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RESEARCH MEMORANDUM

for

President's Special Board of Inquiry on Air Safety

SOME TESTS AND CALCULATIONS PERTAINING TO THE DIVE PATH AND TO WING AND TAIL LOADS IN THE ACCIDENT TO EASTERN AIRLINES C54B AIRPLANE, NC-88814, NEAR BAINBRIDGE, MARYLAND, MAY 30, 1947

By

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Several dive paths were calculated for a C54 airplane starting from level flight at an altitude of 4000 feet and from an initial indicated airspeed of 200 miles per hour. The results show that, within the limits of the possible paths permitted by the evidence of the crash at Bainbridge, the speed of impact would be about 370 miles per hour and the time to crash would be between $12\frac{1}{2}$ and $15\frac{1}{2}$ seconds.

Tail-load calculations indicate that, with moderate negative acceleration of the airplane, the tail would fail near the end of the dive in a manner consistent in several important respects with the evidence.

A number of tests were made of the elevator tab control system to determine whether the tab would move by an amount sufficient to have caused the observed dive if the stored energy in the tab control cable were suddenly released. The results of these tests indicated that the probable tab movement is such as to be capable of causing a dive similar to the one observed at Bainbridge.

INTRODUCTION

Evidence of the wreckage of C54B airplane, NC-88814, which crashed following a steep dive near Bainbridge, Md., on May 30, 1947, disclosed that the horizontal tail structure failed in the air but that the wings remained with the fuselage until impact with the ground occurred. In order to clarify certain points relative to the failure of the tail and the lack of failure of the wing, the President's Special Board of Inquiry on Air Safety requested the NACA "to make an analysis of wing and tail loads on a typical transport airplane in approximately vertical dives." In accordance with this request, tail-load calculations have been made for a C54 airplane, loaded as was the airplane that crashed, in several flight conditions, including dives, falling within a probable range of flight paths stipulated by the evidence of the crash. These results are contained in this report.

Although the detailed calculations are specifically applicable to the C54 airplane, the general features of the results may be taken as applicable to any large transport airplane with performance similar to that of the C54.

In addition to flight-path and tail-load calculations, the report contains results of a number of tests made to determine elevator tab movements when the stored energy in the tab control cables was suddenly released. These tests were made because several explanations or speculations that had been advanced as to the cause of the crash could not, in the opinion of the senior author, be supported against reasonable interpretation of the evidence of the crash. These explanations included:

(a) "Unporting" of left elevator, resulting from loss of left outboard hinge pin with ensuing elevator overbalance

(b) Failure of right elevator tip in torsion bridge at outboard hinge cut-out due to prior damage, followed by unporting and overbalance of elevator section between outboard and middle hinges

(c) Fabric failure on upper surface of right elevator with resulting overbalance

(d) Heart failure or other incapacitation of the pilot, followed by slumping forward against control column

The tab tests were made to determine whether sufficient tab movement could occur to account for the observed dive.

CONDITIONS STIPULATED BY EVIDENCE OF THE CRASH

The airplane was stated to be cruising normally at an altitude of 4000 feet in clear, smooth air and at an indicated airspeed of 200 miles per hour. The weight was estimated, from the known weight at take-off and from the known fuel consumption, to have been 67,542 pounds at the time of the crash. The center-of-gravity position was not known, except that it lay between 25.8 and 32 percent of the mean aerodynamic chord, with a probable value of about 30 percent.

The airplane was observed to have nosed over rapidly into an approximately vertical dive, and to have finally crashed in a somewhat inverted attitude. The wings remained with the fuselage, but the horizontal tail surfaces failed in the air and came to earth in several fairly closely grouped parts near the main wreckage, indicating, together with eye-witness accounts, that the failure of the tail occurred in the dive shortly before the impact.

DATA USED IN CALCULATIONS

The basic data used to effect all calculations are given in table I and figure 1. In table I the geometrical values listed were taken from available Army reports, from the Douglas three-view drawing, and from direct measurements on a C54 airplane. The aerodynamic values listed were assigned by usual engineering procedures from general test data. The flight-test results are based on NACA flight tests of Army C54D-10-DC airplane, AAF Serial No. 42-72713 at Langley Field, Va.

The assumed airplane polar shown in figure 1 was taken from tests of a transport airplane generally similar to the C54. Subsequently to the performance of the flight-path calculations, several C54 polars for various tail settings and elevator angles were obtained. The appropriate C54 polars were found to differ from the originally assumed polar to some degree, but the effect of the differences on the calculations is not large. The calculations were, therefore, not repeated.

FLIGHT PATHS, ACCELERATIONS, AND STICK FORCES

Figure 2 shows three flight paths calculated for the subject airplane loaded to 67,540 pounds. The "-2g" flight path, curve A, represents a limiting condition set by the wing strength. Because the wings did not fail in flight, the acceleration could not have exceeded about -2g, which corresponds to the wing strength in inverted loading. The "0g" flight path, curve C, represents another limit that is somewhat arbitrarily defined. In setting this limit, it was presumed that the stick force would have to be sufficiently high to give the pilot a difficult recovery problem. It was also felt that some negative acceleration, which would lift the pilot off the seat, would also help to explain the fact that the pilot failed to effect recovery.

In calculating figure 2 it was assumed that the normal acceleration changed instantly from 1g to 0g or -2g. From knowledge of rates at which airplanes will rotate in pitch upon application of sudden tail load, it is estimated that about $1\frac{1}{2}$ seconds would be required to change the normal acceleration from 1g to -2g. Therefore, from about $\frac{1}{2}$ to $1\frac{1}{2}$ seconds should be added to the times shown on figure 2 to obtain time to crash. With the foregoing allowance for transition time, it can be seen from figure 2 that the time to crash must have been between about $12\frac{1}{2}$ seconds and $15\frac{1}{2}$ seconds. It is also evident that the final speed at impact must have been very close to 370 miles per hour in any case.

Both the -2g and 0g flight paths shown are for the condition of constant acceleration. Such a condition requires decreasing downward elevator angle throughout the dive. Other possible limiting -2g conditions are for constant elevator angle of such magnitude that -2g is attained at the end of the dive and for constant airplane lift coefficient. This latter case approximates the former and is shown as curve B on figure 2. The airplane lift or normal force coefficient for this case has a value of -0.264.

The elevator angles and stick forces corresponding to any point on curves A, B, and C of figure 2 can be found from figures 3 and 4 and from the stick-force equation given as a flight-test result in table I. Figures 3 and 4 show the experimental points obtained in tests under steady straight flight and under steady curvilinear flight conditions, respectively. Since the tests were made with weights and center-of-gravity locations differing from the conditions appropriate to the Bainbridge crash, these experimental results must be transformed to the appropriate conditions through the use of proper theoretical equations. The equations thus used to obtain the families of curves in figures 3 and 4 are as follows:

For steady straight flight

$$\delta_e = -\frac{\left(C_{m_0} + \frac{dC_L}{d\alpha}\alpha\frac{d}{c}\right)Sc - \frac{dC_{L_t}}{d\alpha_t}S_t x_t\left[\alpha\left(1 - \frac{d\epsilon}{d\alpha}\right) + i_t + \epsilon_0\right]}{\frac{dC_{L_t}}{d\alpha_t}S_t x_t\frac{d\alpha_t}{d\delta_e}}$$

where

δ_e elevator angle, radians

C_{m_0} zero-lift pitching-moment coefficient for airplane less tail

$dC_L/d\alpha$ slope of wing lift curve, per radian

α wing angle of attack, radians

d distance from aerodynamic center of wing to center of gravity, feet

$\bar{c}$ mean aerodynamic chord, feet

$dC_{L_t}/d\alpha_t$ slope of tail lift curve, per radian

S wing area, square feet

S_t horizontal tail area, square feet

x_t distance from aerodynamic center wing to center of pressure of tail, feet

$d\epsilon/d\alpha$ downwash factor

$d\alpha_t/d\delta_e$ elevator effectiveness factor

i_t tail setting, radians

ϵ_o initial downwash angle, radians

For steady curvilinear flight

$$\delta_e = -\frac{\left(C_{m_o} + \frac{dC_L}{d\alpha}\alpha\frac{d}{\bar{c}}\right)S\bar{c} - \frac{dC_{L_t}}{d\alpha_t}S_t x_t\left[\alpha\left(1 - \frac{d\epsilon}{d\alpha}\right) - \frac{\frac{C_L q}{W/S} - 1}{V^2}gx_t K + i_t + \epsilon_o\right]}{\frac{dC_{L_t}}{d\alpha_t}S_t x_t\frac{d\alpha_t}{d\delta_e}}$$

where

C_L airplane lift coefficient

q dynamic pressure, pounds per square foot

W airplane weight, pounds

g acceleration of gravity, 32.2 feet per second per second

K damping factor assumed equal to 1.1

V true airspeed

and

V_e equivalent airspeed

The elevator angles, stick forces, and other pertinent quantities for the several cases of interest are given for the initial and final points of the dives in table II. The stick forces listed are either (a) those required to be exerted by the pilot as push forces to perform the dives by pilot action, or (b) those required to be exerted by the pilot as pull forces to maintain level flight or to pull out if the dives were caused by trimming of the elevator to the angles shown by some unwanted aerodynamic force. The tab-angle increments listed are those required to cause the corresponding elevator-angle increments, assuming the unwanted aerodynamic force originated in the tabs.

TAIL LOADS

Calculated chord load distributions are shown in figure 5 for the beginning and terminal points of the limiting 0g and -2g dives. Also shown on this figure for comparison are the Army specified limit and ultimate design loads. The actual strength of the tail is not known to the authors at this writing, but is probably greater than the required design strength. Nevertheless, a comparison of the calculated and specified design loads is of interest.

Figure 5(a) shows that the tail has sufficient strength to take care of the equilibrium condition of -2g at 200 miles per hour, but that at 373 miles per hour the elevator and the forward portion of the stabilizer are considerably overloaded. The torsional load on the whole tail assembly is high, and structural deflections would be expected to cause considerable augmentation of load. In this condition, therefore, failure of the tail may be expected.

Figure 5(b) shows substantial margin of strength throughout the 0g dive, except in the case of the elevator, which is overloaded with respect to specified strength at the maximum speed. The torsional load is moderately high, and some augmentation of load may be expected as a result of structural deflections. Failure in this case is, however, uncertain in the absence of a divergence calculation.

In general, the tail-load calculations show that tail failure would not be expected early in any of the possible dives but that failure would probably occur near the end of any of the dives involving substantial negative acceleration of the airplane. In such failure the stabilizer would be expected to rotate downward and to the rear. This point is mentioned to show that the results of the tail-load calculation are consistent with the evidence in the Bainbridge crash that the elevator was forced down, relative to the stabilizer (or vice versa), to an excessive angle beyond the stops.

TESTS OF ELEVATOR TAB CONTROL SYSTEM

A number of tests were made under varied conditions on C54D and R5D-3 airplanes to determine whether the elevator tabs might move by a sufficient amount to have caused the Bainbridge crash if the energy in the tab control cable had been suddenly released.

The first of these tests was made on Army C54D-10-DC, AAF Serial No. 42-72713, in the loads calibration laboratory of the NACA at Langley Field, Va. The tab cable was rigged to a tension of 35 pounds, which was in accordance with the value specified by the manufacturer for the laboratory temperature at the time of test. The turnbuckle barrel in the cable-tension adjuster was replaced with heavy safety wire so that the stored energy in the cable could be suddenly released by cutting this wire.

Upon cutting the safety wire, the left tab angle jumped 4.1° in the nose-heavy direction.

This test was repeated several days later under the same conditions, and the left tab again jumped 4.1° in the nose-heavy direction. In neither of these tests was the movement of the right tab measured. In the second test, however, the pilot's tab position indicator was found to have moved 1° in the tail-heavy direction.

The airplane on which these tests were made was recalled from the NACA by the Army and it was subsequently given a complete overhaul at an Army base. During the latter stages of the overhaul period, arrangements were made to conduct further tests of the tab system on this same airplane. As found following overhaul, the tab control cable was rigged with a tension of 70 pounds at a temperature of about 65°F. The following tests were made with the results shown:

Test no.	Approximate temperature (°F)	Cable tension (lb)	Engines	Left tab jump (degrees nose heavy)	Right tab jump (degrees nose heavy)	Pilot indicator (degrees tail heavy)
1	65	35	Off	1.3	2.1	0.1
2	65	70	Off	2.8	4.8	.5
3	90	35	2 and 4, 1900 rpm	1.5	2.4	.2
4	90	[a]78	1 and 2, 1900 rpm	4.2	7.0	.8

[a]Cable rigged in hangar to 70-pound tension; test made with airplane outdoors in the sun.

From these results it is seen that the tab movement at 35-pound tension and with engines off was much less than the movement measured before overhaul under the same conditions at Langley Field, Va. It is also seen that the movement is greater when the airplane is vibrating as a result of engine operation. The right tab moved a greater amount than the left tab by a nearly constant ratio averaging 1.65. From this last result the right tab movement may be estimated for the original tests at Langley to have been 6.8°.

Tests were also made on two Navy R5D-3 airplanes, Bureau No. 50871 and Bureau No. 56507, at a Navy base. All of these tests were made with engines off and with 35-pound tension in the tab cable. The results follow:

Test no.	Left tab jump (degrees nose heavy)	Right tab jump (degrees nose heavy)	Pilot indicator (degrees tail heavy)
Bureau No. 50871			
1	1.0	1.9	0.5
2	.9	2.0	.5
3	1.0	1.9	.5
Bureau No. 56507			
[a]1	0.6	1.2	0.2

[a]Following this test, it was found that the cable motion had been restrained by bits of safety wire and other foreign material lodged between pulleys and pulley guides. The tests were not repeated.

These Navy airplanes were found initially to have had the tab cables rigged to about 60-pound tension. The reason for these excessive cable tensions was found primarily to be in misuse by the mechanics of the tensiometer calibration cards supplied with the commonly used commercial instruments. The nature of the misuse is such that C54 elevator tab cables are likely to be rigged to about twice the specified tension. A further factor is an assumption by mechanics that the exact magnitude of the cable tension is unimportant owing to the large margin of strength available in the cable. In any event, it appears that tab cable tensions on C54 airplanes of about twice the specified values may frequently occur – perhaps more often than not.

An idea of the probable magnitude of tab jump under actual operating conditions may be gained from the foregoing results by correcting the data approximately for the effect of excessive cable tension and for engine operation. The average multiplying ratios required for such correction may be obtained from the data of the second series of tests on the C54D airplane. Results corrected to 70-pound cable tension and engines on for all cases follow:

Test no.	Left tab jump (degreesnose heavy)	Right tab jump (degreesnose heavy)	Average
C54D airplane (before overhaul)			
1	12.2	20.2	16.2
2	12.2	20.2	16.2
C54D airplane (after overhaul)			
1	3.9	6.3	5.1
2	8.4	14.3	11.4
3	3.6	5.8	4.7
4	3.8	6.3	5.1
R5D-3 airplane (Bureau No. 50871)			
1	3.0	5.7	4.4
2	2.7	6.0	4.4
3	3.0	5.7	4.4
R5D-3 airplane (Bureau No. 56507)			
1	1.8	3.6	2.7

For these 10 tests, six involve values of tab jump between 4.4° and 5.1°, three involve values greater than 10°, and one involves a value of only 2.7°. Or, counting the C54D after overhaul as a separate airplane, two airplanes showed tab jump between 4.4° and 5.1°, two showed tab jump greater than 10°, and one showed only 2.7°. Referring these values to the tab angle increments listed in table II indicates that, if tab jump occurred in flight, destruction of the airplane is almost certain and also that a dive and tail failure similar to that observed in the case of the Bainbridge crash is highly probable.

The foregoing results and remarks refer to conditions in which none of the tab cable energy is dissipated in operating the tabs against aerodynamic force. Figure 17(d) of NACA TN No. 734 shows that when the elevator moves down as the tab moves up the tab hinge moment remains zero throughout the range of conditions of interest here. According to this result the tab does no work against aerodynamic force under the conditions with which we are concerned, and the test values of tab jump given herein are applicable in flight.

CONCLUSIONS

The results of the dive path and tail-load calculations and of the tests of the tab control system indicate the following conclusions:

1. The final speed at impact is about 370 miles per hour.

2. The time to crash is between $12\frac{1}{2}$ and $15\frac{1}{2}$ seconds.

3. With negative acceleration of the airplane, the tail will fail under torsional loading near the end of the dive, but will not fail in the early or middle regions of the dive.

4. The tail may fail in flight without the wing failing until after the tail failure has occurred.

5. If the energy in the elevator tab control cable is suddenly released under flight conditions and with cable tensions as found on several airplanes in service, the tab will probably move within the narrow limits required to cause the dive observed at Bainbridge.

6. Tab cable tensions were found on several service airplanes to be rigged to higher than specified values of tension by a factor of approximately 2. No service airplanes examined were found rigged with

specified tension. This discrepancy is known to have been caused in some cases through misunderstanding of the use of the tensiometer and its calibration.

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TABLE I

CHARACTERISTICS OF C54 AIRPLANE

Geometric values

Wing area, sq ft	1462
Wing aspect ratio	9.48
Wing taper ratio	0.308
Tail area, sq ft	324.8
Tail aspect ratio	4.8
Tail taper ratio	0.48
Elevator area aft of hinge line, sq ft	86.6
Elevator tab area, total, sq ft	6.72
Tail span/wing span	0.336
Mean aerodynamic chord, ft	12.46
Tail length, aerodynamic center to c/4 of tail, ft	–51.8
Elevator-flap chord ratio	0.5
Tab-flap chord ratio:	
Elevator chord	0.15
Total chord	0.073
Incidence, wing, deg	4
Incidence, tail, deg	1
Weight at time of accident, lb	67,542
Center of gravity in percent M.A.C.	30

Aerodynamic values

Slope, airplane lift curve, per degree	0.0867
Slope, horizontal tail lift curve, per degree	0.0681
Elevator effectiveness factor $\left(\frac{d\alpha}{d\delta_e}\right)$	0.473
Tab values, per degree	$\frac{dC_{n_t}}{d\alpha} = 0.008$; $\frac{dC_{n_t}}{d\delta_e} = 0.015$; $\frac{dC_{n_t}}{d\delta_t} = 0.03$
Pitching-moment coefficient, airplane less tail	–0.01
Aerodynamic center, percent M.A.C.	15.0

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TABLE I – Concluded

CHARACTERISTICS OF C54 AIRPLANE – Concluded

Flight test results

Stick force per g (c.g. in percent M.A.C.) . . .	$\frac{W}{67,542}(316 - 5.07\ c.g.)$
Ratio, elevator to tab travel	1.44
Stick force required to balance 1° of out of trim tab . . .	$53\left(\frac{V_{mph}}{200}\right)^2$
Initial elevator angle, speed 200 mph, c.g. at 30 percent M.A.C., deg	1.2 down
Initial tab angle, speed 200 mph, c.g. at 30 percent M.A.C., deg	1.4 up

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TABLE II

ELEVATOR ANGLES AND STICK FORCES FOR

SEVERAL POSSIBLE DIVES

Case	Factor held constant	V_e (mph)	Acceleration (g units)	C_N	Elevator angle (deg)	Elevator-angle increment (deg)	Stick force (lb)	Required tab-angle increment (deg)
A	Acceleration	200 373	−2.00 −2.00	−0.906 −.264	15.6 down 8.5 down	14.4 down 7.3 down	492 492	10.1 5.1
B	C_N	200 374	−.58 −2.00	−.264 −.264	9.5 down 8.5 down	8.3 down 7.3 down	259 492	5.8 5.1
B'	Elevator angle	200 374	−.36 −2.00	−.165 −.264	8.5 down 8.5 down	7.3 down 7.3 down	223 492	5.1 5.1
C	C_N and acceleration	200 377	0 0	.000 .000	7.0 down 5.4 down	5.8 down 4.2 down	164 164	4.0 2.9

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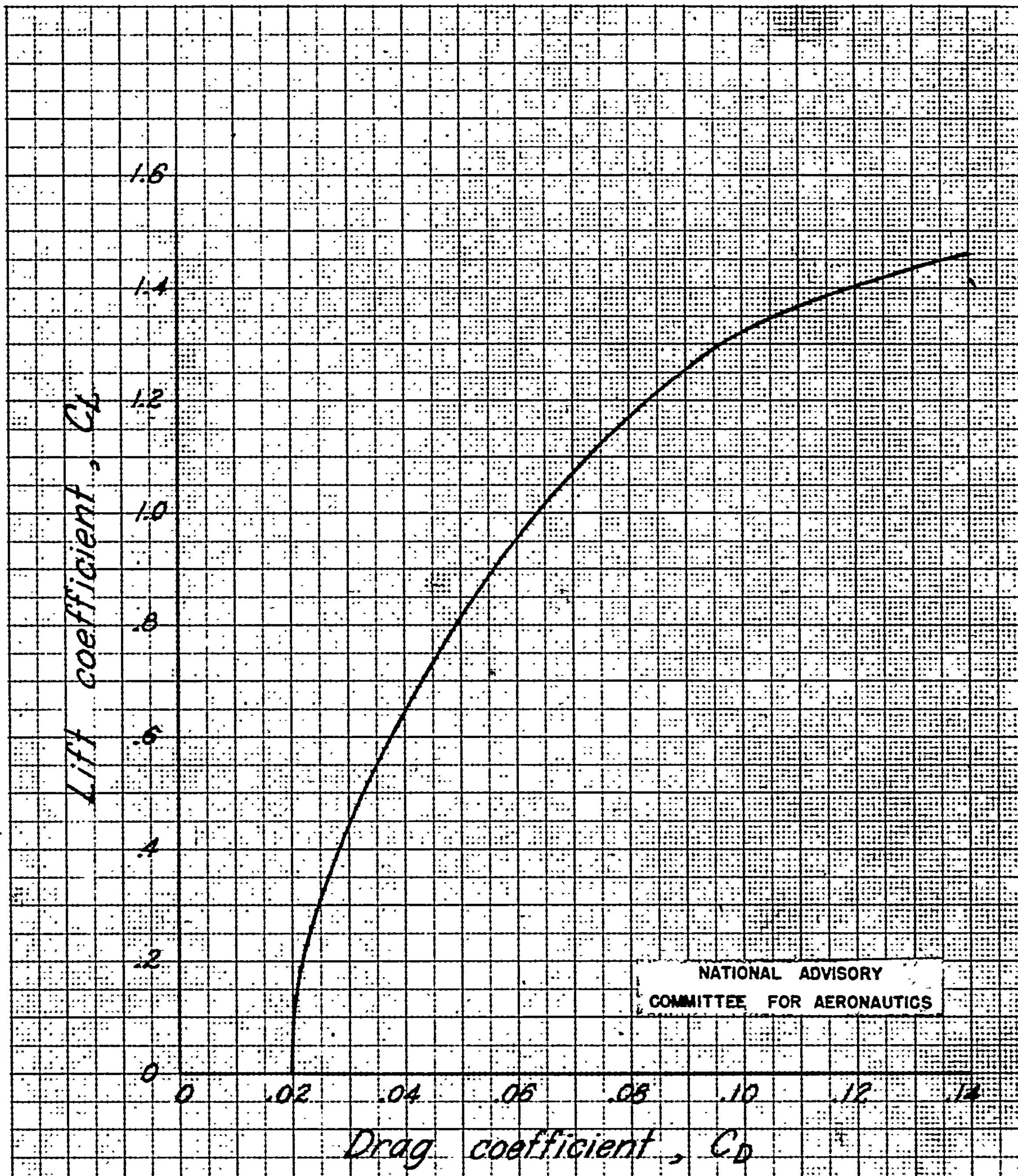


Figure 1.- Assumed lift and drag polar for C-54 airplane.

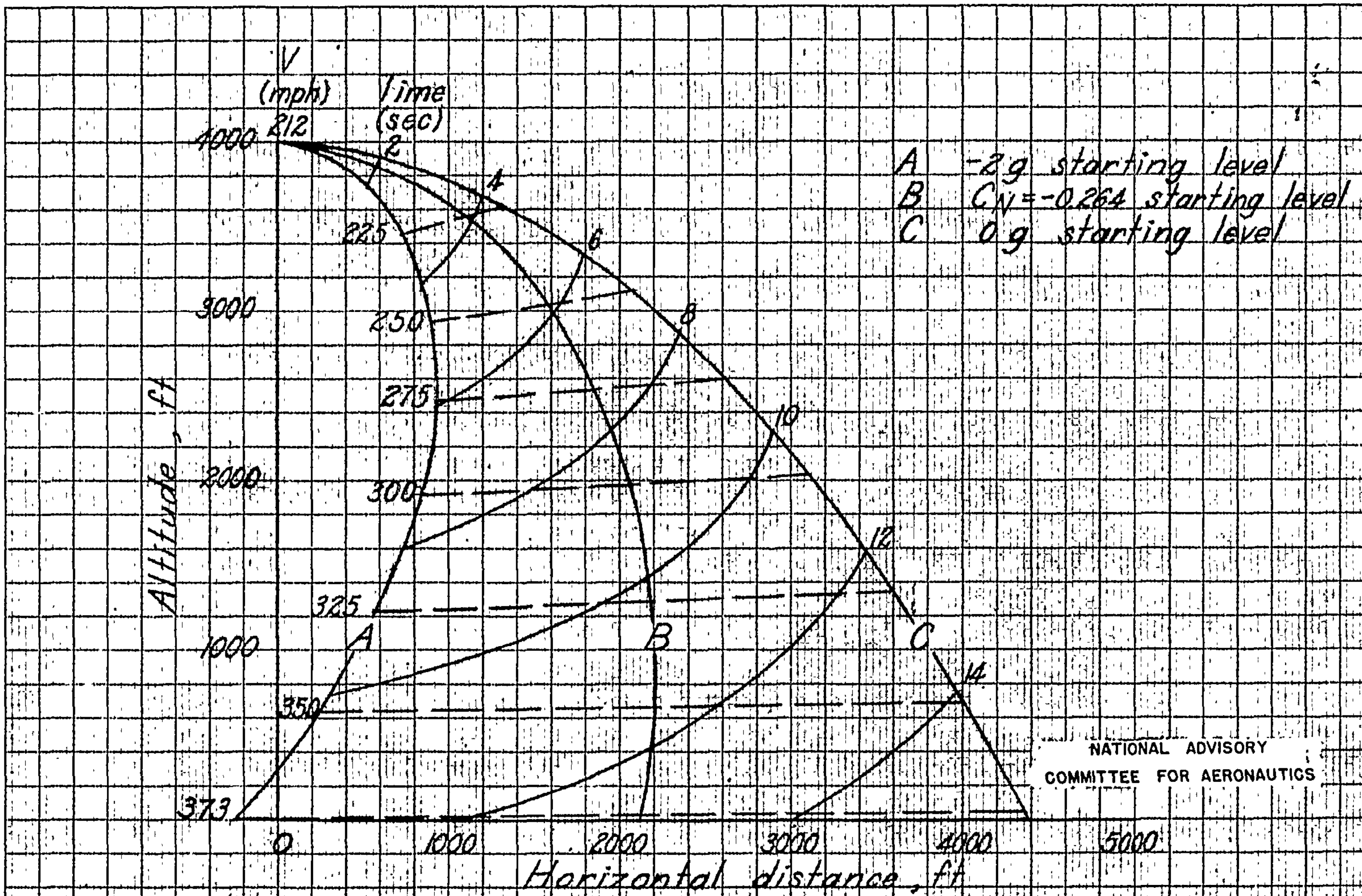


Figure 2. Calculated flight paths of C-54 airplane weighing 67540 pounds.

Note - Maximum velocity in zero "g" vertical dive equals 392 mph.

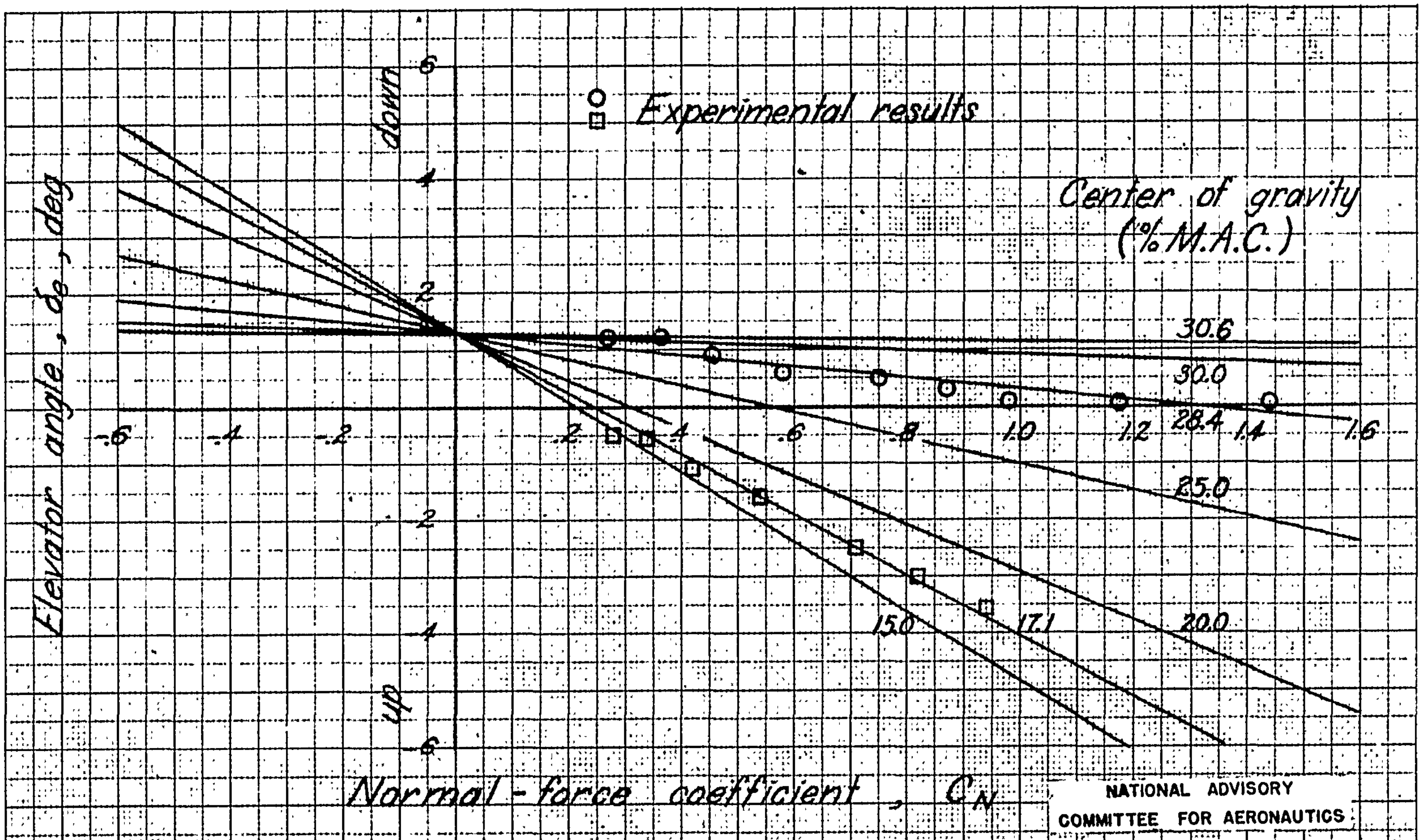
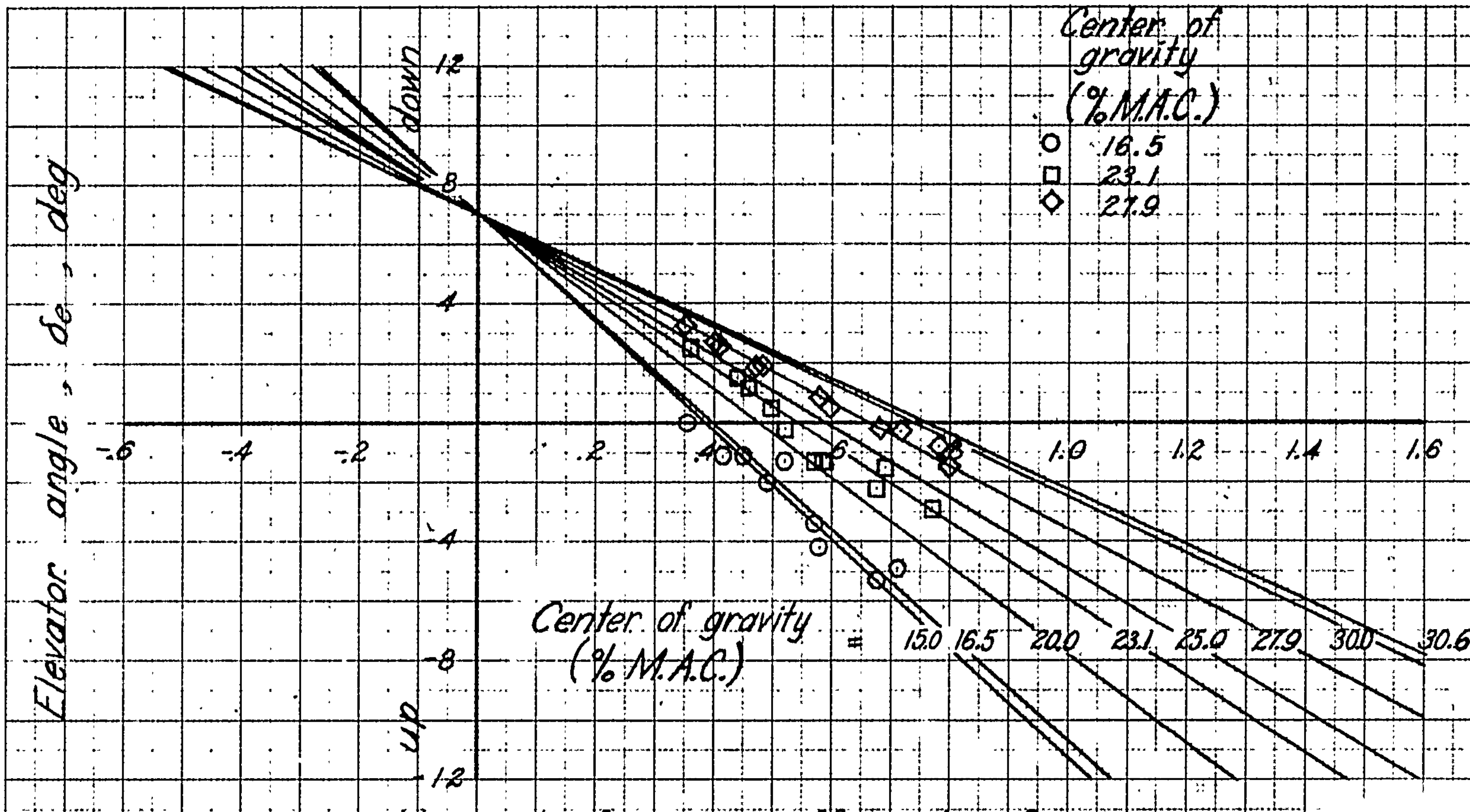
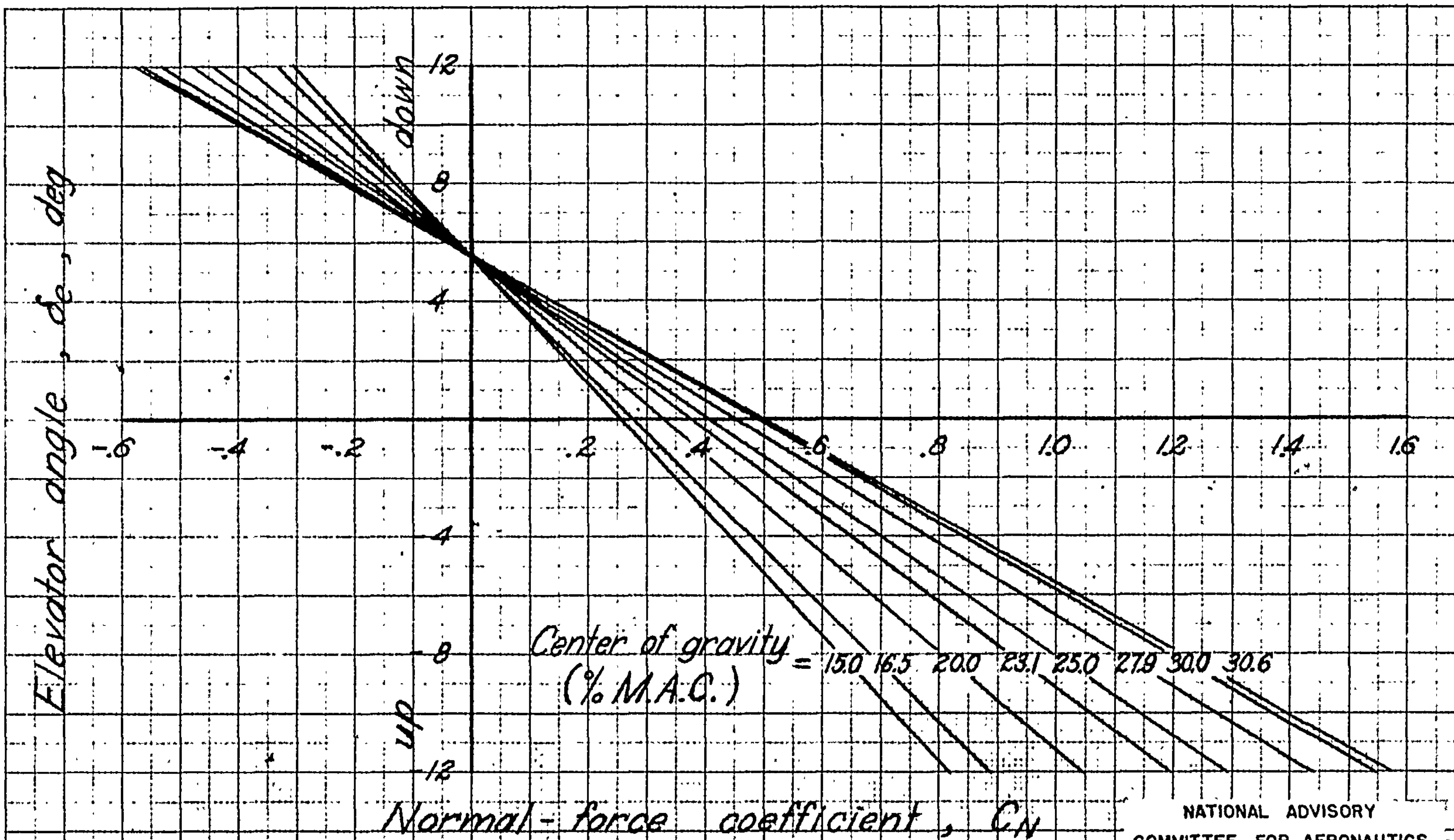


Figure 3.- Elevator angles required for trim in steady straight flight for C54 airplane for various center-of-gravity locations.



(a). V_e = 200 mph ; altitude = 5,000 ft

Figure 4.-Elevator angles required for trim in steady curvilinear flight for C-54 airplane for various center-of-gravity locations.



(b). V_e = 375 mph ; altitude = sea level.

Figure 4.- Concluded.

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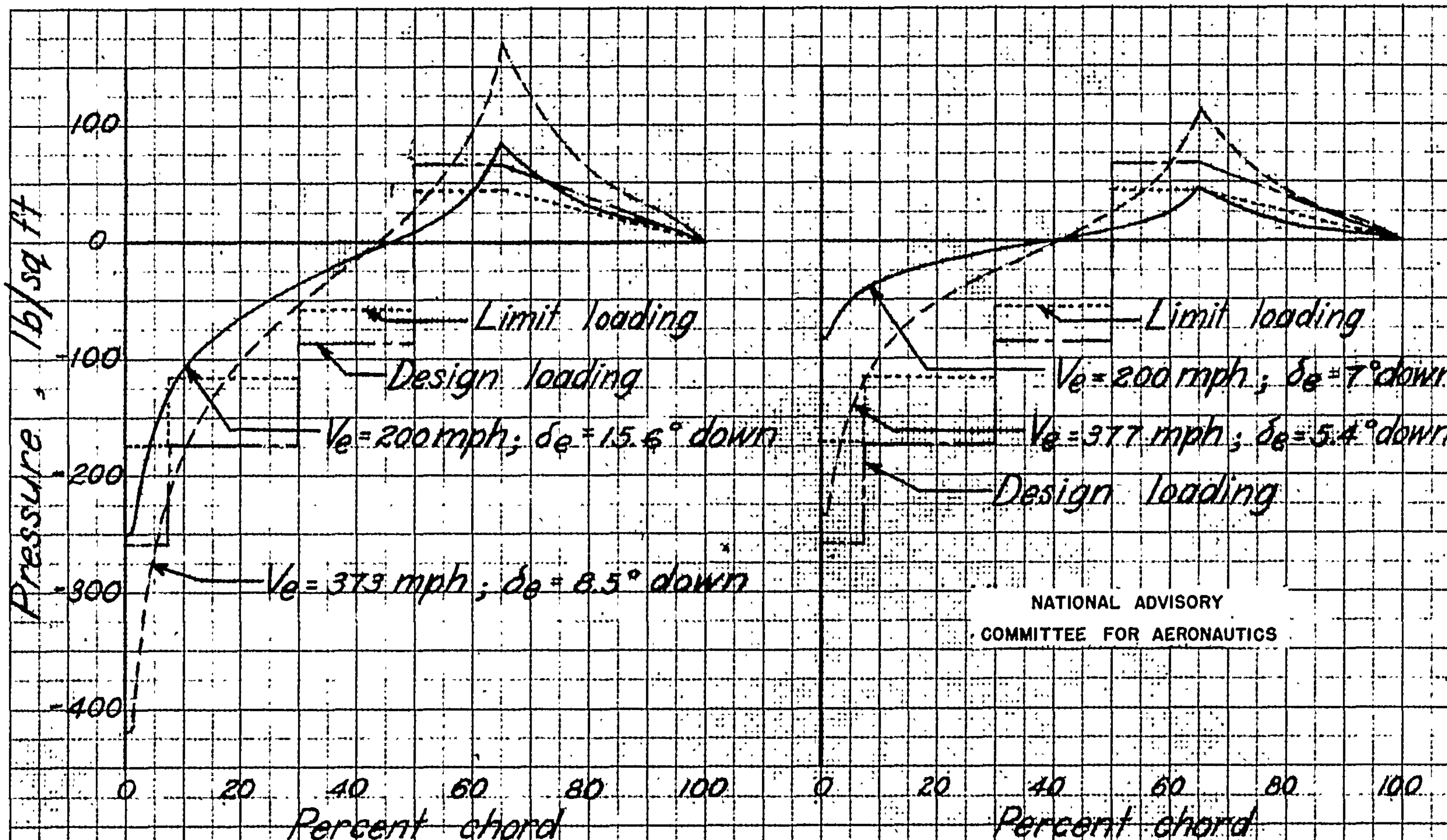

(a) $n = -2g$.

(b) $n = 0g$.

Figure 5.- Comparison of calculated chordwise loadings for the C54 airplane in various flight conditions with the design loading of 17550 pounds Center-of-gravity location at 30 percent M.A.C.