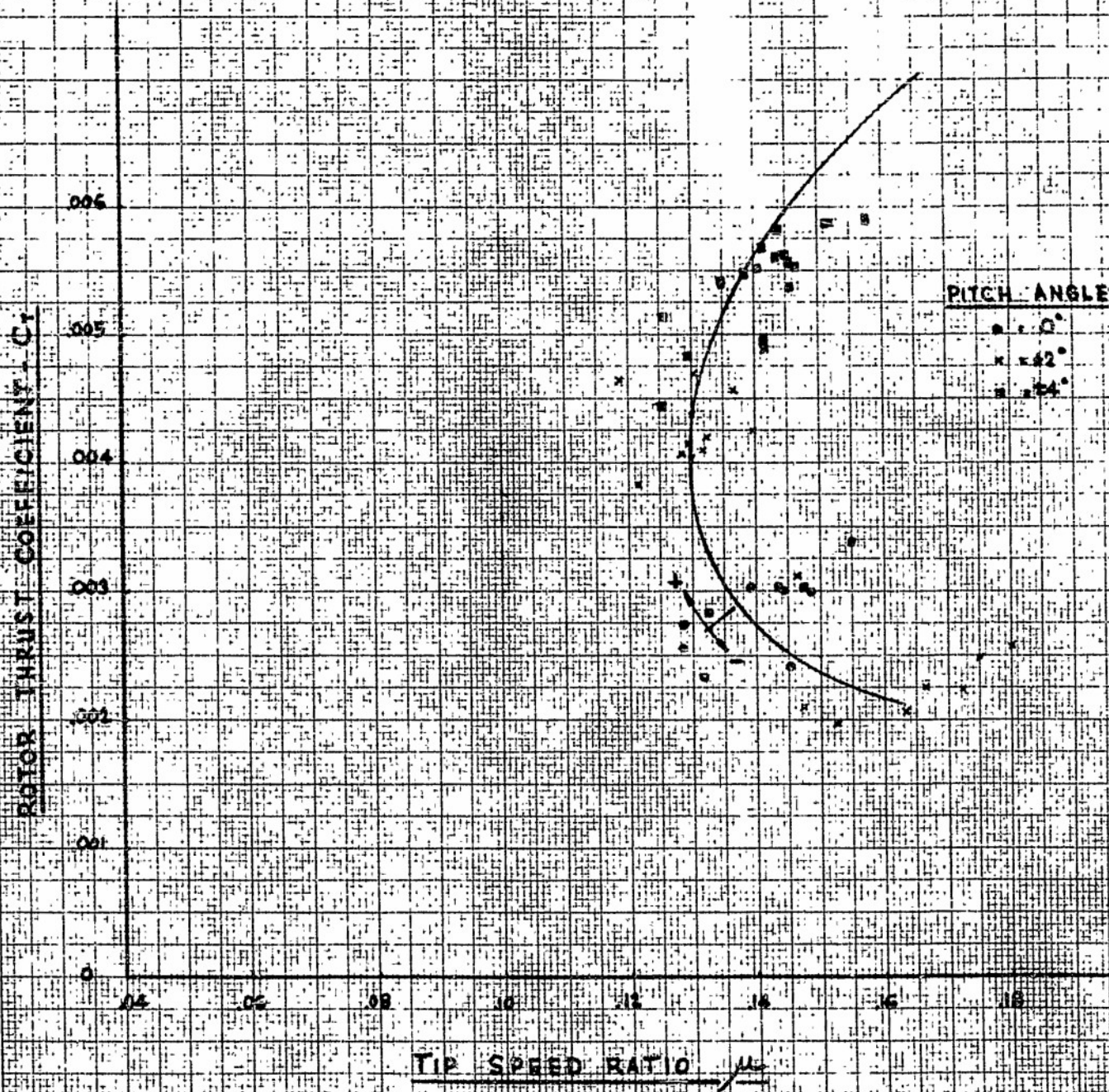


FIGURE 13

MODEL 113 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS #26 & 27 [MOD. EXIT #2]

ROTOR ANGLE = 34°

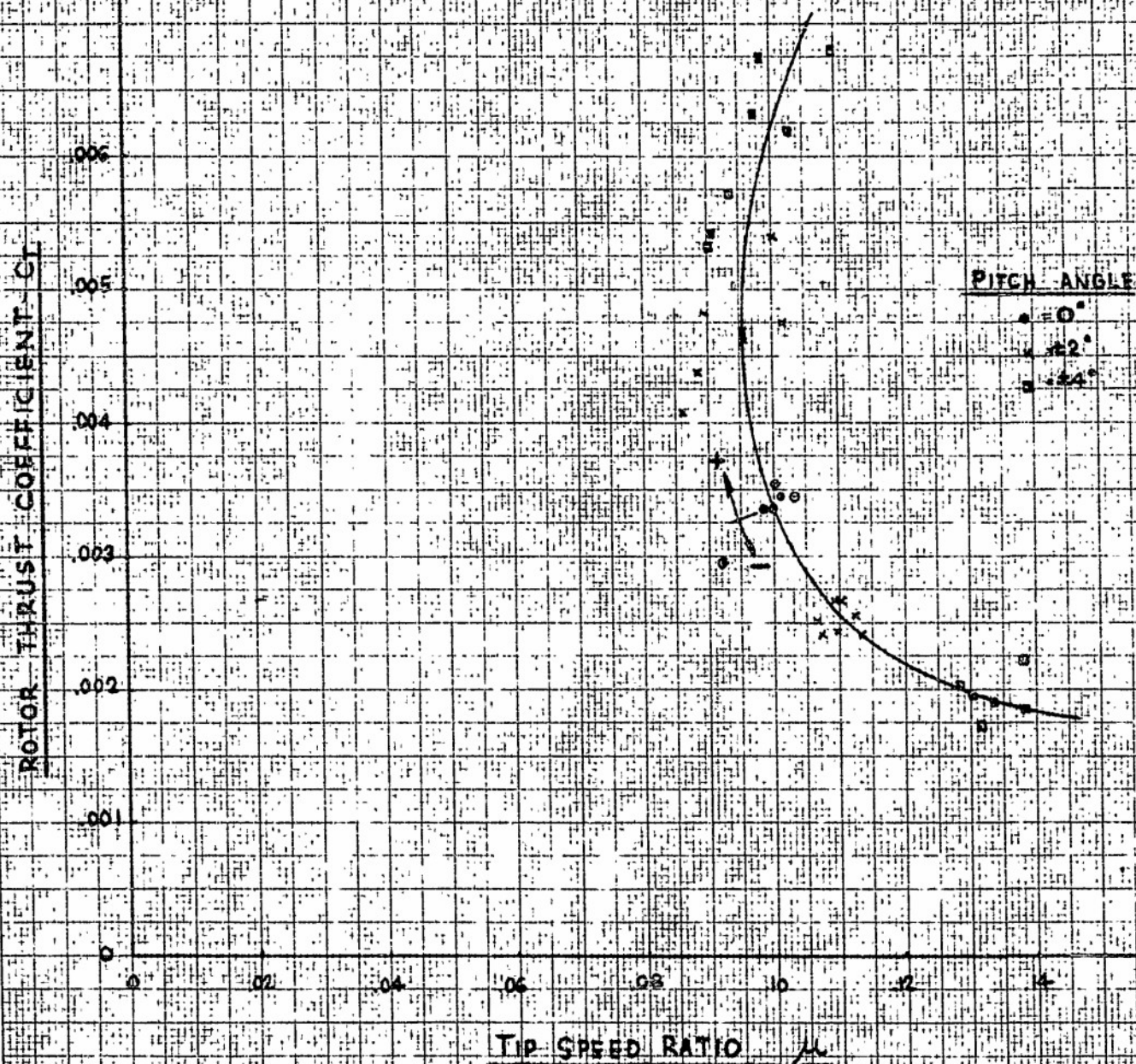


FIGURE 14

MODEL XH20 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS #26 & #27 [MOD. EXIT #2]

ROTOR ANGLE = 44°

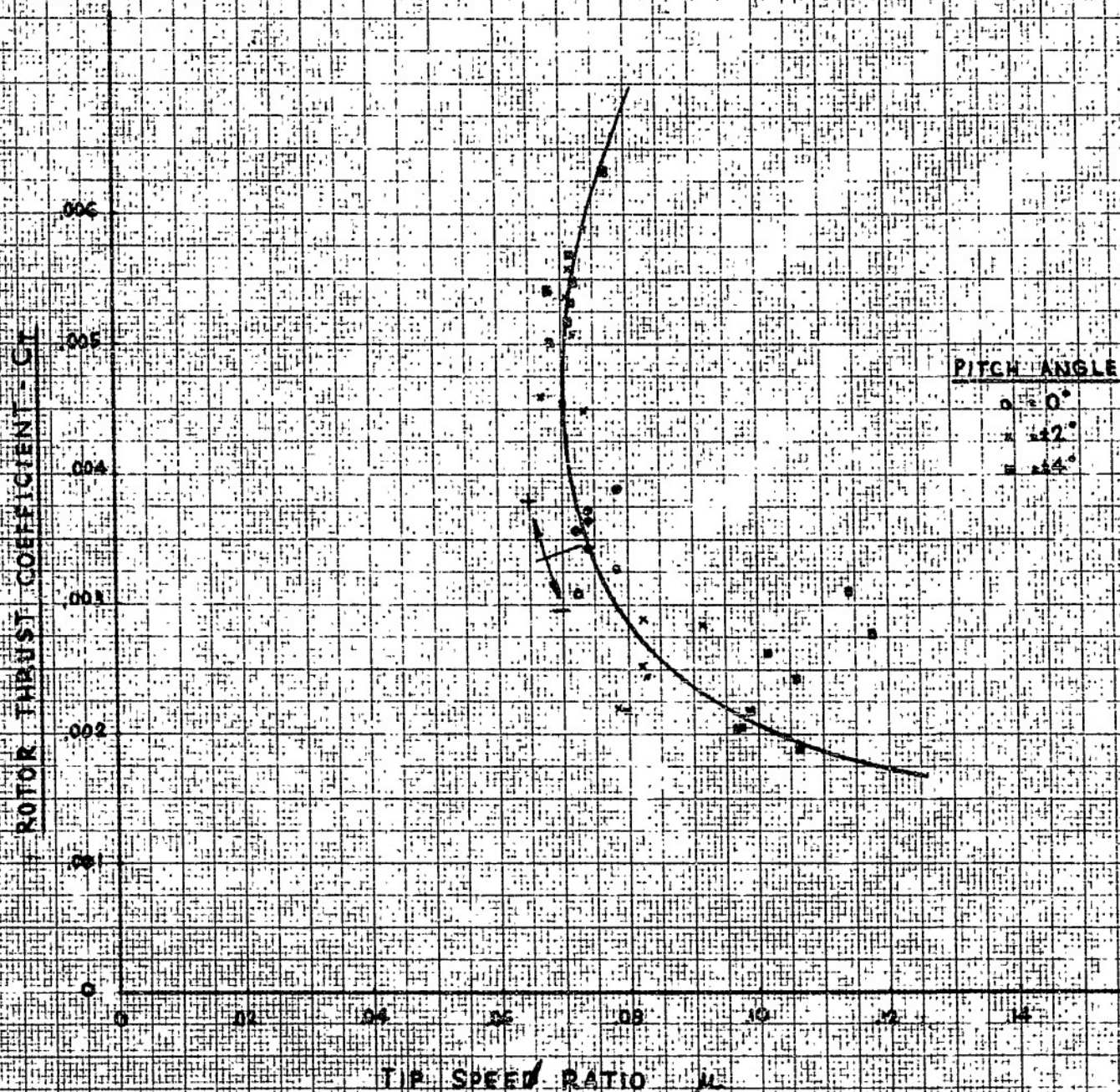


FIGURE 15

MODEL IN-2 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS #26 & #27 [MOD. EXIT #2]

ROTOR ANGLE = 53°

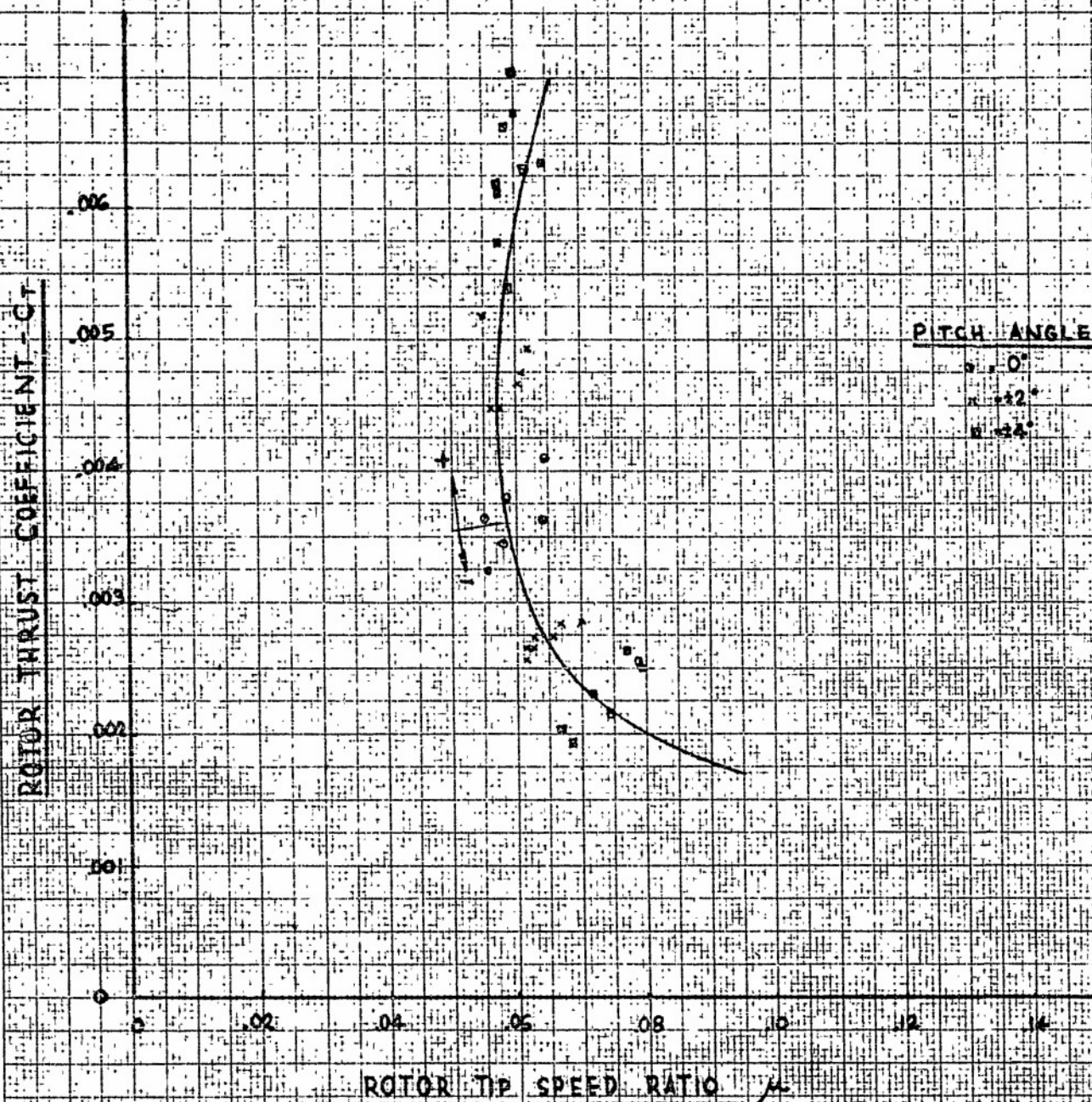


FIGURE 16

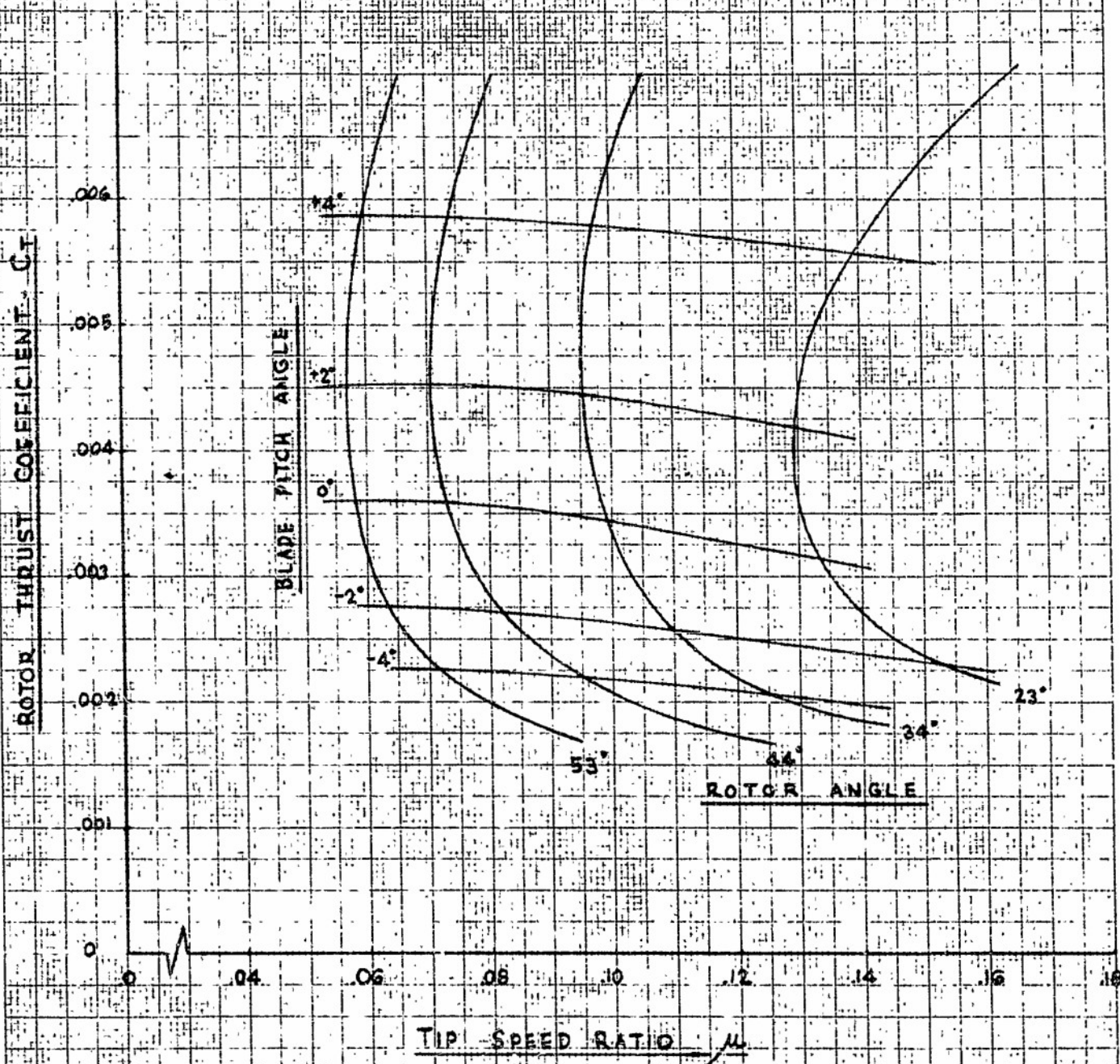
MODEL XH-20 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO & ROTOR ANGLE

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS #26 & #27 MOD. EXIT #2



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MODEL _____

TABLE 3

Theoretical Dimensional Plot for Rate of Descent

Gross Weight = 550 pounds

Rotor Diameter = 20 feet

Rotor Solidity = .0435

Ram Jet CD_J = .000122

μ	ΩR	350	400	450	500
	C_T	.00601	.00461	.00364	.00295
	C_T/σ	.139	.106	.084	.0678
.10	$\left[\frac{D}{L}\right]_R$	.440	.370	.335	.323
	$2\left[\frac{D}{L}\right]_J$	.206	.270	.334	.424
	$\tan \gamma$	.646	.640	.669	.757
.15	$\left[\frac{D}{L}\right]_R$	.230	.196	.186	.188
	$2\left[\frac{D}{L}\right]_J$	.140	.182	.224	.287
	$\tan \gamma$	.370	.380	.410	.475
.20	$\left[\frac{D}{L}\right]_R$	.151	.136	.130	.135
	$2\left[\frac{D}{L}\right]_J$	.108	.140	.173	.220
	$\tan \gamma$	.259	.276	.303	.355
.25	$\left[\frac{D}{L}\right]_R$	.111	.103	.101	.105
	$2\left[\frac{D}{L}\right]_J$	.088	.116	.144	.184
	$\tan \gamma$	.189	.219	.245	.289
.10	V_H	55	40	45	50
	V_V	22.6	25.6	30.1	37.9
.15	V_H	52.5	60	67.5	75.
	V_V	19.4	22.8	27.7	35.6
.20	V_H	70	80	90	100
	V_V	18.1	22.1	27.3	35.5
.25	V_H	87.5	100	112.5	125
	V_V	17.4	21.9	27.6	36.1

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TABLE 4
Test Dimensional Plot for Rate of Descent
Gross Weight = 550 pounds
Rotor Dia. = 20 feet
Rotor Solid. = .0435
Ram Jets #26 and #27 with modified exit #2

γ	ΩP	350	400	450	500
	C_T	.00601	.00461	.00364	.00295
23°	μ	.145	.1305	.1298	.136
	V_h	50.6	52.1	58.4	68.0
	V_v	21.5	22.1	24.8	28.9
34°	μ	.0982	.0955	.098	.104
	V_h	34.4	38.2	44.1	52.0
	V_v	23.2	25.8	29.7	35.1
44°	μ	.0745	.0705	.0725	.0785
	V_h	26.1	28.2	32.6	39.2
	V_v	25.2	27.2	31.5	37.8
53°	μ	.060	.057	.058	.0615
	V_h	21.0	22.8	26.1	30.7
	V_v	27.9	30.2	34.6	40.8

FIGURE 17

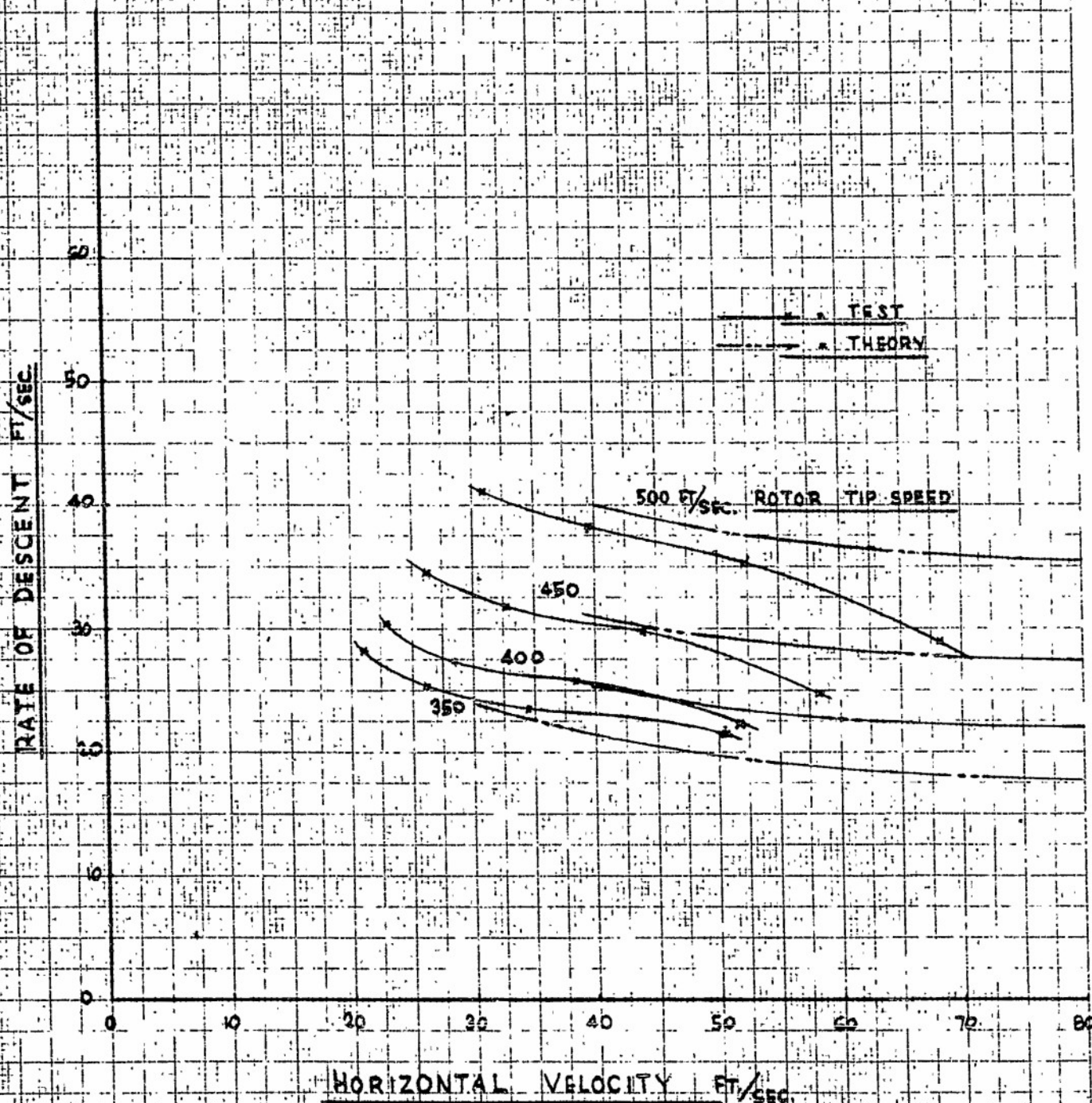
MODEL XH-20 ROTOR AND RAMJETS

VARIATION OF RATE OF DESCENT WITH
HORIZONTAL VELOCITY AND TIP SPEED

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.435

RAMJETS #26 & #27 (MOD. EXIT #2)



MODEL XH-35 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO FOR

ROTOR DIA. = 10 FT.

ROTOR SOLIDITY = 0.531

RAMJETS #26 & #27 MOD. EXIT #2

ROTOR ANGLE = 23°

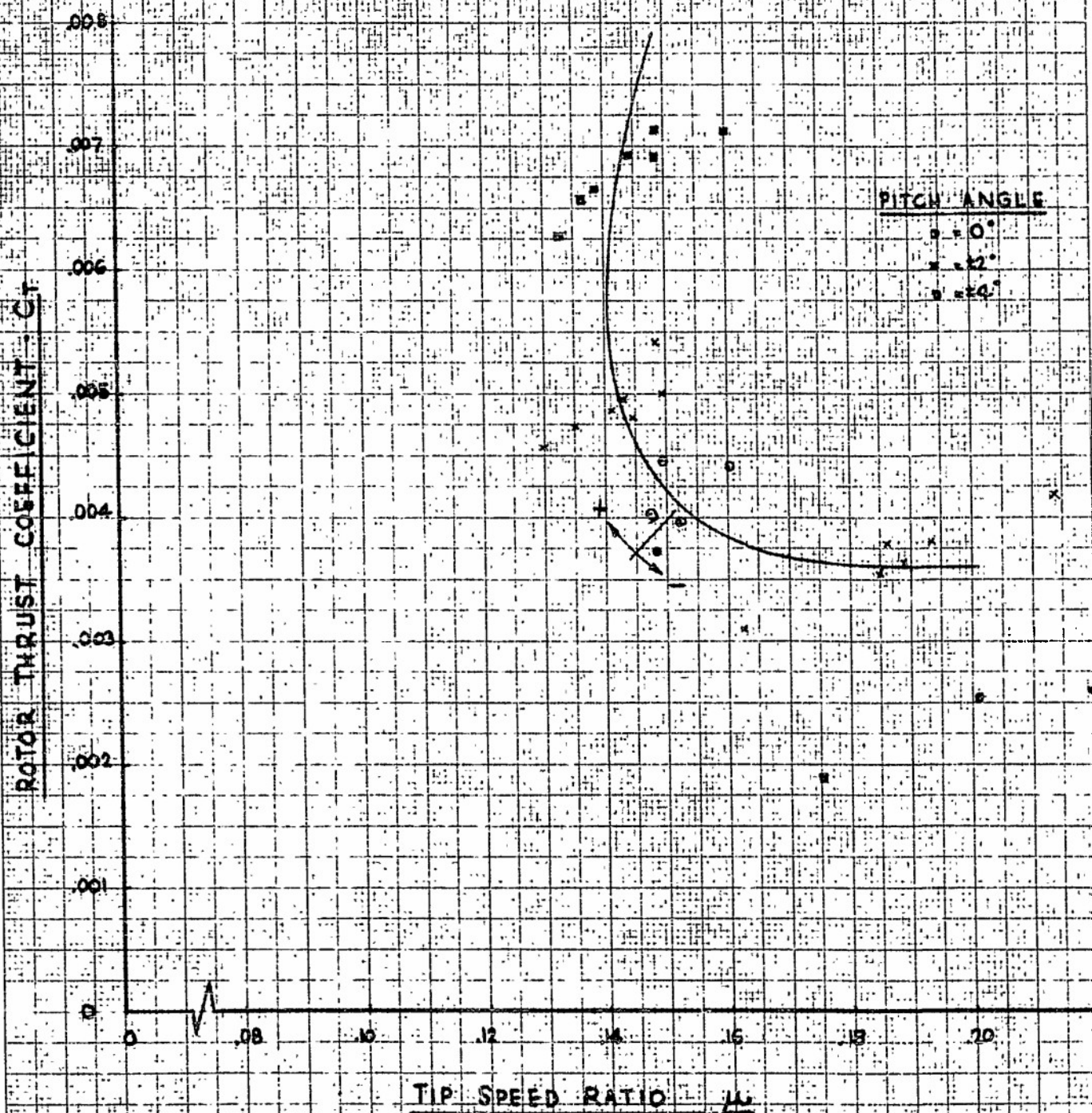


FIGURE 12

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MODELING ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT

WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.531

RAMJETS #26 & #27 (NO EXIT #2)

ROTOR ANGLE = 34°

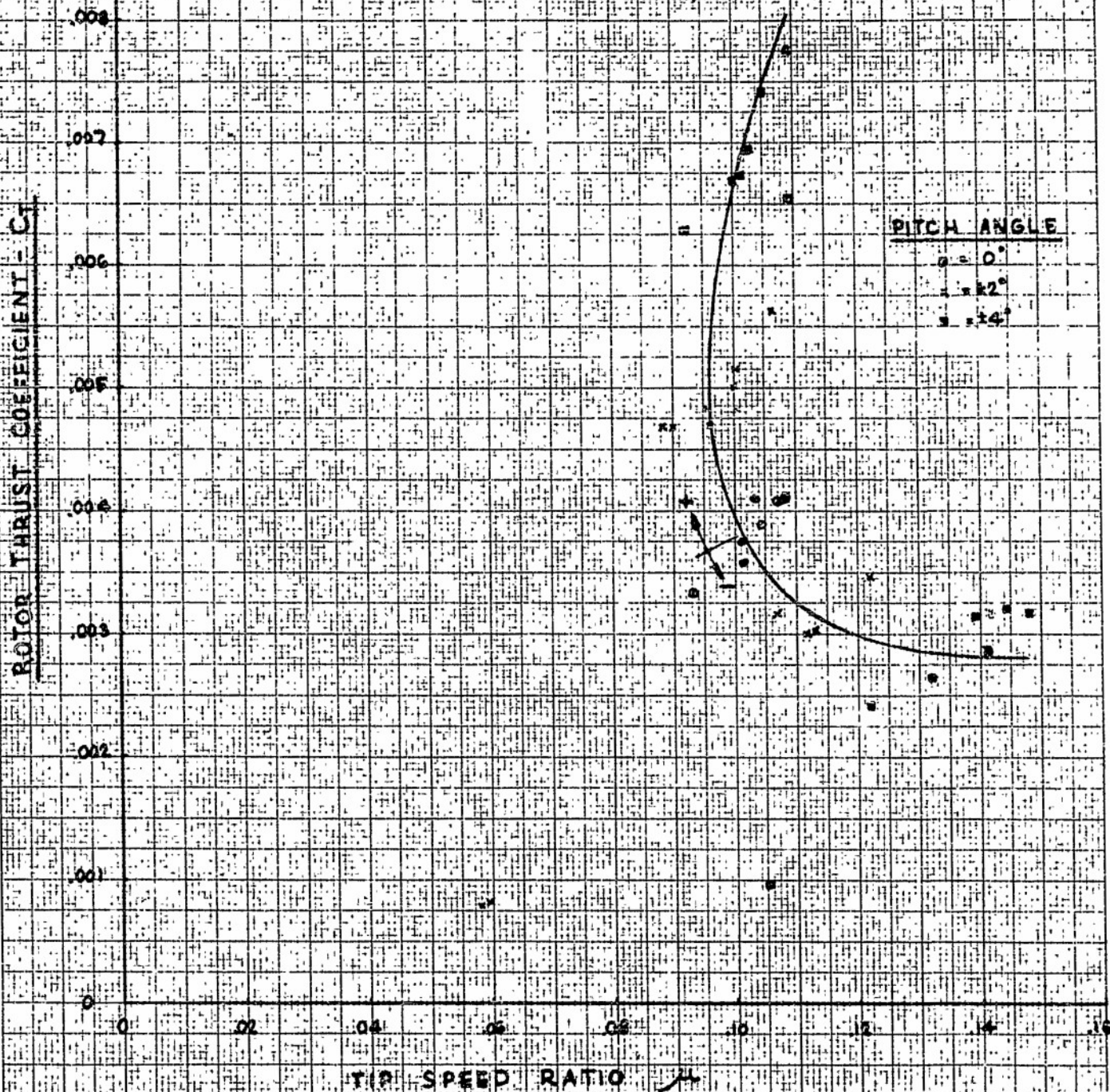


FIGURE 20

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MODEL M-20 ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT

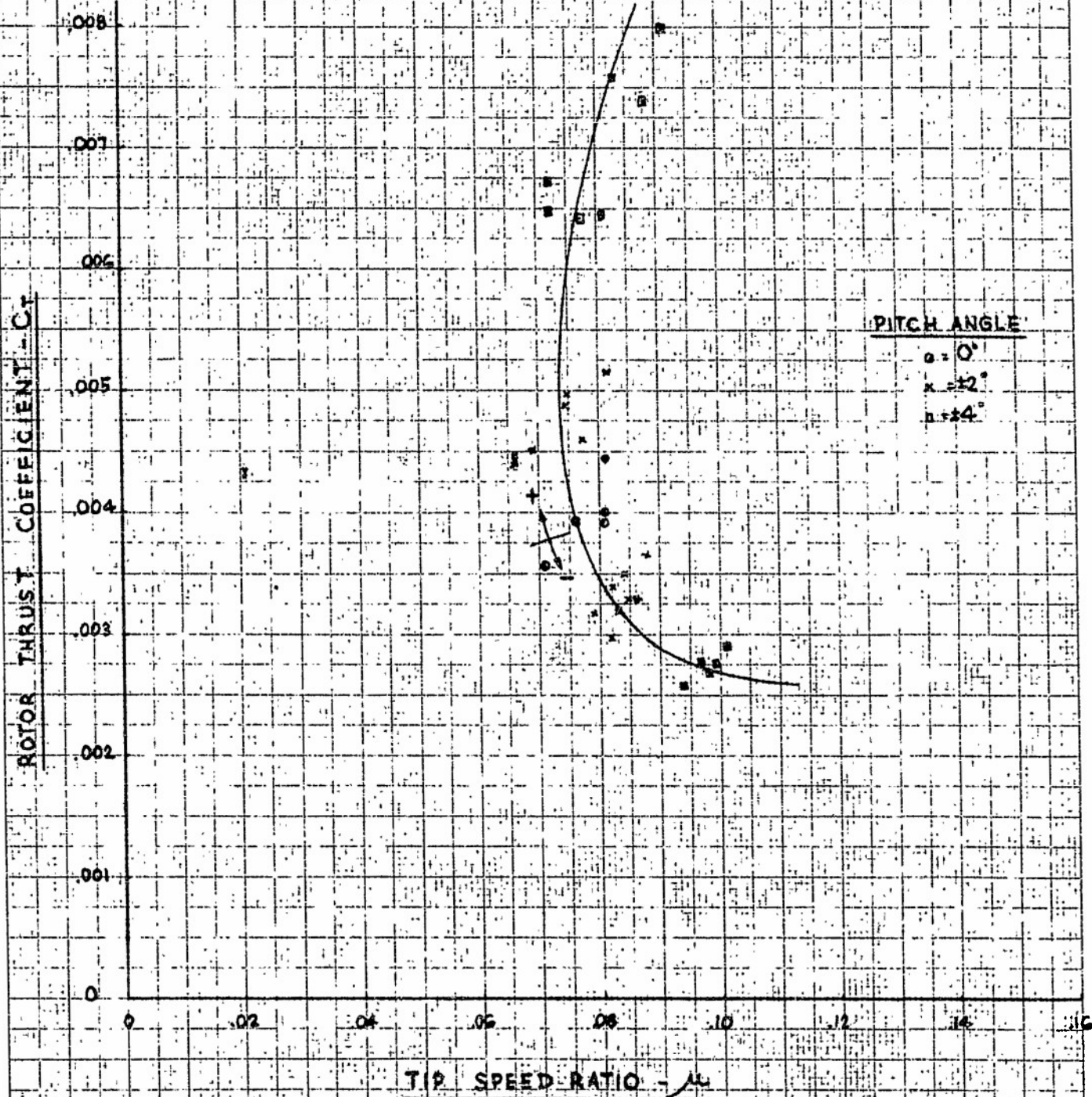
WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 IN.

ROTOR SOLIDITY = 0.0531

RAMJETS #26 & #27 (MOD. EXIT #2)

ROTOR ANGLE = 44°



MODEL X-29 ROTOR AND RAMJETS

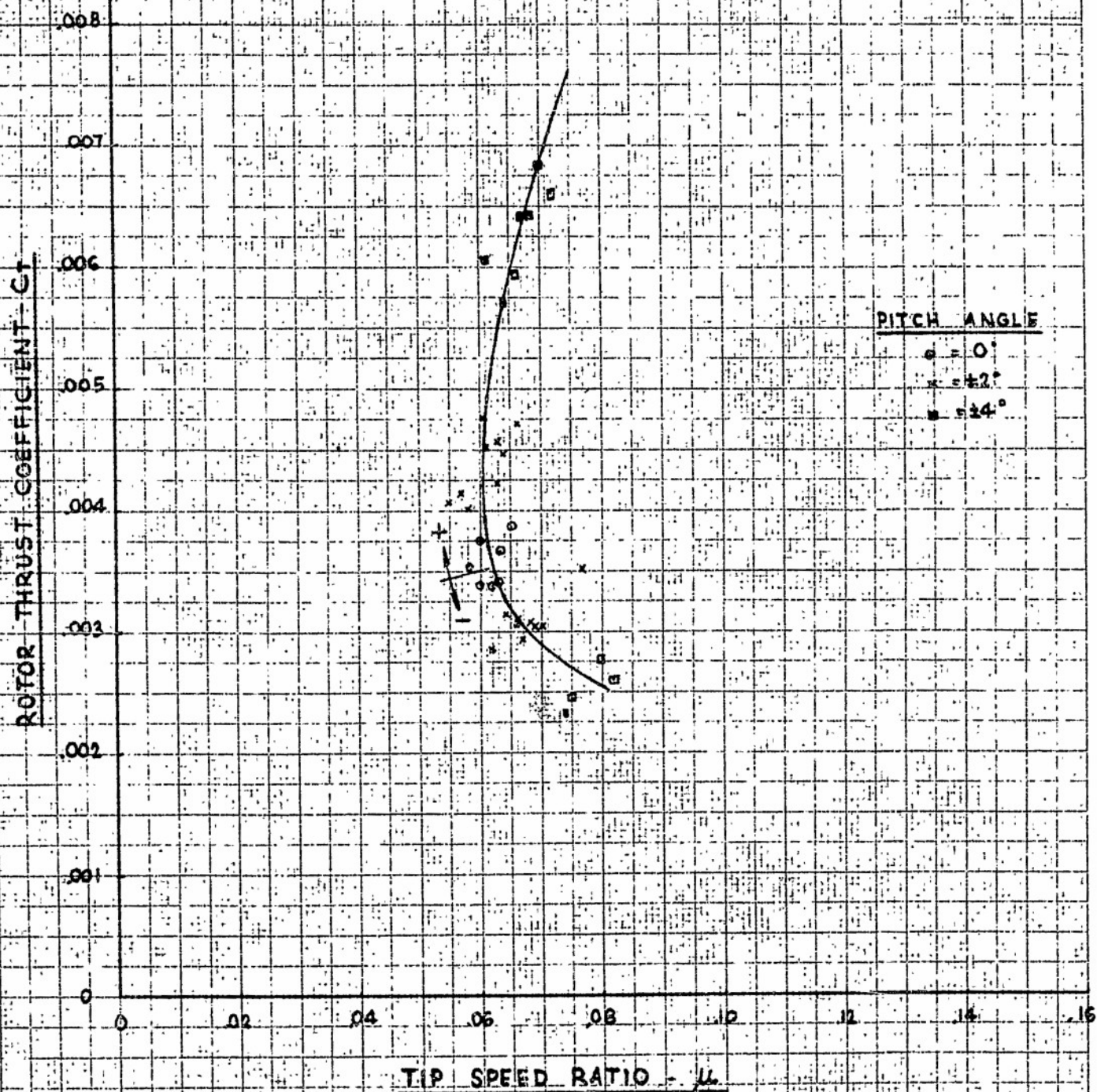
VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO FOR

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = .0531

RAMJETS #26 & #27 MOD. EXIT #2

ROTOR ANGLE = 53°



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TABLE 6

Test Dimensional Plot for Rate of Descent

Gross Weight = 550 pounds

Rotor Diameter = 20 feet

Rotor Solidity = 0.031

Ram Jets #26 and #27 (Mod. exit #2)

γ	ΩR	350	400	450	500
	C_T	.00601	.00461	.00364	.00295
23°	μ	.141	.152	.17	
	V_h	49.3	60.7	76.4	
	V_v	20.9	25.8	32.4	
34°	μ	.098	.0972	.1038	.123
	V_h	34.3	38.9	46.6	61.5
	V_v	23.1	26.2	31.4	41.5
44°	μ	.073	.074	.078	.089
	V_h	26.2	29.6	35.1	44.5
	V_v	25.3	28.6	33.9	43.0
53°	μ	.0646	.0608	.0615	.0685
	V_h	22.6	24.3	27.7	34.2
	V_v	30.0	32.2	36.8	46.4

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TABLE 6

Theoretical Dimensional Plot for Rate of Descent

Gross Weight = 550 pounds
 Rotor Diameter = 20 feet
 Rotor Solidity = .0531
 Ram jet C_{Dj} = .000122

μ	$n R$	350	400	450	500
	C_T	.00601	.00461	.00364	.00295
	C_T/σ	.1132	.0868	.0704	.0555
.10	$\left[\frac{D}{L}\right]_R$	.435	.382	.356	.348
	$2\left[\frac{D}{L}\right]_J$	2(.104)	2(.136)	2(.163)	2(.214)
	$\tan \gamma$	.643	.654	.682	.776
.15	$\left[\frac{D}{L}\right]_R$	.230	.210	.205	.210
	$2\left[\frac{D}{L}\right]_J$	2(.070)	2(.092)	2(.114)	2(.143)
	$\tan \gamma$	.370	.394	.433	.496
.20	$\left[\frac{D}{L}\right]_R$	.153	.140	.142	.152
	$2\left[\frac{D}{L}\right]_J$	2(.054)	2(.071)	2(.086)	2(.112)
	$\tan \gamma$	.261	.282	.314	.376
.25	$\left[\frac{D}{L}\right]_R$	.112	.108	.110	.118
	$2\left[\frac{D}{L}\right]_J$	2(.044)	2(.059)	2(.083)	2(.092)
	$\tan \gamma$	.200	.226	.276	.302
.10	V_H	35	40	45	50
	V_V	22.5	25.2	30.7	38.8
.15	V_H	52.5	60	67.5	75
	V_V	19.4	23.7	29.2	37.2
.20	V_H	70	80	90	100
	V_V	18.25	22.6	28.3	37.6
.25	V_H	87.5	100	112.5	125
	V_V	17.5	22.6	31.1	37.8

FIGURE 22

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MODEL AND ROTOR AND RAMJETS

VARIATION OF ROTOR THRUST COEFFICIENT
WITH TIP SPEED RATIO AND ROTOR ANGLE

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.531

RAMJETS #26 & #27 MOD. EXIT #2

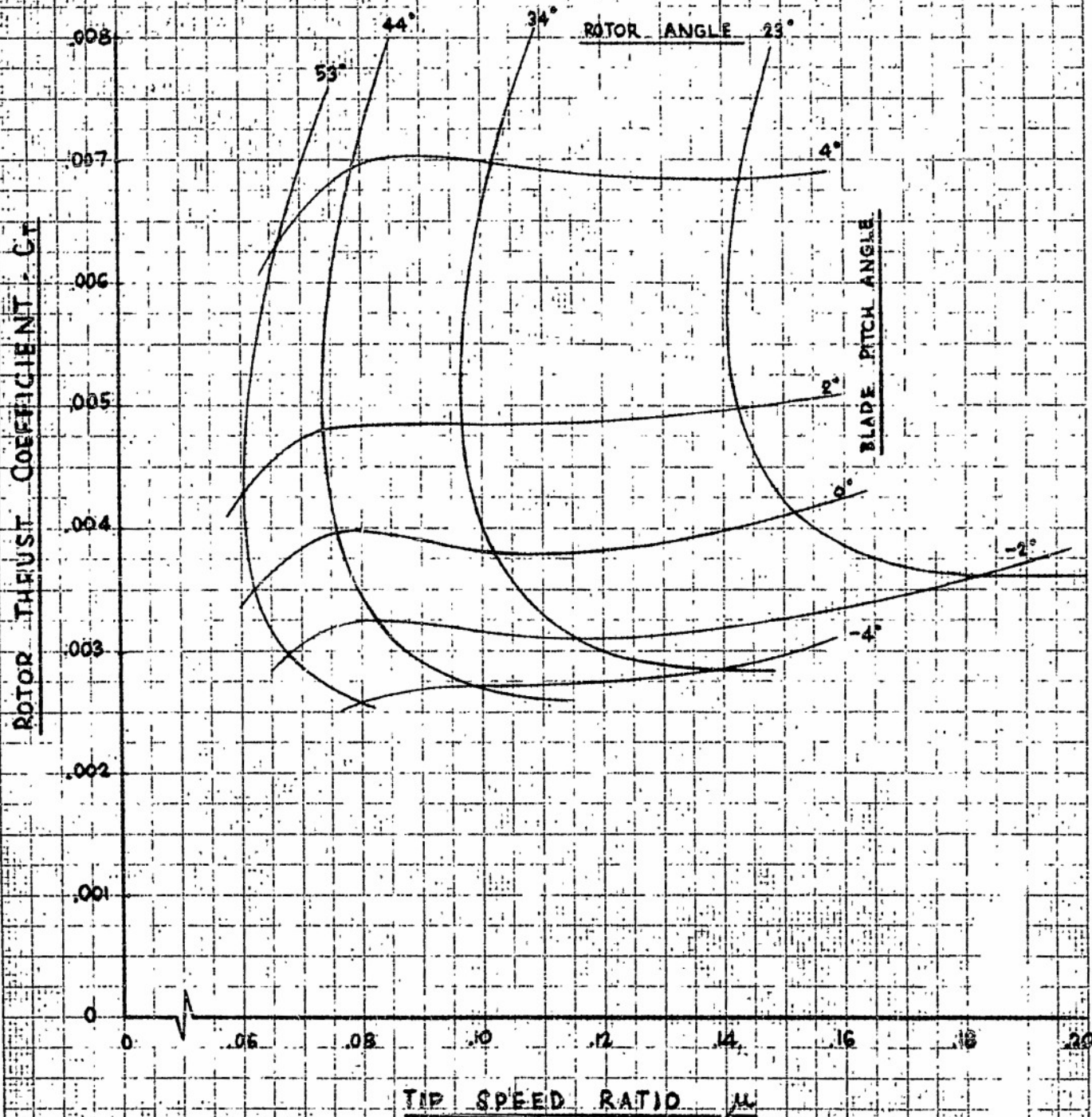


FIGURE 23

MODEL YH10, ROTOR AND RAMJETS

VARIATION OF RATE OF DESCENT WITH
HORIZONTAL VELOCITY AND TIP SPEED

ROTOR DIA. = 20 FT.

ROTOR SOLIDITY = 0.531

RAMJETS #26 & #27 [MOD. EXIT #2]

RAMJET DRAG COEFFICIENT = 0.00022

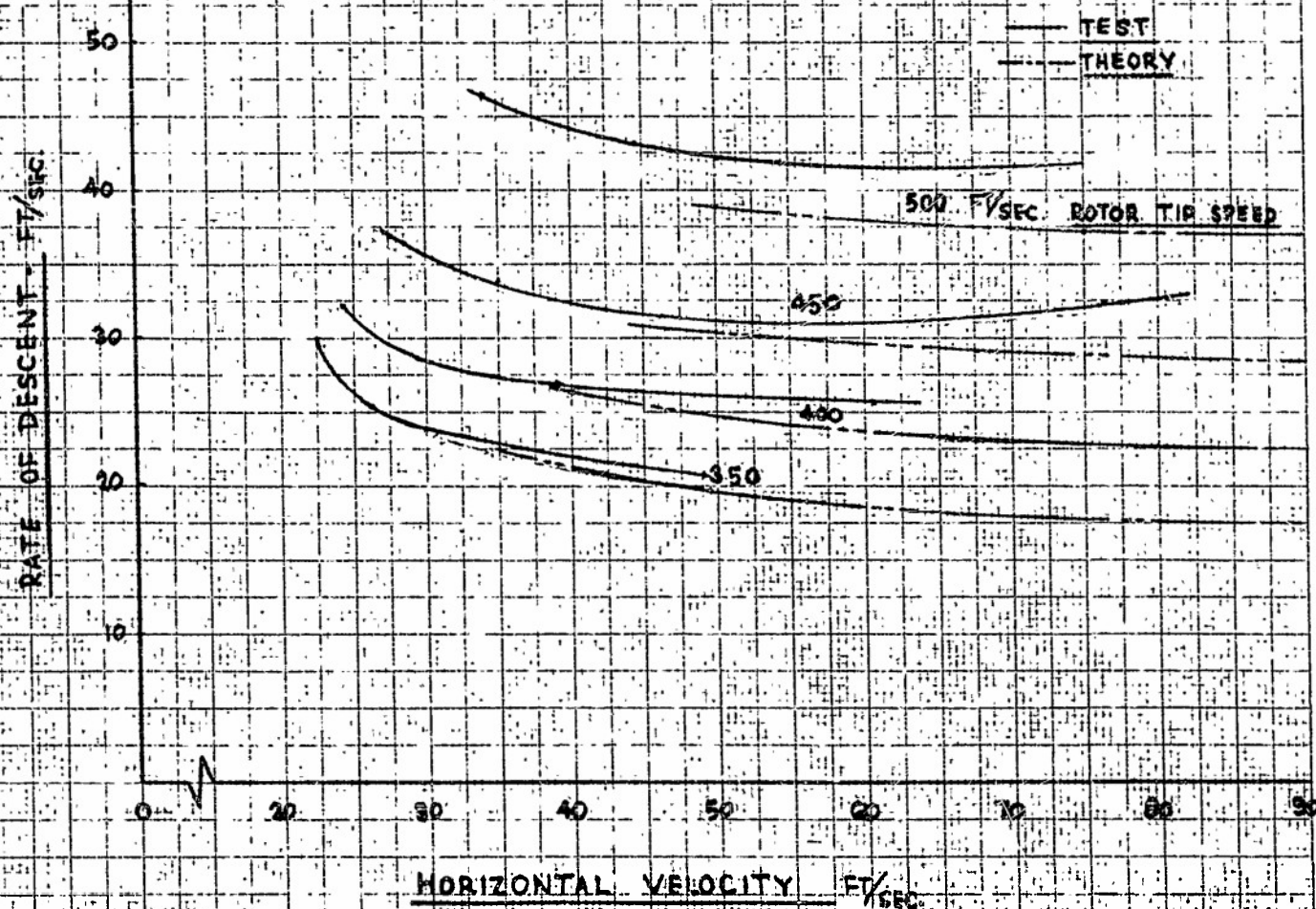


FIGURE 24

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KEUFFEL & ESSER CO.

No 359-14. Millimeters, 5 mm lines accented, mm lines heavy.
"ACE" U. S. A.

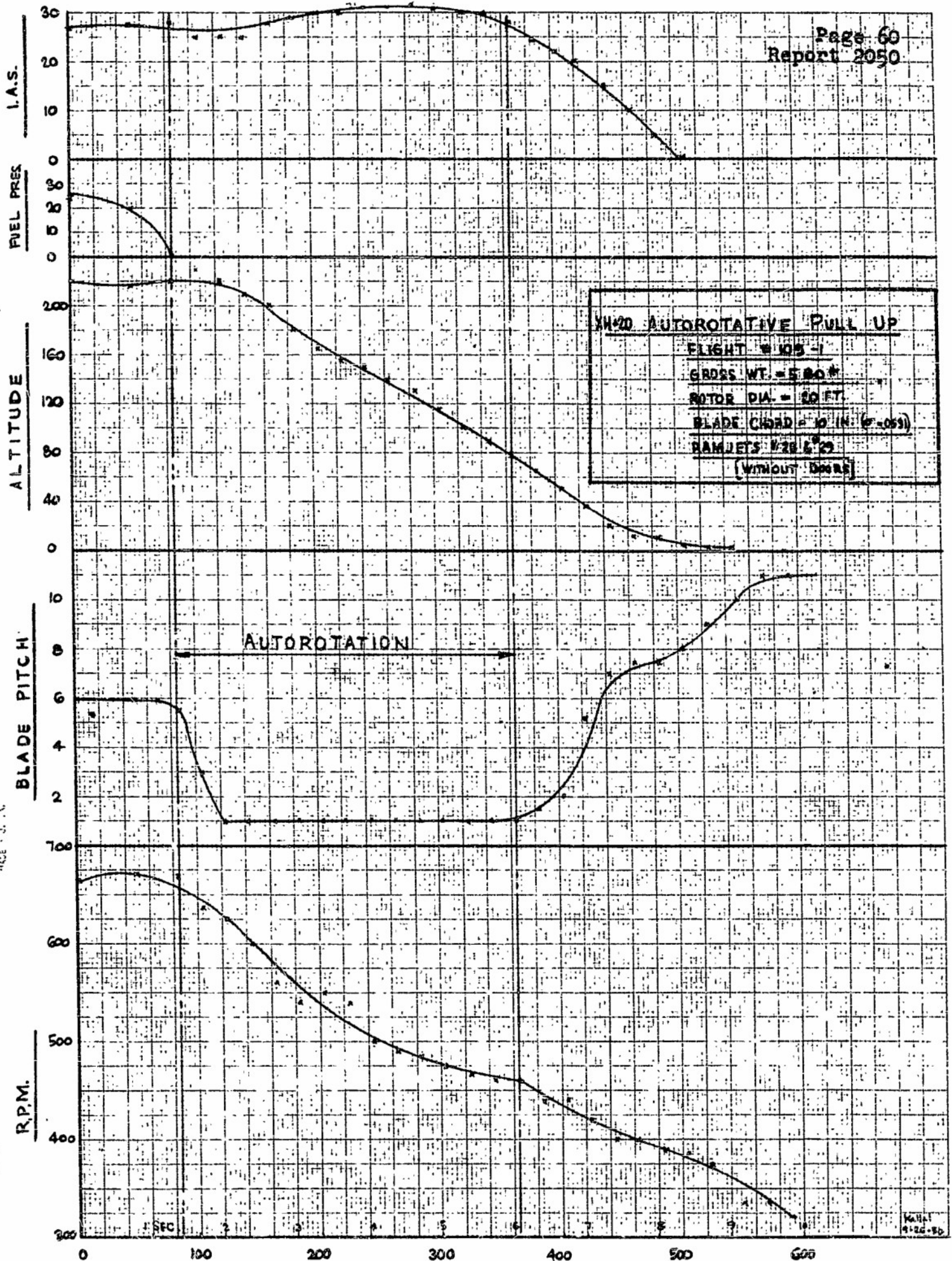


FIGURE 25

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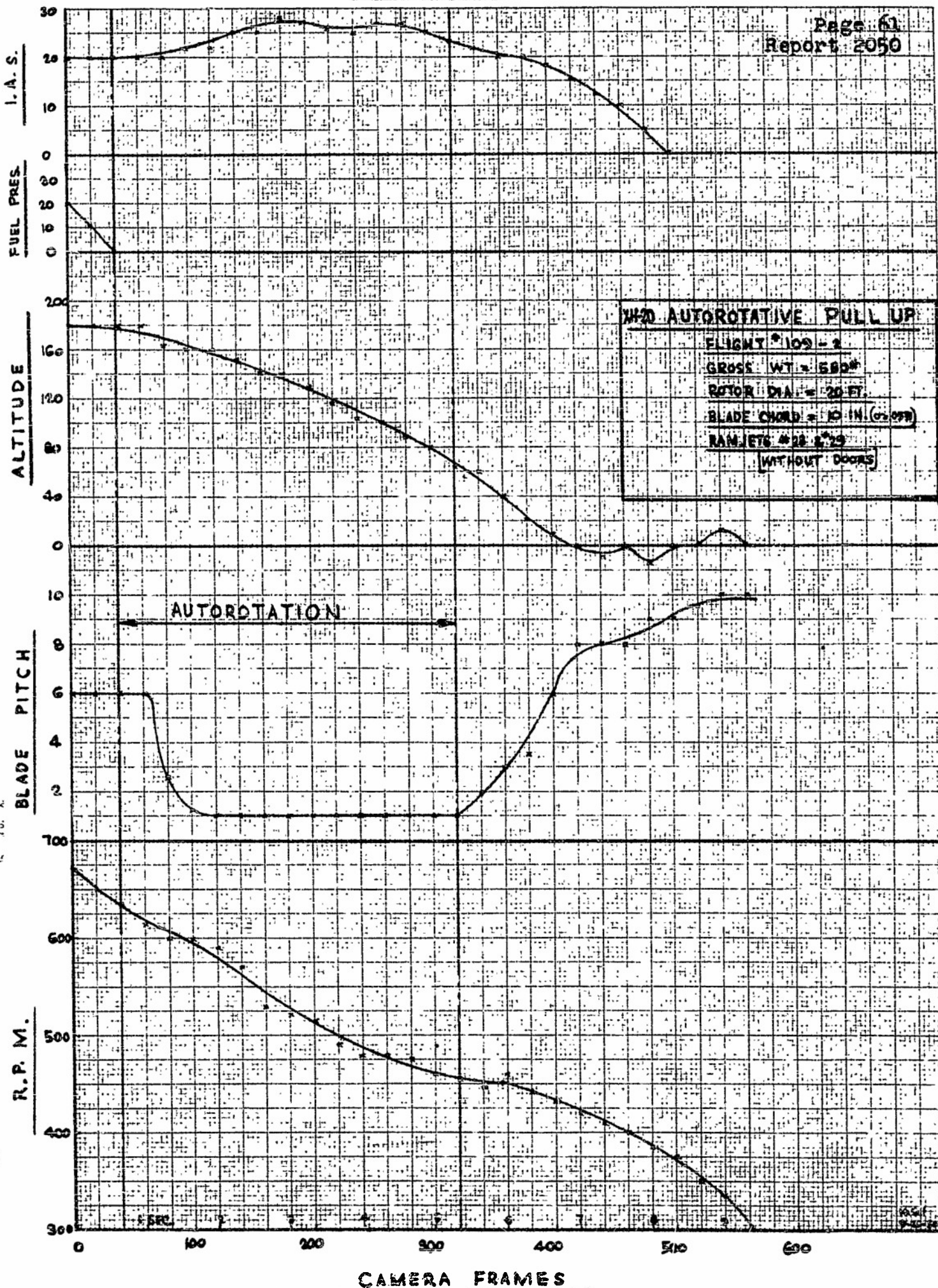


FIGURE 26

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KEUFFEL & ESSER CO.

No. 359-14. Millimeters, 5 mm lines accented, cm lines heavy.

MADE IN U.S.A.

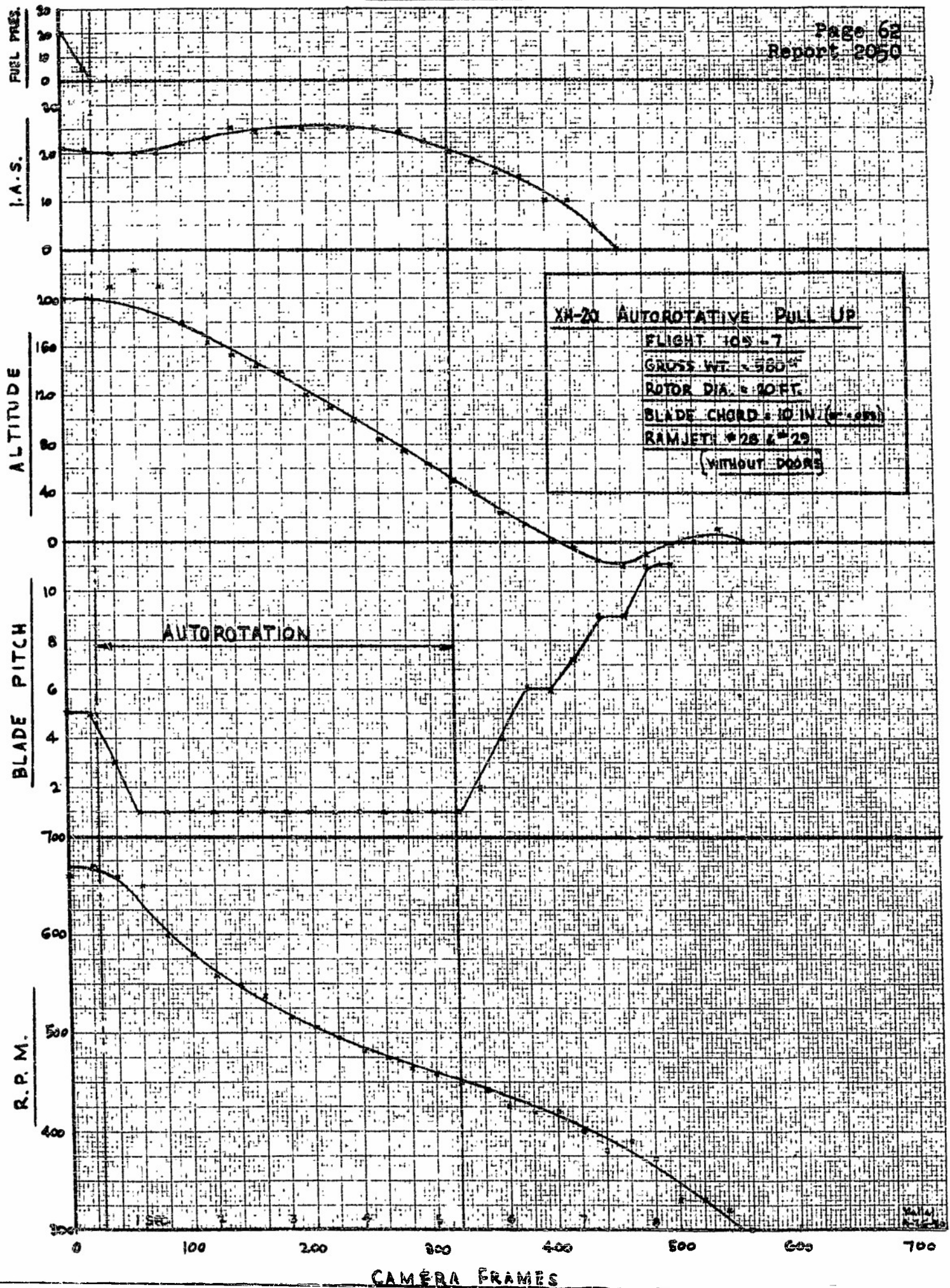


FIGURE 21

KEUFFEL & ESSER CO.

7. 359-14. 1/4 in. high, 5 in. in diameter, 10 in. in length, 10 in. in weight.

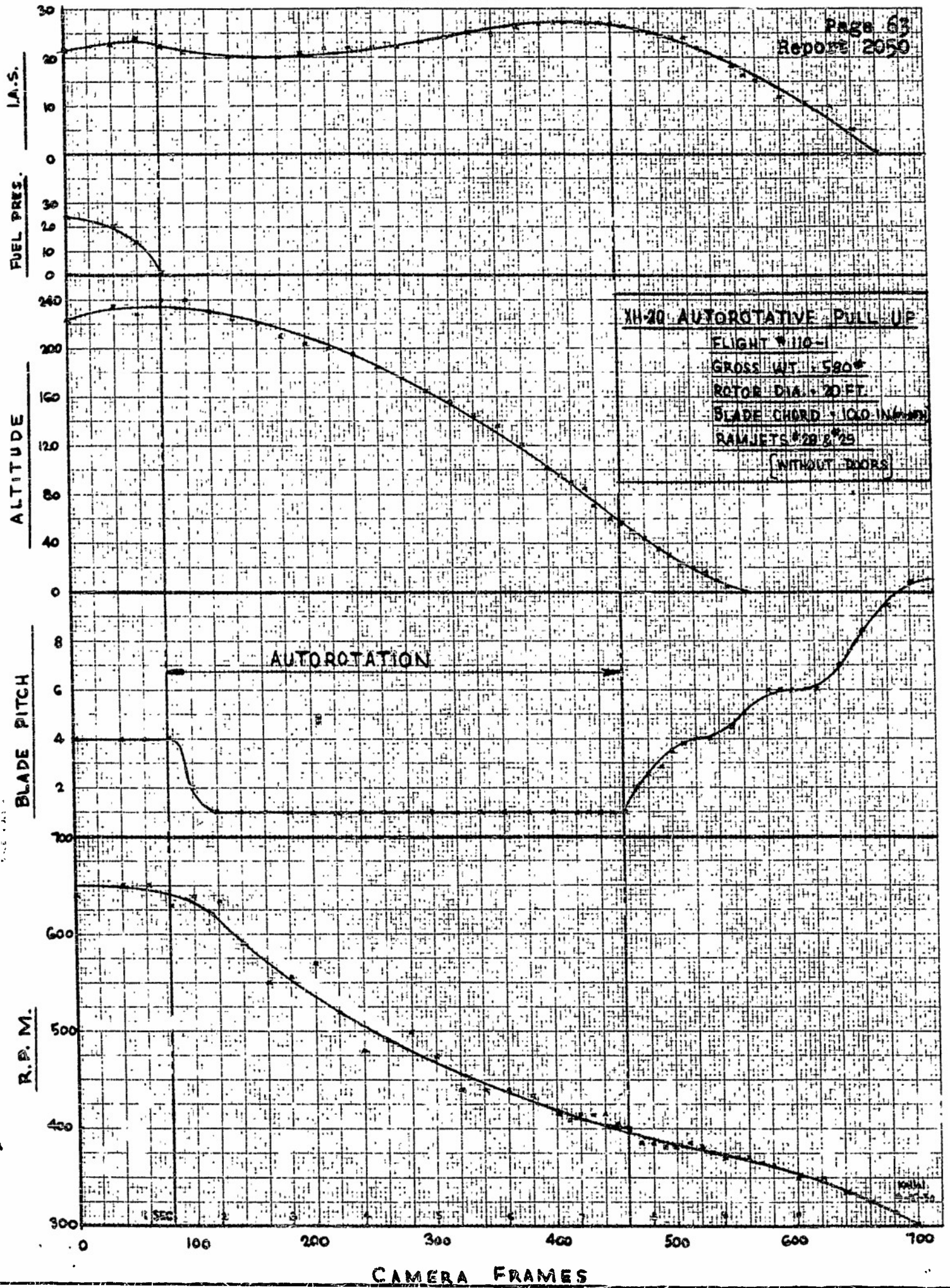


FIGURE 28

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KEUFFEL & ESSER CO.

No. 359-14. Millimeter lines, 5 p. n lines, 10 lines, 20 lines, 40 lines, 80 lines, 160 lines, 320 lines, 640 lines, 1280 lines, 2560 lines, 5120 lines, 10240 lines, 20480 lines, 40960 lines, 81920 lines, 163840 lines, 327680 lines, 655360 lines, 1310720 lines, 2621440 lines, 5242880 lines, 10485760 lines, 20971520 lines, 41943040 lines, 83886080 lines, 167772160 lines, 335544320 lines, 671088640 lines, 1342177280 lines, 2684354560 lines, 5368709120 lines, 10737418240 lines, 21474836480 lines, 42949672960 lines, 85899345920 lines, 171798691840 lines, 343597383680 lines, 687194767360 lines, 1374389534720 lines, 2748779069440 lines, 5497558138880 lines, 10995116277760 lines, 21990232555520 lines, 43980465111040 lines, 87960930222080 lines, 175921860444160 lines, 351843720888320 lines, 703687441776640 lines, 1407374883553280 lines, 2814749767106560 lines, 5629499534213120 lines, 11258999068426240 lines, 22517998136852480 lines, 45035996273704960 lines, 90071992547409920 lines, 180143985094819840 lines, 360287970189639680 lines, 720575940379279360 lines, 1441151880758558720 lines, 2882303761517117440 lines, 5764607523034234880 lines, 11529215046068469760 lines, 23058430092136939520 lines, 46116860184273879040 lines, 92233720368547758080 lines, 184467440737095516160 lines, 368934881474191032320 lines, 737869762948382064640 lines, 1475739525896764129280 lines, 2951479051793528258560 lines, 5902958103587056517120 lines, 11805916207174113034240 lines, 23611832414348226068480 lines, 47223664828696452136960 lines, 94447329657392904273920 lines, 188894659314785808547840 lines, 377789318629571617095680 lines, 755578637259143234191360 lines, 1511157274518286468382720 lines, 3022314549036572936765440 lines, 6044629098073145873530880 lines, 12089258196146291747061760 lines, 24178516392292583494123520 lines, 48357032784585166988247040 lines, 96714065569170333976494080 lines, 193428131138340667952988160 lines, 386856262276681335905976320 lines, 773712524553362671811952640 lines, 1547425049106725343623905280 lines, 3094850098213450687247810560 lines, 6189700196426901374495621120 lines, 12379400392853802748991242240 lines, 24758800785707605497982484480 lines, 49517601571415210995964968960 lines, 99035203142830421991929937920 lines, 198070406285660843983859875840 lines, 396140812571321687967719751680 lines, 792281625142643375935439503360 lines, 1584563250285286751870879006720 lines, 3169126500570573503741758013440 lines, 6338253001141147007483516026880 lines, 12676506002282294014967032053760 lines, 25353012004564588029934064107520 lines, 50706024009129176059868128215040 lines, 101412048018258352119736256430080 lines, 202824096036516704239472512860160 lines, 405648192073033408478945025720320 lines, 811296384146066816957890051440640 lines, 1622592768292133633915780102881280 lines, 3245185536584267267831560205762560 lines, 6490371073168534535663120411525120 lines, 12980742146337069071326240823050240 lines, 25961484292674138142652481646100480 lines, 51922968585348276285304963292200960 lines, 103845937170696552570609926584401920 lines, 207691874341393105141219853168803840 lines, 415383748682786210282439706337607680 lines, 830767497365572420564879412675215360 lines, 1661534994731144841129758825350430720 lines, 3323069989462289682259517650700861440 lines, 6646139978924579364519035301401722880 lines, 13292279957849158729038070602803445760 lines, 26584559915698317458076141205606891520 lines, 53169119831396634916152282411213783040 lines, 106338239662793269832304564822427566080 lines, 212676479325586539664609129644855132160 lines, 425352958651173079329218259289710264320 lines, 850705917302346158658436518579420528640 lines, 1701411834604692317316873037158841057280 lines, 3402823669209384634633746074317682114560 lines, 6805647338418769269267492148635364229120 lines, 13611294676837538538534984297270728458240 lines, 27222589353675077077069968594541456916480 lines, 54445178707350154154139937189082913832960 lines, 108890357414700308308279874378165827665920 lines, 217780714829400616616559748756331655331840 lines, 435561429658801233233119497512663310663680 lines, 871122859317602466466238995025326621327360 lines, 1742245718635204932932477990050653242654720 lines, 3484491437270409865864955980101306485309440 lines, 6968982874540819731729911960202612970618880 lines, 13937965749081639463459823920405225941237760 lines, 27875931498163278926919647840810451882475520 lines, 55751862996326557853839295681620903764951040 lines, 111503725992653115707678591363241807529902080 lines, 223007451985306231415357182726483615059804160 lines, 446014903970612462830714365452967230119608320 lines, 892029807941224925661428730905934460239216640 lines, 1784059615882449851322857461811868920478433280 lines, 3568119231764899702645714923623737840956866560 lines, 7136238463529799405291429847247475681913733120 lines, 14272476927059598810582859694494951363827466240 lines, 28544953854119197621165719388989902727654932480 lines, 57089907708238395242331438777979805455309864960 lines, 114179815416476790484662877555959610910619729920 lines, 228359630832953580969325755111919221821239459840 lines, 456719261665907161938651510223838443642478919680 lines, 913438523331814323877303020447676887284957839360 lines, 1826877046663628647754606040895353774569915678720 lines, 3653754093327257295509212081790707549139831357440 lines, 7307508186654514591018424163581415098279662714880 lines, 14615016373309029182036848327162830196559325429760 lines, 29230032746618058364073696654325660393118650859520 lines, 58460065493236116728147393308651320786237301719040 lines, 116920130986472233456294786617302641572474603438080 lines, 233840261972944466912589573234605283144949206876160 lines, 467680523945888933825179146469210566289898413752320 lines, 935361047891777867650358292938421132579796827504640 lines, 1870722095783555735300716585876842265159593655009280 lines, 3741444191567111470601433171753684530319187310018560 lines, 7482888383134222941202866343507369060638374620037120 lines, 14965776766268445882405732687014738121276749240074240 lines, 29931553532536891764811465374029476242553498480148480 lines, 59863107065073783529622930748058952485106996960296960 lines, 119726214130147567059245861496117904970213993920593920 lines, 239452428260295134118491722992235809940427987841187840 lines, 478904856520590268236983445984471619880855975682375680 lines, 957809713041180536473966891968943239761711951364751360 lines, 1915619426082361072947933783937886479523423902729502720 lines, 3831238852164722145895867567875772959046847805459005440 lines, 7662477704329444291791735135751545918093695610918010880 lines, 15324955408658888583583470271503091836187391221836021760 lines, 30649910817317777167166940543006183672374782443672043520 lines, 61299821634635554334333881086012367344749564887344087040 lines, 122599643269271108668667762172024734689499129774688174080 lines, 245199286538542217337335524344049469378998259549376348160 lines, 490398573077084434674671048688098938757996519098752696320 lines, 980797146154168869349342097376197877515993038197505392640 lines, 1961594292308337738698684194752395755031986076395010785280 lines, 3923188584616675477397368389504791510063972152790021570560 lines, 7846377169233350954794736779009583020127944305580043141120 lines, 15692754338466701909589473558019166040255888611160086282240 lines, 31385508676933403819178947116038332080511777222320172564480 lines, 62771017353866807638357894232076664161023554444640345128960 lines, 125542034707733615276715788464153328322047108889280690257920 lines, 251084069415467230553431576928306656644094217778561380515840 lines, 502168138830934461106863153856613313288188435557122761031680 lines, 1004336277661868922213726307713226626576376871114245522063360 lines, 2008672555323737844427452615426453253152753742228491044126720 lines, 4017345110647475688854905230852906506305507484456982088253440 lines, 8034690221294951377709810461705813012611014968913964176506880 lines, 16069380442589902755419620923411626025222029937827928353013760 lines, 32138760885179805510839241846823252050444059875655856706027520 lines, 64277521770359611021678483693646504100888119751311713412055040 lines, 128555043540719222043356967387293008201776239502623426824110080 lines, 257110087081438444086713934774586016403552479005246853648220160 lines, 514220174162876888173427869549172032807104958010493707296440320 lines, 1028440348325753776346855739098344065614209916020987414592880640 lines, 2056880696651507552693711478196688131228419832041974829185761280 lines, 4113761393303015105387422956393376262456839664083949658371522560 lines, 8227522786606030210774845912786752524913679328167899316743045120 lines, 16455045573212060421549691825573505049827358656335798633486090240 lines, 32910091146424120843099383651147010099654717312671597266972180480 lines, 65820182292848241686198767302294020199309434625343194533944360960 lines, 131640364585696483372397534604588040398618869250686389067888721920 lines, 263280729171392966744795069209176080797237738501372778135777443840 lines, 526561458342785933489590138418352161594475477002745556271554887680 lines, 1053122916685571866979180276836704323188950954005491112543109775360 lines, 2106245833371143733958360553673408646377901908010982225086219550720 lines, 4212491666742287467916721107346817292755803816021964450172439101440 lines, 8424983333484574935833442214693634585511607632043928900344878202880 lines, 16849966666969149871666884429387269171023215264087857800689756405760 lines, 33699933333938299743333768858774538342046430528175715601379512811520 lines, 67399866667876599486667537717549076684092861056351431202759025623040 lines, 134799733335753198973335075435098153368185722112702862405518051246080 lines, 269599466671506397946670150870196306736371444225405724811036102492160 lines, 539198933343012795893340301740392613472742888450811449622072204984320 lines, 1078397866686025591786680603480785226945485776901622899244144409968640 lines, 2156795733372051183573361206961570453890971553803245798488288819937280 lines, 4313591466744102367146722413923140907781943107606491596976577639874560 lines, 8627182933488204734293444827846281815563886215212983193953155279749120 lines, 17254365866976409468586889655692563631127772430425966387906310559498240 lines, 34508731733952818937173779311385127262255544860851932775812621118996480 lines, 69017463467905637874347558622770254524511089721703865551625242237992960 lines, 138034926935811275748695117245540509049022179443407731103250484475985920 lines, 276069853871622551497390234491081018098044358886815462206500968951971840 lines, 552139707743245102994780468982162036196088717773630924413001937903943680 lines, 1104279415486490205989560937964324072392177435547261848826003875807887360 lines, 2208558830972980411979121875928648144784354871094523697652007751615774720 lines, 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18092513943330655534932966407607485602073435104006338131165247501236426506240 lines, 36185027886661311069865932815214971204146870208012676262330495002472853012480 lines, 72370055773322622139731865630429942408293740416025352524660990004945706024960 lines, 144740111546645244279463731260859884816587480832050705049321980009891412049920 lines, 289480223093290488558927462521719769633174961664101410098643960019782824099840 lines, 578960446186580977117854925043439539266349923328202820197287920039565648199680 lines, 1157920892373161954235709850086879078532699846656405640394575840079131296399360 lines, 2315841784746323908471419700173758157065399693312811280789151680158262592798720 lines, 4631683569492647816942839400347516314130799386625622561578303360316525185597440 lines, 9263367138985295633885678800695032628261598773251245123156606720633050371194880 lines, 18526734277970591267771357601390065256523197546502490246313213441266100742389760 lines, 37053468555941182535542715202780130513046395093004980492626426882532201484779520 lines, 74106937111882365071085430405560261026092790186009960985252853765064402969559040 lines, 148213874223764730142170860811120522052185580372019921970505707530128805939118080 lines, 296427748447529460284341721622241044104371160744039843941011415060257611878236160 lines, 592855496895058920568683443244482088208742321488079687882022830120515223756472320 lines, 1185710993790117841137366886488964176417484642976159375764045660241030447512944640 lines, 2371421987580235682274733772977928352834969285952318751528091320482060895025889280 lines, 4742843975160471364549467545955856705669938571904637503056182640964121790051778560 lines, 9485687950320942729098935091911713411339877143809275006112365281928243580103557120 lines, 18971375900641885458197870183823426822679754287618550012

FIGURE 29

KEUFFEL & ESSER CO.

No. 359-14. Millimeters, 5 r m lines accepted, cm lines heavy.
SCALE 1/4" = 1"

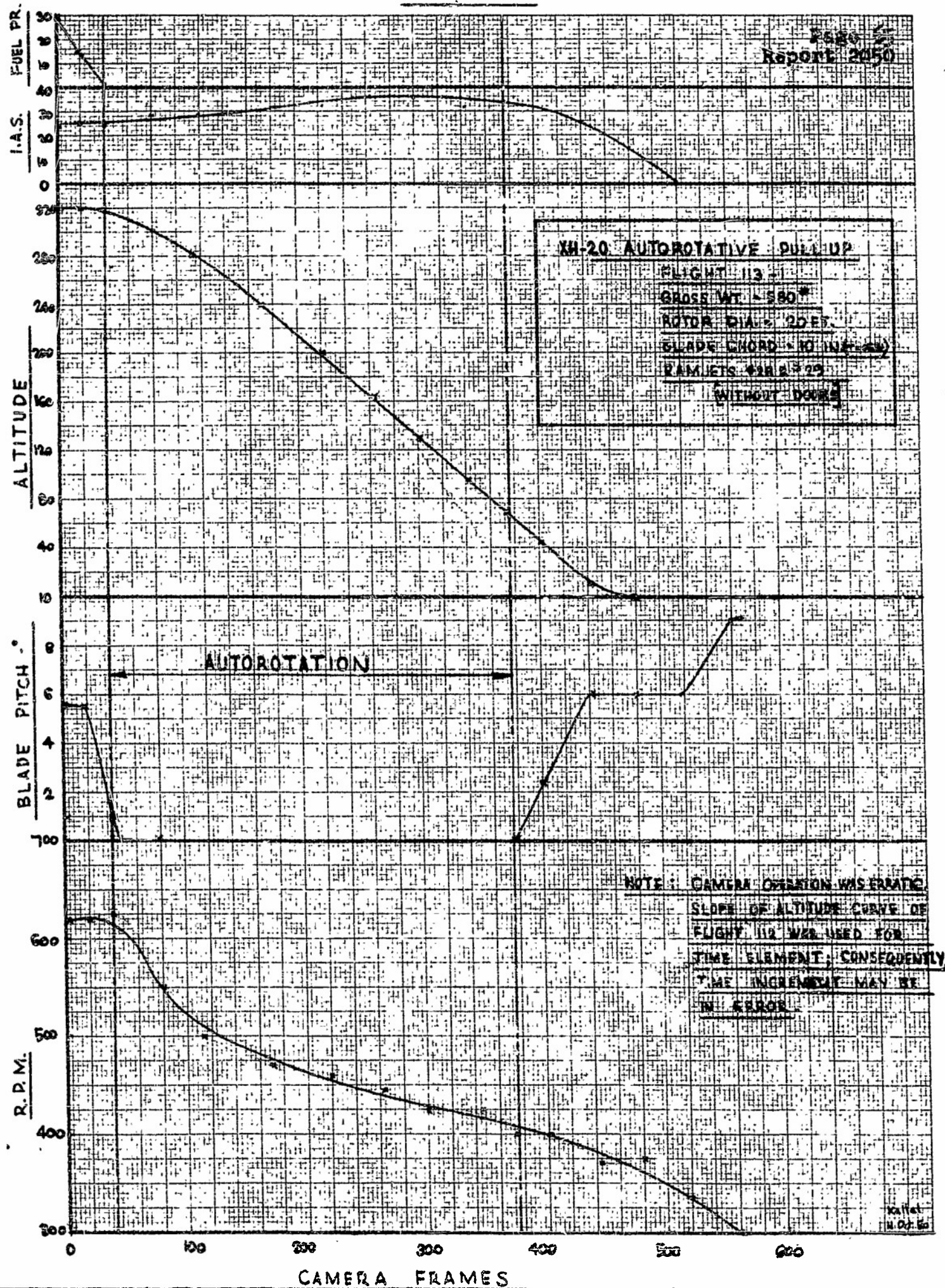


FIGURE 30

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KEUFFEL & ESSER CO.

No. 359-14. Millimeters, 5 mm lines accented, cm lines heavy.

1957-1-15

