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TAIL-LOAD MEASUREMENTS ON THE XB-15 BOMBER IN GUSTY AIR

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NACA

WASHINGTON

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MEMORANDUM REPORT

for the

Army Air Corps

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Introduction

Statistical measurements of the accelerations encountered in gusty air have been accumulated over a period of years in order to determine the loads to which airplanes may be subjected. On the basis of certain concepts and hypotheses regarding gust shapes, the statistical measurements have generally been evaluated so as to yield either so-called "effective" or "true" gust velocities as applied to the wings of airplanes. Subsequent application of these values to the design of new airplanes yields a resulting design which is substantially correct as far as the wing is concerned but there is no certainty that these values can properly be applied to the design of tail surfaces.

Because of the meager data concerning the gust loads on tail surfaces, the NACA undertook to make direct measurements in flight on two airplanes. In both of these investigations which were conducted on a small and a moderately large airplane, the tail surfaces were modified in such a way that the gust load was measured by the deflection of calibrated springs inserted in the struts that braced the tail surfaces. The results of these tests agreed qualitatively with expectations based on an early preliminary theoretical study in placing the "effective" design gusts as increasing in intensity in the following order: (1) horizontal tail, (2) wings, and (3) vertical tail. However, since the instruments used in the above tests were of the type which gave envelope curves of either the tail load or elevator deflection against air speed, some doubt existed as to the time correlation of the measured quantities.

Meanwhile, the theoretical studies have been considerably extended (reference 1) to indicate the horizontal tail loads to be expected when airplanes of different stabilities encounter hypothetical gusts that consist of a constantly graded portion followed by a constant value. However, as the theoretical studies of tail loads are hampered by lack of knowledge regarding the exact gust shapes likely to be encountered and by the complex character of the flow in the region of the tails of powered airplanes subjected to irregular motions by gusts, further tests on larger airplanes appeared to be desirable. The Army Air Corps agreed to cooperate in such a project by allowing suitable equipment to be installed in their large XB-15 bomber.

This report presents the results of tests which cover a total of about 240 flying hours on the XB-15 airplane. These measurements were made under authority granted by the Air Corps in October 1938.

Airplane and Instruments

Airplane.- The XB-15 airplane on which the tail-load measurements were made is shown in figures 1 and 2 and its pertinent dimensions are listed in table 1. The elevator and rudder on the XB-15 are both statically balanced by means of concentrated lead weights arranged within the fuselage. In flight the tail surfaces are moved by a modified servo-control system. Although the fixed portions of the surfaces were metal covered, the movable portions were covered with fabric.

Instruments.- The following standard NACA photographically recording flight instruments were installed in the airplane (see fig. 3 for location):

1. Air-speed recorder located in the nose compartment of the airplane and connected to a swiveling pitot head 8 feet forward of the nose.

2. Single-component accelerometer mounted below the catwalk of the bomb bay near the center of gravity of the airplane.

3. Single-component accelerometer mounted on the walkway leading to the tail at a distance of 39 feet behind the center of gravity.

4. Control-position recorders attached to the rudder and the elevator. These instruments were used to distinguish between accelerations and tail deflections caused by gusts and those caused by control deflections.

In addition to the above standard instruments, a photographically recording optical system was used on the horizontal and the vertical tail surfaces to measure their deflection under load. This system consisted basically of a light source mounted at the tip, the movement of which, relative to the root of the spar, was recorded on a moving strip of film carried by a film magazine containing 20 feet of film located within the fuselage. This amount of film was sufficient to give a total duration of 30 minutes.

The installation comprised a 32 candle-power bulb mounted inside the fixed portion of the tail surface close to a spar and near its tip. The bulb was shielded by a metal shield which contained a 0.010-inch hole located between the filament of the bulb and the camera. The complete unit, which weighed less than 8 ounces, was attached to the skin next to the spars in as rigid a manner as possible so as to minimize any relative motion between the spar and the light. The continuous film cameras were placed inside the fuselage and attached rigidly to the spar running nearest the light unit. The cameras were fitted with telephoto lenses in order to give sufficient magnification to provide convenient and accurate reading of the film record.

The deflection apparatus was so alined (see fig. 4) that the small hole in the light shield directed a beam of light from the filament of the bulb into a 1/4-inch hole in the fuselage skin located within the outline of the fixed tail surface. The beam of light then entered the telephoto lens of the camera and was directed through a 3/16-inch slot onto the sensitive film which traveled across this slot. The original alinement was somewhat tedious and difficult to obtain, but after each unit was properly placed, further adjustments were comparatively simple.

All instruments were synchronized by a standard NACA motor timer connected into the circuit and having a timing interval of 1 second.

Flights

The flights made during this investigation cover a period of about one complete year and are representative of the average type of flying made by Army personnel when operating in the vicinity of Langley Field in fair weather. The actual flying time spent in local flying was 65 hours during which 108 minutes of record were taken. Records were taken whenever, in the opinion of the observer, airplane acceleration increments of ±1/4g were likely to be encountered in a given stretch of turbulence. All gusts recorded during the local flights were very mild in nature, never producing greater than a ±0.4g acceleration.

However, during these tests a number of flights were made to distant points in North, Central, and South America, but only on two such flights was it permitted to keep the test equipment aboard. In both of these instances records were taken by members of the ship's crew.

A list of flights made away from Langley Field is as follows:

Date	Destination	Flying time, hours	Instr. time, minutes
7/22-23/40	Langley, Mitchell, Langley	3.8	15
10/26-27/40	Langley, Maxwell, Langley	18.7	55
2/26/40	Langley, Wright, Langley	5.3	18
*4/8-5/12/40	Langley, Panama, operations over Central America and out to the Galapagos Islands, Langley	103.0	25
6/6/40	Langley, Wright, Langley	6.0	0
6/13-14/40	Langley, Wright, Langley	6.2	8
*7/2-6/40	Langley, Amarillo, March, Seattle, Spokane, Selfridge, Langley	37.1	0
	Total	180.1	121
	Local	64.9	108
	Total	245.0	229

* No NACA personnel accompanied these flights.

The above total does not represent the entire flying time placed on the XB-15 between the dates 7/5/39 and 9/27/40 (the dates covering the tests) but only some fraction (probably 75 percent) due to the fact that the instruments on several occasions had to be removed or disconnected, depending upon the mission involved.

Although the total time with test equipment aboard was fairly large, with respect to other flight investigations, the size of the gusts encountered was quite small, having at no time exceeded an acceleration increment of 0.75g. It might be mentioned here that during one of the flights on which no test equipment was permitted the ship encountered particularly severe weather as indicated by the V-G records.

Calibration of Deflection Recorders

In order to convert the measured tip deflection into tail loads and subsequently into effective gust velocities, it was necessary to obtain a curve of surface deflection against load. This calibration, in the case of the horizontal tail surface, consisted of two parts: (1) a static calibration on the ground using a dead-weight loading to produce a deflection at the tip, and (2) a flight calibration in which the c.g. position of the airplane was shifted during flight, thereby changing the balancing load on the horizontal tail.

Since the actual span loading at the tail under flight conditions was unknown, an "influence" type of loading was used in the static calibration in order to permit a later estimation of the effect of possible changes in span load distribution on the calibration. The actual calibration procedure in the static tests consisted of: (1) laying out convenient loading stations along the span, (2) setting up dial gages at various locations to give a true reading of the deflection of the surface at the point of attachment of the light source, (3) applying a unit load at each of the loading stations in turn, and (4) reading the dial gages and taking a short record on the deflection recorder for each weight location.

In order to obtain sufficient points for an adequate calibration, the unit load was given several different values and also disposed in several different chordwise distributions. This procedure gave a curve of the deflection at the tip produced by various amounts and types of chordwise loading when placed at a given spanwise station. Since the light source was mounted near the apex of a substantially triangular beam, it was found, as would be expected, that the chordwise load distribution had no measurable effect on the deflection for a given total load. It was found that the static-load deflections based on the influence-line results checked the deflections obtained in the flight calibration when the static load was distributed along the span in proportion to the chord at each station.

Although it was intended to calibrate the vertical tail surfaces in flight by producing a yawing moment with a parachute drogue attached to the wing at the outer engine nacelle, the good agreement in the above case caused the flight tests to be dispensed with since they would have been of a hazardous nature. Thus, for the vertical tail only a static ground test was performed and the influence type of loading previously described was used. Assuming in this case as before that the spanwise air load along the vertical surfaces was similar to the spanwise chord distribution, it was found that a load of 3100 pounds would cause an actual deflection of 1 inch at the position of the light source in the fin. The corresponding load value for the horizontal tail surfaces was found to be 5300 pounds.

In accelerated flight, the deflection measured is due to a combination of air and inertia loads and it would be necessary, in a truly accurate determination of the loads, to take into account both these distributions. However, because neither the air load nor the weight distributions were accurately known, the assumption was made in evaluating the records that both the air load and the inertia load were similar in form to the chord distribution of the surfaces. Additional assumptions implicitly used in evaluating the data were that the gusts encountered never stressed the tail beyond the elastic limit and that the gusts were of sufficient size to envelop the entire surface in a uniform field of velocity.

Methods and Results

In the evaluation of the records to obtain effective gust velocities, the following methods were used: For each flight the c.g. accelerometer record was examined and all points which indicated acceleration increments of approximately 0.2g or over were marked to be read. These points were compared with the elevator and rudder control-position records and all accelerations and loads which might have been caused by control deflections were then eliminated. The air speed, tail acceleration, and horizontal tail deflections were then read for the remaining points. There appeared to be no apparent relation, with respect to time, between a normal acceleration and a side load on the vertical tail. Therefore, the record of the vertical tail surface was not read as described above but was read at each point where the actual deflection of the surface appeared to be greater than one-tenth of an inch, i. e., corresponding to 310 pounds load.

The solution for the effective gust velocities over the wing was made as follows:

$$U_{e_W} = \frac{\Delta n_{c.g.} W/S\ V}{\frac{dC_L}{d\alpha} q} \qquad (1)$$

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where $\Delta n_{c.g.}$ is the acceleration increment from 1g measured at the c.g.

W average weight as flown, 55,000 pounds

S wing area, square feet

$\frac{dC_L}{d\alpha}$ slope of wing lift curve, taken as 5.01

q dynamic pressure, pounds per square foot

V indicated air speed, feet per second

The effective gust velocities over the tail surfaces were found in a similar manner and were determined with respect to the free air stream. In this manner, any changes in the direction or velocity caused by the gust first striking the wings is included in the solution for the effective gust velocity. Therefore, for example, the differences which appear between the effective gusts on the wing and the horizontal tail are largely due to the action of the wing in producing downwash at the tail. The value of the effective gust velocity at the tail surfaces was determined from the equation

$$U_t = \frac{\Delta L_{a_t} V}{\frac{dC_{L_t}}{d\alpha_t} qS_t} \qquad (2)$$

where ΔL_{a_t} is the increment in aerodynamic load on the tail surface, pounds. The increment in aerodynamic load is not that load which is recorded directly on the strain recorder, but is the recorded load plus the load due to the inertia of the tail surface itself. In the case of the vertical tail, the inertia load could not be obtained because no means were at hand for accurately measuring the lateral acceleration at the tail. Since it is known, however, that these accelerations are very small due to the combination of a relatively small side area and large moment of inertia, it was necessary to assume that the effect of inertia on the vertical tail load was negligible.

S_t the tail surface area, square feet

$\frac{dC_{L_t}}{d\alpha_t}$ slope of the lift curve for the tail-load surface, taken as 4.23 for the horizontal and 2.58 for the vertical surface.

Rather than give the results of the tests as separate plots of effective gusts for the horizontal and vertical tail surfaces, these quantities have been plotted as ratios with the effective gust velocity determined for the wing. These ratios are given in figures 5 and 6 plotted against the effective gust velocity measured on the wing. In the case of the wing and horizontal tail there was a definite correlation which indicated that the same gusts striking the wings also struck the horizontal tail. Thus the points of figure 5 represent the same gust striking the wing and tail surfaco in turn. In this figure, as well as in later ones, no attempt was made to distinguish between up or down or right and left gusts as there appeared to be about an equal distribution.

Since there appeared to be no time correlation between the gusts striking the vertical tail and those striking the wing, the ratios of these quantities given in figures 6 were formed from the maximum values found within the various runs.

Table II summarizes the effective gust velocities evaluated for the wing, the horizontal, and the vertical tail surfaces of this airplane. It includes all gusts obtained during the entire period of measurements which were considered worth evaluating. Since one or the other of the deflection recorders failed to operate at times, the total number of gusts for the respective surfaces are not equal.

In addition to the evaluation of effective gust velocities at the wing and tail, some of the peak accelerations obtained with the c.g. accelerometer were evaluated to give "true" gust velocities and gust gradient distances. For this purpose all acceleration peaks which were preceded by reasonably constant values of acceleration for about 2 seconds or more were used. Only a relatively small number of the gusts evaluated fit this criterion.

The gradient distance, H, in which the gust reaches a maximum value was determined by multiplying the time elapsing from the start to the peak of the acceleration by the true air speed. Theoretical studies indicate that such a procedure is justified since for the gusts encountered in the atmosphere the gradients are apparently such that there is little, if any, lag between the point of maximum acceleration and that of maximum gust velocity.

The true gust velocities associated with these accelerations were obtained by dividing the effective gust velocities of equation (1) by an alleviating factor which corrects for the proportion of the gust velocity that is acquired by the airplane in traversing the gradient distance, H. The true gust velocities evaluated in this manner are plotted in figure 7 against the gust gradient distance, H.

Precision

The following are estimates of the accuracy to which the various quantities used in the evaluation of effective gust velocities were known:

Acceleration (c.g.)	±0.10g
Acceleration (tail)	±0.10g
Air speed	±2 mph
Airplane weight	±10 percent
Increment in control position	$\pm 1/4^{\circ}$
Load (horizontal surface)	±200 pounds
Load (vertical surface)	±300 pounds

The above limits on the loads and accelerations apply mostly when the peak values are read so that the question of time correspondence is not involved. An idea of the discrepancy in synchronization between the standard instruments and the deflection records can be gained from the typical time history given in figure 8. Part of this discrepancy in the case of the horizontal tail-load measurements can be explained by the fact that the light source of the deflection recorder had a slight chordwise motion as well as that normal to the chord. Any motion of the light beam across the 3/16-inch slot caused by chordwise motion of the tip represents a movement along the time scale of the film which could not be corrected when reading the records. However, since most of the results given in this report were obtained by reading the various quantities at peak values, which obviously correspond, (such as points A, B, C, of fig. 8), the lack of time synchronization is of small importance.

Discussion

Although the results of these tests cannot be classed as completely conclusive because of the relatively small gust velocities encountered during the tests, they do show variations that are in agreement with expectations and with the results of other tests.

On the basis of very simple reasoning, it would be expected that any gust of intensity, U, that strikes the wing would cause a change in wing angle of attack approximately equal to $\frac{U}{V}$. At the horizontal tail, the corresponding change in angle of attack, if the gust could be assumed to persist, would be $\left(1 - \frac{d\epsilon}{d\alpha}\right)\frac{U}{V}$ where $\frac{d\epsilon}{d\alpha}$ is the rate of change of downwash with angle of attack. Since $\frac{d\epsilon}{d\alpha}$ is about 0.5 for airplanes of normal stability, it would be expected that the effective gust for the horizontal tail would be about one-half of that for the wing. The actual picture is, however, not as simple as this because a number of other items such as pitching velocity, free vortices shed from the wing, and the gust gradient influence the effective horizontal tail gust. At present these influences are only known qualitatively. If a simple flat-top gust with constant positive gradient is considered, it can be said that the free vortices shed from the wing would tend slightly to increase the effective gust velocity at the tail over that given by $\left(1 - \frac{d\epsilon}{d\alpha}\right)\frac{U}{V}$ whereas the gradient distance and pitching velocity ordinarily tend to decrease the effective gust velocity. The gradient distance accomplishes this decrease by virtue of the fact that the tail would be in an area of lower gust velocity than the wing while tests in the gust tunnel show that the usual airplane has acquired a diving angular velocity by the time the peak gust velocity is reached, which in turn relieves the effect of the gust.

Figure 5 indicates that in spite of the relatively low gust velocities measured in the tests there is tendency for the ratio of the horizontal tail and wing gust velocities to approach a constant value of about 0.4 somewhat in accord with what would be expected from the above reasoning, i. e., $\frac{d\epsilon}{d\alpha} \cong 0.6$. The wide scatter at the lowest wing gust velocities can partially be explained by the fact that the accuracy of measurements in this range is relatively poorer than in the high range and by the fact that slight elevator movements, pitching velocities, etc., have a predominating influence on the small tail loads involved. Another explanation is that in some instances gusts were encountered which, although they were of sufficient extent to envelope the tail surfaces, struck only a portion of the wing. The gust of small extent is thus more likely to yield high ratios of the quantity U_{t_h}/V_w. The ratios of gust velocities for the vertical tail (fig. 6) show no definite variation with increase in the wing gust velocity. It must be remembered, however, in connection with this figure that the gusts on the vertical tail did not correspond in time with the measured wing gusts but are ratios of maximum values occurring in a given zone of turbulence. In view of the fact that the gustiness in such a zone is likely to be of a heterogeneous nature, the ratios of figure 6 may not be those which would be obtained if the individual runs could have been longer.

A relatively simple analysis indicates that the ratio of the effective lateral gust acting on the vertical tail, which would give it unit linear acceleration, to the normal gust acting on the entire wing, which would give to the whole airplane a unit linear acceleration, is equal to

$$\frac{U_{tail}}{U_{wing}} = \frac{\frac{dC_L}{d\alpha} S_w}{\frac{dC_{L_t}}{d\alpha_t} S_t} \left(\frac{k_z}{l}\right)^2$$

where k_z is the radius of gyration in yaw, feet

l distance from c.g. to aerodynamic center of vertical tail surfaces, feet

S_w wing area

S_t tail area

$\frac{dC_L}{d\alpha}$ slope of lift curve for airplane, radians

For ordinary airplanes this ratio might vary between 3 and 10 although obviously if the entire surfaces were not involved, considerably different ratios could be obtained. No special quantitative significance can be attached to a ratio computed as above but it does reveal that the effective "wing loading" on the vertical tail is higher than that of the wing. This, in turn, means that there is less "yielding" of the airplane in yaw so that in traversing a lateral gust with a finite gradient distance, the tail surface would have acquired a smaller amount of the gust velocity by the time the maximum value was reached than would be the case for the wings traversing a similarly graded vertical gust. The results of figure 6 are in qualitative agreement with this reasoning.

Since in the tests it was usual to cruise within a close range of air speeds on automatic pilot, the propeller-operating conditions were always nearly the same. For this reason as well as the fact that a yaw of about 6° would be necessary before the slipstream could strike the vertical tail, it is felt that gusts measured were unaffected by slipstream conditions.

The results shown in figure 7 indicate, in agreement with other data (e.g., reference 2), that the maximum true gust velocities measured are associated with a gradient distance slightly larger than the wing span. Such a result is partly in keeping with the hypothesis advanced in reference 3 which gives the result that the maximum gust velocity varies as the cube root of the gradient distance, the lateral extent being approximately the same as the gradient distance, H. Thus, in order to produce a fairly large normal acceleration, the gust should at least envelope the whole wing which would call for a gradient distance equal to or greater than the wing span. For gusts with longer gradient distances the airplane would have time to pitch into the gust and thus relieve its effect. Therefore, it would be expected that the evaluated gust velocities would decrease beyond a certain gradient distance which would seem to be indicated by an envelope curve around the results of figure 7. Results similar to those of figure 7 are also included in reference 2 for considerably larger gust velocities.

Concluding Remark

The results of these tests are in qualitative agreement with expectations and with the results of previous unpublished tests of two small airplanes in indicating that the effective gusts on the horizontal tail are about one-half those on wing while those measured on the vertical tail average substantially higher than those on the wing.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 26, 1941.

References

1. Williams, D., and Hanson, J.: Gust Loads on Tails and Wings. R. & M. No. 1823, British A. R. C., 1937.

2. Pearson, H. A.: Acceleration, Stress, and Deflection Measurements on the XB-15 Bomber in Gusty Air. NACA MR, June 16, 1939.

3. Rhode, Richard V.: Gust Loads on Airplanes. SAE Trans., vol. 40, no. 3, March 1937, pp. 81-88.

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TABLE I

General Characteristics of XB-15

Over-all span	149 ft 0 in.
Over-all length	87 ft 7 in.
Over-all height	25 ft 10 in.
Wheel tread	25 ft
*Weights	
Empty	37,709 lb
Gross	70,706 lb
Average as flown	55,000 lb
Engines	
4-R-1830-11 P & W twin Wasp B	
Gear ratio	3:2
Blower ratio	10:1
1000 hp 2450 38 in. Hg (take-off)	
850 hp 2450 31 in. Hg 6000 ft	
Wing	
Section NACA 0018-0010	
Chord (root)	29 ft 0 in.
Incidence	4° 30'
Dihedral 3° (upper) 6°-30' (lower)	4° 45'
Area	
Net	2480
Gross	2780
Flap area	252
Horizontal stabilizer	
Span	45 ft
Area to elevator hinge center line	Net 276.0
Area to elevator hinge center line	Gross 324.4
*Weight	569.7 lb
Elevator	
Area (total)	180.8
*Weight - surface	497.3
- counterweight	151.8
Vertical fin	
Height above center line fuselage	14 ft 10 in.
Area to rudder hinge center line	60.9
*Weight - surface	123.8 lb
Rudder	
Area (total)	82.2
*Weight - surface	328.0 lb
- counterweight	175.7 lb

* Weights taken from Boeing Weighing Report D-939A No. 8

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TABLE II

Summary of Effective Gust Velocities

Effective gust velocity, fps	Number of gusts evaluated		
	Wing	Horizontal tail	Vertical tail
0-1	-	40	-
1-2	35	141	2
2-3	81	57	38
3-4	105	22	73
4-5	80	2	71
5-6	26	-	56
6-7	14	-	35
7-8	6	-	33
8-9	2	-	17
9-10	-	-	13
10-11	-	-	11
11-12	-	-	12
12-13	-	-	8
13-14	-	-	7
14-15	-	-	5
15-16	-	-	11
Total	349	262	392

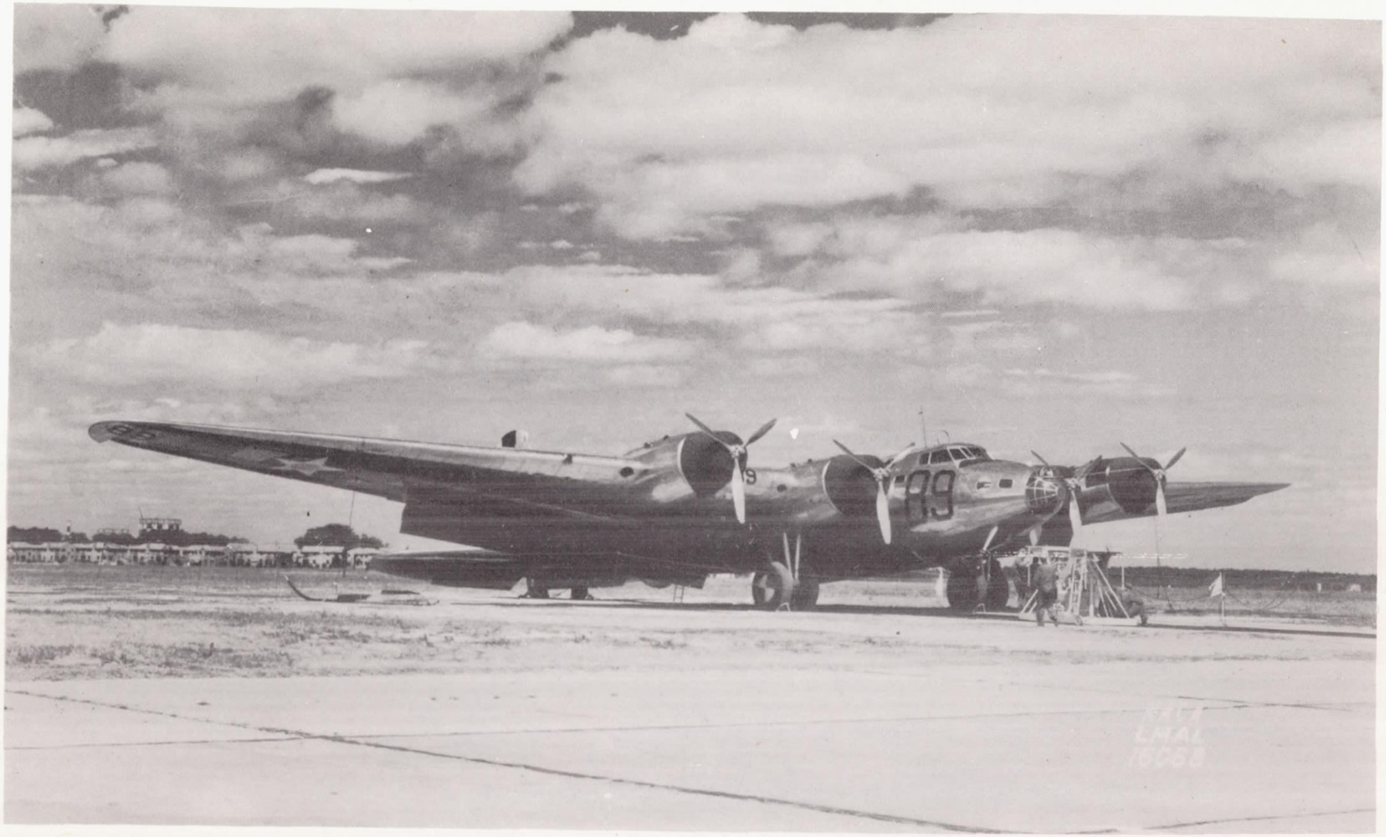

Figure 1.- Three-quarter front view of XB-15 airplane.

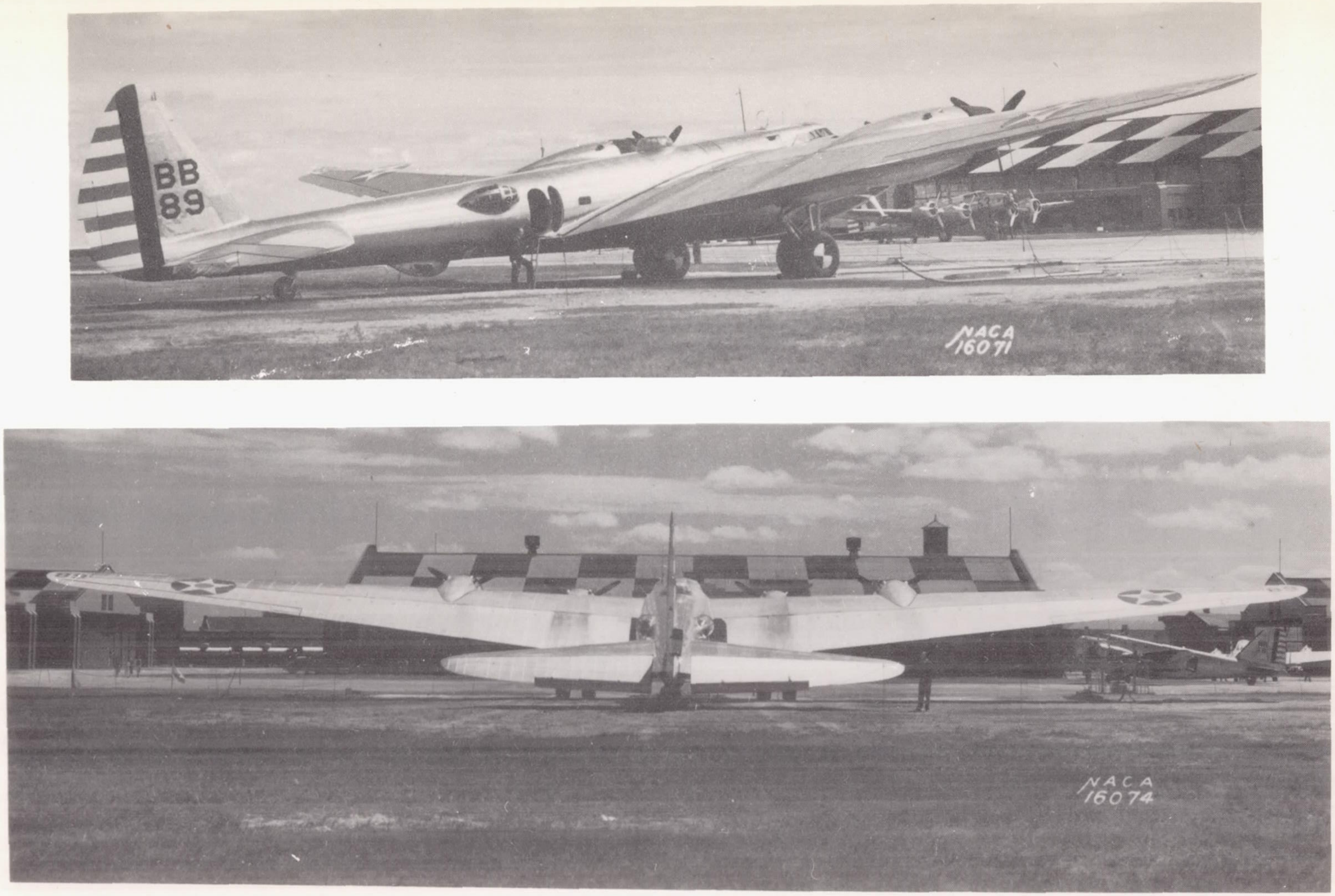

Figure 2.- Side and rear views of horizontal and vertical tail surfaces of XB-15.

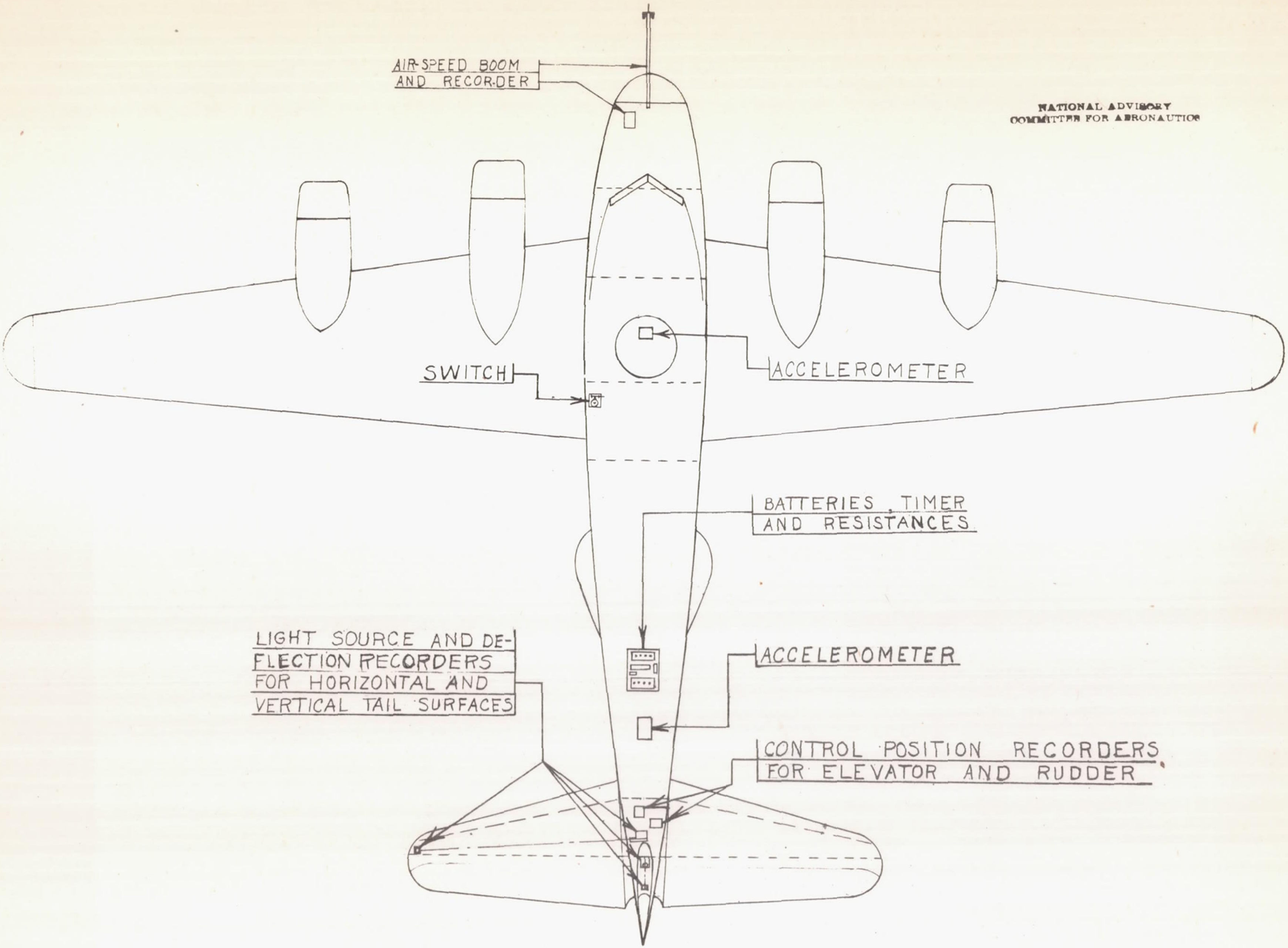

FIGURE 3.- INSTRUMENT INSTALLATION IN XB-15 AIRPLANE.

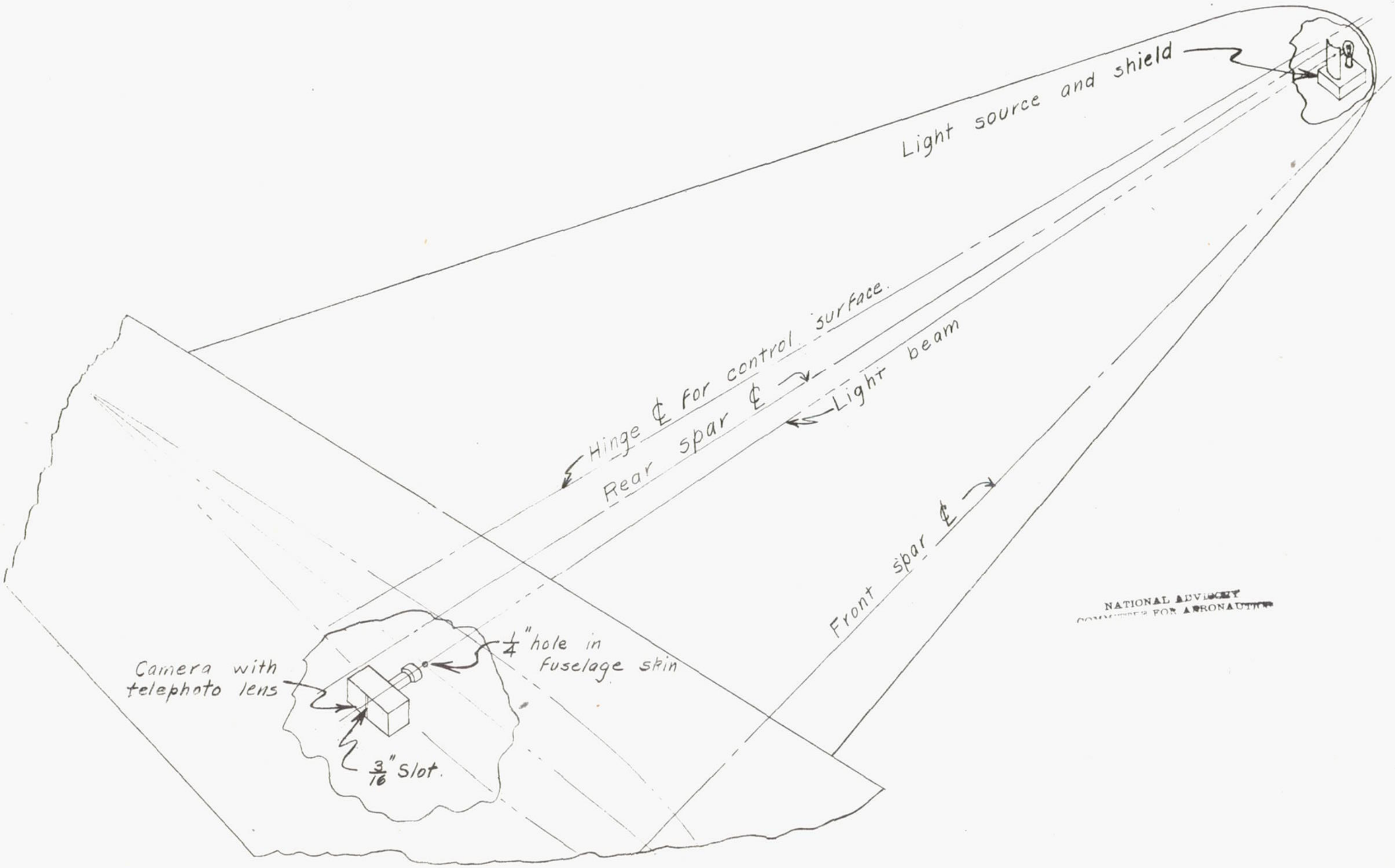

Figure 4.– Schematic diagram of deflection recorder located in tail surfaces of XB-15 airplane.

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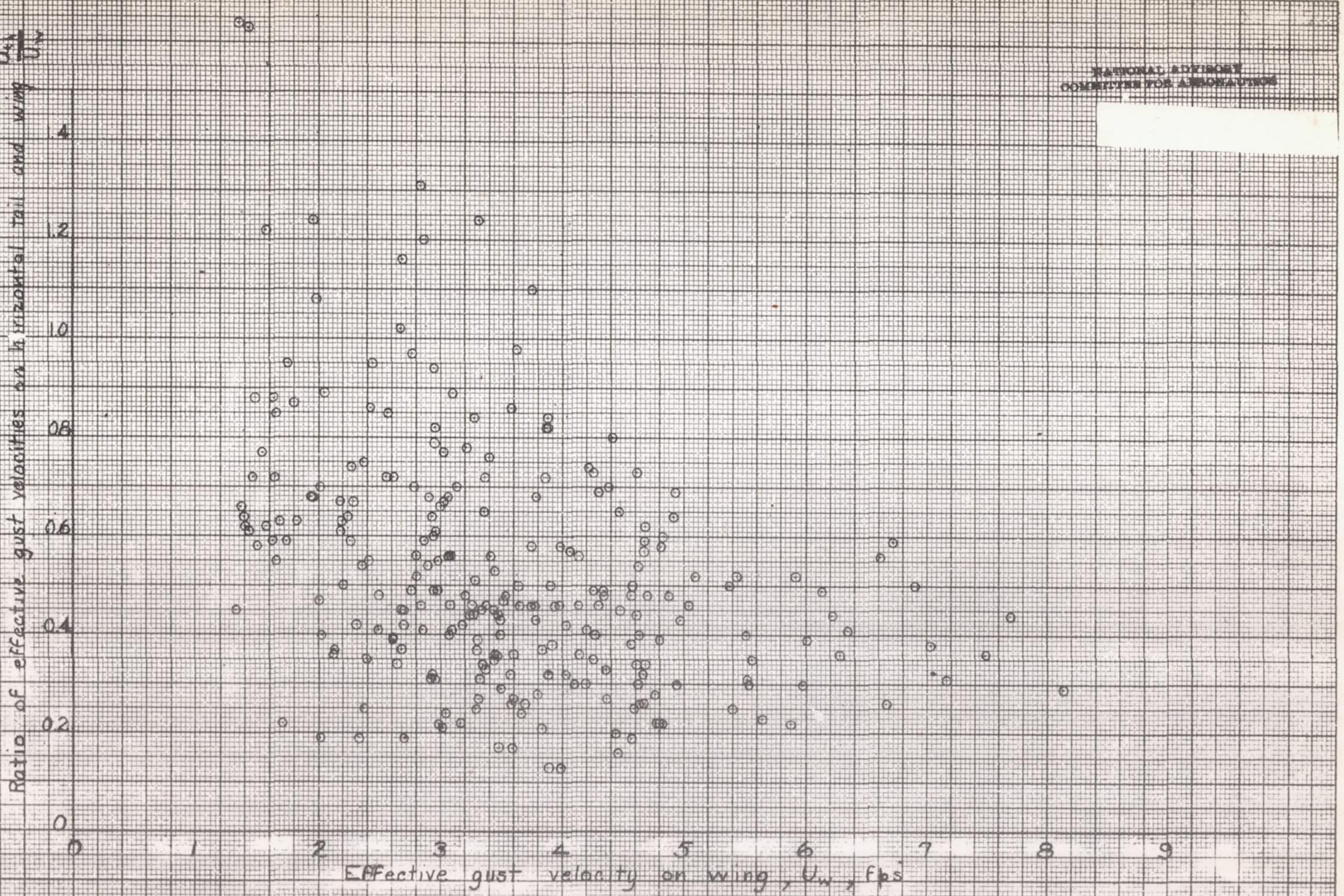

Figure 5 – Relative gust effectiveness on wing and horizontal tail

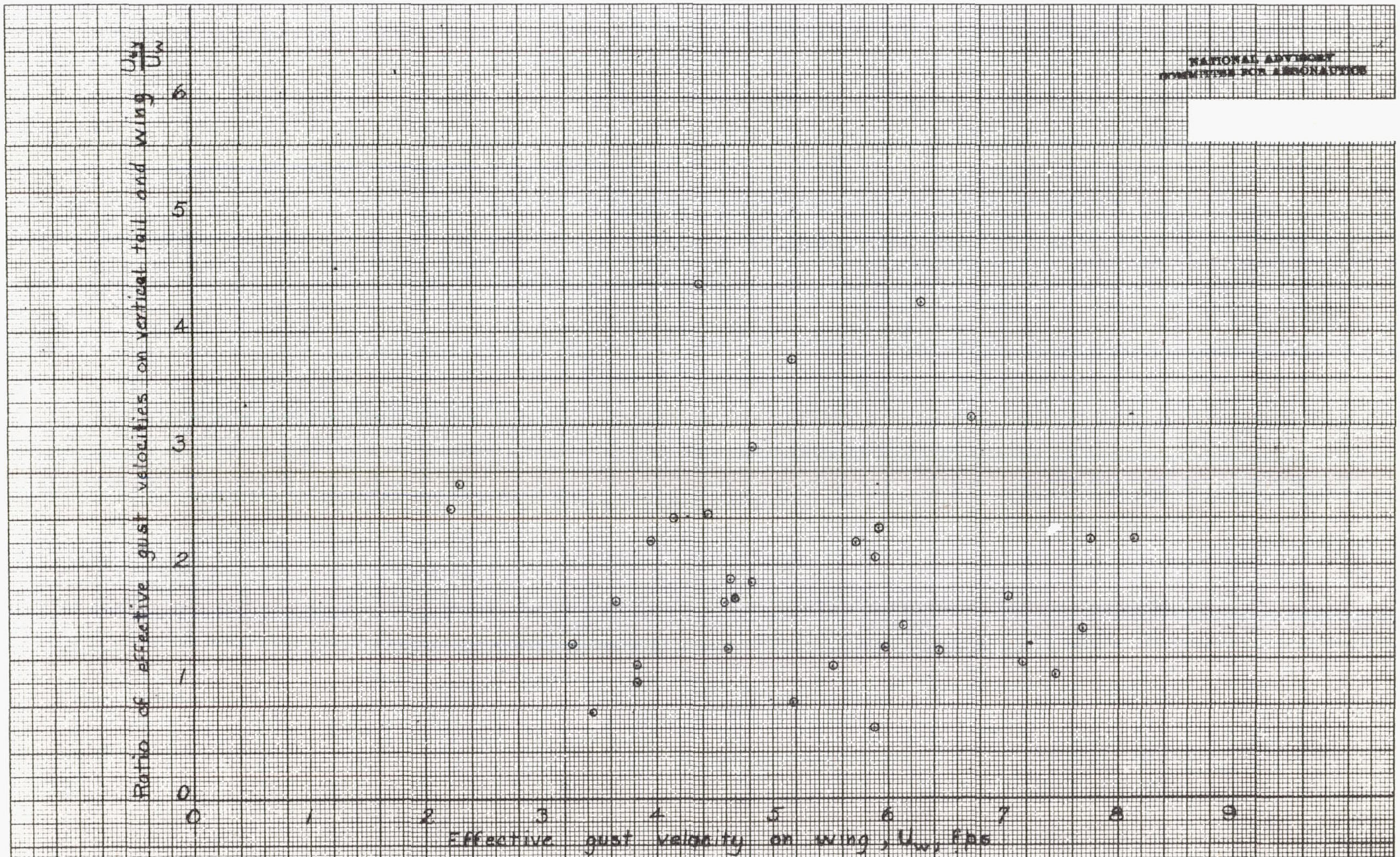

Figure 6 - Relative gust effectiveness on wing and vertical tail - maximum gust velocities occurring in each run.

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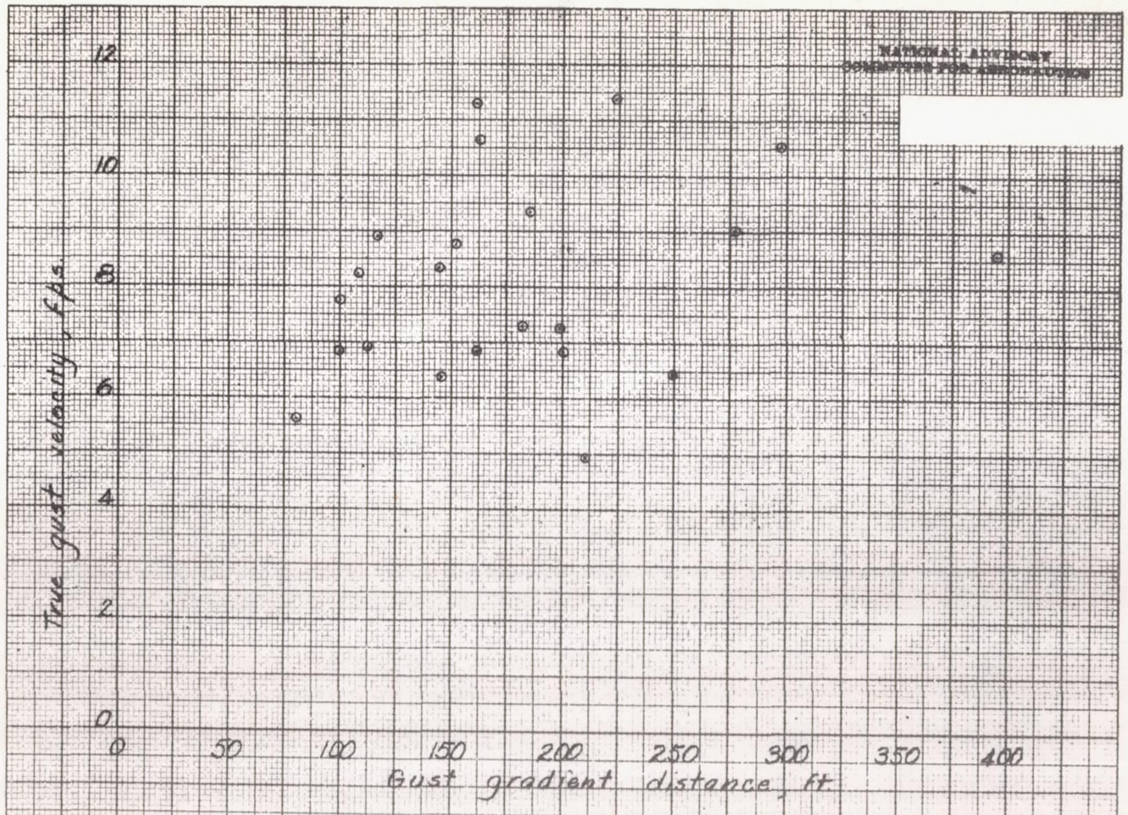

Figure 7 - Summary of gust gradient distances.

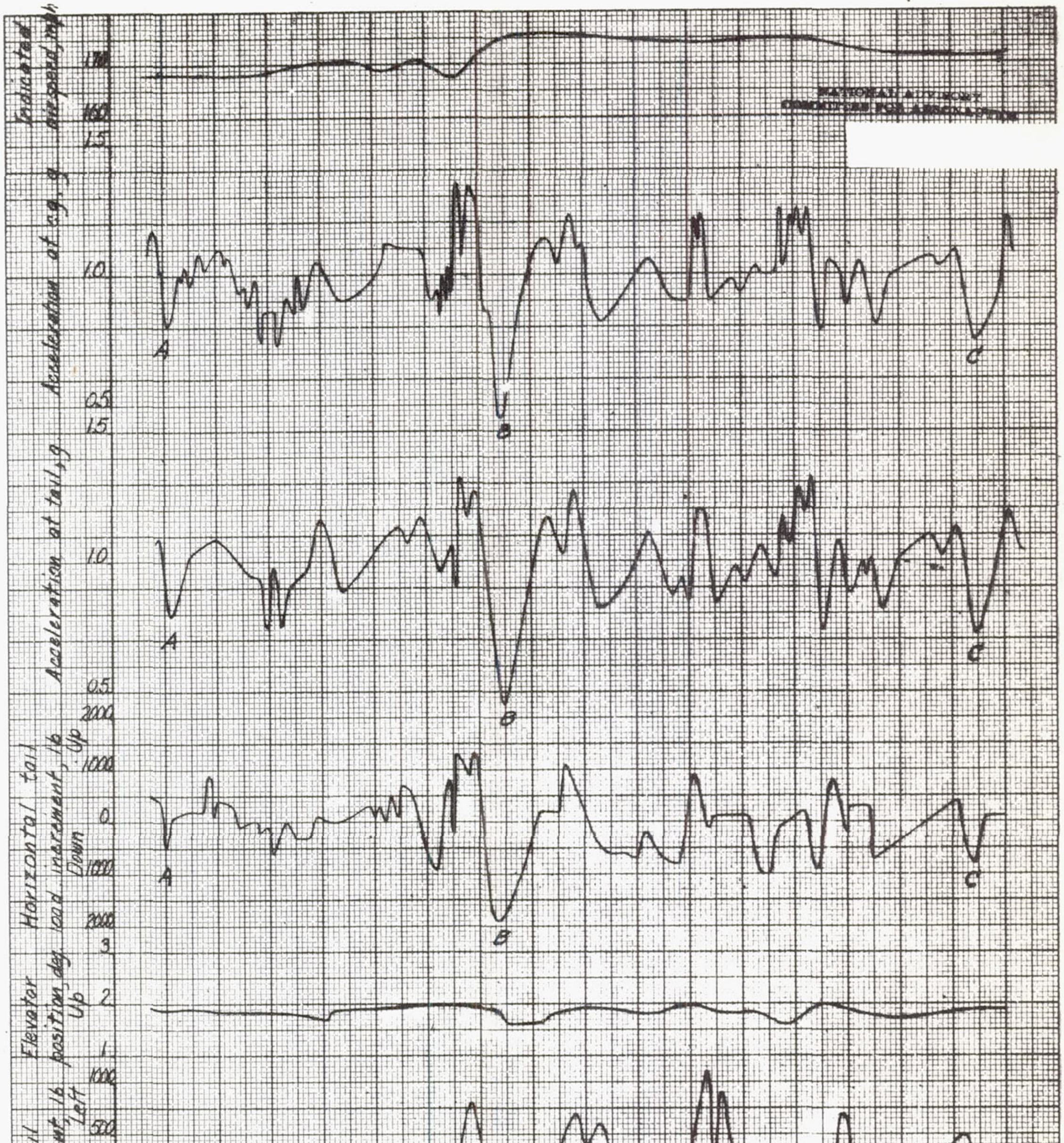

Figure 8. — Sample time history of all instruments from Flight #11, run #11

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