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CURRENT PAPERS

A Flight Investigation into the Persistence of Trailing Vortices behind Large Aircraft

by

T. H. Kerr, B.Sc., A.F.R.Ae.S. & F. Dee, A.F.R.Ae.S.

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A flight investigation into the persistence of trailing vortices large aircraft.

Dee.

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1 INTRODUCTION

The wake produced by an aircraft may be separated into three categories:

(a) the slipstream effects from propellers (or jet engines),

(b) the turbulence associated with fuselage and drag-producing excrescences and

(c) the trailing vortices.

When considering the effect of this wake on following aircraft, it has been shown by Andrews[1] that (a) and (b) are negligible compared with (c). This Note, therefore, deals exclusively with the disturbances caused by trailing vortices, and their effect on aircraft which fly into them.

Theory indicates that the strength of trailing vortices increase directly as the weight and inversely as the span and speed of the aircraft. It may be expected, therefore, that the problem will assume serious proportions at an airport, where landing rates are high, approach speeds reasonably low, and where traffic may be varied, with small aircraft landing behind large airliners. In order to investigate the time during which such disturbances exist in a dangerous form, tests have been made using a Lincoln and a Devon aircraft, with varying amounts of flap deflection, undercarriage up and down, the former simulating a heavy airliner, and the Devon a small aircraft. No special apparatus was fitted, beyond the installation of smoke canisters on the Lincoln's wing-tips, which were used to mark the position of the wing-tip vortices, and the results obtained have been derived from pilots impressions of the severity of the disturbance at various distances behind the Lincoln. The theory on the growth of the vortex suggested by Squire[4] has been applied to the results of these tests and those by Kraft[2]. The flight tests indicate that this theory holds for the first 160 seconds aircraft clean, and approximately 105 seconds flaps down, after which the vortices start to decay much more rapidly. Although there is insufficient evidence from the tests to give a clear indication of the mechanisms of this rapid decay, there is some support for the suggestion that the time for the start of the rapid decay is independent of the circulation.

2 METHOD OF TEST

The aircraft employed were a Lincoln, ballasted to 66,000 lb A.U.W., to 'lay' the wake, and a Devon as the following aircraft. No special instrumentation was fitted in the Devon; the Lincoln was fitted with racks under each wing-tip to carry a total of four smoke generators, (Fig.1 and 2), which could be ignited electrically by switching from the cockpit, and each burned for 45-50 seconds. These were used to enable the pilot of the Devon to locate and fly along the centre of the disturbance. Various optical methods were used to estimate separation distance, but the following technique was adopted to deal with the large separations involved: when the Lincoln's speed and altitude was adjusted to the test condition, one of the smoke generators was fired, and the timing was started from the instant that smoke was first visible. The Devon then circled near the beginning of the trail until a given time interval had elapsed, and then flew into the trail from astern (Fig.3). Knowing the speed of the aircraft, the separation distance could be calculated. The pilot attempted to fly the Devon so that its fusalage was in the centre of the smoke trail and he then estimated the maximum aileron angle required to hold the wings level. When both aircraft were flying at the same speed, the separation time remained absolutely constant and on each occasion that the Devon left the smoke trail (due to its irregularity), the pilot re-entered as soon as possible. Thus for each separation time, the pilot could spend an appreciable period within the vortex and thereby get a very good idea of the

aileron angle required to hold the wings level. Fig.4 shows a typical trail produced with the Lincoln flying at 130 kts in the clean condition, at an approximate range of $1\frac{1}{2}$ n.m.

The initial tests were done with both aircraft flown at 130 kt., but at a later stage, the Lincoln's speed was reduced to 110 kt., and the Devon's to 85 kt., to simulate more closely the approach speeds of the two aircraft. In all cases, calm non-turbulent conditions were sought, to ensure maximum wake persistence. The altitude at which the tests were made varied between 3,000 and 8,000 ft depending upon weather conditions. Most tests were made at approximately 6,000 ft.

The rate of roll of the Devon using full aileron was measured by timing the aircraft through 60 degrees of bank from zero rate of roll. Although it was not measured directly, the effective time lag has been estimated from Ref.3 as 0.5 seconds and the tests give a rate of roll of 21 ±2 degree/second in both clean and flaps down conditions.

3 RESULTS

The tests were made in three stages, at altitudes between 3,000' and 8,000'.

(i) Both aircraft "clean", at V_i = 130 knots.

(ii) Lincoln undercarriage down, half flap. Devon "clean". Both aircraft V_i = 130 knots.

(iii) Lincoln undercarriage down, full flap, V_i = 110 knots Devon 20° flap, V_i = 85 knots.

3.1 Both aircraft clean V_i = 130 knots

Initially, separation distances of less than 2,000 yards were investigated, but the rolling disturbance was so violent that the distance was increased to 4,000 yards, and systematic tests begun from this distance.

At separation times up to 110 seconds, it was found that full opposite aileron was insufficient to prevent the aircraft being rolled rapidly to about 45°, and flung clear of the wake with height losses of 100 ft or more. At about 160 seconds full aileron was just sufficient to counteract the imposed rolling moment although it was not until a separation of 7 n.m. (t = 180 seconds), was attained that the Devon could be controlled relatively easily. One half or less of the available aileron was needed to hold wings level, and considerable bumpiness was felt. The bumpiness could be detected up to 240 seconds. Observation of the smoke trail (Fig.4) showed it to be a compact filament, rotating at very high speed, which showed little tendency to disperse for 2-3 minutes after it had been laid.

3.2 Lincoln undercarriage down, half flap, Devon 'clean', both aircraft 130 knots

A preliminary test at a separation distance of 6 n.m. (t = 150 seconds) showed that, with flaps down, the disturbance was negligible, and consequently, all further tests were made at shorter separations.

At 90 seconds, aileron displacements of more than $\frac{3}{4}$ full travel were required to hold wings level; at 110 seconds, 2/3 aileron was necessary; but at 120 seconds, rolling tendencies were slight, although some bumpiness persisted.

Evidence in support of the greatly reduced separation times was forthcoming from visual observation of the smoke trail. The rate of rotation was very much slower, and instead of the compact filament of smoke seen in case (i), the trail was rapidly broken up after 1 minute, and had become virtually invisible after $2\frac{1}{2}$ minutes.

3.3 Both aircraft in 'approach' condition (Lincoln full flap, 110 kt. undercarriage down, Devon 20° flap 85 kt.

This test represented most closely the conditions likely to be encountered by an aircraft on the final approach to touch-down. The Lincoln was flown with full flap and undercarriage down at 110 kts, on approach speed in line with current practice; and the Devon was flown with 20° of flap at 85 kts. The Devon's undercarriage was not lowered.

It was found that full aileron was necessary to hold wings level at a separation of 60 seconds but that at 105 seconds, the disturbance required about 2/3 aileron to control.

3.4 Summary of results

The results obtained in the foregoing sections are summarised in the table below (Table 1) and Fig.5. Many more tests were made than those listed below but results which indicated lower induced rates of roll were rejected, as it was thought that these did not represent the worst cases since the Devon may not have flown into the centre of the trailing vortex.

TABLE 1
Summary of Flight Test Data

Aircraft condition	Separation time	Comments	Point No. figure
Lincoln clean	160 secs.	Full aileron required to hold rolling moment	1
130 knots 6000 ft	150 secs.	Full aileron required to hold rolling moment	
	180 secs.	Roll easily controlled	2
	240 secs.	Bumpy with very little roll tendency	3
	180 secs.	Half aileron required to stop rolling moment; very bumpy	4
Lincoln full flap	120 secs.	Smoke dissipated; bumpy, little tendency to roll	5
U/C down 110 knots	60 secs.	Full aileron required to hold rolling moment	6
5000 ft	105 secs.	Approximately 2/3 aileron required to hold rolling moment	7
Lincoln ½ flap	105 secs.	¾ aileron required to hold rolling moment	8
130 knots 6000 ft	110 secs.	2/3 aileron required to hold rolling moment	9
	60 secs.	Full aileron required to hold rolling moment	10
	150 secs.	Smoke dissipated;no rolling effect	11
	120 secs.	Bumpy small roll tendency	12
	90 secs.	¾ aileron to hold rolling tendency	13

4 INTERPRETATION OF THE FLIGHT TEST RESULTS

4.1 Theoretical and experimental studies

Very little work has been done to investigate the mechanism of the growth of the trailing vortices behind a wing. The only studies available are by H.B. Squire[4] and B.G. Newman[5]. Squire suggested that the growth of the trailing vortex would depend upon the 'eddy viscosity' ε and the circumferential velocity w of the vortex at a radius and at any time t would be given by:-

$$w = \frac{K}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{4(\nu + aK)t}\right)\right]$$

where a = a constant

K = the circulation of a line vortex

and ε = the eddy viscosity = aK.

For the flight conditions considered in this Note, ν, the kinematic viscosity is small compared with ε, the eddy viscosity, and therefore ν has been ignored in further calculations.

4.2 Application of the theory to the flight case

4.2.1 Introduction

Before going into the detail of the application of the theory to the flight case, it is worth while giving a short resumé of the overall approach so that the assumptions made during the application can be more easily followed.

The constant 'a' in the Squire theory was calculated using the flight test data of Kraft[2]. In these tests, a wake was laid by a Mustang fighter and marked using smoke. A jet aircraft was then flown through the wake on a track at right angles to that of the Mustang and by suitable instrumentation, the vertical velocities in the wake were measured. From the flight results and using a definition of r_v* so that

$$\frac{r_v^2}{4\varepsilon t} = 1.6 \qquad \text{(Fig.10)}$$

a value of 'a' = 0.0004 was calculated. A comparison of the change of vortex core diameter calculated using this constant and the measured diameter is given in Fig.6(a).

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* The vortex core radius r_v is defined as that at which the cimcumferential velocity is a constant percentage (20%) below the value it would have had in potential flow about a line vortex. This was chosen for convenience during the induced rate of roll calculations and is also quite close (within 7%) of the radius at which the maximum circumferential velocity occurs.

Using the same value for the constant 'a' the velocity distribution in one of the tip vortices of the Lincoln in the clean condition was calculated at various times (Fig.7). Assuming that the fuselage of the Devon was flown into the core of the vortex, the change in incidence on the two wings will produce a rolling moment which has been calculated, using simple strip theory, and equated to the rolling moment due to rolling to give the induced steady rate of roll. This induced rate of roll has been calculated for a range of separation times from the Lincoln with flaps up and down. When the Lincoln's flaps are down, it was assumed that the total circulation was shared between a vortex shed by the wing tip and one from the outboard end of the flap. (This is discussed in detail later).

The flight results have been compared with these calculations in Fig.6(b). (It should be remembered when examining this diagram that, all results which were obtained in flight requiring more than full aileron cannot be represented and therefore one would not expect flight results in the clean condition at separation times below 150-160 seconds).

From these results, it seemed that there were probably two different rates of decay; one predicted by Squire which continued until a certain condition in the vortex was reached and after this, a second much more rapid decay, possibly due to a change in the stability of the system. There is insufficient evidence in the flight test to give a real clue to the cause of this rapid decay, although there is some evidence to support the suggestion that the time for the start of the rapid decay is independent of the circulation.

4.2.2 The induced rolling velocities due to the Lincoln (clean)

The results obtained on the Devon have been extrapolated using the above theory to give the induced rate of roll for a range of aircraft size. These have been plotted as a function of span ratio and separation time on Fig.8. It can be seen that the small span aircraft would be severely affected up to separation times of 100 seconds.

It should be remembered that after 160 seconds there appears to be a rapid decay of the vortices and by 200 seconds only bumpiness and minor rolling effects remain.

4.2.3 The induced rolling velocities due to the Lincoln (Flaps down)

The consideration of the flaps down case is somewhat more complicated as two vortices are shed from each side of the aircraft; one from the outboard edge of the flap and one from the wing tip. For these calculations it has been assumed that the vortices are of equal strength $\frac{1}{2}K$ where K is the total circulation of the aircraft. The vortices shed from the tip and flap will rotate about each other and in the simple picture they have been graphically summed to make one vortex.

The diagram showing the vertical velocity distribution is given in the upper part of Fig.9. It has also been assumed that the radius of this vortex system increases as $\sqrt{K}$ as before.

This means that it has been assumed that the rate of growth of the tip and flap vortex is proportional to the combined or total circulation of the aircraft. The effective vortex radius r_{eff} is then approximately equal to half of the distance between the tip and flap vortices (r_o) plus the radius of the tip vortex r_T or flap vortex at any time.

$$r_{eff} = r_o + r_T = r_o + \sqrt{4 \times 1.6 \times aKt}$$

The induced rates of roll for the Devon were calculated using this single vortex structure and have been plotted in Fig.6(b). [The use of the effective vortex radius leads to induced rates of roll which are slightly higher than those which would be calculated using the full formula].

It can be seen that the agreement between the calculated and flight results between 60 and 100 seconds is surprisingly good.

The calculations were extended to cover aircraft of other span ratios, and the result of these calculations is shown in lower part of Fig.9. Again it should be remembered that the flight tests indicate a rapid decay of the vortex after 100 seconds, the disturbance falling to zero at 120 seconds.

4.2.4 The life of the trailing vortices

In the comparison between the calculated vortex decay and the flight results (Fig.6(b)) it can be seen that at 150-160 seconds (aircraft clean) and 100-110 seconds (flaps down), the induced rates of roll fall rapidly to zero. At these large separation times, a considerable amount of dispersion of the smoke has taken place. This usually takes the form of a vertical separation between sections of the smoke trail which breaks up into short lengths and eventually the complete dissipation of the smoke trail.

The mechanism of this rapid decay may be controlled by changes in the stability of the vortex system, by external forces such as atmospheric turbulence or, most probably, by a combination of both.

The characteristics which are most likely to change the stability of the vortex system are:-

(1) The growth of the core of each of the tip vortices until these interfere with each other sufficiently to cause the rapid decay. If this occurs, the time for the start of the rapid decay will be proportional to the span of the aircraft and inversely proportional to $\sqrt{K}$. Although the evidence from the flight tests is not conclusive, it does not support this as a possible mechanism.

(2) The loss of rotational velocity and therefore the inherent stability of the vortices themselves as the core grows.

This may be considered in terms of:

(a) The angular velocity within the core, or

(b) The rate of change of circumferential velocity with distance dw/dr.

In both of these cases, it can be shown that the time required to reach a given condition is independant of K. This is supported from the very limited evidence available.

Whatever the mechanism of this rapid decay in calm air, the time for this rapid decay will be appreciably modified by atmospheric turbulence, i.e. the more severe the turbulence, the earlier the effect of the vortices will disappear. It is most important that further investigations be made at low altitude and in typical approach conditions to establish the effects of turbulence when the surface wind velocities are about 10 knots or less.

5 EXTRAPOLATION TO OTHER AIRCRAFT

These results can be extrapolated to other aircraft, with taper ratios and aspect ratios similar to the Devon, by using a change of span ratio Fig.8 and 9.

To calculate the rate of roll induced on a tracking aircraft of span b_T by a lead aircraft of span b_L and having a circulation K, at any given time, the following procedure should be adopted.

(1) Aircraft clean:

(a) calculate K at sea level $K = \frac{316\ W}{V\ b_L}$ where W = AUW lb, V = speed knots, b_L = span of lead aircraft

(b) calculate the equivalent span ratio $\frac{b_T}{b_L}\sqrt{\frac{1470}{K}}$

(c) using Fig.8 look up the induced rate of roll using the span ratio calculated in (b) above at the required separation time.

This rule will hold for all equivalent span ratios less than 1.0. For values above 1.0 a complete recalculation is necessary.

(2) For aircraft with flaps down:

(a) calculate K as above

(b) calculate equivalent span ratio $\frac{b_T}{b_L}\sqrt{\frac{1720}{K}}$

(c) using Fig.9 and the equivalent span ratio, look up induced rate of roll at the required separation time. If the circulation is increased by a factor of two or four times the Lincoln values, the formulae will give induced rates of roll approximately 6% and 15% too low respectively. The error depends upon the relation between r_o and r_T.

A summary of the A.U.W., span and speeds at take-off and landing for a number of large civil aircraft is given in Table 2.

This extrapolation holds up to the time when the vortices start to decay rapidly. At present, whilst there is insufficient evidence to define the mechanism of this rapid decay, it is best to assume that the start of the rapid decay will occur at 160 seconds and 105 seconds with the aircraft clean and with flaps down respectively.

6 THE APPLICATION OF THESE RESULTS TO AIRFIELD CONTROL

In these tests an attempt was made to simulate the worst possible conditions by

(a) doing the tests in non-turbulent air (equivalent to calm air at ground level),

(b) by marking the core of the vortex and flying into it,

(c) by using the test results in which the worst effects were obtained for a given separation time.

At ground level, the chances of an aircraft being dangerously disturbed by the wake of another aircraft will depend upon:

(a) The circulation of the lead aircraft.

(b) The relative spans of the two aircraft.

(c) The rolling performance of the tracking aircraft.

(d) The separation times between the aircraft.

(e) The effect of atmospheric disturbances such as wind and thermals on the life of the vortices.

(f) The distance of the wake below the path of the aircraft at separation times of one minute or more.

The accidents and dangerous incidents, reported in Ref.6 and 7 have been examined. They include aircraft over a range of span ratios from 0.25 to 1.0 and the common features in all cases are that the separation times were of the order of 60 seconds or less and the weather conditions were such that the wind velocities were very low, almost calm, and the time was either evening or night when one would expect very few thermals.

At the present time it is felt that insufficient is known about effects such as (e) and (f) above to make an adequate prediction of safe separation times. It is possible to suggest some simple rules which could be applied until further tests are made to establish the mechanism of the rapid decay of the vortices and to investigate the effects of turbulence and the downward deflection of the wake at large distances behind the aircraft.

7 RECOMMENDATIONS FOR FURTHER WORK

(1) If the effects of the vortices are to be avoided under all weather conditions during both take-off and landing, the separation times should not be reduced below a minimum of two minutes for aircraft using part-span flaps with flaps deflected and three minutes for aircraft not using flap or with full span flaps.

(2) The separation times could be reduced to 60 seconds if the crosswind component of the surface wind is 5 knots or greater. (A 5 knot wind will move the wake 500 ft in 60 seconds).

8 CONCLUSIONS

The persistence of wing tip vortices has been investigated using a Lincoln and Devon aircraft. The results show that:

(1) With both aircraft in the 'clean' configuration (flaps up) flying at 130 knots, the vortices persist behind the Lincoln in a dangerous form for 160 seconds, (full aileron required to counteract the rolling moment applied to the Devon) but reduce rapidly to a safe form at 180 seconds, when control of the Devon could be maintained using little aileron.

(2) With the Lincoln using half flap deflection and undercarriage down and the Devon 'clean', both at 130 knots, and with full flap and undercarriage down at 110 knots, full aileron was required at 60 seconds, 2/3 aileron at 105 seconds and decaying rapidly to little aileron required at 120 seconds.

The flight results have been compared with the theoretical predictions and it appears that the theory suggested by Squire fits the experimental results quite well up to separation times of 160 seconds aircraft clean and 105 seconds with flaps down. After this, the vortices decay rapidly. Although there is insufficient evidence from the flight tests to give a clear indication of the mechanism of this rapid decay, there is some support for the suggestion that the time for the start of the rapid decay is independent of the circulation.

When using this evidence to predict conditions with other aircraft, it must be emphasised that future civil aircraft will have values of circulation up to three times those experienced in the present tests. Until further evidence is available, it is recommended that to avoid dangerous disturbance on the approach and during take-off due to another aircraft,

(a) the separation times between aircraft should not be less than 120 seconds when the aircraft are using part or full flap deflection and 180 seconds when the aircraft are clean,

(b) separation times can be reduced to 60 seconds provided that the crosswind component of the surface wind relative to the runway in use is 5 knots or greater.

Further work is required to establish a hypothesis predicting the time for the rapid decay of the vortices and to establish (a) the effects on the vortex of turbulence due to wind and thermals near the ground and (b) the distance of the wake below the flight path of an aircraft at separation times of the order of one to two minutes.

LIST OF SYMBOLS

a — a constant

b — span (ft) suffices L lead aircraft
T tracking aircraft

b' — $\frac{\pi b}{4}$ distance apart of the trailing vortices

K — circulation $K = \frac{4W}{\rho U \pi b}$

p — rate of roll (deg/sec)

r — a radius of the tip vortex (ft)

r_v — radius of the vortex core (ft) Fig.10

r_o — $2 r_o$ is equal to the distance between the centre of vortex core shed from the wingtip and the outboard edge of the flap

t — separation time records

U — true speed of the aircraft ft/sec

V — EAS knots

w' — potential flow velocity at any point due to a fully rolled up vortex pair (ft/sec) $w' = \frac{K}{2\pi} \frac{b'}{b'^2/4 - y^2}$

w — circumferential velocity of the vortex at radius r

$$w = \frac{K}{2\pi r}\left[1 - \exp\left[\frac{-r^2}{4(\nu + aK)t}\right]\right]$$

LIST OF SYMBOLS (Contd.)

W	weight (lb)
y	distance from centre line of aircraft (ft)
ρ	air density (slugs)
ε	eddy viscosity $\varepsilon = aK$

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Ref.No.	Author	Title, etc.
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7		Big plane turbulence can cause a flight hazard Safety suggestion No.8 Beech Aircraft Corporation Wichita, Kansas, 1952

TABLE 2

Summary of aircraft take-off and landing data

Aircraft	Span	A.U.W.	Speed V_i Knots	ft^2/sec K at sea level
D.C.8	139.7'	190,500 (landing)	125	3450
		287,000 (take-off)	162	4010
Boeing 707	141.5'	195,000	130	3350
		295,000	161	4100
Comet IV	115	113,000	122	2540
		152,000	138	2970
Britannia 100	142.3	123,000	110	2490
		155,000	128	2470
Viscount 700	94	52,000	105	1660
		60,000	114	1770
Lincoln (Test)	120	66,000	130 } 6000 ft	1470 } 6000 ft
		66,000	110	1720

Lincoln wing area 1326 sq.ft

Devon span 57 ft 6 ins.

WT.2078.C.P.489.K3 - Printed in England

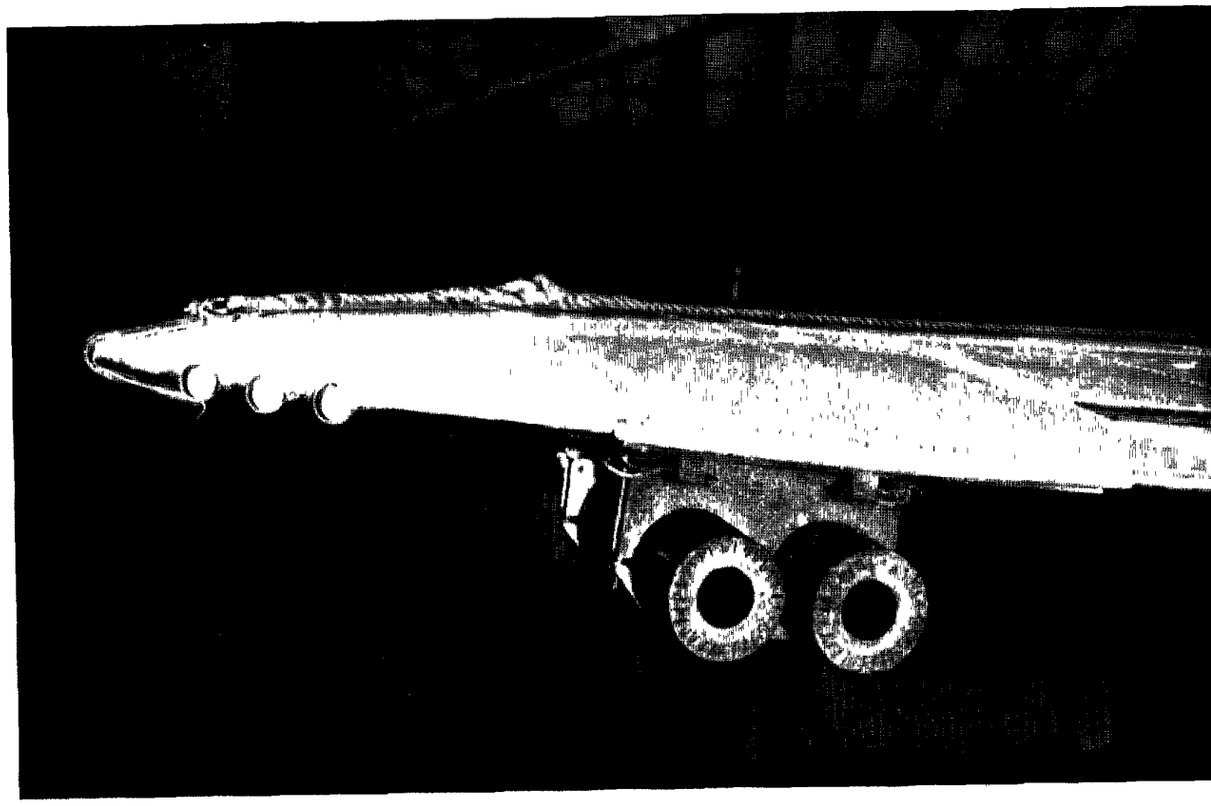


FIG.1. INSTALLATION OF SMOKE GENERATORS

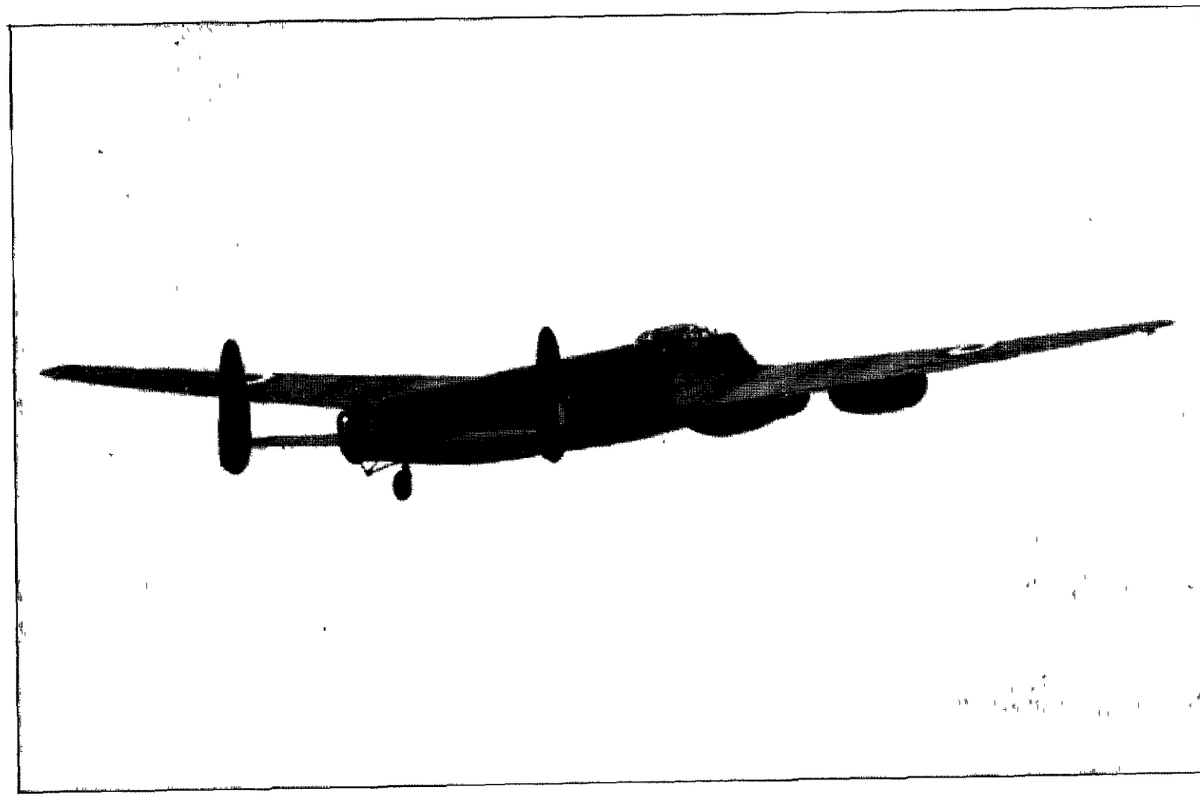


FIG.2. GENERAL VIEW OF LINCOLN

SMOKE CANISTERS VISIBLE UNDER STARBOARD WING-TIP

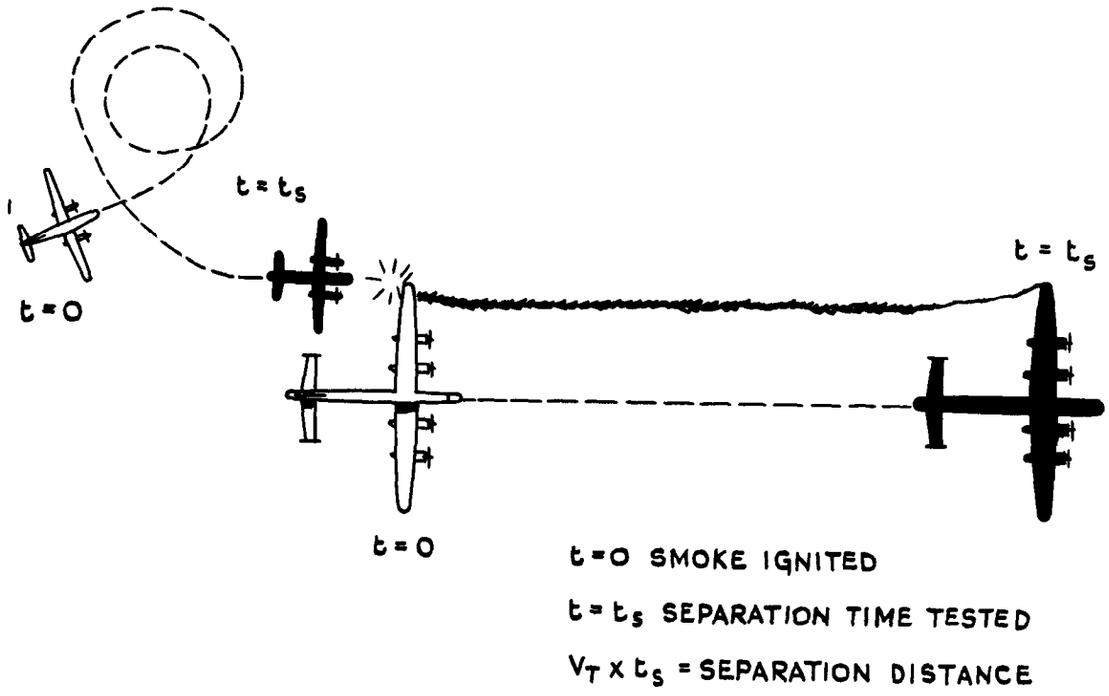


FIG.3. DIAGRAM SHOWING METHOD OF TEST

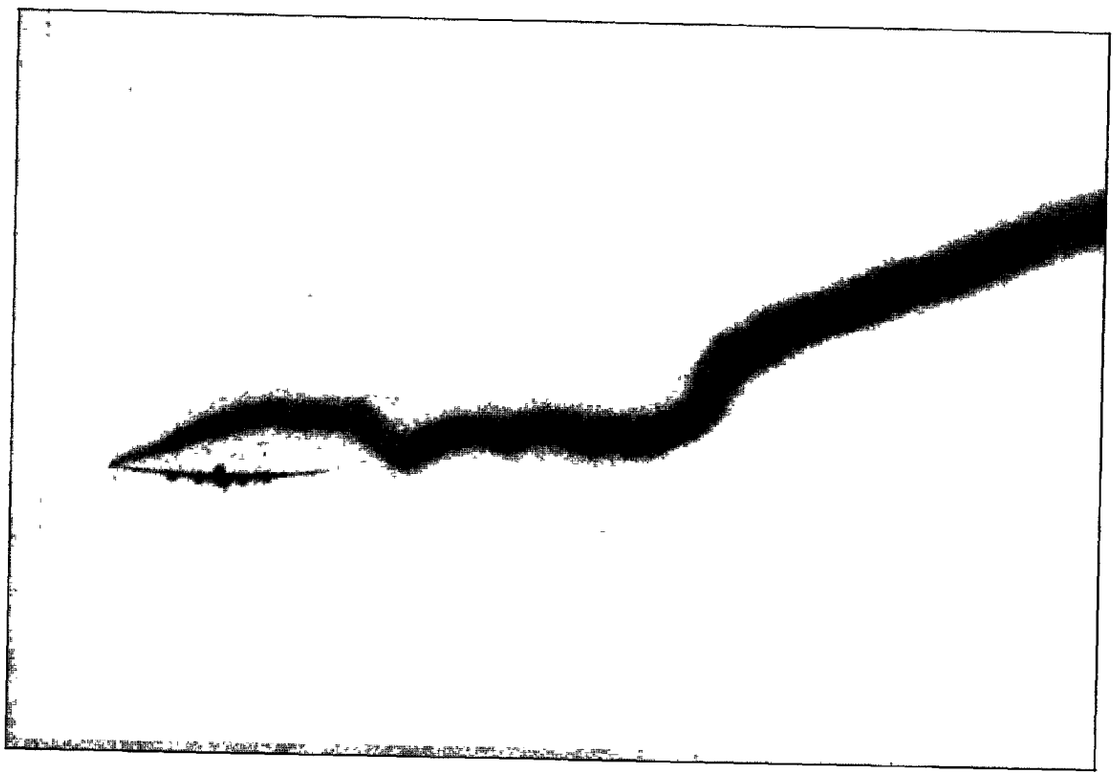


FIG.4. TYPICAL SMOKE TRAIL

AIRCRAFT CLEAN V_L = 130 kt. RANGE 1.5 N.M

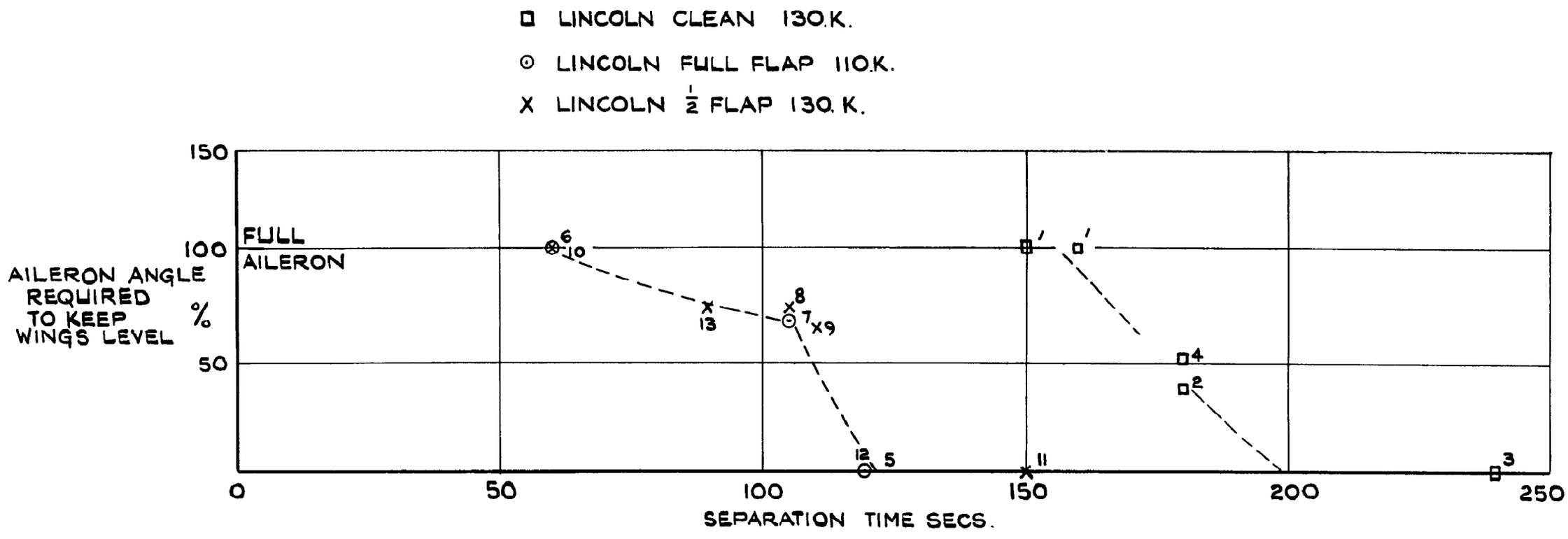


FIG. 5. SUMMARY OF THE AILERON ANGLE REQUIRED V SEPARATION TIMES OF TESTS USING A DEVON AIRCRAFT FLYING INTO THE TRAILING VORTICES OF A LINCOLN.

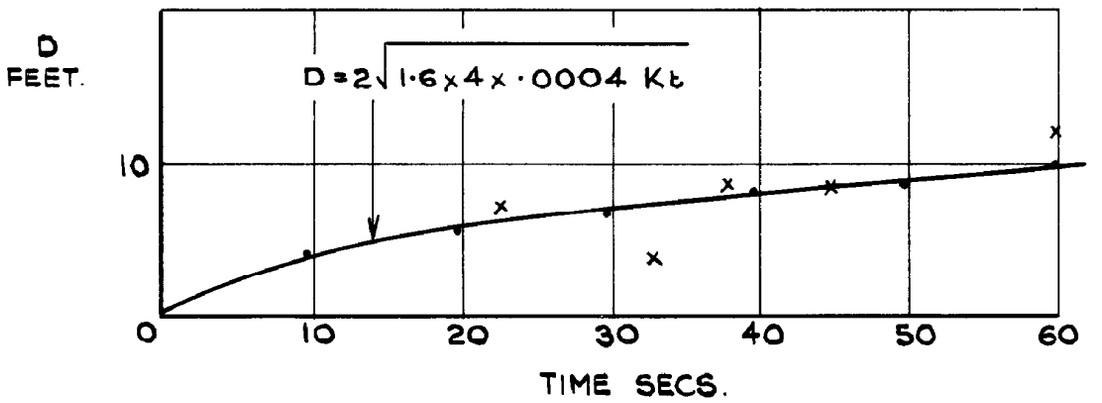


FIG.6 (a) COMPARISON OF FLIGHT TEST RESULTS OBTAINED BY KRAFT & SQUIRE THEORY (USING ε =·0004 K)

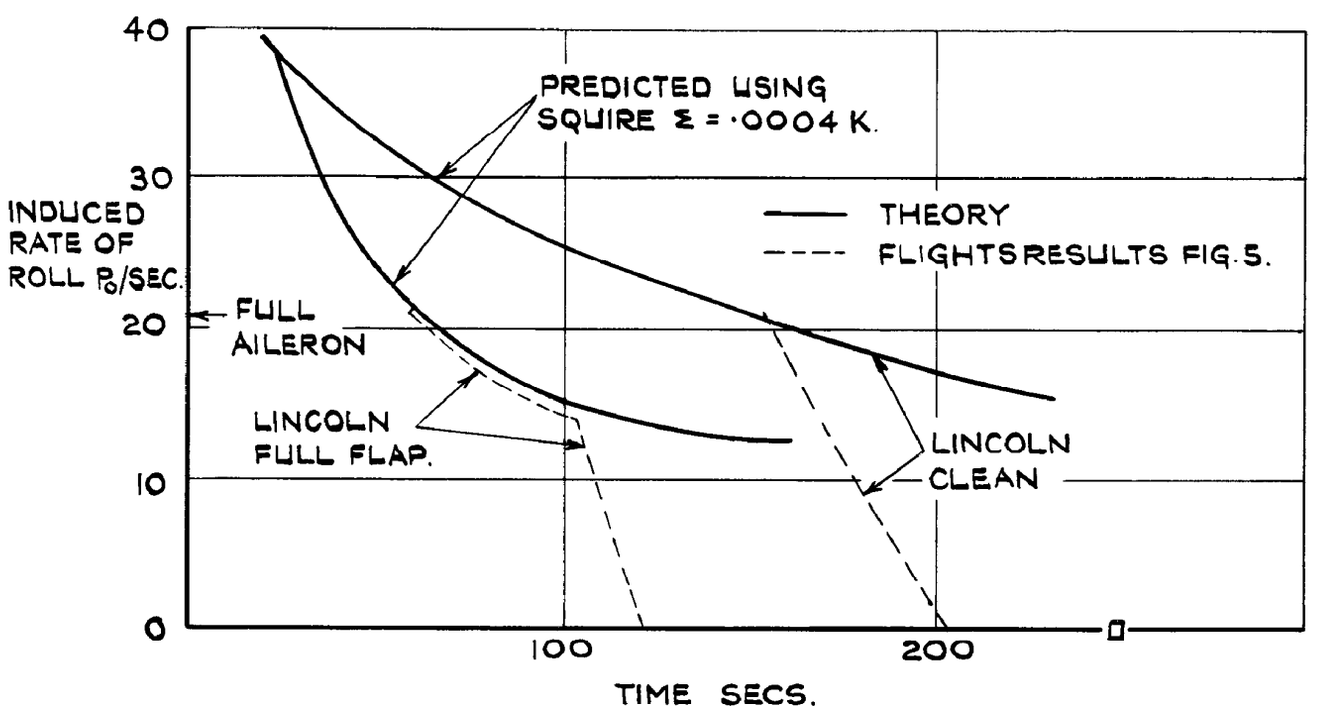


FIG. 6 (b) COMPARISON OF FLIGHT TEST RESULTS AND THE PREDICTIONS USING THE SQUIRE THEORY.

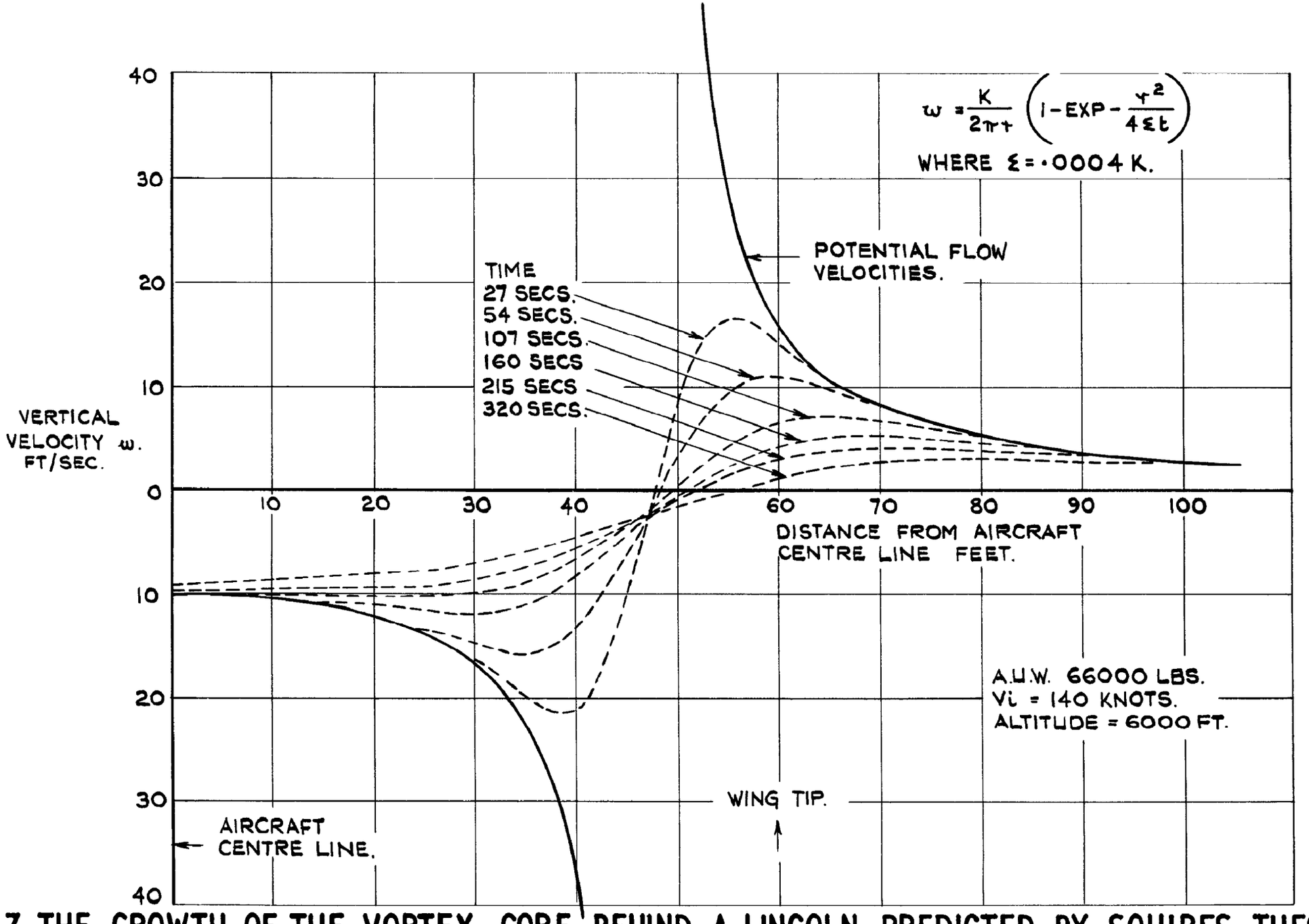


FIG.7. THE GROWTH OF THE VORTEX CORE BEHIND A LINCOLN PREDICTED BY SQUIRES THEOREM.

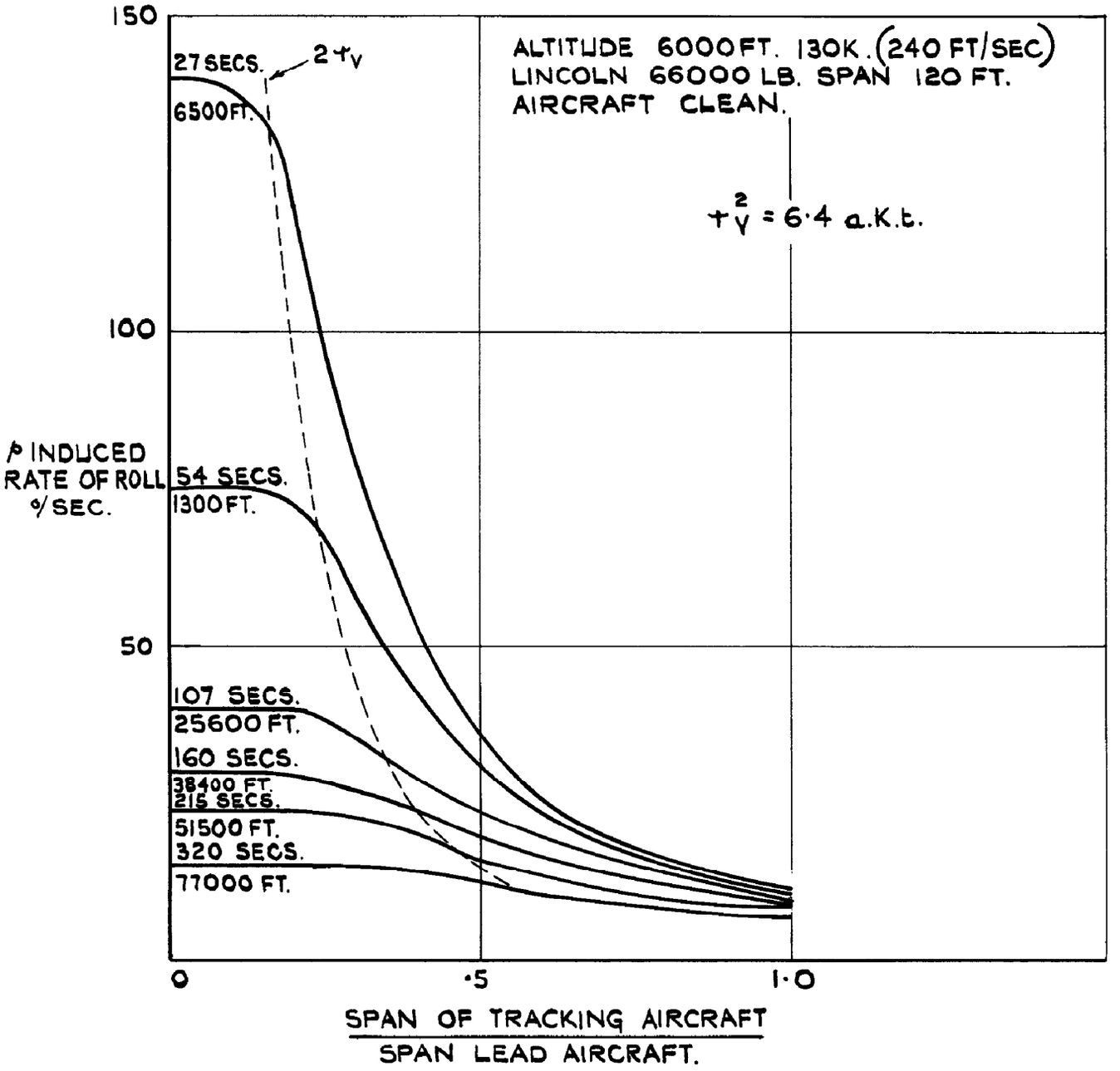
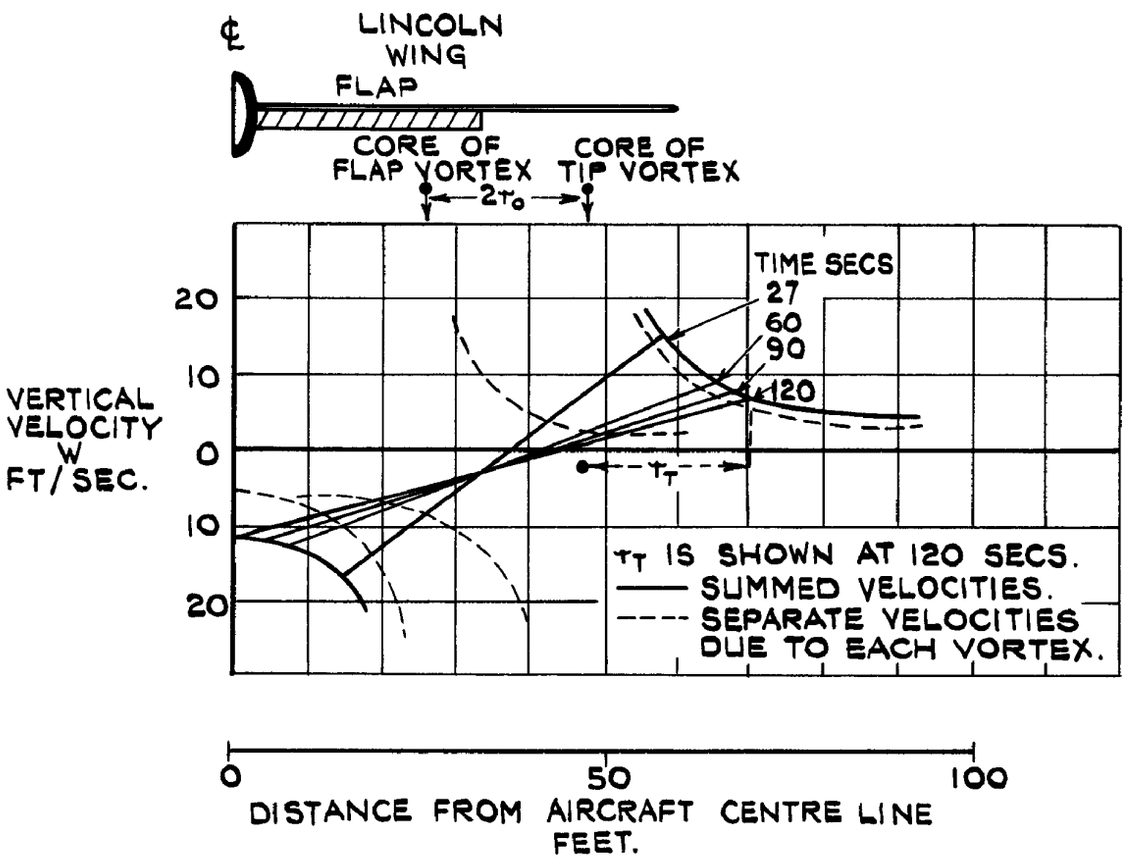


FIG.8. THE CALCULATED INDUCED RATES OF ROLL OF A TRACKING AIRCRAFT FLYING INTO A TRAILING VORTEX BEHIND THE LINCOLN IN THE CLEAN CONFIGURATION



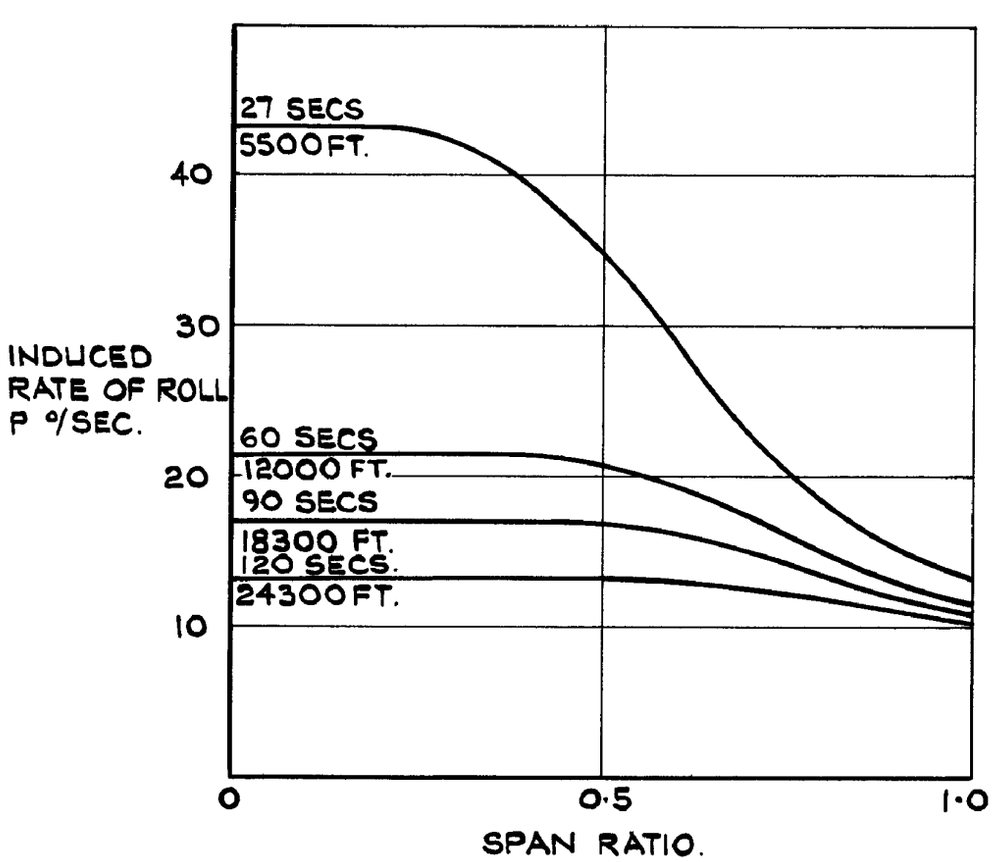


FIG. 9. THE CALCULATED INDUCED RATES OF ROLL OF A TRACKING AIRCRAFT FLYING INTO THE TRAILING VORTICES BEHIND A LINCOLN WITH FLAPS DEFLECTED.

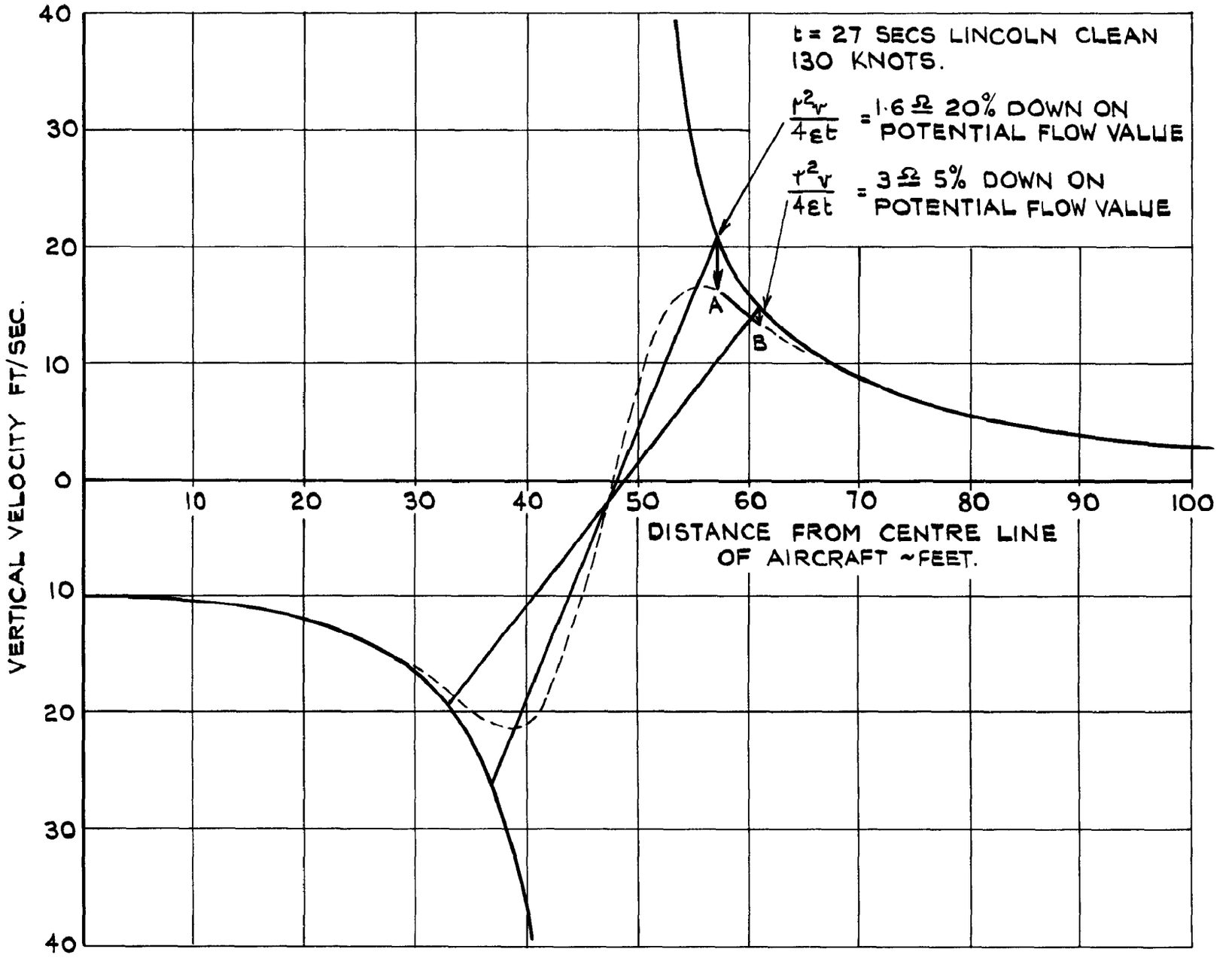


FIG.10 THE EQUIVALENT VORTEX RAD. USING TWO DIFFERENT DEFINITIONS.

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