REPORT No. FAA-FS-71-1

VORTEX WAKE TURBULENCE

Flight Tests Conducted During 1970

Federal Aviation Administration Task Force

in Joint Participation With

National Aeronautics and Space Administration

and the Boeing Company

FEBRUARY 1971

FINAL REPORT

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Flight Standards Service
Washington, D. C. 20590

CONTENTS

PREFACE

Vortex wake turbulence has been the subject of extensive study, testing and analysis by the academic, scientific and aviation community for many years. The scope of these studies is illustrated by the extensive number of reports and papers previously issued on this subject.

The introduction of the jumbo jets, Lockheed C5A and Boeing 747, focused renewed attention on wing-tip vortices because the earlier studies and theoretical projections indicated that airplane size and weight were significant factors affecting the core diameter, tangential velocities and field of influence of wing-tip vortices.

This report covers the 1970 flight test program conducted by the Federal Aviation Administration in joint participation with the National Aeronautics and Space Administration and the Boeing Company.

Other organizations that actively participated or provided personnel/ resources include:

Atomic Energy Commission
Environmental Science Services Administration
Flying Tiger Air Line
Japan Air Lines
Pan American World Airways
Trans World Air Lines
United Air Lines
United States Air Force

Key participants in the test program include:

Mr. William Andrews, Senior Research Scientist, NASA Flight Research Center
Mr. Glenn H. Robinson, Research Scientist, NASA, Flight Research Center
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Mr. Walt Luffsey, Systems Research & Development Service, FAA
Mr. Ray Baran, Air Traffic Service, FAA
Mr. Dave Snowden, Flight Standards Service, FAA
Mr. Joseph Bailey, Project Pilot, NAFEC

In addition to the active participation of these individuals and organizations, liaison was maintained and input received from many segments of the scientific, academic and aviation community. This input is reflected in several of the conclusions, recommendations, and descriptive sections of this report.

SUMMARY

A flight test program designed to obtain data on the characteristics of wing-tip vortices generated by large jet aircraft was initiated on 12 February 1970. The objective was to update the interim air traffic separation standards issued on 21 January 1970 restricting the airspace behind the B-747 and C-5A aircraft 60° either side and 2,000 feet below to a distance of 10 miles.

The program involved flight tests at three different locations, which were conducted simultaneously.

1. At the Edwards Air Force Base test range, a NASA CV-990 and F-104 probed the vortices of a C-5A. This supplemented previous flight tests in U-3A and F-104 behind a B-52 and C-5A.

2. At Seattle, the Boeing Company probed the vortices of a B-747 and a B-707-300 with a B-737 and F-86. In addition, approach, landing, takeoff, and crossing runway tests were conducted with a B-737 trailing a B-747. Immediately following the Edwards tests, the NASA CV-990 proceeded to Seattle and engaged in probing flights behind the same B-747 and B-707-300.

3. At Idaho Falls, Idaho, FAA personnel, utilizing the Atomic Energy Commission and Environmental Science Services Administration facilities and a 200 ft. instrumented tower, conducted 114 flights past the tower. The aircraft were positioned to permit their vortices to descend into the air flow sensors and smoke generated from various levels on the tower. This permitted obtaining measurements and photography of the vortex core diameters, tangential velocities and related characteristics.

Immediately following this test phase, analysis of the interrelated data was completed by the project managers representing NASA, Boeing and FAA and a Compilation of Work Papers was issued on 30 April 1970.

These data were the basis of a revised General Notice issued on 26 February 1970 which, in essence, modified the restricted airspace to five miles behind heavy jets in the 300,000 lb. gross takeoff weight category.

The test results dictated the need for a Phase II program having three objectives:

1. To obtain additional data on the effect of the vortices generated by jumbo and medium weight jet transports on the short-haul class of jet transport airplanes.

2. To further evaluate the effect of vortices generated by light, medium, and heavy jet transports on representative executive jets and general aviation type aircraft.

3. To determine the attenuation factors when vortices are generated in ground effect or descend into ground effect, combined with time history characteristics of vortex systems under various ambient surface wind conditions.

The follow-on (Phase II) test program and submission of test results was completed on 23 November 1970.

It should be noted that the body of this report covers only the highlights of the test programs in summary format. The complete coverage of the individual test programs is contained in the reports tabulated in the list of references.

SCOPE OF THE TEST PROGRAM

1. FLIGHT TEST PROGRAM - PHASE I

A. Tests Conducted by NASA at Edwards and Seattle

This portion of the program was directed by the NASA Flight Research Center. A summary of the test airplanes used in the program and the related aircraft configurations and separation distances investigated is shown in Figure 1.

Wake Generating Aircraft

Aircraft	Test configuration range
C-5A	Airspeed - 135 to 170 knots Altitude - 10,000 to 12,500 ft Gross weight - 440,000 to 590,000 lb Flaps - clean, takeoff, landing
Boeing 747	Airspeed - 170 to 250 knots Altitude - 15,000 ft Gross weight - 558,000 to 606,000 lb Flaps - clean, approach
Boeing 707-320C	Airspeed - 165 to 250 knots Altitude - 15,000 ft Gross weight - 265,000 to 280,000 lb Flaps - clean, approach

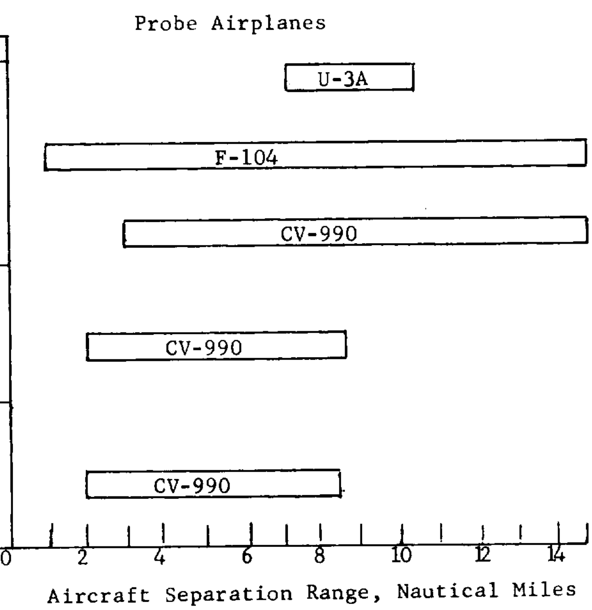


FIGURE 1. Phase I - NASA - Edwards AFB and Seattle, Washington

During this phase of the tests, the probe airplane was positioned in the right-hand vortex and the pilot was requested to fly and maintain the airplane in the wake from the maximum range of detection to a minimum separation distance specified. Also, during a major portion of this phase of the testing, the pilot of the probe airplane was further instructed to return the airplane to the wake path as soon as possible following an upset generated by the wake. The main reason for conducting the test in this manner was to establish the wake persistence, the apparent intensity, the associated airplane upset tendency, and the vertical location of the wake relative to the generating airplane.

During the flight testing performed in the local area of Edwards, California, a race-track pattern was established between Mojave and Harpers Dry Lake at the assigned altitude. The normal engine exhaust smoke trail from the C-5A was relied on to identify the location of the vortex trail. In the region from 1 to 4 nautical miles, the smoke trail was well defined; however, the region of highest wake intensity was not easily located. During these tests, the probe and generating aircraft separation distance was resolved by the Air Force Space Positioning Branch. FPS-16 and Nike Ajax radars were used, and a major portion of the tests were observed and recorded on a video tape system.

<u>Instrumentation.</u> During the tests conducted with the Convair 990 and U-3A probe aircraft, the same data package was used to record the basic airplane responses. The recorded parameters included the following:

- Airspeed
- Altitude
- Normal acceleration, Longitudinal acceleration, Transverse acceleration — Center of Gravity
- Pitch velocity
- Roll velocity
- Yaw velocity
- Lateral-control positions -
  - Wheel position of CV-990
  - Aileron position of U-3A

The data were recorded on a 14-track FM tape recorder installed in the package.

A summary of the average vertical vortex location as a function of aircraft separation range recorded during tests with the C-5A and earlier B-52 flights at low altitude in the clean and landing configurations is shown in Figure 2. The atmospheric lapse rate for these data varied from -1.9°C to -2.7°C per 1000 feet of altitude change.

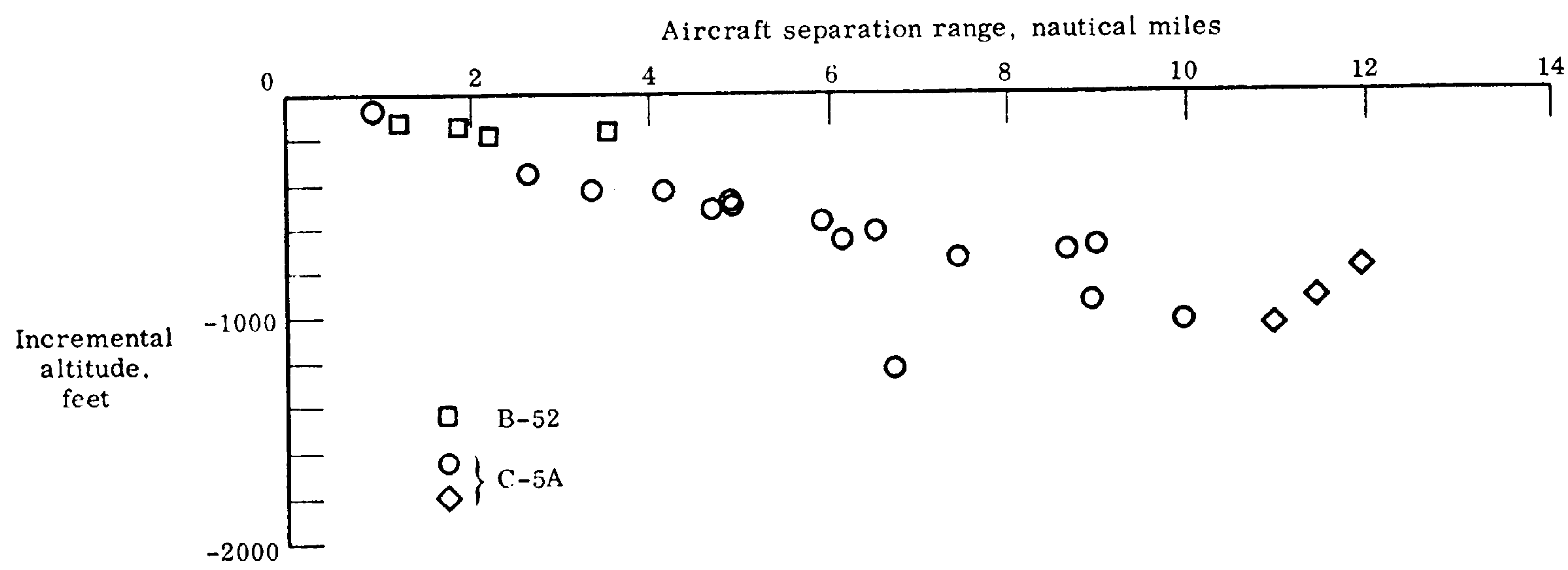
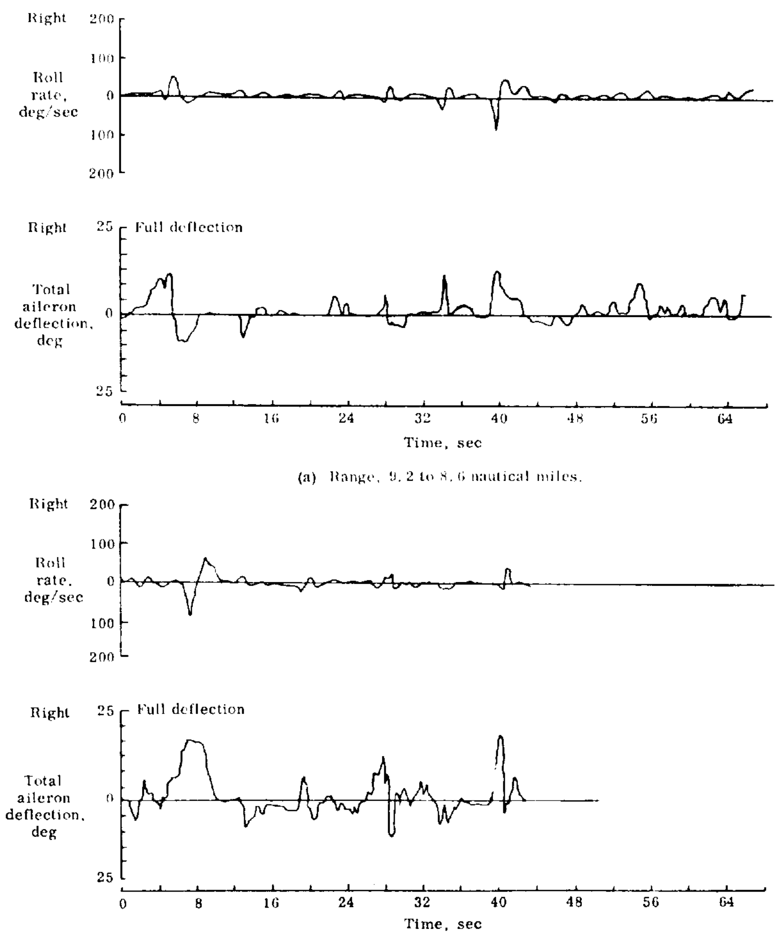


FIGURE 2. Average vertical wing vortex location behind the generating airplane determined from FPS 16 radar tracking data. Lapse rate -1.9° C to -2.7° C per 1000 ft.

In addition to the above data runs, the F-104 was used to observe the vertical vortex path of the C-5A during cruise at a Mach number of approximately 0.8 and an altitude of 37,000 feet. The vortex path was identified by condensation trails.

The F-104 response while flying behind the C-5A in the clean and landing-flaps configurations is shown in Figures 3, 4, and 5. Vortex penetration speed of the F-104 varied from 250 to 300 knots. By observing Figures 3(a) and (b) and comparing the aileron inputs with the roll response at discrete points, it can be seen that excessive and large aileron control displacement is required to maintain position in the vortex path. It appeared in some cases that the generated roll rate may have been exceeding the lateral-control power available to the pilot. During the test runs at the close range; i.e., 3.6 nautical miles, the control activity increased considerably in spite of the fact that the roll velocity appeared to be reduced.



(a) Range, 9.2 to 8.6 nautical miles.

(b) Range, 3.6 nautical miles.

FIGURE 3. Typical time histories of the F-104 airplane probing the wing vortex of the C-5A airplane. C-5A: airspeed - 170 knots, altitude - 12,500 ft., gross weight - 456,000 lb, clean configuration; F-104: airspeed - 250 knots.

On several occasions during this type of vortex penetration run, the F-104 was actually thrown from the wake and large excursions in airspeed and altitude resulted. Figures 4(a) and (b) illustrate two such occurrences at separation ranges of 4.2 and 9.2 nautical miles. The time and aileron deflection scale of this time history have been expanded so that the initial roll accelerations (slope of the roll rate) may be observed with the corresponding lateral-control input. For the conditions at 4.2 nautical miles, it was obvious that the roll acceleration resulting from the vortex wake influence far exceeded the lateral-control power, even considering that an initial lead input was made with aileron to prevent the roll from developing. At 9.25 nautical miles, the maximum roll acceleration attained appeared to be slightly greater than that experienced at 4.2 nautical miles. However, in this case it appeared that the lateral control applied was sufficient to prevent the peak roll from exceeding 120 degrees per second. In either case, based on the related roll accelerations experienced, there does not appear to be an appreciable attenuation of the vortex influence over the range of test conditions. During these runs, the respective airplane upsets resulted in altitude and airspeed excursions of approximately 1200 feet and +15 knots.

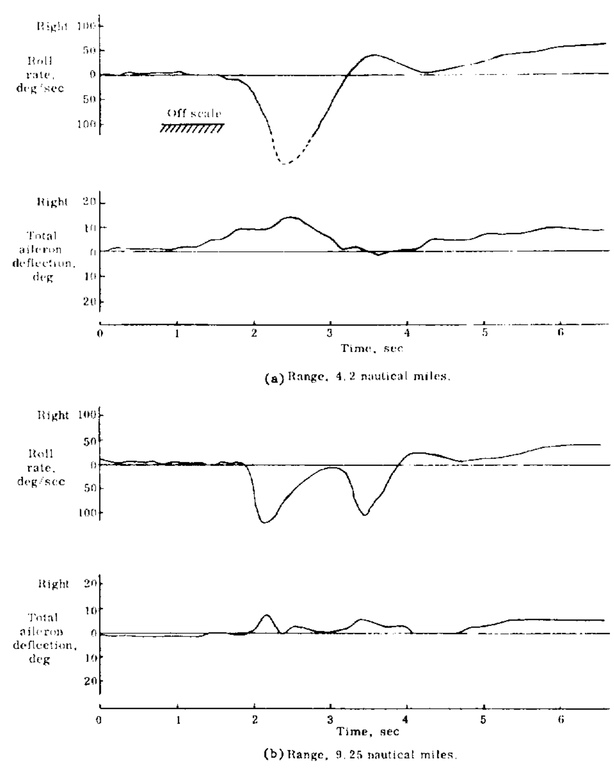


FIGURE 4. C-5A: airspeed - 170 knots, altitude - 12,500 ft, gross weight - 584,000 lb, clean configuration; F-104: airspeed - 300 knots.

Figure 5(a) and (b) presents similar data to illustrate the influence of the extended flaps on the C-5A. In general, the pilots indicated that the flaps appeared to diffuse the smoke in the wake, and the control task was believed to have been reduced. For the conditions illustrated, some slight reduction in the induced roll rates may be observed; however, there still appears to be a comparable amount of control activity. This may be attributed to the superimposed influence of the deflected flap on the basic wing vortex flow field, which could produce an increase in the turbulence level and a reduction in the rotational flow with a subsequent reduction in induced roll rate.

The data obtained in both the U-3A and the F-104 served to illustrate the responsive behavior of a short-span airplane flying in the vortex wake of a large jet airplane.

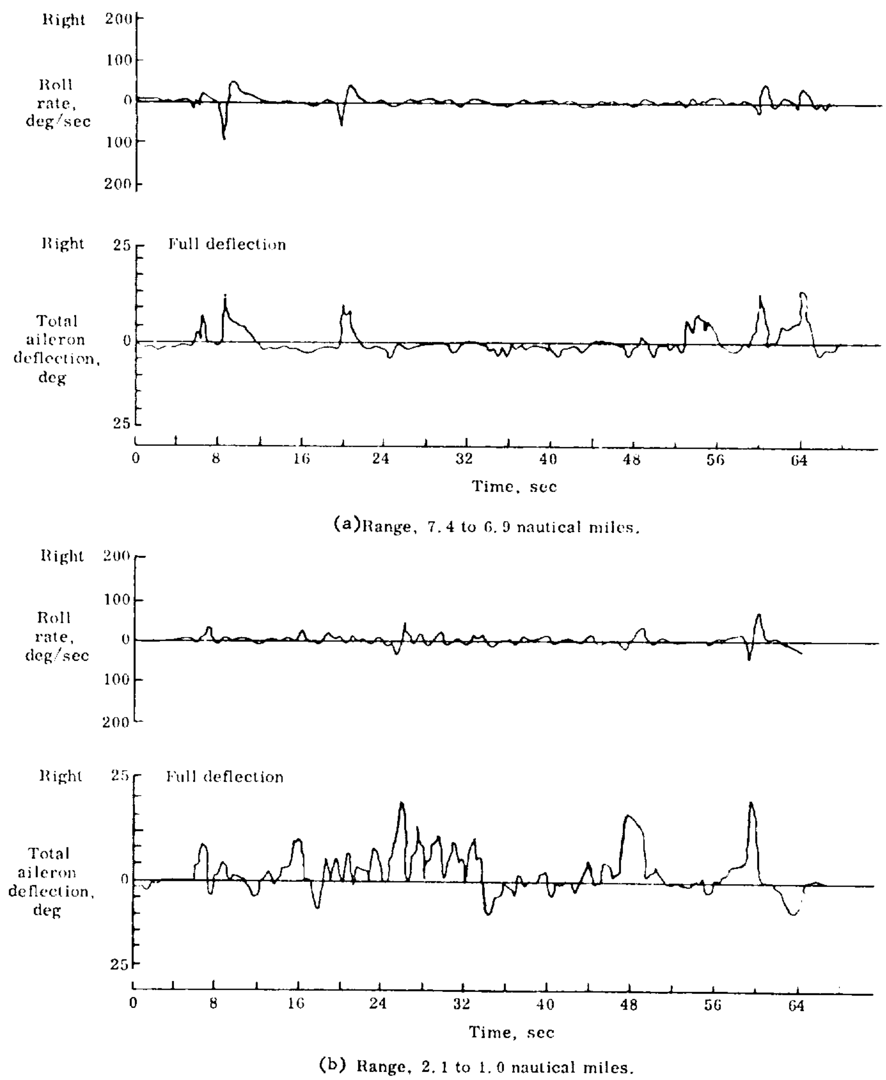
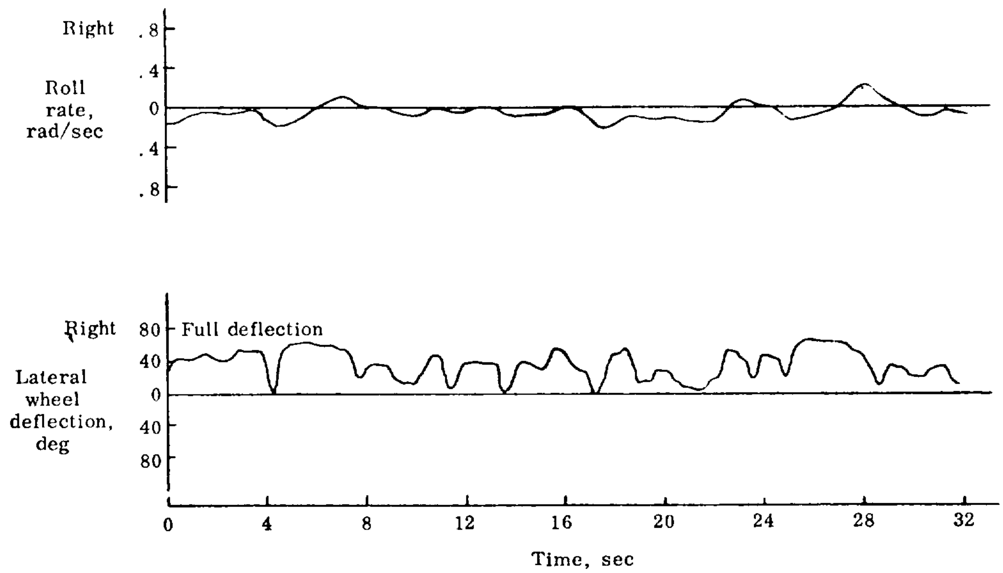
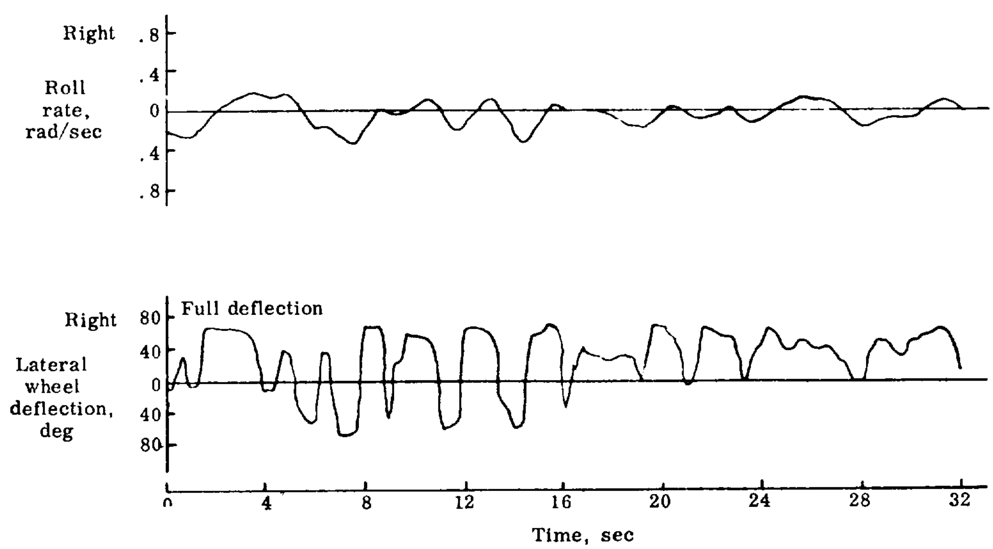


FIGURE 5. C-5A: airspeed - 170 knots, altitude - 12,500 ft, gross weight - 452,000 lb, landing-flap configuration; F-104: airspeed - 250 knots.

Time histories of the Convair 990 airplane flying in the wake of the C-5A are shown in Figure 6. It may be seen that the roll responses of this larger airplane are considerably reduced from those observed in the tests with the smaller airplanes.



Range, 3.0 nautical miles.



Range, 8 nautical miles.

FIGURE 6. Typical time histories of the Convair 990 airplane probing the wing vortex of the C-5A airplane. C-5A: airspeed - 170 knots, altitude - 12,500 ft, gross weight - 496,000 lb, clean configuration; CV-990: airspeed - 250 knots.

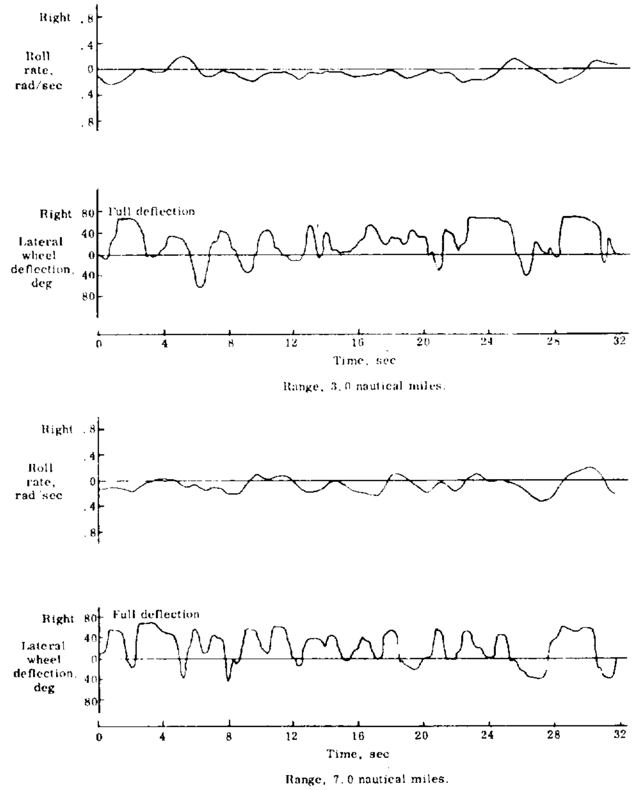


FIGURE 6. (Continued) C-5A: airspeed - 165 knots, altitude - 12,500 ft. Gross weight - 489,000 lb, landing approach configuration; CV-990: airspeed - 250 knots.

A time history of the Convair 990 response to the B-747 airplane wing vortex at ranges of 3, 7, and 8 nautical miles is shown in Figure 7. As in the C-5A tests, the CV-990 probed the B-747 wake at an airspeed of 250 knots. The B-747 was flown in the clean and approach-flap configuration. A general observation of the roll-response and control input data is that the roll rates are maintained within the region of 0.3 and 0.4 radian per second, whereas control-wheel motions vary between 70° right and 70° left, which is full travel for the CV-990. The only noticeable differences are that in the close separation ranges, for both configurations, the frequency of control motion is somewhat reduced and in many cases full wheel is maintained to oppose the rolling moment of the vortex for approximately 5 to 6 seconds. In the region of 7 nautical miles separation, it appears that the amount of wheel deflection is slightly reduced while the frequency of control input is somewhat increased. From these data, there does not appear to be an apparent effect of configuration on the control required although the pilots indicated that the workload appeared to be reduced in the landing configuration.

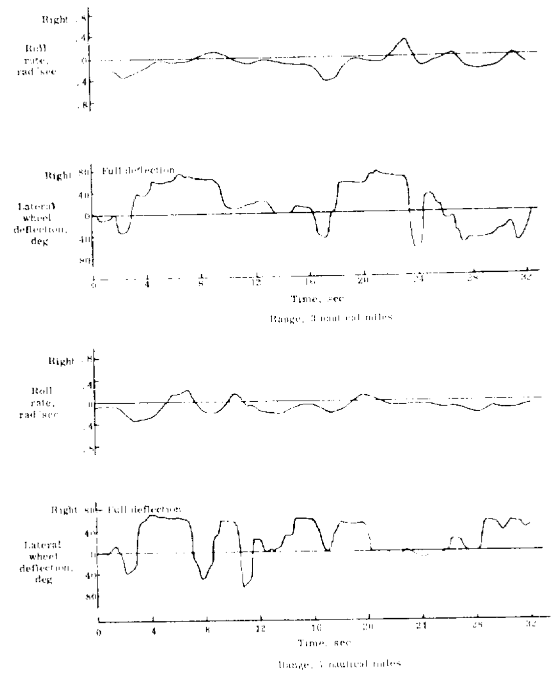


FIGURE 7. Typical time history of the Convair 990 airplane probing the wing vortex of the Boeing 747 airplane. Boeing 747: airspeed - 252 knots, altitude - 15,000 ft, gross weight - 570,000 lb, clean configuration; CV-990: airspeed - 250 knots.

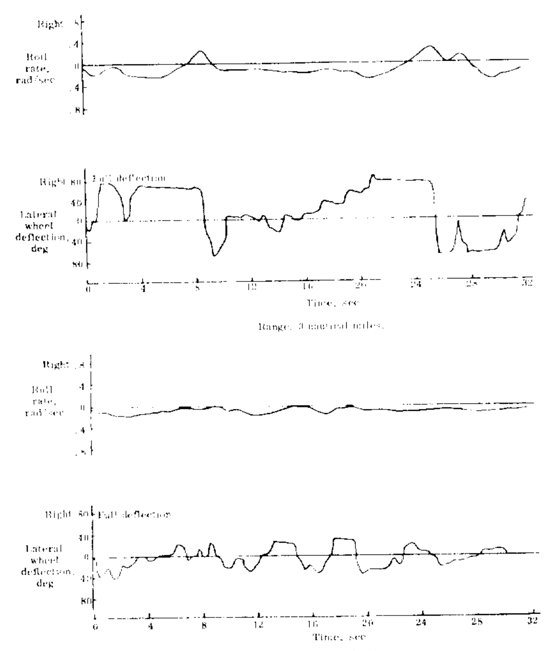


FIGURE 7. (Continued) Boeing 747: airspeed - 172 knots, altitude - 15,000 ft, gross weight - 565,000 lb, landing approach configuration, gear down; CV-990: airspeed - 175 knots.

Time histories of the CV-990 probing the wake of the Boeing 707-320C airplane at ranges of 3, 7, and 8 nautical miles is shown in Figure 8. The B-707 clean and landing-approach configurations were evaluated. The roll rates observed during these four runs varied up to 0.3 radian and the control activity was comparable to that experienced behind the B-747. At the ranges of 8 and 7 nautical miles, there is some indication that the wake intensity had dissipated; however, it should be noted that the location of the wake of the 707 was more difficult to find, particularly at the larger separation ranges.

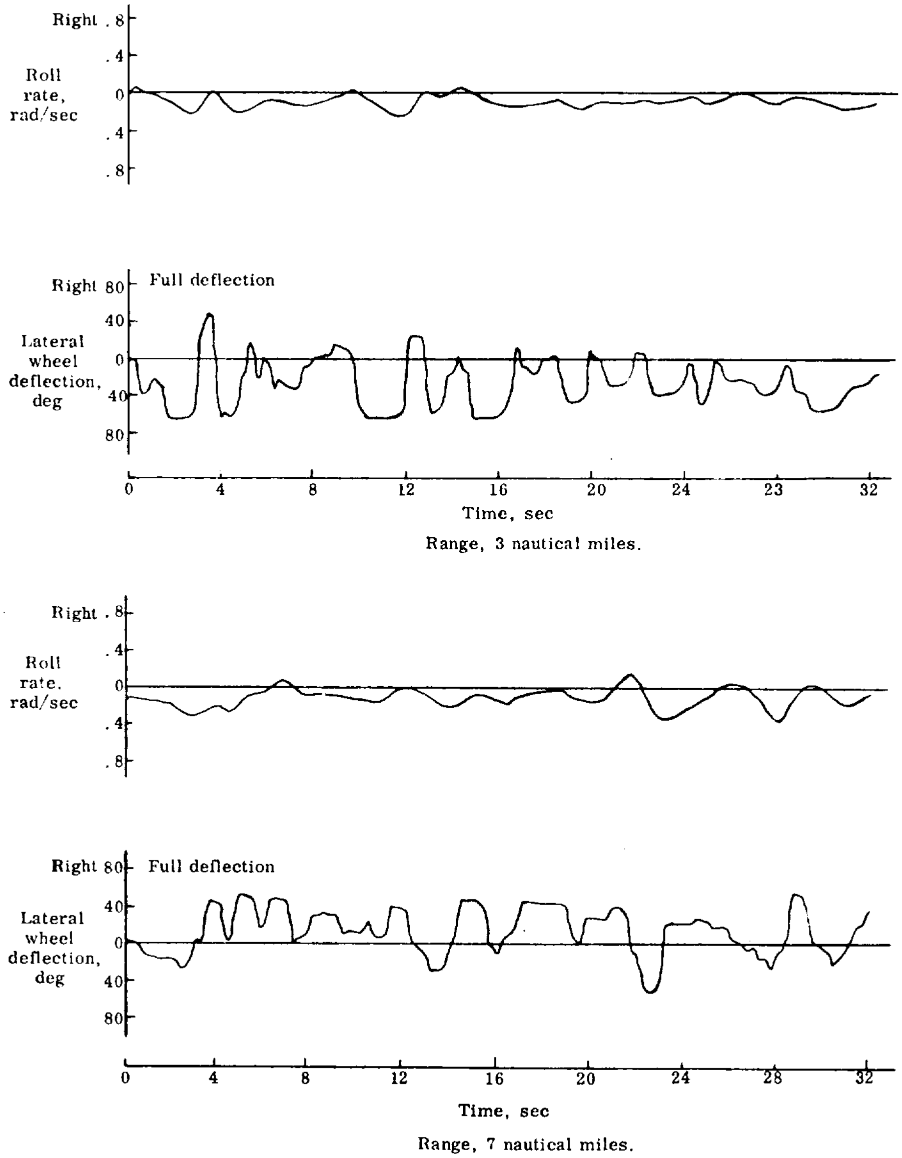
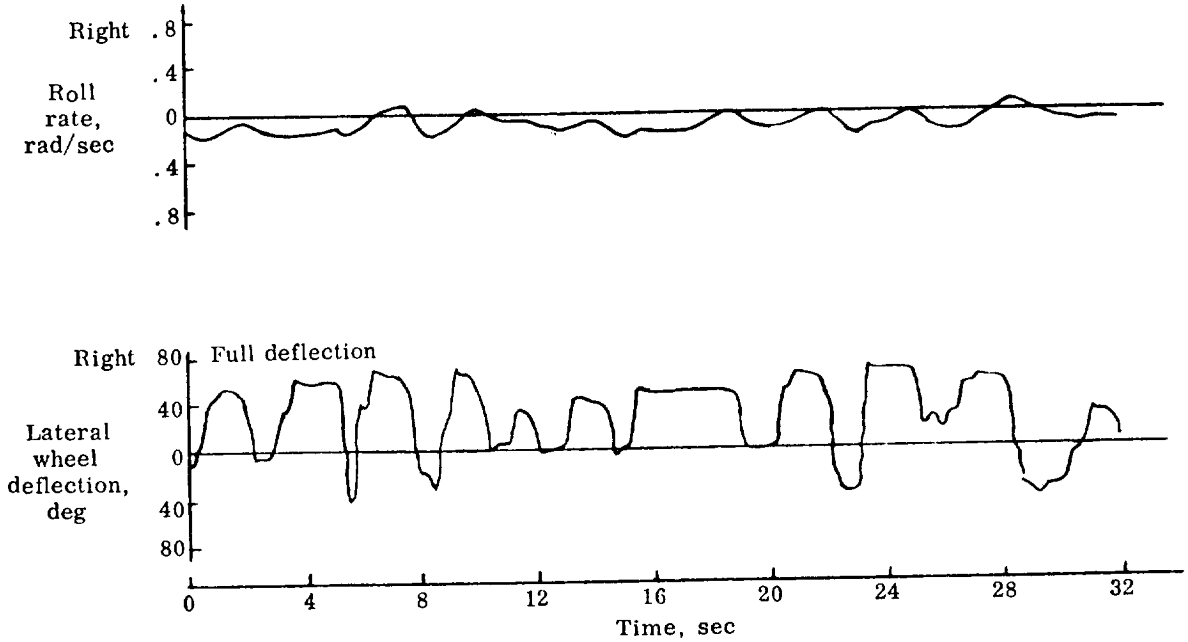
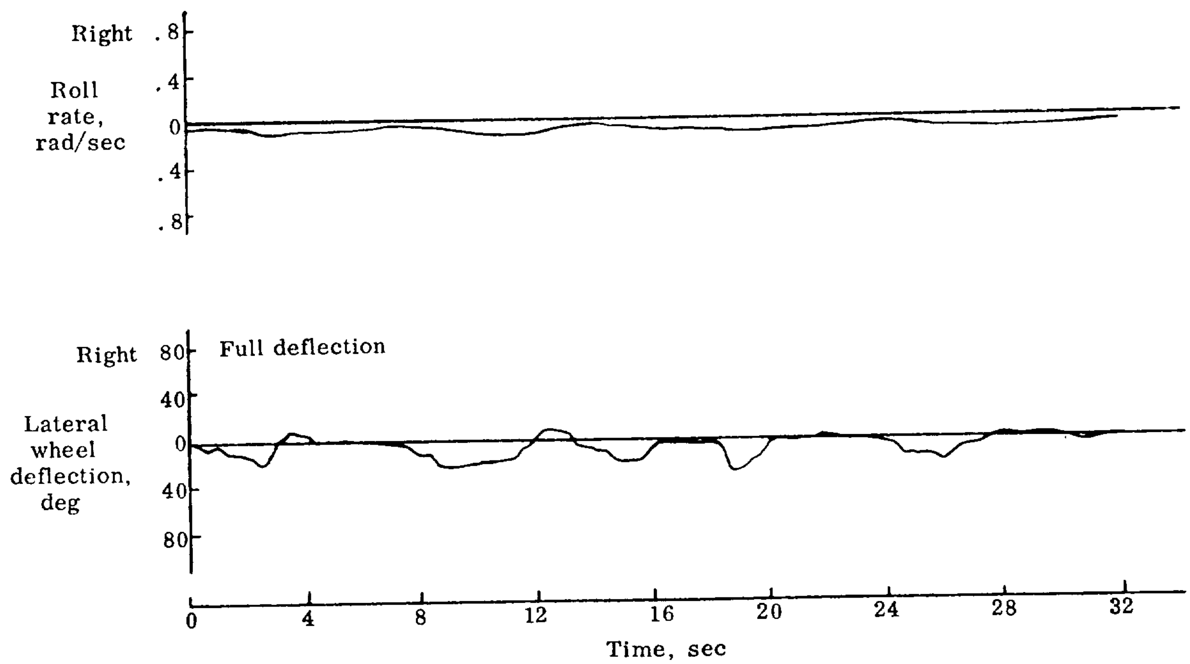


FIGURE 8. Typical time history of the Convair 990 airplane probing the wing vortex of the Boeing 707-320C airplane. Boeing 707-320C: airspeed - 248 knots, altitude - 15,000 ft, gross weight - 280,000 lb, clean configuration; CV-990: airspeed - 250 knots.



Range, 3 nautical miles.



Range, 8 nautical miles.

FIGURE 8. (Continued) Boeing 707-320C: airspeed - 165 knots, altitude - 15,000 ft, gross weight - 275,000 lb, landing approach configuration, gear down.

A summary of the roll-rate excursions experienced by the probe airplanes over the range of separation distances investigated as a function of the wing-span ratio of the probe to the generating airplane is shown in Figure 9. A comparison of the CV-990 response with that of the F-104 illustrates the sensitivity of the short-span airplanes to the vortex of the large generating airplanes. The symbols (and faired curves) included in the figure for separation ranges of 1.4, 3.5, and 9.5 nautical miles were derived by the technique presented in "A Flight Investigation Into the Persistence of Trailing Vortices Behind Large Aircraft" by T. H. Kerr and F. Dee. This calculation represents the predicted roll rate that would be induced on the F-104 and CV-990 by the wing vortex system on the C-5A airplane for the conditions flown. This simplified calculation appeared optimistic for the airplanes with a short wing span and conservative for the larger transport airplanes. A more detailed evaluation of the onboard recorded data from the probe airplanes revealed that the magnitude of sideslip response in conjunction with the phasing of lateral-control input had a considerably stronger impact on the overall roll excursions experienced than the induced roll-rate calculation would predict.

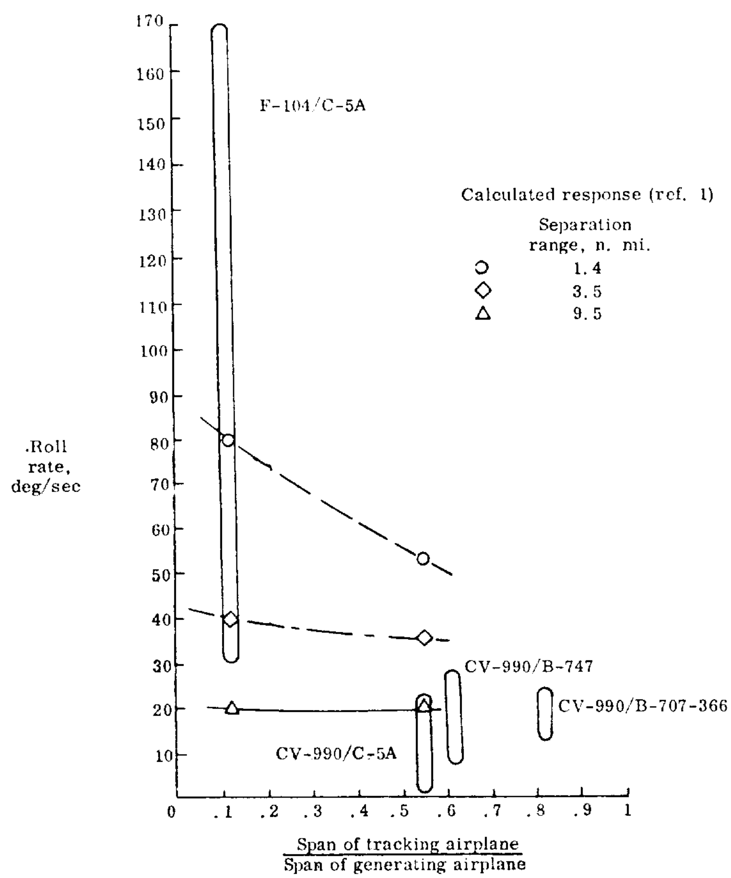


FIGURE 9. Summary of the roll-rate response of the probe airplanes as a function of wing-span ratio.

Based on this portion of the flight test program, the following highlight observations were noted.

(1) Wing vortex wake behavior is significantly different from that anticipated and that more comprehensive tests would be required.

(2) Vortex wake may be "detected" up to distances of 20 nautical miles.

(3) Wake intensity or strength is influenced by the generating aircraft speed and configuration. The strongest wake is generated by the C-5A and B-747 airplanes in the clean configuration. When the C-5A was in the landing configuration, there was a noticeable reduction in the vortex influence within the 6.5 to 8.5 nautical mile range.

(4) At holding or landing approach speeds, the average vertical downwash path of the vortex extends to 750/1000 ft. below the generating airplane at a range of 9 to 11 nautical miles.

(5) The CV-990 airplane did not experience any uncontrollable upsets or large airspeed/altitude excursions while probing the vortex wake of the C-5A, B-747 or B-707-300 airplanes.

(6) The upset and resulting excursions experienced in the U-3A and F-104 tests with the B-52 and C-5A indicate that the separation criteria should be expanded for small, general aviation and executive jet classes of airplanes.

B. Tests Conducted by Boeing at Seattle

The Boeing portion of the wake turbulence test program was aimed at a direct comparison between the B-747 and a representative from the current fleet. A 707-320C was chosen for this role in the test program. The effects of a wake encounter were measured with the smallest Boeing jet transport, the 737-100. An F-86 was also used in order to obtain subjective data on the effects of span.

Wake Generating Aircraft

Aircraft	Test configuration range
Boeing 747	Airspeed - 170 to 268 Altitude - Touchdown to 8905 ft Gross Weight - 513,000 to 608,000 lb Flaps - Clean, takeoff, approach, landing
Boeing 707-320C	Airspeed - 182 to 271 Altitude - 6,960 to 8,920 ft Gross weight - 264,000 to 275,000 lb Flaps - clean, approach

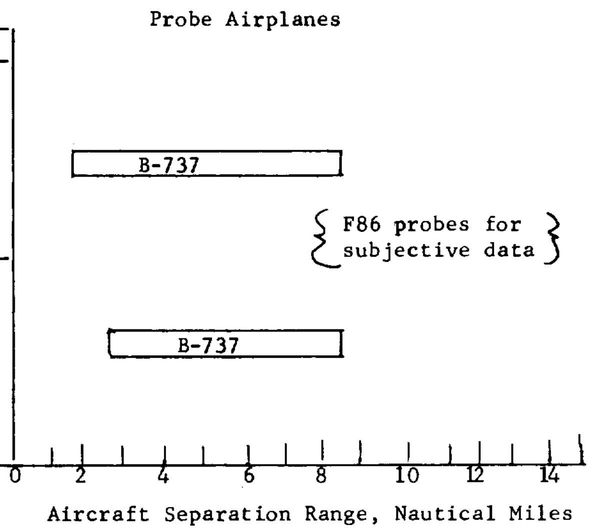


FIGURE 10. Phase I - Boeing- Seattle, Washington

Special Equipment. Based on earlier testing, it was found desirable to visualize the vortex wake. Two systems were designed for this purpose; wing tip mounted smoke grenades and oil introduced into the primary nozzle of the outboard engines. The tip smoke system used 12 grenades, wired to fire in salvos of 3. Flight tests indicated that all 12 grenades were required to provide sufficient smoke volume, and the system was discarded as too inefficient. Subsequently, Corvus oil was injected into the hot section of the outboard engines. The smoke flow from the outboard engines was entrained into the trailing vortices. This system worked very well and was used during most of the test program.

Both of the Boeing chase aircraft were equipped with bore-sighted Milikan movie cameras. These cameras were calibrated so that range information could be obtained by measuring the span (or engine span) of the lead aircraft. For the landing tests, a forward looking 35 mm APAC camera was installed in the nose radome of the B-737.

Conduct of the Testing. The comparative testing behind the B-747 and B-707 was conducted with the two lead aircraft flying formation approximately 3000 feet apart. This assured similar flight conditions and allowed the chase aircraft to encounter the wake at the same separation and make a direct comparison. Two flight conditions were used; clean at 250 knots and approach flaps at approximately 160 knots.

Takeoff and landing tests were conducted with the 737 following the 747 at spacings from 1.7 to 3.1 nautical miles. These tests were conducted to evaluate wake turbulence near the runway. An intentional vortex encounter was set up by flying low and to the left on one approach.

A runway crossing condition was flown with the 747 rotating prior to the intersection and the 737 lifting off through the intersection 68 seconds later.

Data Systems. The B-737 was equipped with a standard set of flight test instrumentation. From this instrumentation, the following data was selected for display as a function of time:

Flight Condition
- Indicated Airspeed
- True Airspeed
- Altitude
- Ambient Temperature

Airflow
- Angle of Attach Vane
- Sideslip Pressure

Response
- Pitch Angle
- Bank Angle
- Yaw Angle
- Lateral Acceleration
- Normal Acceleration (cg and pilot's station)

Control Positions
- Elevator Angle
- Spoiler Angles
- Aileron Angle
- Control Wheel Position

For range information, three independent sources were used. A visual, hand-held sight was used by the copilot in the chase aircraft to get approximate range. The engine smoke could be started sharply and by measuring the time from the start of smoke until it reached the chase aircraft, the range could be computed. Also, ground radar ranging, provided by the FAA, was used as primary range information for the B-737 probes behind the B-747 and B-707.

Range information for the landing tests was obtained on the ground by timing the separation between the 747 and 737 over the threshold. For these tests, smoke was provided on the ground as well as from both outboard engines of the 747. Smoke grenades on poles were positioned at the threshold and at 500 and 1000 feet down the runway on both sides. Camera coverage was provided from under the approach path looking down the runway and from the side. The final two items were the position of the wake relative to the generating aircraft and the ground, and the duration of the wake. The arrangement of the smoke and cameras is shown in Figure 11.

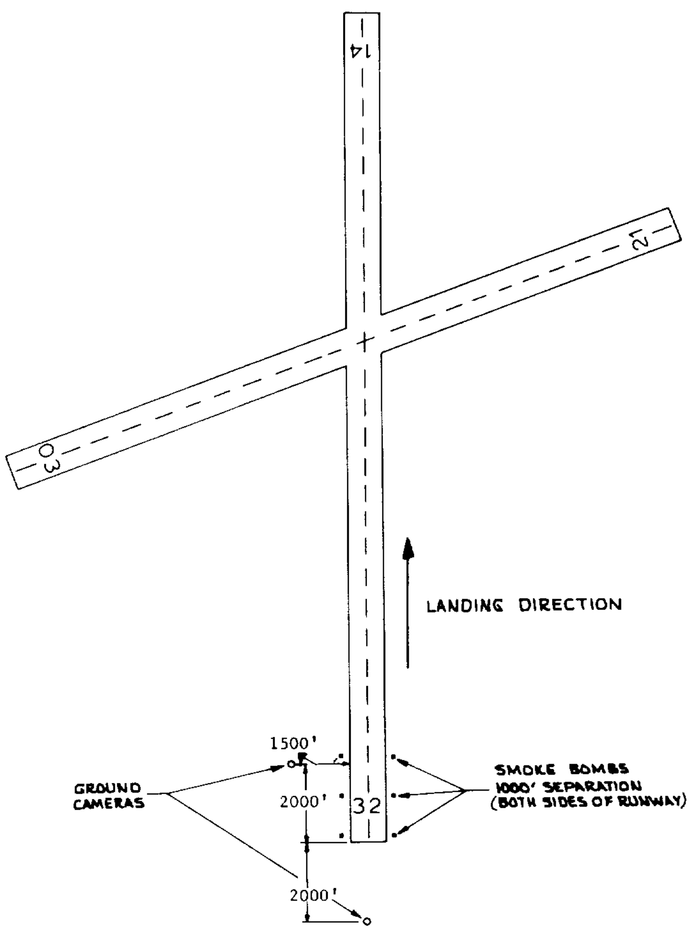


FIGURE 11. Grant County Airport Test Arrangement

747/707 Comparative Wake Strength. In order to obtain a direct comparison of the wake turbulence generated by the 747 and 707, the 737 encountered one wake and then the other at the same separation distance (Figure 12).

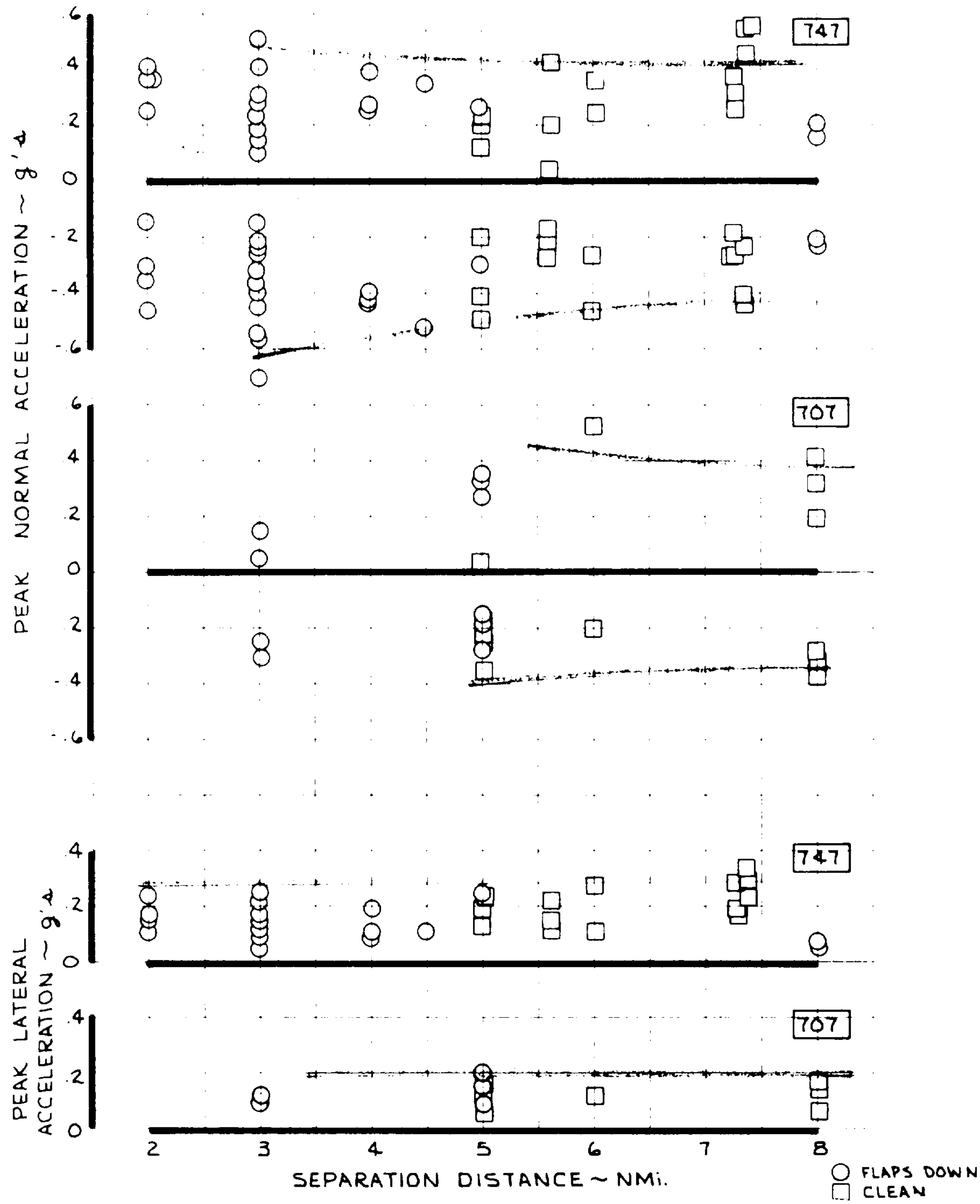


FIGURE 12. 737 Peak Accelerations Flying in Wakes of 747/707.

Some of the subjective comments by the pilots of the chase aircraft were as follows:

> "...there was not a gross difference in the characteristics of strength between the 707 and 747."
>
> "I was impressed by the very little, if any difference between the 707 wake and the 747 wake."
>
> "I couldn't really tell the difference."
>
> "Moving over to the 707, again in the approach configuration, it seemed almost the same."
>
> "They did all seem to be in the same ball park (C-5A, 747, 707) and it doesn't look to me like there is any new big problem associated with the really heavy airplanes compared to the others."
>
> "...I have to agree that there doesn't seem to be very much difference between the 747 and a 707."

In order to examine both the effects of encountering aircraft span and generating aircraft weight, data from the NASA testing was combined with the Boeing test data. Figure 13(a) shows the effect of span on peak induced roll rate. These roll rates were measured with the pilot attempting to remain in the vortex and maintain wings level. The effect of generating aircraft gross weight is shown in Figure 13(b).

Test results on the effect of separation indicated little change in response over the separation range tested until breakup terminated the wake. Boeing noted the agreement with the theoretical projections made earlier by Professor Barnes W. McCormick, Pennsylvania State University.

Wake Encounter Dynamics. During this phase of the test program, the wake was approached from all directions in order to evaluate the effect of encounter direction on response. One item was common to all encounters, without concerted effort by the pilot, the airplane would be expelled from the wake. In no case did the pilots feel that there was a possibility of losing control. Airplane response data and pilot comments indicated that there were no structural implications over the range of separations tested (1.7 to 9 nautical miles).

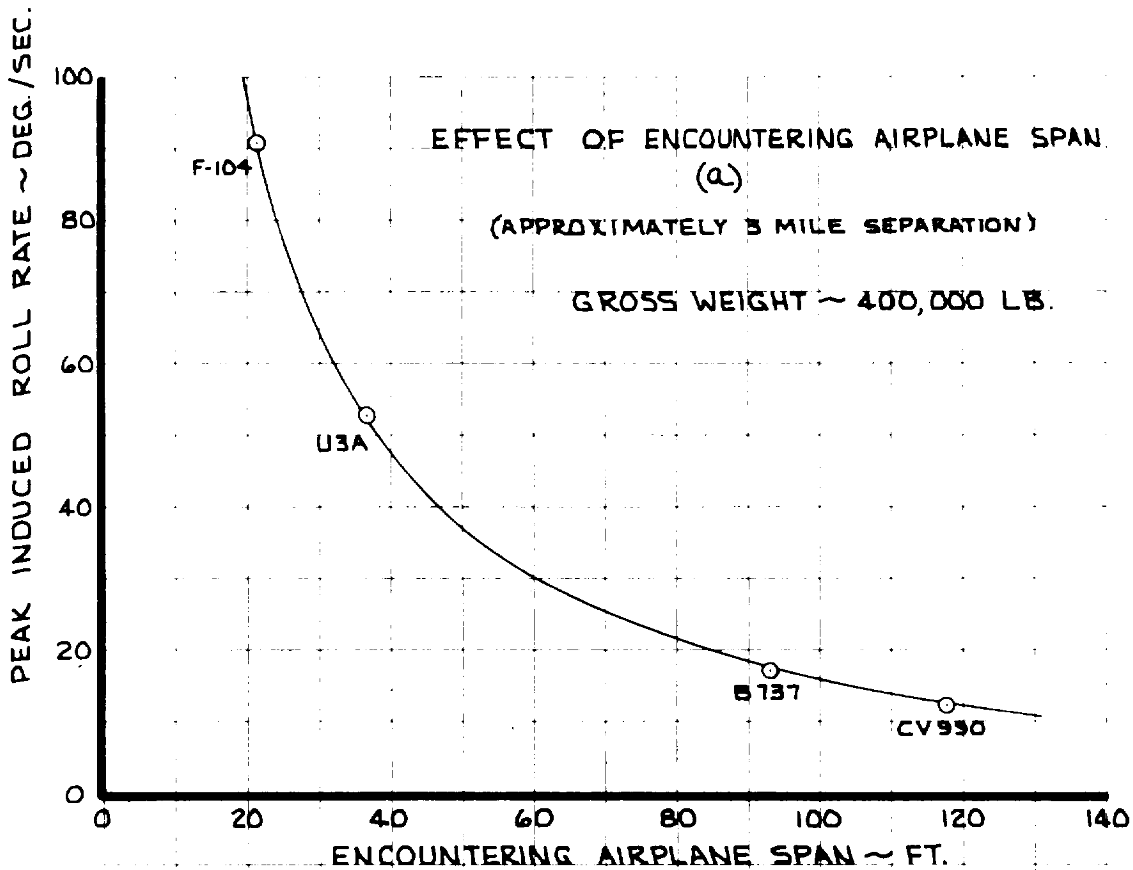


Figure 13(a)

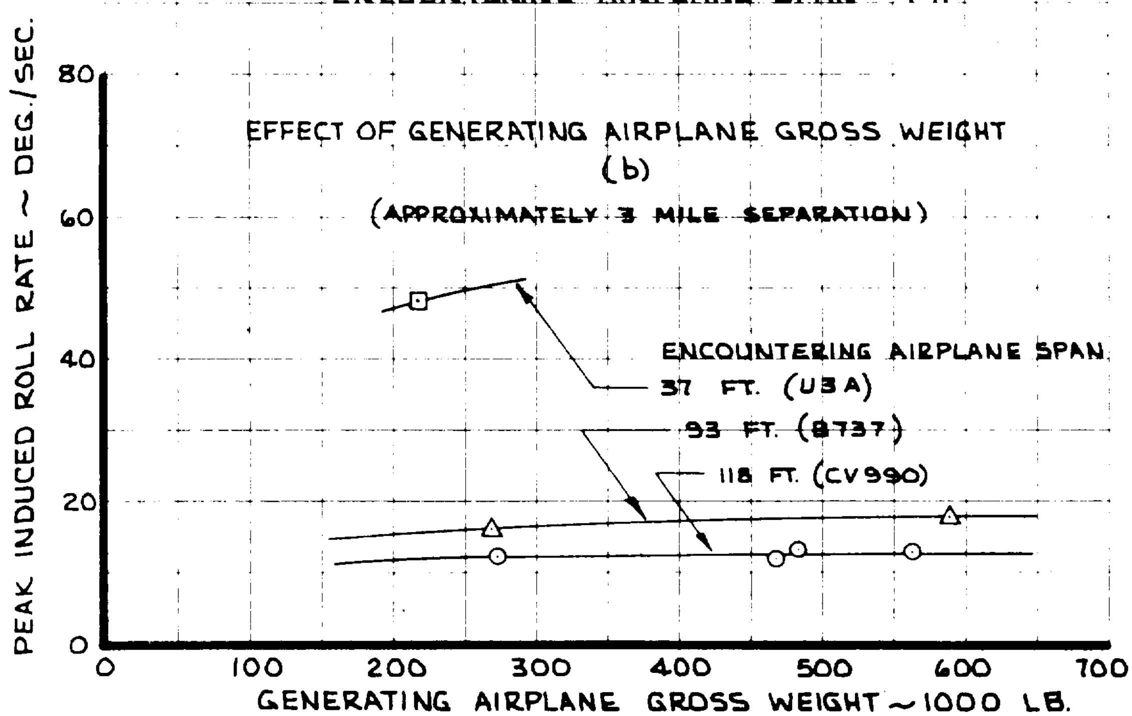


Figure 13(b)

FIGURE 13. Experimental Effects of Span and Gross Weight.

During one approach involving the B-737 behind the B-747, the pilot deviated to the left and below the normal flight path to encounter the wake. The encounter occurred with very little loss in altitude and with a bank angle of 28 degrees. The encounter, while dramatic, was followed by normal recovery to level flight.

Wake Position. The test pilots observed that the wake seemed to "level off," never descending more than 900 feet below the generating aircraft. These observations were confirmed by the vertical wake position data shown in Figure 14 for the approach configuration.

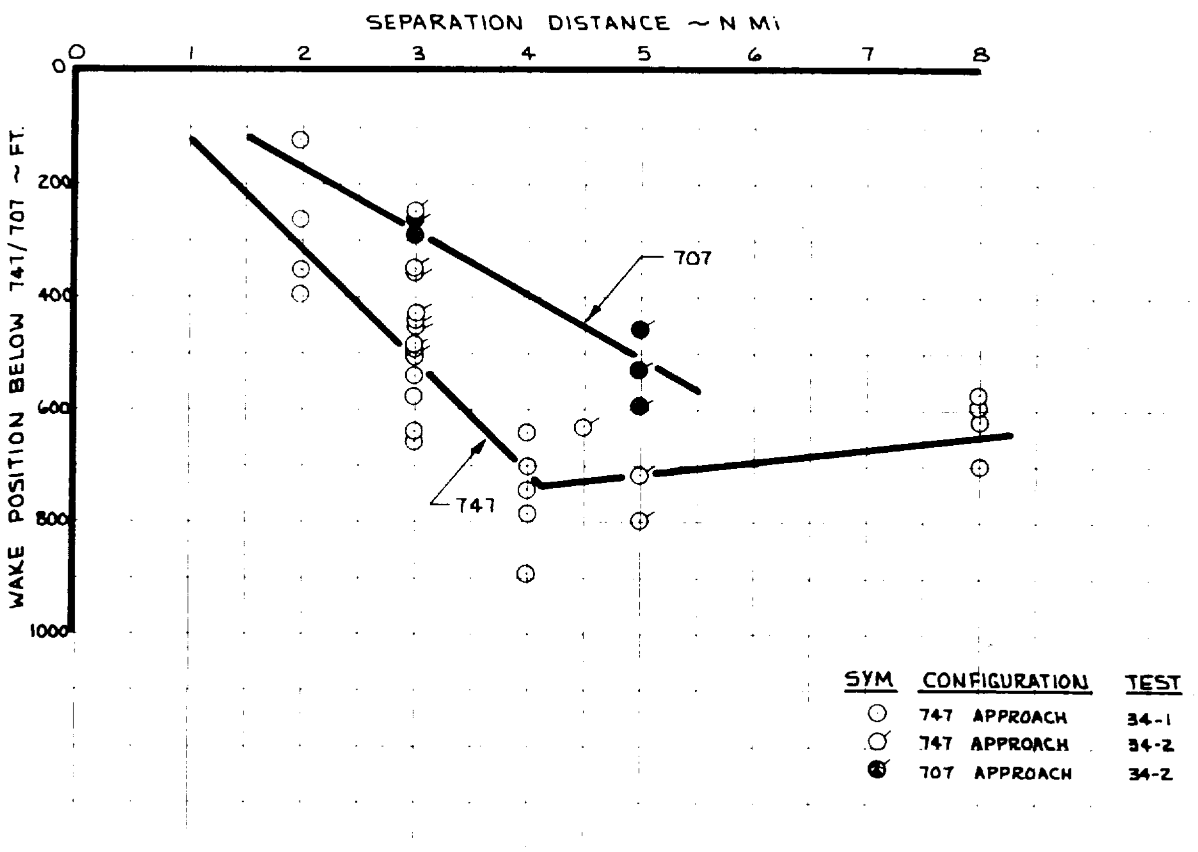


FIGURE 14. Vertical Wake Position 707/747 Approach

Aft of the 5 mile separation, the wakes were observed to oscillate vertically and laterally. Vertical oscillations were estimated at ±200 feet about a mean level altitude. These oscillations and level off of the wake appeared to be directly related to wake breakup.

Wake position near the ground was observed during tests in which the 737 flew approach and landings behind the 747. (Figure 15 shows typical effect of crosswind on lateral movement of vortices near the ground).

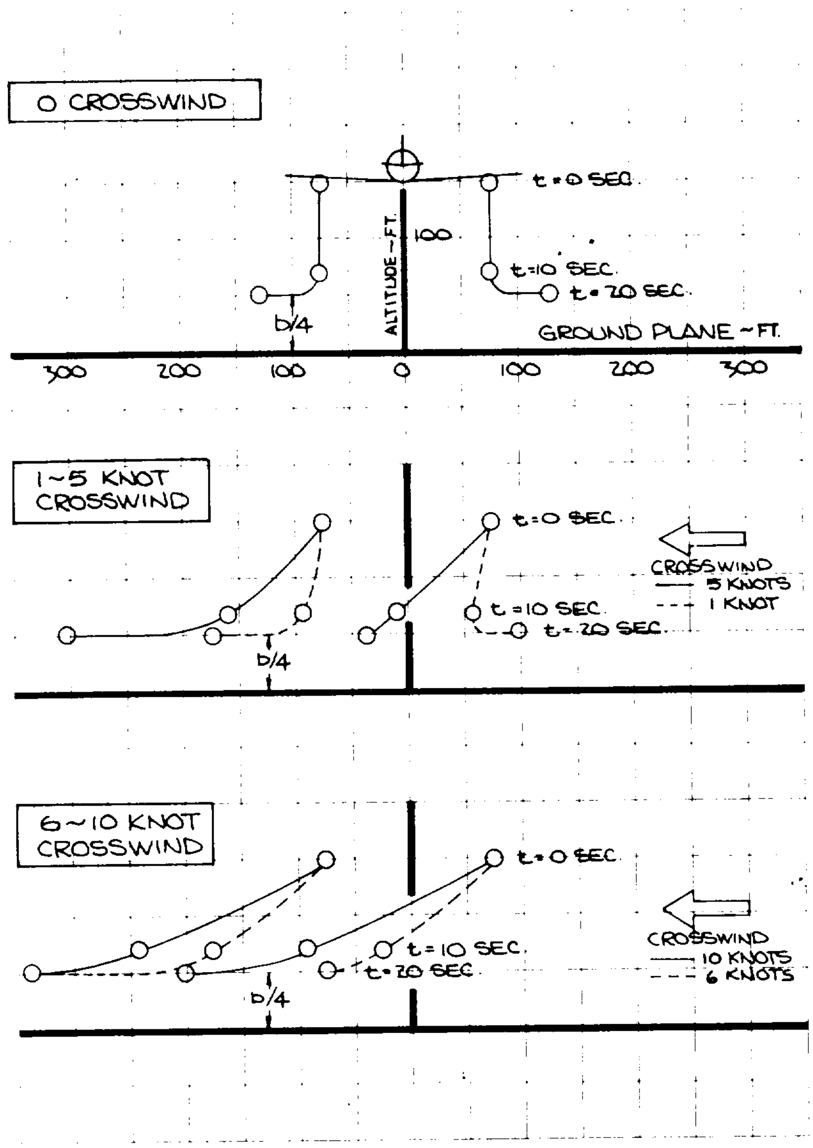


FIGURE 15. Typical Effect of Crosswind on Lateral Movement of Vortices Near the Ground. (Dee, F. W., and Nicholas, O. P., "Flight Measurements of Wing Tip Vortex Motion Near the Ground," RAE TR 68007, January, 1968.)

During these approach and landing phase tests, the wake of the 747 was observed descending below the approach path to an altitude of approximately 1/4 to 1/2 span (50 feet). At this point, the downward descent of the wake ceased and lateral movement of the vortices occurred. With no crosswind, the vortices moved laterally apart, but with a 1 to 3.5 knot crosswind, the upwind vortex was held near the ground track of the 747. (Maximum ground wind speed during the test was 3.5 knots).

Boeing noted that the wake generated in ground effect did not form strong trailing vortices but produced a strong outward flow. The turbulence generated in ground effect was found to be relatively weak and was described as "light chop" by the 737 pilots. The data shows that below 50 feet altitude the 737 never experienced more than 2° of roll and 0.15 g center of gravity normal accelerations in landings made as close as 1.7 n.mi. behind the 747. The implication was that aircraft, of this type, will not encounter hazardous turbulence at liftoff or during the landing flare. Further investigation of the behavior of vortex systems generated in, or descending into, ground effect was covered in Phase II of the test program. (Note: Information derived during NAFEC Phase II tests clarified the ground effect data noted by Boeing.)

<u>Wake Breakup</u>. During the Boeing test program, evidence was found which indicated that the vortex wake would break up through other than purely viscous mechanisms. The test procedure involved real time film sequence of a 10 second burst of oil into the hot sections of engines No. 1 and No. 4 during the B-747 over-flight at 5,000 ft. Boeing presented films of the sinusoidal oscillations leading to wake breakup. This data triggered attention to the relationship of vortex persistence to atmospheric turbulence.

Based on this portion of the flight test program, the following highlight observations were noted.

(1) The 747 and 707 produce a similar dynamic response in an airplane encountering their respective wakes.

(2) Induced roll rate (and bank angle) is a strong function of the encountering airplane's span and a relatively weak function of the generating airplane's gross weight.

(3) A wake encounter results in the airplane leaving the wake immediately. No structural or control implications were indicated for a small jet transport encountering the wake of a large transport.

(4) The wake was observed to move down initially and then level off. The wake was never encountered at the same flight level as the generating airplane or more than 900 feet below the generating airplane.

C. Tower Fly-by Tests Conducted by FAA at Idaho Falls, Idaho

This portion of the flight test program was conducted to gather quantitative data on the vortex wake turbulence characteristics of large, medium and small jet transport aircraft by low altitude tower fly-by techniques.

Test Tower. The tower used for the tests was the ESSA 200-foot Grid III Research Tower (Figure 16). This tower is located on the National Reactor Testing Station 46 miles west of Idaho Falls. The tower is a rectangular upright scaffold of a kind especially designed for meteorological research and presents extremely low blockage to air currents from any direction and, accordingly, caused very little interference with airflow measurements.

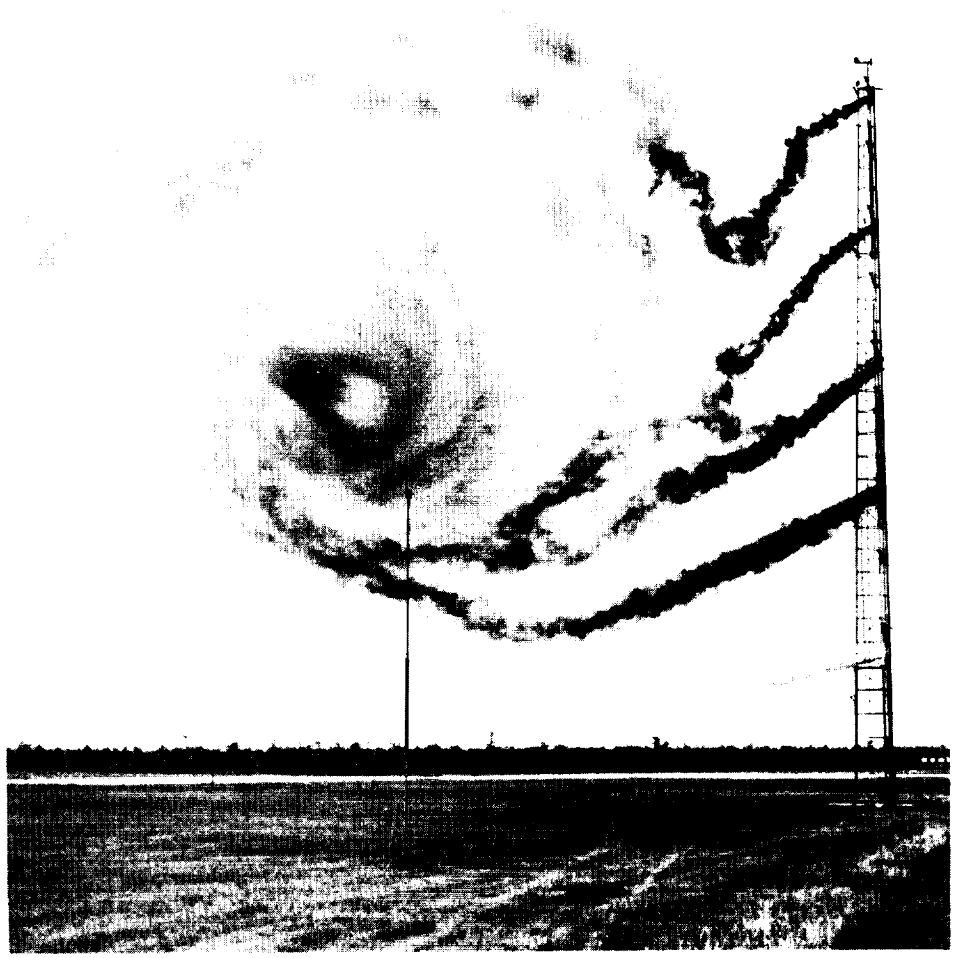


FIGURE 16. Aircraft Vortex Flow Visualization

The tower was instrumented by ESSA and NAFEC personnel with hot-wire and hot-film anemometers to measure vortex airflow velocity and direction and with colored smoke dispensers which would become entrained in the passing vortex system thus producing a visual indication of its movement and structure.

Test Instrumentation. The meteorological instruments mounted on the tower and used during the tests were divided into two groups. Group one consisted of high frequency hot wire and film anemometers to measure the vortex velocities. Group two consisted of standard meteorological instruments for measuring the low frequency atmospheric components such as horizontal and vertical wind direction, wind velocity, air temperature and humidity.

Atmospheric Measurement. Meteorological supporting measurements of the ambient atmosphere were made by ESSA personnel using sensors positioned mostly on a 200-foot Grid III research tower.

Slow Response Instrumentation and Recording

Sensors. Wind and temperature sensors were located at the 50-, 100- and 200- foot levels of the tower. Beckman and Whitley K 100A cup anemometers were used to measure wind speed. NRTS annular finned bivanes were used to measure horizontal and vertical wind direction. Temperature was measured by copper-constantan thermocouples in Climet aspirator shields with a 150°C Pace reference junction.

Fast Response Instrumentation and Recording

Data Recording and Reduction. Signals from all of the hot film and thermocouple sensors installed on the tower were recorded on magnetic tape recorders that were located in an instrumentation trailer located near the base of the tower. The incoming signals from the anemometers were conditioned to a voltage level compatible to the magnetic tape recorder. In order to record all of the signals from the TSI, ESSA, and BGS and thermocouples sensors, three 14 track analog magnetic tape recorders were utilized. A marker channel was used on each tape to serve as a data recording reference related to each aircraft fly-by. To limit and identify the desired analog data strings, the marker channel voltage was switched between 0 and 10 volts to indicate the beginning and stopping points of hot wire data during a fly-by.

Digitization of Analog Tapes. The analog tapes were digitized at a rate of either 80/sec with 1/160 sec filtering or 10/sec with 1/20 sec filtering on a Minneapolis-Honeywell DDP-124 analog-to-digital converter and transferred to magnetic digital tape.

The number of channels containing data varied with the number of inputs produced by the sensors at specific tower levels. The digital tape produced by each data set contains separate strings of data from each channel.

Digital Computer Processing Programs on IBM 360-75 Computer

Channel Merge and Data Conversion. This program merged the data from each channel. During this merging process, the data were converted from scaled units to voltages using scaling factors and from voltages to either velocities or temperatures. The procedure used to convert voltages to velocities was accomplished by using the A' and B' values obtained from the hot wire calibrations in the wind tunnel and solving the equation $C = (A' + B'E^2)^2$ to obtain the cooling velocity. Then the cooling velocity was converted to a wind velocity by applying the density and viscosity correction factors based on the mean temperature during each aircraft series of fly-bys. The thermocouple output voltages were converted to temperature units through use of the appropriate standard copper-constantan equation for the reference junction. A merged digital tape containing data in velocity and temperature units and the digitized contents of the marker channel was derived.

Photography. Four camera positions were selected around the instrumented tower for motion picture data acquisition. Two of the cameras were positioned along the test aircraft's flight path facing the tower so as to obtain coverage of the tangential flow and core diameter. The third camera was positioned upwind of and facing perpendicular to the flight path so as to obtain coverage of the vortex axial flow.

Test Techniques. The tower fly-by technique as shown in Figure 17 was used and basically consists of flying the test aircraft perpendicular to the ambient surface wind at an appropriate distance vertically and upwind laterally from the tower so as to have the trailing aircraft vortex system drift laterally into the instrumented tower. By vertical and lateral positioning of the test aircraft, the "age" of the vortex system was varied.

FIGURE 17. Boeing 747 flying abreast of instrumented tower for vortex data acquisition.

Test Aircraft. Eight different model jet transport-type aircraft were used in this phase of the test program. The geometric, gross weight, and performance data for these aircraft are shown in Figure 18.

	Boeing 747	Boeing 707-320C	Boeing 727-100	Douglas DC-8-63F	Douglas DC-8-33	Douglas DC-9-10	Lockheed C-5A	Learjet Mod 24
Wing Span (ft)	195.67	145.75	108.00	148.42	142.42	89.30	222.71	35.58
Wing Area (ft^2)	5500	2892	1650	2927	2884	934	6200	232
Aspect Ratio	6.95	7.36	7.67	7.52	7.03	7.40	7.20	5.02
Mean Aerodynamic Chord (in)	327.8	272.3	180.0	272.8	275.9	141.5	370.5	84.5
Takeoff Weight (max) (lbs)	710,000	336,000	160,000	355,000	315,000	90,700	728,000	13,000
Takeoff Speed (kts) Flap Setting	170 1°	170 14°	138 25°	163 23°	162 25°	144 20°	140 10°	132 20°
Landing Weight (max) (lbs)	564,000	247,000	142,500	275,000	207,000	81,700	635,850	11,880
Landing Speed (kts) Flap Setting	142 40°	137 50°	133 40°	150 50°	133 50°	134 50°	131 41°	127 40°

FIGURE 18. Pertinent Physical and Performance Characteristics of Test Aircraft

Flight Tests. Figure 19 shows the type of aircraft, configurations and number of runs past the instrumented tower.

Aircraft Used	Fam. Runs	Aircraft Configuration T.O.	Ldg.	Hldg.	VMax	Total Runs
B-747	2	4	4	2	2	14
C5A	2	7	7	9	0	25
B707-320C	1	4	4	2	2	13
DC-8-63F	1	6	3	3	0	13
DC-8-33	1	6	3	3	0	13
B727-100	2	4	3	5	0	14
DC-9-10	1	3	4	5	0	13
Lear Jet-24	1	2	5	1	0	9
Totals	11	36	33	30	4	114

FIGURE 19. Aircraft Used in Vortex Wake Turbulence Investigations at Idaho Falls, Idaho

Based on the tower fly-by portion of the flight test program, the following highlight observations were noted.

(1) For "clean" and low flap setting configurations of the Boeing 747, C-5A and 707 aircraft, the maximum velocities of the respective aircraft trailing vortex systems are similar in magnitude, approximately 140 feet/sec., under the existing environmental flight test conditions.

(2) More persistent, clearly defined "tubular-type" vortex systems are generated as the flap setting is decreased on an aircraft.

(3) "Tubular-type" vortex systems are very persistent, up to approximately 2 minutes in age, as sighted visually and recorded photographically, in close proximity to the ground; i.e., not exceeding tower height.

(4) For "dirty," full flap configurations, the short-age (up to 40 seconds) vortex systems of the Boeing 747 aircraft exhibited higher velocities, on the order of 100 feet per second, as compared to the Boeing 707 vortex velocities, which were on the order of 60 feet per second.

(5) The trailing vortex system of the Boeing 747, in full flap configuration, breaks up very rapidly from "ordered" flow to turbulent-type flow as noted by visual observation and photographic coverage.

(6) As the trailing vortex system approaches the "tubular-type" structure, the tangential velocities increase whereas the vortex diameter; i.e., the field of influence as sensed by the anemometers and seen visually in the 16mm motion picture coverage, decreases. Conversely, as the trailing vortex system deviates from a tubular-type structure, the tangential velocities decrease and the vortex diameter increases.

(7) Axial flow either does not exist or is insignificant for relatively long-age vortex systems.

2. FLIGHT TEST PROGRAM - PHASE II

The second phase of the wake turbulence flight test program was conducted at two locations. The NASA Flight Research Center conducted additional flight tests on the Edwards test range which had two objectives. The first was to evaluate the effect of the wake generated by jumbo and medium weight jet transports on the short haul class of jet transport airplanes. The second objective was to further evaluate the effect of wing-tip vortices generated by light, medium and heavy jet transports on representative executive jets and general aviation type of aircraft.

At NAFEC, the Phase II program consisted of tower fly-bys having two objectives. The first was to determine the relatively long time history characteristics of vortex systems under various ambient surface wind conditions. The second objective was to determine the characteristics of vortex systems generated within or descending into ground effect.

A. Tests Conducted by NASA at Edwards Air Force Base

As in the Phase I portion of this program, the evaluation was based on the probe aircraft roll response at discrete separation distances behind the generating aircraft. This program, similar to Phase I, was performed in the area of Edwards Air Force Base under the supervision of NASA Flight Research Center in cooperation with the FAA, Air Force, and the NASA Ames Research Center.

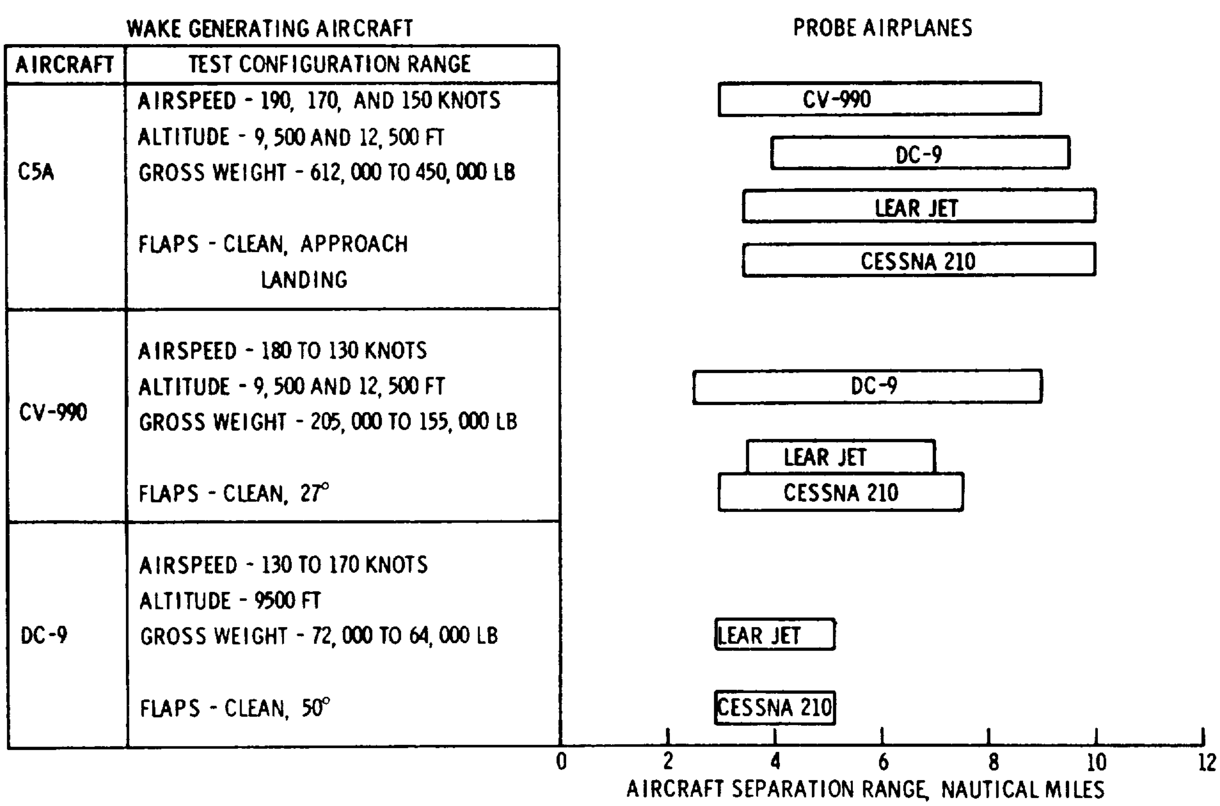


FIGURE 20. Phase II - NASA Edwards AFB

Test Procedures. The test procedures used were similar to those that had been employed in the Phase I program. The generating aircraft established the specified test altitude and airspeed conditions. The probe aircraft was then positioned by radar at a specified distance behind the generating aircraft. From this point the probe aircraft essentially flew for periods of 2 to 3 minutes in the wake to record a sufficient sample of airplane response data. The generating aircraft was usually evaluated in both the landing flap and clean configuration and at airspeeds consistent with standard operation practice in the terminal area of the flight envelope. In two of the test sequences, the C-5A and the Convair 990 were flown on a parallel course and the indicated probe aircraft probed the wakes of the two airplanes alternately. Another combination that was flown was to have the Convair 990 and the DC-9 fly along a parallel ground track and the indicated aircraft probed the respective wakes, again, in an alternate fashion. During all of the tests the Mojave and Harper's Dry Lake area was used for the primary test site. The Air Force Radar Tracking facility was used to derive the space positioning information of both the generating and probe aircraft. To establish the position of the vortex wake, the smoke from the engines of the generating aircraft was relied upon to mark the wake trail. This system was quite satisfactory with regards to the C-5A airplane; however, to improve the marking of the wake and the smoke generated by the Convair 990 and the DC-9, JP-6 fuel was burned in the engines during the specific test periods. In the case of the DC-9, there was still a lack of adequate smoke to mark the wake and as a consequence, the probe data was limited.

Instrumentation. The instrumentation package used during the Phase I program was modified to include bank angle information and was reinstalled in the Convair 990 and the DC-9 airplanes during this series of tests. The Lear Jet and the Cessna 210 were instrumented with comparable data acquisition and recording equipment which was installed by the Ames Research Center and the FAA test personnel, respectively. The information systems recorded primarily airspeed and altitude information in conjunction with a set of standard handling-quality parameters. The accuracies and ranges were consistent with those used during the Phase I program. The test aircraft data recording was time correlated with the radar space positioning data.

Discussion of Results. During the Phase I test program, it was noted that the wing vortex wake generated by an airplane in the clean configuration was more persistent and of an apparently higher intensity than that generated by an airplane in the landing configuration. To illustrate this point, Figure 21 presents the control effort exerted by the pilot while flying the Convair 990 in the wake of the C-5A. The data are presented in terms of the percentage of lateral control used in a 30 second data sample time period for different separation distances. During this time the control wheel deflection was measured for 1/3, 2/3, and full-wheel displacement. By observing the clean configuration data, it may be seen that in the region of 8 to 10 nautical miles there is a considerable amount of control activity, however, from the data present for the landing configuration, it may be seen that at a corresponding separation range the control activity is considerably reduced.

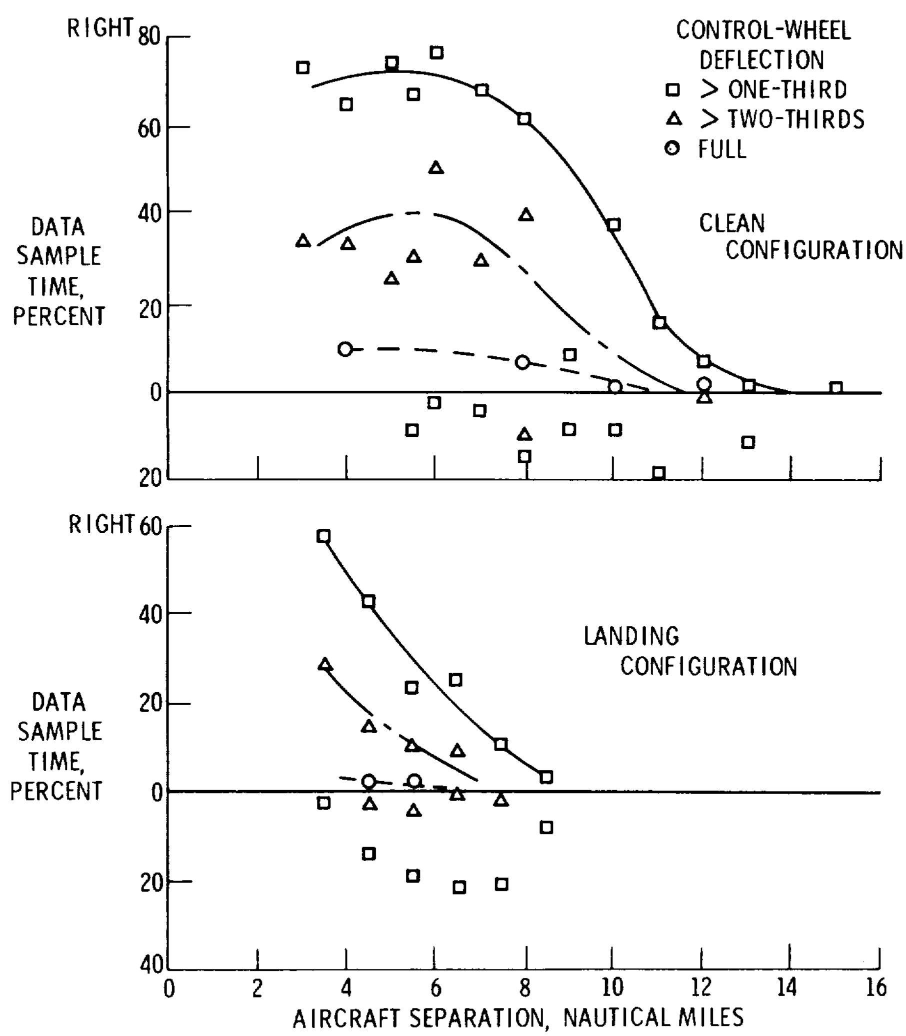


FIGURE 21. CV-990 Lateral Control Effort Flying in the C-5A Vortex Wake

Roll Response Summary. To summarize the overall roll response characteristics of the various probe-to-generating aircraft combinations, Figures 22 through 24 present the maximum closed loop bank angle and roll velocities experienced as a function of separation distance. For the most part, these data were measured during the initial period of probe airplane upset where the pilot was initially applying a lateral control input to oppose the vortex induced rolling moment.

Figure 22 presents the DC-9 response resulting from the vortex wake of the Convair 990 and C-5A generating aircraft between the separation ranges at 10 and 2 nautical miles. The airspeed of both the probe and generating aircraft was approximately 150 knots. From a general observation, as would be expected, the DC-9 response to the C-5A is considerably greater than that experienced behind the Convair 990. For example, at a separation distance of 5 nautical miles, the maximum bank angle and roll response behind the C-5A is in the order of 48 degrees and 38 degrees per second, respectively. With regards to the response to the Convair 990 at the corresponding range, the maximum bank angle and roll rate are essentially 18 degrees and 13 degrees per second, respectively. The test behind the C-5A was terminated at 3.7 nautical miles due to the pilot's concern for the aircraft safety.

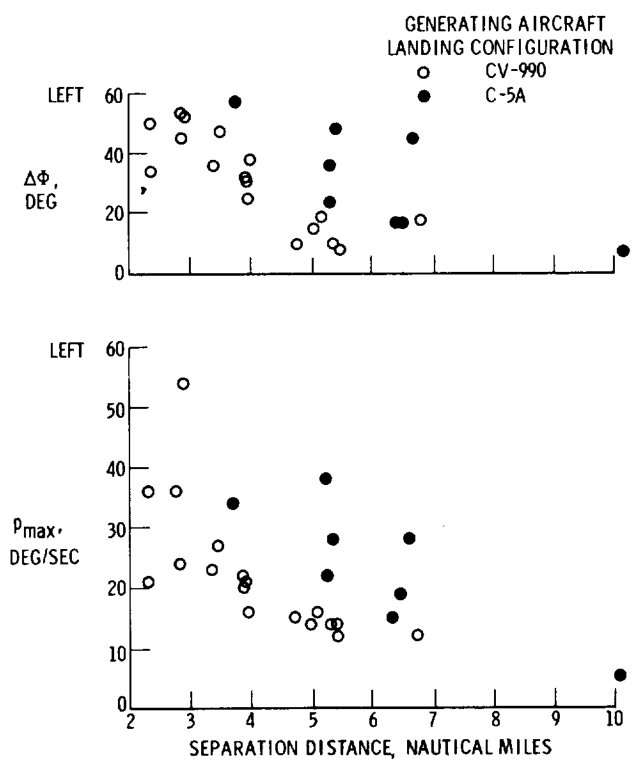


FIGURE 22. DC-9 Maximum Roll Response

Figure 23 summarizes the Cessna 210 roll response to the Convair 990, DC-9, and C-5A generating aircraft over separation distances of between 2.5 and 8.7 nautical miles. In this series of tests, the airspeed of the Cessna 210 was maintained at 130 knots while the generating aircraft maintained an airspeed of 150 knots. Again the influence of the C-5A is readily apparent by the high roll and bank angles experienced, particularly in the region of 4 to 5 nautical miles. These data were obtained primarily from pilot notes as both of the on board data acquisition systems in the Cessna 210 were damaged from the violent maneuvering that the airplane experienced during the final set of data runs. In this region of separation, the response to the Convair 990 is considerably reduced. However, in the region between 2 and 4 nautical miles it is obvious that the intensity of the wake, even from this airplane, significantly increased. For example, at 4 nautical miles, the maximum indicated bank angle is approximately 42 degrees while the corresponding roll velocity is in the order of 60 degrees per second. The DC-9 data as mentioned previously, was limited primarily because of the inability to detect the wake much beyond the 5 nautical mile distance.

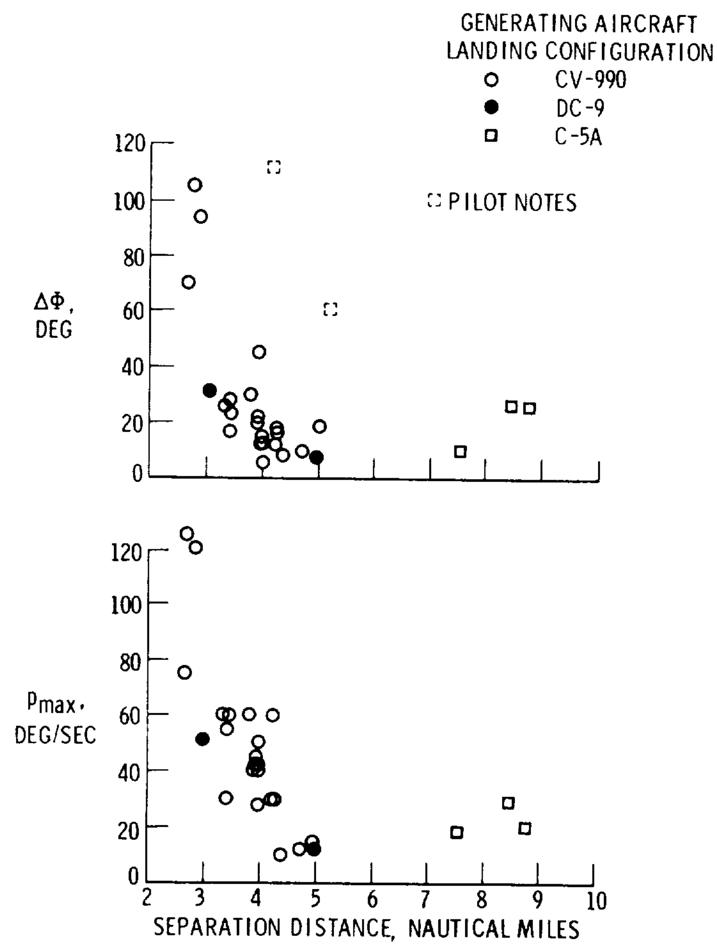


FIGURE 23. Cessna 210 Maximum Roll Response

Figure 24 presents the Lear Jet roll response to the C-5A, Convair 990, and the DC-9 generating aircraft. The generating aircraft speeds were approximately 150 knots. A comparison of the Convair 990 and C-5A data indicates the increased strength and influence of the wake generated by the C-5A airplane. For example, in the region of approximately 5 nautical miles separation distance, the response to the Convair 990 in terms of maximum bank angle and roll velocity is 40 degrees and approximately 30 degrees per second, respectively. The corresponding data for the C-5A bank angles are in the order of 120 degrees with a corresponding rolling velocity of approximately 70 degrees per second. The limited data from the Lear Jet and the DC-9 combination appears to be consistent with the general trend established by other data.

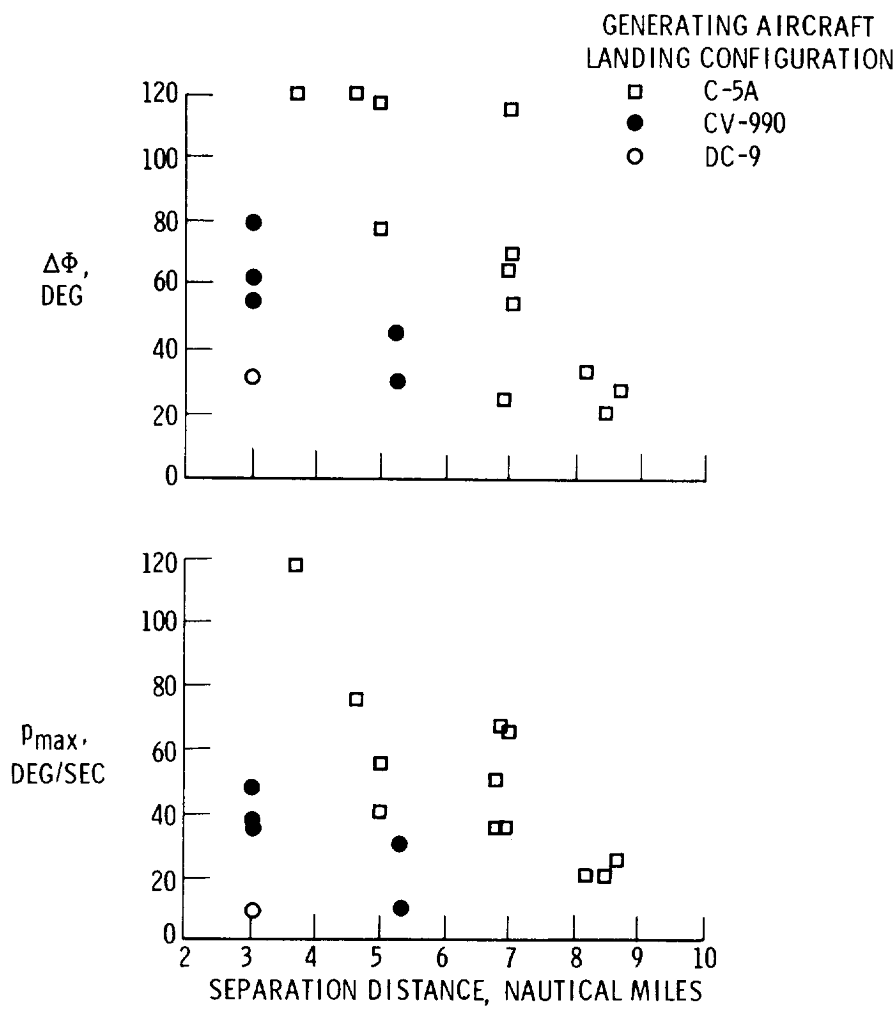


FIGURE 24. Lear Jet Maximum Roll Response

In general, the roll response summary data substantiates the suspected influence of the generating aircraft size and weight on wake strength and persistence. In all of the cases tested, at comparable separation distances, the probe aircraft response was increased as the wake penetration progressed from the DC-9 to the Convair 990 and finally to the C-5A airplane. However, an exact correlation with aircraft gross weight is not feasible from these data. There are no data available to establish the exact location of the probe aircraft relative to the vortex core of the generating aircraft wake on successive test runs.

Following this part of the Phase II test program, NASA developed a "Flight Test Comparison with Theory" which they related to the projections outlined in Figures 25 and 26.

THELANDER

(1) $$w = \frac{\Gamma}{2\pi y}\left[1 - e^{-\frac{y^2}{4\gamma t}}\right]$$

$\Gamma = \frac{4W}{\pi \rho v b}$ (VORTEX CIRCULATION)

$\gamma = 0.2$ FT^2/SEC (EFFECTIVE KINEMATIC VISCOSITY)

y = WAKE RADIAL DIMENSION, FT

t = TIME, sec

KERR, ROSE, DEE

(2) $$w = \frac{\Gamma}{2\pi y}\left[1 - e^{-\frac{y^2}{4(\gamma + \varepsilon)t}}\right]$$

γ = KINEMATIC VISCOSITY

$\varepsilon = .0002\Gamma$ FT^2/SEC (EDDY VISCOSITY)

$\gamma \lll \varepsilon$ ASSUMED

MC CORMICK

(3) $$w = \frac{\Gamma}{2\pi y}\left[.16 + .16\, l\, n\left(3.91\,\frac{\pi^2 b}{S}\,\frac{y}{\sqrt{1 + .0065\frac{vbt}{S}}}\right)\right]$$

WETMORE, REEDER

(4) $$w = \frac{\Gamma}{2\pi y}\left[1 - e^{-\frac{y^2}{.0042\, b^2 + .00012\,\frac{S}{b}\Gamma t}}\right]$$

FIGURE 25. Expressions for Calculation of Vertical Velocity as Functions of Vortex Radius and Age.

Using these four equations, Figure 26 shows computed velocity profiles across the vortex at 4 nautical miles behind a C-5A aircraft flying in the landing configuration. A nominal gross weight of 450,000 pounds, airspeed of 140 knots, at 12,500 feet altitude were the flight conditions included in the calculations. The vortex origin is oriented horizontally relative to the C-5A semispan. Radius of the vortex core may be determined as the horizontal distance from the vortex origin to the peak vertical velocity point.

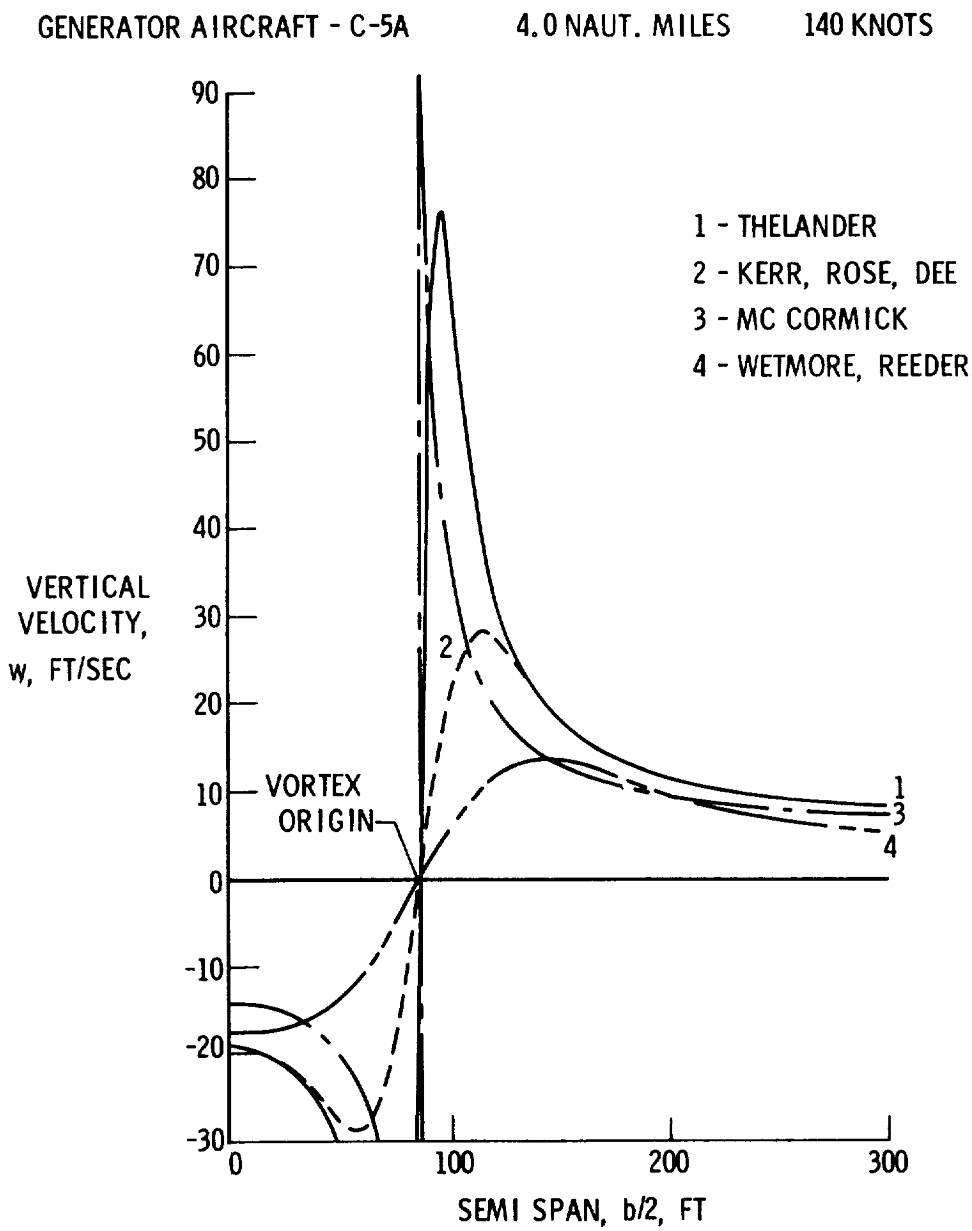


FIGURE 26. Calculation of Vortex Vertical Velocity Profile.

Figure 27 shows predicted growth in the core size as a function of time, or as plotted, separation distance between the C-5A and any following aircraft. From both Figures 26 and 27, expressions 1 and 3 appear to predict the more reasonable core sizes based on observations made during the flight tests. The large differences in predicted core diameter emphasize the sensitivity of these calculations to estimates of viscous flow within the vortex structure. Further, the viscous effects are themselves dependent on meteorological parameters such as local wind gradients and temperatures that might be experienced during a specific flight-test period.

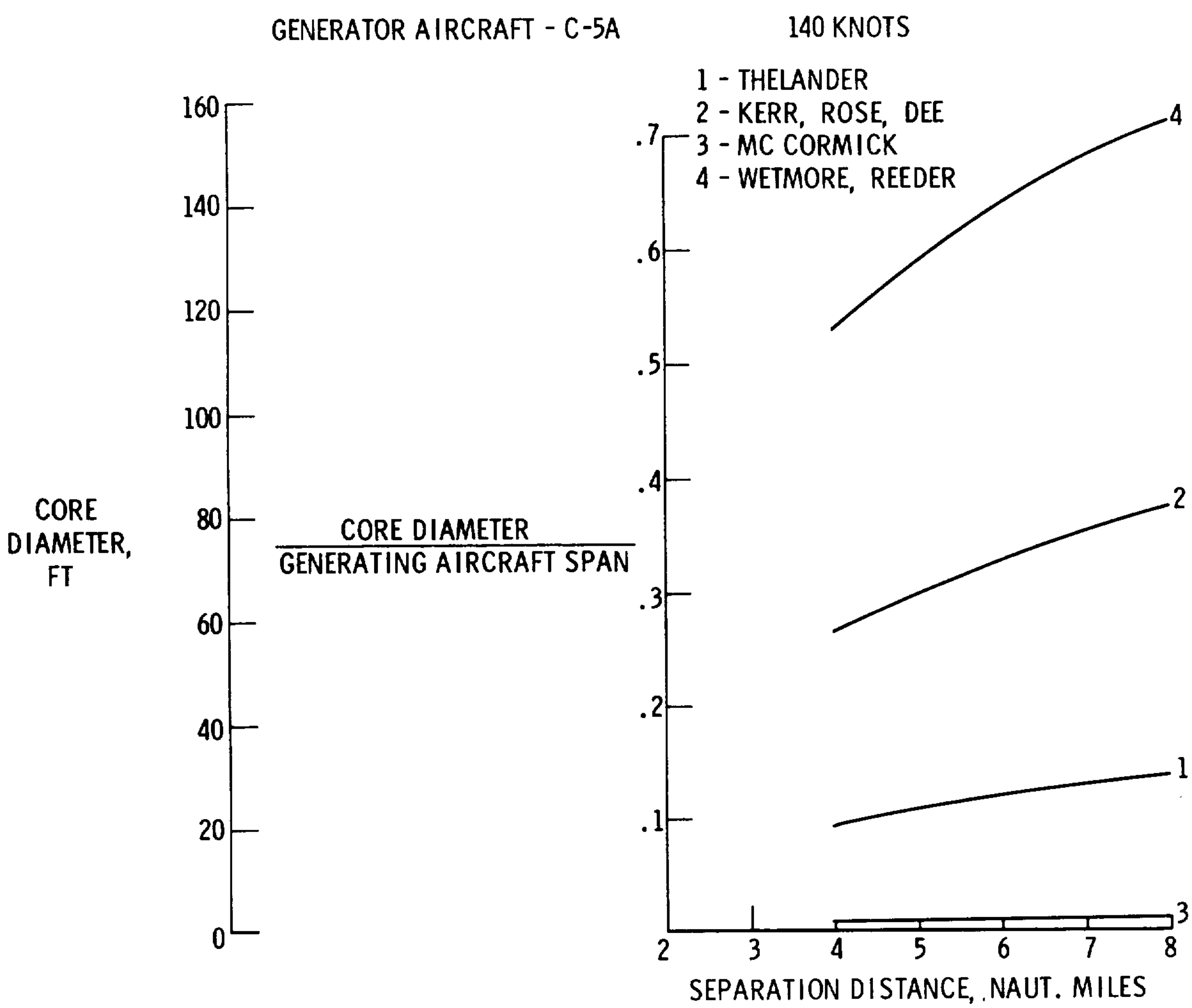


FIGURE 27. Calculated Vortex Core Diameter.

A comparison between the four expressions and a representative flight data sample is presented on Figure 28. The rolling moments measured on the Lear Jet probing the C-5A wake are compared with rolling moments computed using the four equations. The rolling moments are expressed in coefficient form to allow for cross-correlation between the various aircraft tested. In accordance with a technique developed in reference 1, computed rolling moment coefficients were obtained by assuming that the probe aircraft was located in the center of the right vortex of the generating aircraft and evaluating the resulting rolling moment as an integral function of the pertinent vertical velocity profile (see Figure 26). Rolling moment coefficients computed using expression 4 are low compared with the flight measurements, while the results indicated from expression 1 appear to be too conservative. With regard to the majority of the flight measurements, expressions 2 and 3 come the closest to defining the upper boundary of data. The objective of these comparisons between calculated and experimentally determined rolling moment coefficients was to establish which of the equations would provide a realistic, and yet slightly conservative, estimate of the vortex behavior in terms of an induced rolling moment on a trailing aircraft. From the data presented it appears that expressions 2 and 3 more nearly satisfy this requirement than the other two expressions evaluated. In future studies, predictions of the vortex induced rolling moments using these expressions could be compared to the maximum lateral control power of an aircraft under consideration as a means of establishing a safe separation criteria.

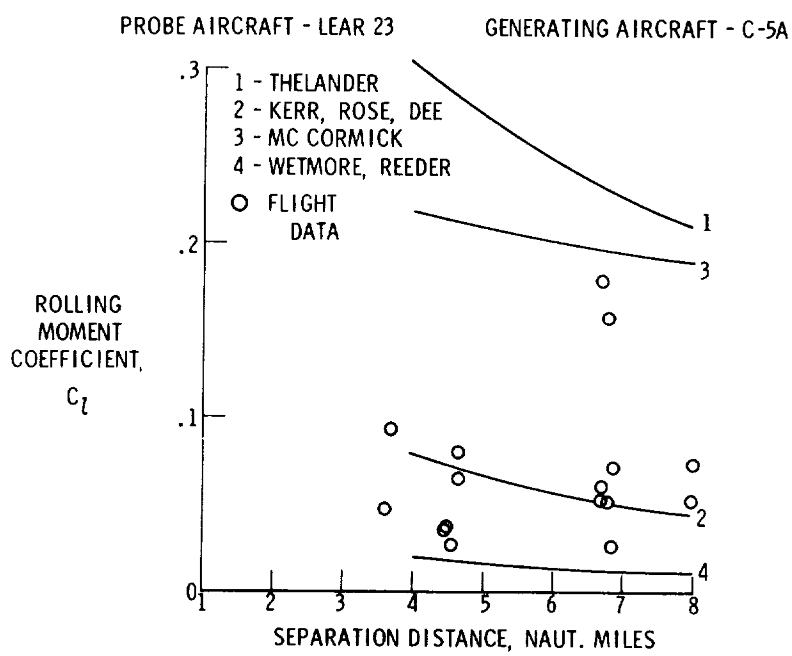


FIGURE 28. Comparison of Calculated Rolling Moment Coefficient with Flight Measurements.

B. Investigation of Jet Transport Aircraft Vortex Systems Descending Into and Generated in Ground Effect - FAA NAFEC

The objective of this task was for NAFEC to investigate the characteristics, particularly persistency, of heavy jet transport aircraft vortex systems generated within ground effect and those generated out of but descending into ground effect, and the relatively long time history vortex characteristics related to terminal area operations.

These tests differed from the other two tasks in that the majority of the flight paths were on a 2.75-degree glide slope to a runway in aircraft approach or landing configurations. The test aircraft were flown past a tower at 20, 40, 60, 80, and 100-foot altitudes above the ground. Very few vortices missed the tower. Glide slope information was provided to the pilots by either Visual Approach System Indicator (VASI) or by TALAR (Product of Singer-General Precision, Inc., Pleasantville, New York) Landing Approach System which is a portable microwave ILS.

The flight tests required that the aircraft be in stabilized flight, either level or on a 2.75-degree glide slope when passing abreast of the tower.

The NAFEC phototheodolites were used to derive accurate space position information on the test aircraft when they were abreast of the tower.

The tower used for these tests was 100 feet high with its base 76 feet above sea level, Figure 29.

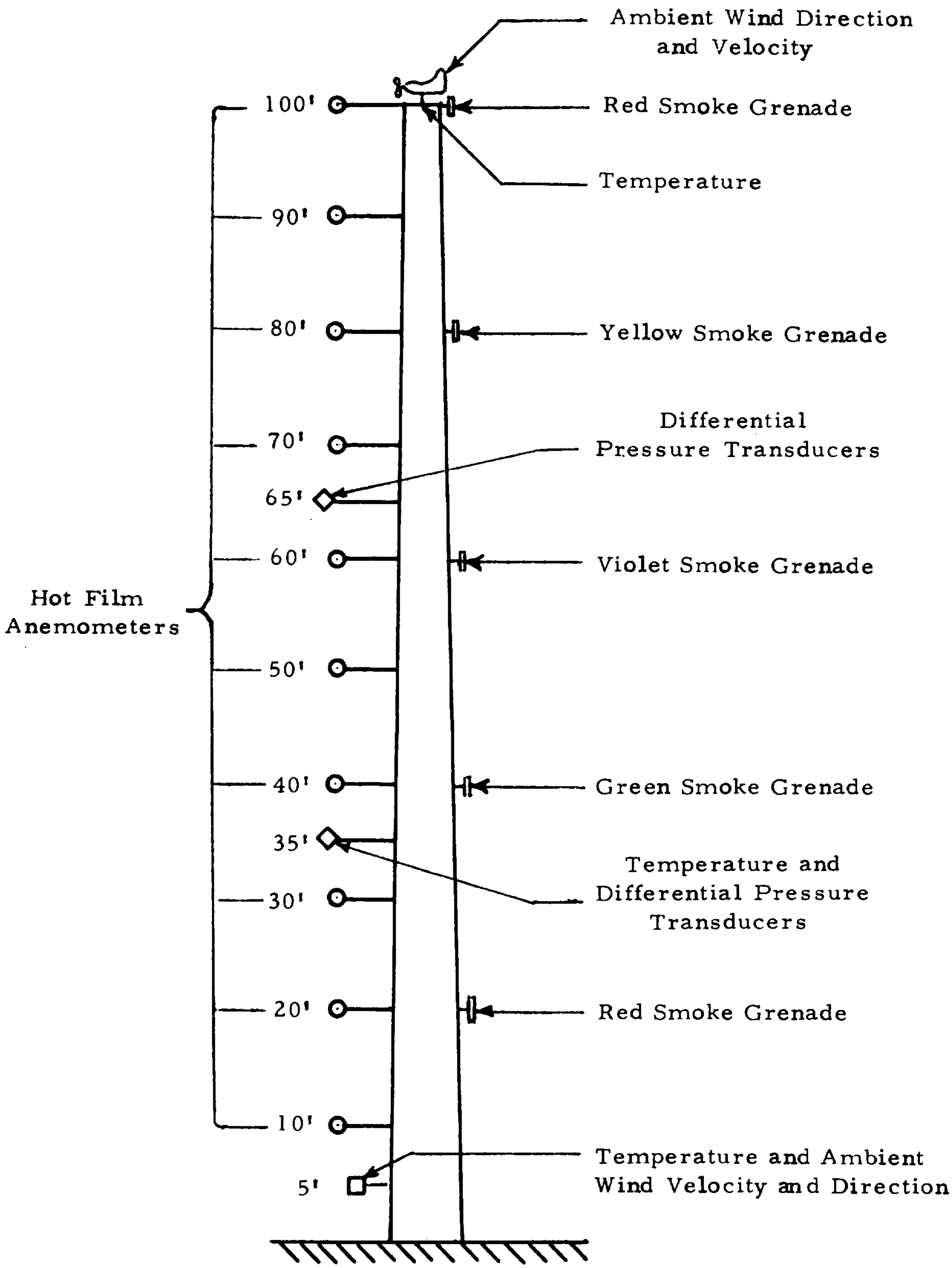


FIGURE 29. Schematic of Instrumented NAFEC Tower Used for Vortex Wake Turbulence Measurements

Scope. A total of 153 aircraft tower fly-bys were flown in support of this task as follows:

B727 - 43
DC-9 - 12
B707 - 11
CV-880 - 87

Of this total, 150 of the passes possessed tower data of sufficient significance to warrant further processing and analyses. All of the B727, B707, and 55 of the CV-880 tower fly-bys were flown on a 2.75-degree glide slope. The remainder of the passes were in level flight for the following reasons: adverse wind direction or flight test run objective was changed. Data from 85 passes were collected for the CV-880, from 42 passes for the 727, and from 12 and 11 passes, respectively, for the DC-9 and TWA-707.

Data output included data tables and graphical depictions as follows: plots of vortex cross-sectional size and shape in the form of isopleths as a function of time, tangential speed versus distance from the vortex center, plots of vortex tangential flow velocities as a function of time, radius of maximum velocity, peak recorded tangential velocity and age, rate of atmospheric transport and supplemental atmospheric characteristics.

A summary plot of maximum speeds versus vortex core diameters is given in Figure 30 for all the aircraft and configurations. This is a first approximation at core diameter estimation. For large vortex speeds the core diameter remains small. As the speeds diminish toward 50 to 65 feet per second, the estimated diameter sizes are scattered over a large range. A summary plot of maximum record vortex tangential velocities versus ages is given by Figure 31. Considerable scatter exists in the data, particularly at slower speeds. The major value of this figure probably is the suggested boundary along the edge of the data points. This boundary of the observed data represents an estimate of the maximum vortex tangential speeds expected at a given vortex age, if all other conditions are held constant.

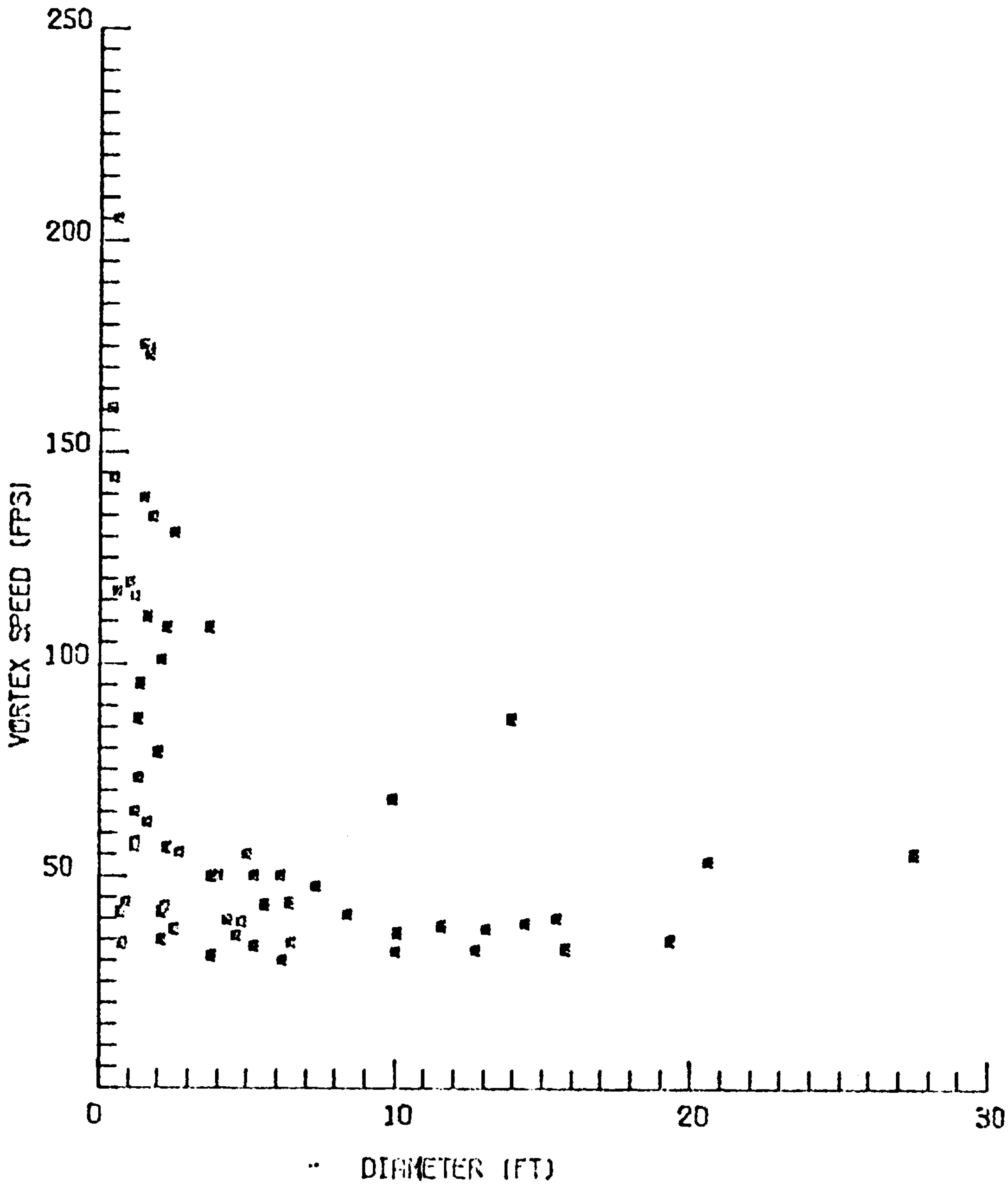


FIGURE 30. Summary of Peak Vortex Tangential Velocities Versus Estimated Core Diameters (All Aircraft).

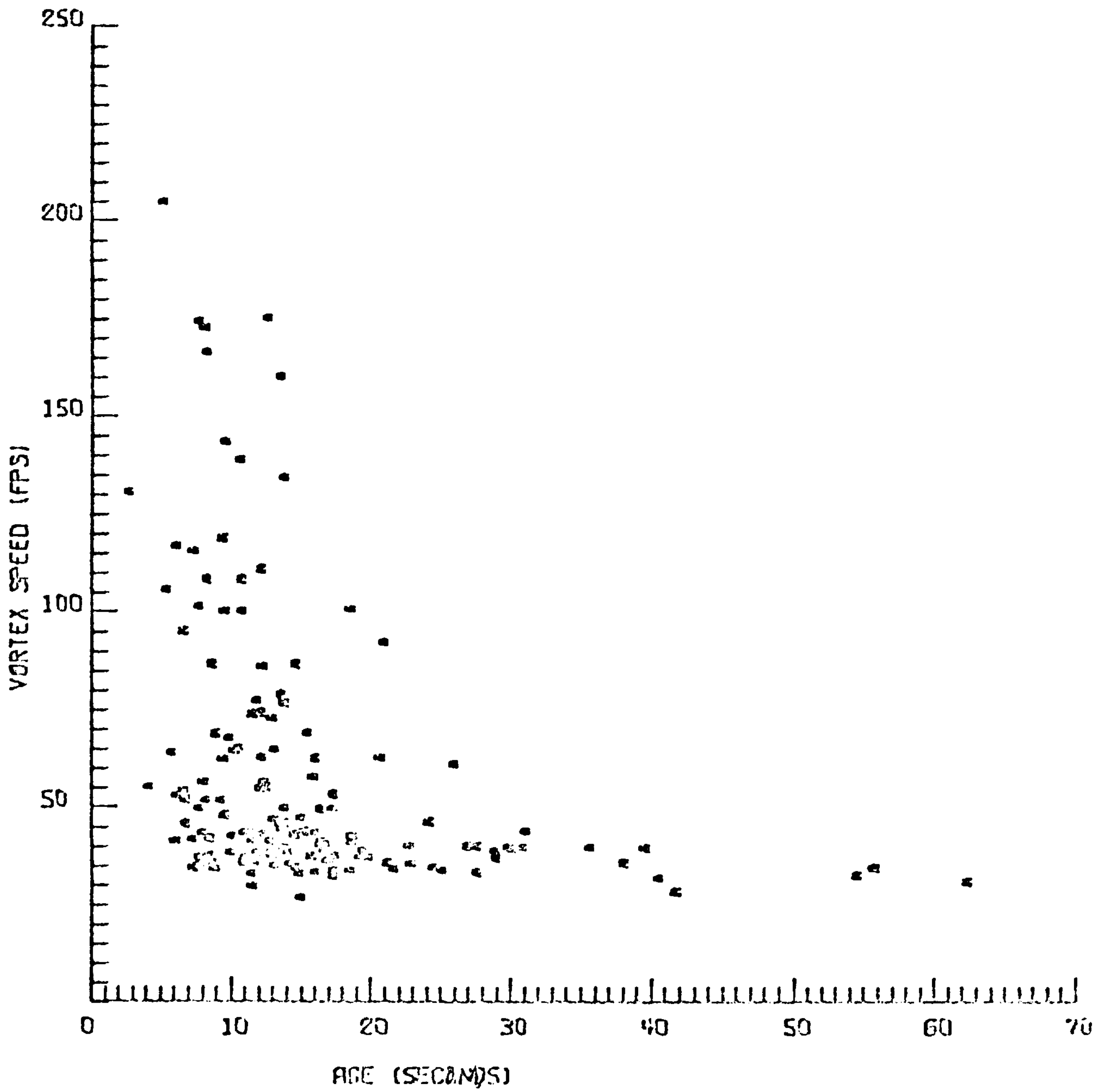


FIGURE 31. Summary of Peak Vortex Tangential Velocities Versus Age (All Aircraft).

Based on this portion of the test program, the following highlight observations were noted.

Aircraft Models Tested: Boeing B-707 and B-727; Douglas DC-9; and Convair 880.

(1) Aircraft Vortex Characteristics

(a) Specific:

Aircraft Model	Configuration	Vortex Characteristics
All except B-727 and DC-9	"Dirty", Full-Flap, Gear Down (Landing)	Non-tubular flow "Cores": Not noticeable as such Relatively large field of influence (1/3 to 1/2 Wing Span) $V\theta$: 60 to 100 FPS Breaks up rapidly from "ordered" flow to turbulent-type flow: (up to 1-1/2 minutes age)
All Aircraft	Partial-Flap, Gear up/down (T.O. or holding)	Semi-Tubular "Cores": Random (Diameter:.04 to .06 Wing Span) Medium Field of influence (1/3 Wing Span) $V\theta$: Approx. 140 FPS More persistent than dirty configuration: (up to 1-1/2 - 2 minutes age)
All Aircraft	"Clean", No Flaps (Holding, Enroute)	Tubular "Cores": Consistently noticeable (Diameter: .02 to .04 Wing Span) Small to medium field of influence (1/6 - 1/3 Wing Span) VO: Approx. 140 FPS Very persistent: (up to 2 minutes of age) Artillery Shell Whine
B-727, DC-9	"Dirty", Full Flap	Tubular "Cores": Consistently noticeable (1 - 2 feet diameter) Medium Field of Influence (1/3 Wing Span) VO: Approx. 190 - 200 FPS Very persistent: (up to 2 minutes of age) Artillery Shell Whine - B-727

(b) General:

1. Vortices generated by aircraft in T.O. or landing configuration, that is with some flap deflection, tended to become unstable and degenerate to discontinuous, segmented-type vortices or a random-type motion in about 90 seconds.

2. A pulsating axial flow appears to signal the onset of vortex core disintegration.

3. When recorded, no significant vortex velocities were noticed for vortex ages $>$ 2 minutes, regardless of whether generated in or out of ground effect.

4. For identical vortex ages, there appears to be a drop-off in vortex tangential velocities as they are generated closer to the ground. However, more data on longer vortex ages and lower test aircraft flight altitudes are required to provide an intelligent analysis of the in ground effect generated vortex structure.

ENGINEERING ANALYSIS - SPAN LOADING/SPAN RATIO

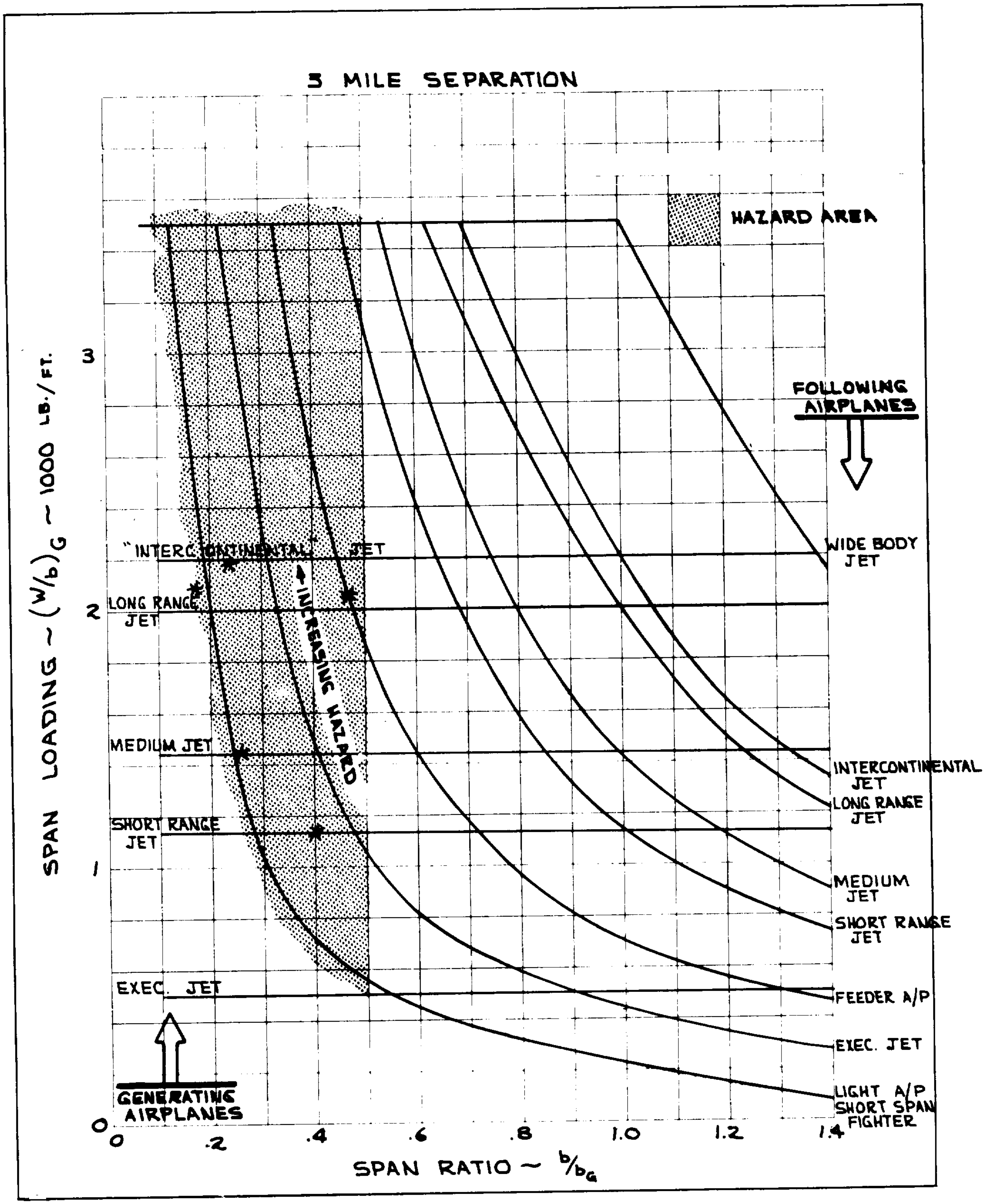
In reviewing the data gathered during the test programs reported herein, it became evident that the parameters of span loading and span ratio provided a very logical method to portray the "degree" of wake turbulence in relation to separation distances by aircraft category.

Span Loading	-	indicates strength of wake generated.
Span Ratio	-	indicates the span of a following aircraft relative to the size of the generated vortex.

Two other parameters are pertinent:

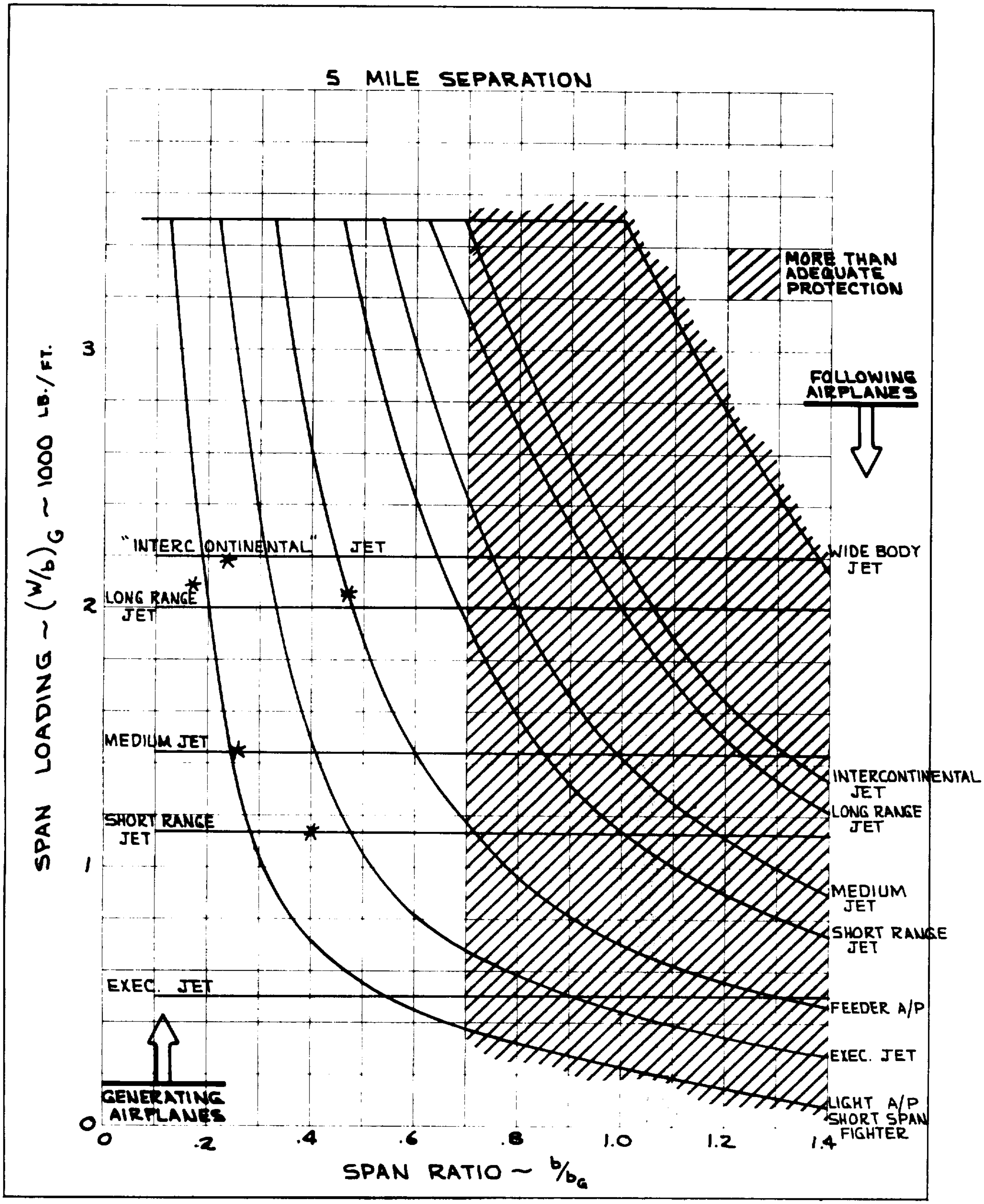
Control Power	-	indicates the ability of the encountering aircraft to counter and recover from an upset.
Configuration	-	affects the character and strength of the wake.

The relationship of separation distances and aircraft categories on the basis of span loading (generating aircraft) to span ratio (encountering aircraft) is depicted in the following set of graphs. In each instance the span loading of the generating aircraft is displayed by categories in the left margin, and the span ratio of the encountering aircraft is shown on the bottom margin. The superimposed overlayed data should be viewed in relation to the conditions that exist as the hazard index is approached. It should also be noted that the overlay projections are made on the basis that a hazard exists at three miles separation for a span ratio less than .5 (Figure 1) while there is more than adequate protection at five miles for span ratios above .7 (Figure 2). Figure 3 shows the categories as defined early in 1970. The overlay data depicted in Graphs 4 and 5 portrays the hazard index on the basis of a two-category division and a three-category division.



3 MILE SEPARATION
HAZARD AREA
FOLLOWING AIRPLANES
GENERATING AIRPLANES
INCREASING HAZARD
"INTERCONTINENTAL" JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
EXEC. JET
WIDE BODY JET
INTERCONTINENTAL JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
FEEDER A/P
EXEC. JET
LIGHT A/P SHORT SPAN FIGHTER
SPAN LOADING ~ (W/b)G ~ 1000 LB./FT.
SPAN RATIO ~ b/bG
0
1
2
3
0
.2
.4
.6
.8
1.0
1.2
1.4

Fig. 1



5 MILE SEPARATION
MORE THAN ADEQUATE PROTECTION
FOLLOWING AIRPLANES
"INTERCONTINENTAL" JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
EXEC. JET
GENERATING AIRPLANES
WIDE BODY JET
INTERCONTINENTAL JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
FEEDER A/P
EXEC. JET
LIGHT A/P
SHORT SPAN FIGHTER
SPAN LOADING ~ $(W/b)_G$ ~ 1000 LB./FT.
3
2
1
0
0
.2
.4
.6
.8
1.0
1.2
1.4
SPAN RATIO ~ b/b_G

Fig. 2

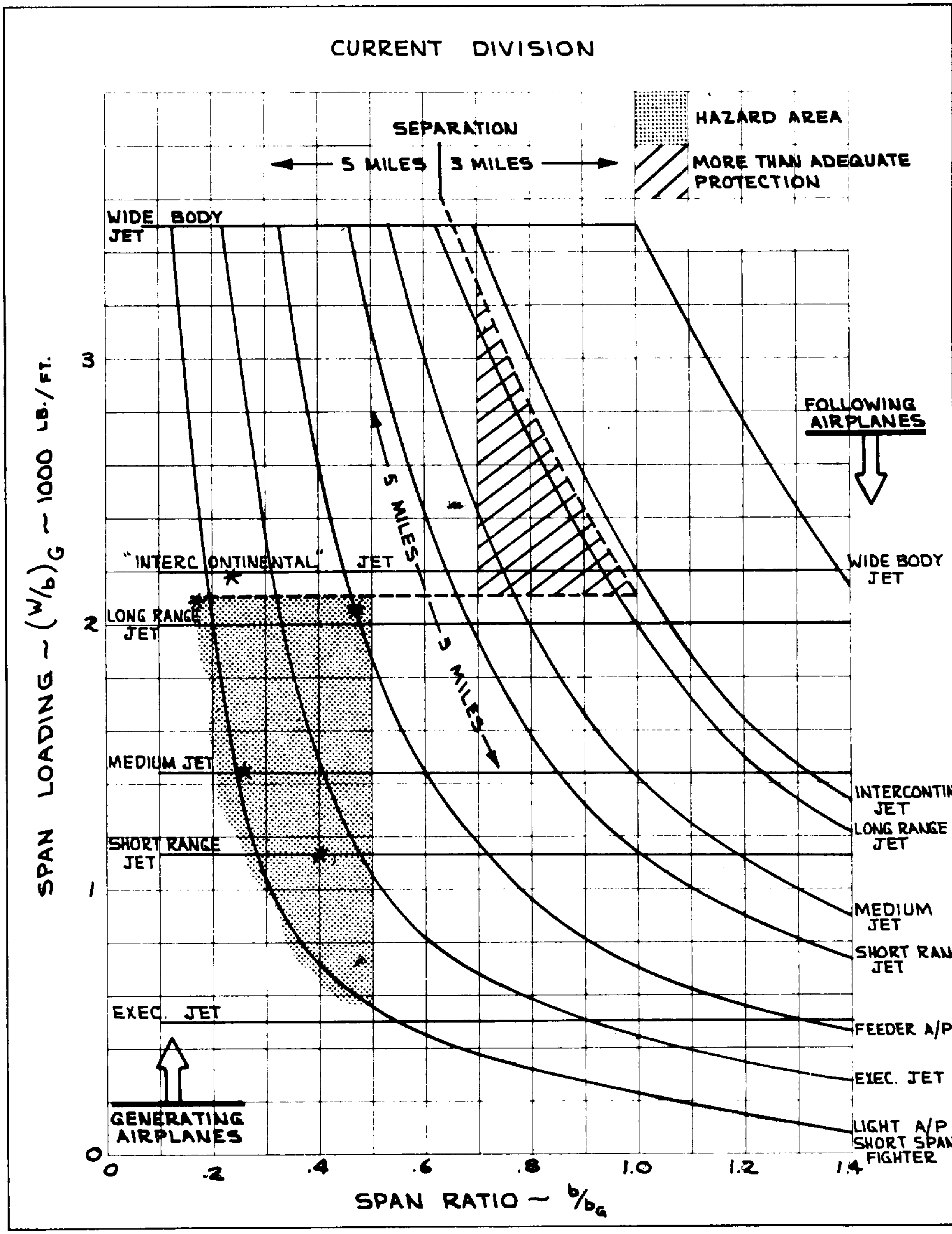
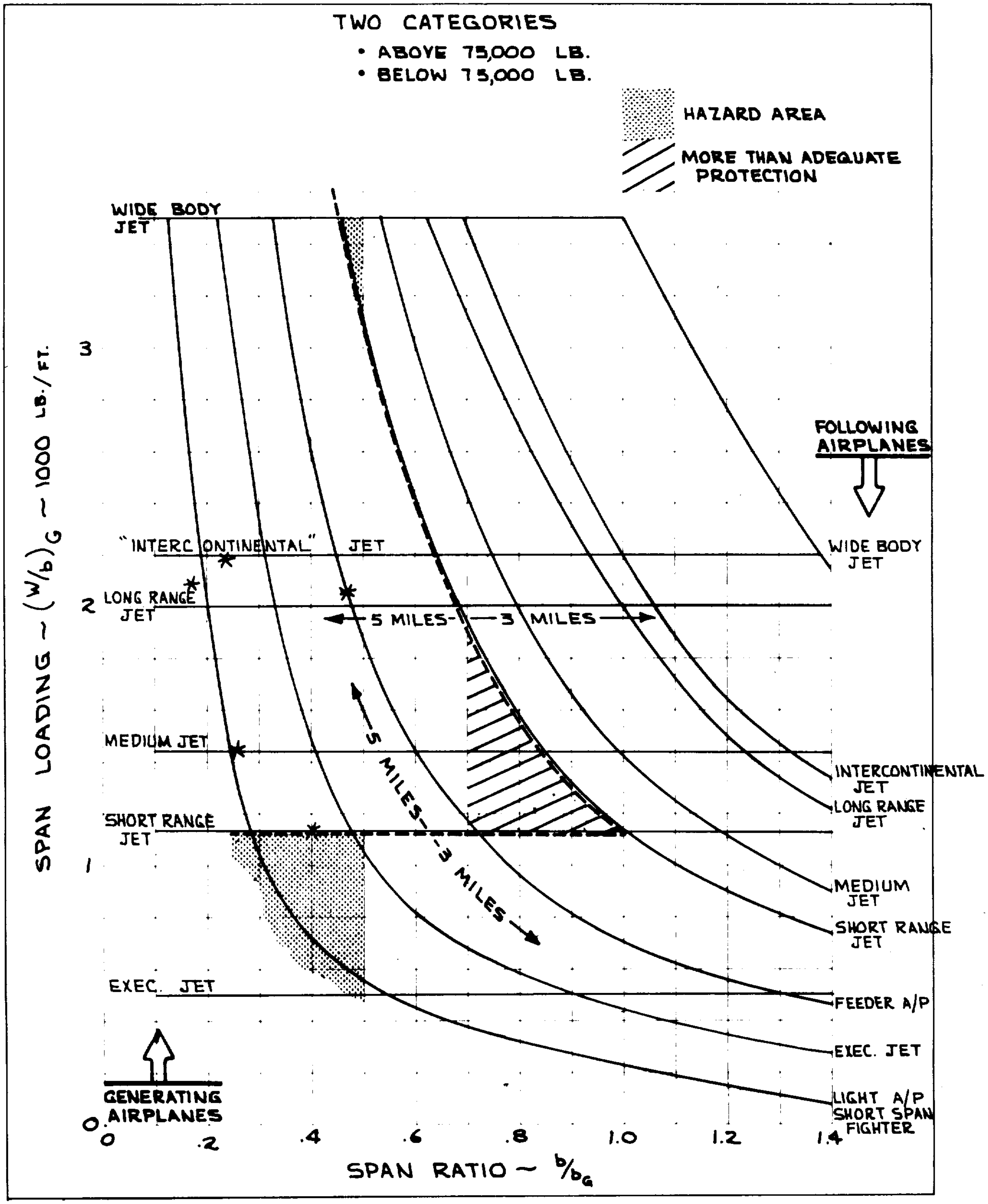

CURRENT DIVISION
HAZARD AREA
MORE THAN ADEQUATE PROTECTION
SEPARATION
5 MILES
3 MILES
WIDE BODY JET
"INTERCONTINENTAL" JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
EXEC. JET
GENERATING AIRPLANES
FOLLOWING AIRPLANES
WIDE BODY JET
INTERCONTINENTAL JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
FEEDER A/P
EXEC. JET
LIGHT A/P SHORT SPAN FIGHTER
SPAN LOADING ~ $(W/b)_G$ ~ 1000 LB./FT.
SPAN RATIO ~ b/b_G
0
.2
.4
.6
.8
1.0
1.2
1.4
1
2
3

Fig. 3



TWO CATEGORIES
• ABOVE 75,000 LB.
• BELOW 75,000 LB.
HAZARD AREA
MORE THAN ADEQUATE PROTECTION
WIDE BODY JET
"INTERCONTINENTAL" JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
EXEC. JET
FOLLOWING AIRPLANES
GENERATING AIRPLANES
5 MILES
3 MILES
5 MILES--3 MILES
INTERCONTINENTAL JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
FEEDER A/P
EXEC. JET
LIGHT A/P SHORT SPAN FIGHTER
SPAN LOADING ~ (W/b)G ~ 1000 LB./FT.
SPAN RATIO ~ b/bG
0 .2 .4 .6 .8 1.0 1.2 1.4
0 1 2 3

Fig. 4

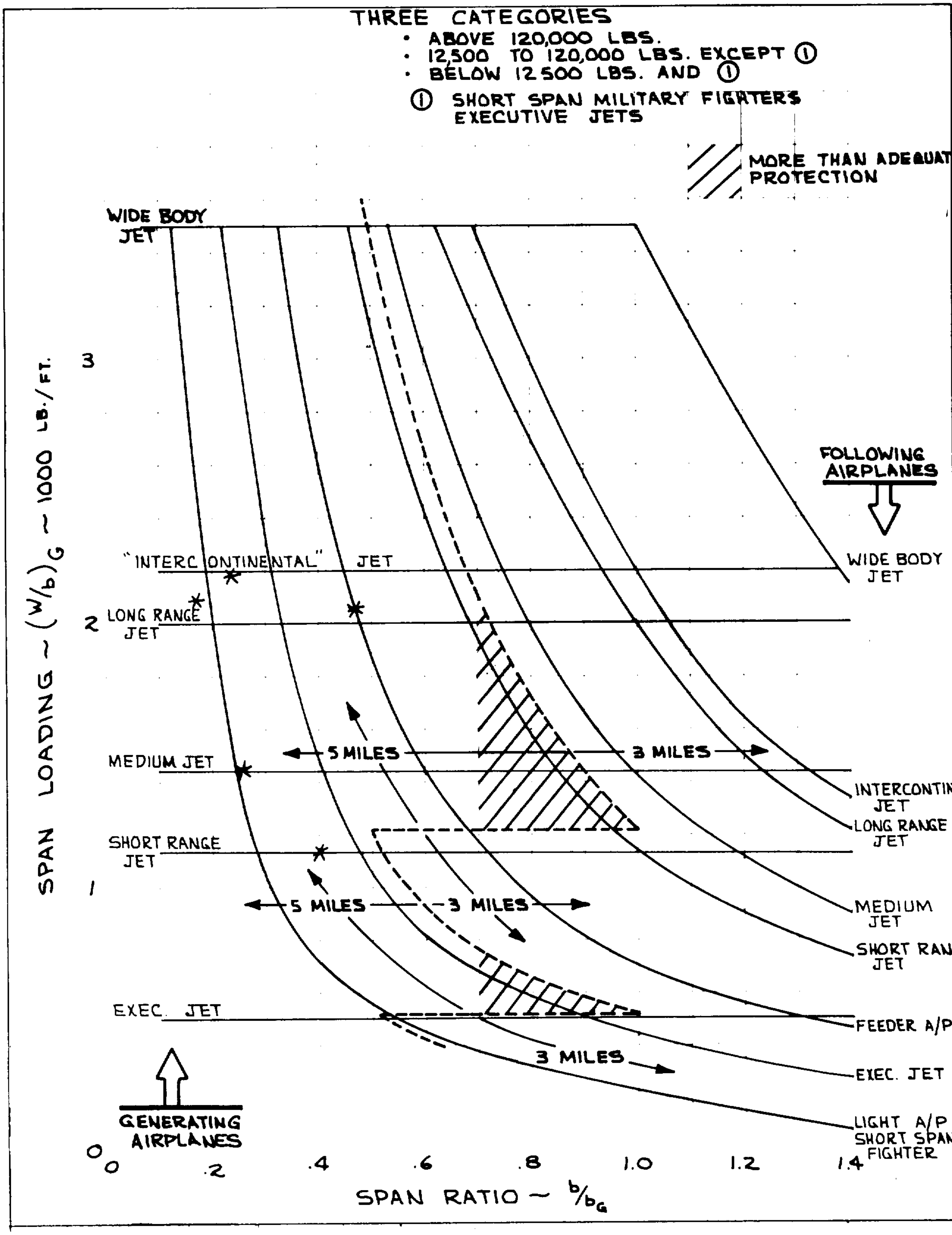

THREE CATEGORIES
• ABOVE 120,000 LBS.
• 12,500 TO 120,000 LBS. EXCEPT ①
• BELOW 12,500 LBS. AND ①
① SHORT SPAN MILITARY FIGHTERS
EXECUTIVE JETS
MORE THAN ADEQUATE PROTECTION
WIDE BODY JET
"INTERCONTINENTAL" JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
EXEC. JET
5 MILES
3 MILES
5 MILES
3 MILES
3 MILES
FOLLOWING AIRPLANES
GENERATING AIRPLANES
WIDE BODY JET
INTERCONTINENTAL JET
LONG RANGE JET
MEDIUM JET
SHORT RANGE JET
FEEDER A/P
EXEC. JET
LIGHT A/P SHORT SPAN FIGHTER
SPAN LOADING ~ $(W/b)_G$ ~ 1000 LB./FT.
SPAN RATIO ~ b/b_G
0
.2
.4
.6
.8
1.0
1.2
1.4
1
2
3

Fig. 5

FINDINGS AND CONCULSIONS

Studies, theoretical projections, and flight tests conducted prior to this 1970 test program provided substantial information onthe formation and behavior of wing-tip vortices. Many of these earlier conclusions were reconfirmed during the tests, some were amplified, and a considerable amount of new information was obtained.

Vortex visualization systems permitted test aircraft to locate the vortices and to position themselves near the core perpendicular to the tangential rotation of the vortex systems. Without visualization systems, the vortices were not easily located; thus, randomly encountered despite probe aircraft pilot efforts.

Vortex System Characteristics

1. The vortex visualization systems employed during these flight tests permitted photographs, films, tower fly-by measurements and in-flight probes in sufficient number to provide quantitative data on the characteristics and behavior of wing-tip vortex systems, described as follows:

   a. Aircraft trailing vortex systems are made up of two counter rotating cylindrical air masses, the centers of which are approximately a $\frac{\pi}{4}$ wing span apart.

   b. The vortices start to descend immediately after the roll-up process and descend at a rate of 400 to 500 feet per minute when generated by a large heavy aircraft tested and at a reduced rate proportionate to the reduced size and weight of the other aircraft tested.

   c. Fully developed vortices were not found more than 1,000 feet below the altitude of the generating aircraft. Leveling off combined with start of breakup usually occurred at 8/9 hundred feet below, with instances of undulations noted both at altitude and in or near ground effect.

   d. The vortices retain their lateral spacing and, at altitude, the vortex system drifts with the wind.

   e. Breakup of the vortices is affected by atmospheric turbulence. During minimum turbulence conditions, the start of breakup was identified with a sinusoidal oscillation of one vortex.

   f. Vortex strength measurements showed little attenuation at altitude, in terms of dynamic response of the probe aircraft, between the closest points probed out to a distance equal to 2 minutes in time from initial formation. Beyond that point and time, the measurements indicated various degrees of attenuation with the variables applicable to (1) dissipation of first one then the other vortex, (2) along flight path sections of one vortex cylinder dissipating with other sections retaining force, and (3) the degree of atmospheric turbulence present.

g. The tangential velocities and persistence of the vortices is reduced when the configuration of the generating aircraft is altered from clean to flaps/gear down.

h. The behavior of the vortex system is altered when the vortices descend to a level approximately equal to 1/2 the wing span of the generating aircraft above the surface of the ground. At this point, the downward movement ceases and the vortices separate laterally and move outward. The vortex height in ground effect is generally $\frac{\pi}{8b}$, where b is the span of the generating aircraft.

i. Vortex systems generated in ground effect have reduced tangential velocities.

j. The vortex systems decay fairly rapidly below 100 feet above the ground.

2. The Tower fly bys and inflight probes also provided the basis for conclusions which have operational applicability, described as follows:

a. Short span test aircraft, when intentionally flown into fully developed vortex cores, experienced uncontrollable roll rates. Medium size span airplanes; i.e., DC-9, CV-990, B-737, similarly positioned did not experience uncontrollable forces. A B-737 intentionally closely spaced and positioned in a vortex generated by a large jet at an altitude of approximately 60' above the runway, experienced a 28° roll before recovery to level flight.

b. During vortex encounters, when the test probe aircraft were centered and held near the core of a vortex, the roll forces imposed were related to the aircraft span, roll rate control capability and pilot reaction time. However, random achievement of this circumstance is remote since the angle and point of vortex intercept will invariably induce flight path changes prohibiting longitudinal alignment of a following aircraft centered in the vortex core. Conversely, these factors highlight the operational significance of the vortex diameter (field of influence). Extrapolation of the data presented in the vortex recorded tangential velocity isopleth plots shows that the field of influence of vortex systems generated, by aircraft weighing 300,000 pounds or more, to have good operational correlation with the degree of undesirable dynamic response that will be experienced with aircraft having a substantially lesser span than the generating aircraft.

c. The vortex systems sink rate and leveling off process indicates little operational significance for a following aircraft when both aircraft are operating at altitude, in level flight with 1,000 feet vertical separation or the normally prescribed IFR lateral/longitudinal spacing.

d. The vortex systems sink rate, leveling off process, and outward movement in ground effect indicates little operational significance for a following aircraft during the final approach phase providing the following aircraft remains at or above the glide slope angle flown by the preceding aircraft.

e. When generated by large heavy aircraft during the final portion of the approach, the possible curtailment of the vortex outward flow due to compensating ambient winds, combined with the possibility of vortex undulations, requires a spacing of (time/distance) 5 miles to preclude undesirable vortex encounters by a following aircraft if that aircraft has a substantially lesser span than the generating aircraft.

f. The behavior of vortex systems generated during the takeoff phase indicates little operational significance for a following aircraft provided the lift off of the following aircraft occurs prior to the rotation point of the preceding aircraft, and further provided that the departure procedure flown by the following aircraft is at or above the preceding aircraft's altitude until established on diverging tracks. Conversely, the potential for the ambient winds or atmospheric conditions to alter the conventional behavior of the vortex system suggests the need for aircraft spacing of (time/distance) 5 miles behind a large heavy aircraft if the following aircraft has a substantially lesser span than the generating aircraft.

g. The movement of a vortex in ground effect, with the lateral movement influenced by the ambient wind and in relation to the earlier breakup of a vortex by increased surface winds or atmospheric turbulence, necessitates the same considerations enumerated above during parallel runway separations unless the runways are separated by 2,500 feet or more.

RECOMMENDATIONS

1. That research efforts be accelerated to develop a measuring technique and operational display of vortex intensity and persistence in the runway threshold and departure areas.

2. That new aircraft in the heavy category or those having unique characteristics different from the aircraft involved in this test program be subjected to tests to measure the intensity of their vortex systems.

3. That an accelerated pilot education/information program be initiated to convey the characteristics, behavior, and need for awareness of the hazards of unexpected vortex encounters.

4. That tests be conducted to determine the effect of "T" tails on the vortex strength in order to resolve apparent differences in C-5A and 747 configurations.

5. That maximum efforts be initiated by government and industry to determine aerodynamic design means of minimizing wing tip vortices at the source.

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