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NASA AIRCRAFT TRAILING VORTEX  
RESEARCH

by

William A. McGowan

W. A. McGowan

NASA Headquarters  
Washington, D.C., U.S.A.

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## NASA AIRCRAFT TRAILING VORTEX RESEARCH

William A. McGowan  
NASA Headquarters  
Washington, D. C.

### SUMMARY

A brief description is given of NASA's comprehensive program to study the aircraft trailing vortex problem. Wind tunnel experiments are used to develop the detailed processes of wing tip vortex formation and explore different means to either prevent trailing vortices from forming or induce early break-up.

Flight tests provide information on trailing vortex system behavior behind large transport aircraft, both near the ground, as in the vicinity of the airport, and at cruise/holding pattern altitudes. Results from some flight tests are used to show how pilots might avoid the dangerous areas when flying in the vicinity of large transport aircraft. Other flight tests will be made to verify and evaluate trailing vortex elimination schemes developed in the model tests.

Laser Doppler velocimeters being developed for use in the research program and to locate and measure vortex winds in the airport area are discussed. Field tests have shown that the laser Doppler velocimeter measurements compare well with those from cup anemometers.

Our hope is to develop the basis for an acceptable method to alleviate the vortex related problems of the general aviation pilots, commercial carriers, passengers, and the air traffic system.

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## NASA AIRCRAFT TRAILING VORTEX RESEARCH

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### 1. INTRODUCTION

Trailing vortex systems of large transport type aircraft are known to have winds of hazardous intensities if encountered by other aircraft in flight (1-10). Additional troublesome aspects of the problem are that the vortices are generally difficult to detect behind the large aircraft and persist for quite some time after generation.

The seriousness of the vortex hazard has been brought into sharp focus by the very large, heavy, transport aircraft being placed in service, coupled with recent efforts to find ways to increase the number of airfield operations. The large transport aircraft trail behind proportionally more intense vortices than their lighter predecessors. These same vortices are also the basis for increased spacing and time delays between departing aircraft, resulting in reduced airfield capacity. There is, then, a real urgency to explore the possible ways to reduce the delays and spacing between aircraft and, in the case of trailing vortices, if possible, eliminate the problem itself. There is an intensified research effort in the NASA to achieve much more enlightenment on the details of trailing vortex formation in the immediate vicinity of the wing. The scientists are, in a manner of speaking, searching for the Achilles heel of the persistent and hazardous trailing vortex system. There is no slackening of the current efforts to better define the behavior of trailing vortices and find ways to monitor their intensity and movement, especially in the airport area. It may well be that the trailing vortex system will not succumb to the onslaught of scientific intent. Recourse to system avoidance procedures and monitoring action might still be necessary.

The major elements of the aircraft trailing vortex problem are discussed along with brief descriptions of NASA programs and plans. Our hope is to develop the basis for an adequate method to alleviate the vortex related problems of the general aviation pilots, commercial carriers, passengers, and the air traffic system. Interpretation of some results from recent flight tests and analytical studies are outlined for operational use of pilots.

### 2. PROBLEM ELEMENTS

Elements of the aircraft trailing vortex problem are related to the in-flight hazards associated with encounters, the economic penalties (as reduced airport capacity and slowdown in traffic) arising from

stretched spacing between departing aircraft, and the passenger discomfort triggered by the unexpected bumpy ride and the often times steep bank angles imposed.

The in-flight hazards encountered by aircraft are illustrated in Figure 1. Induced roll and steep bank angles frequently result. Structural load factors are the concern during a traverse, along a line through the vortex centers, perpendicular to the flight path of the large aircraft. Changes in rate of climb and descent can be troublesome when experienced shortly after take off or just before touchdown. References 1-4 describe accidents related to the various in-flight hazards illustrated.

The economic impact of the trailing vortex problem is now receiving much more consideration than in the recent past. The hazard potential of trailing vortices, and perhaps an inability to assess adequately this potential, during airport operations has been the cause of the increase in time spacing between aircraft. Should the vortices continue to warrant the increased spacing the economic penalties may be severe. Many major airports are now <sup>operating</sup> generating at or near capacity. Land for new airports is very difficult to locate and very expensive to purchase. This lends emphasis to making a concerted effort to eliminate the delays caused by trailing vortices. It may well be that the only way to do this is by eliminating the trailing vortices themselves, a monumental achievement according to some aerodynamicists.

Heretofore, general aviation pilots, in relatively small aircraft, have experienced virtually all of the accidents caused by vortex encounters. There now are frequent reports from professional pilots describing incidents that resulted from encounters with trailing vortices of other large aircraft. From a passenger comfort standpoint it seems obvious that the byproducts of a vortex encounter are not welcome and should be avoided if practical. This then is still another reason to pursue every logical avenue to bring about the elimination of the trailing vortex system as we now know it.

### 3. RESEARCH PROGRAMS

The NASA aircraft trailing vortex research, as illustrated in Figure 2, is a comprehensive effort to learn about the intimate details of vortex behavior, to determine the influence vortices can have on other aircraft, and investigate means to attenuate the hazards. Flight tests and model tests will be described. Measurement techniques, being developed to provide an accurate means to evaluate vortex flow without disrupting either the natural environment or the natural life cycle of the vortex itself, will be discussed.

The near term goal of this research is to enable both the development of pilot avoidance procedures and system avoidance procedures particularly for use in the airport area. The final goal of this research is the elimination of the hazard potential, probably through aerodynamic design.

### 3.1 Flight Tests

Flight tests are carried out to catalogue vortex characteristics, at altitudes above 1,000 feet where ground effect is not a factor, to obtain data applicable to the cruise/holding patterns, and, at altitudes from the ground up to approximately 1,000 feet, to represent operations in the airport area (Figure 3).

Vortices have an inherent characteristic to move downward when formed as shown in Figure 4. Two principal factors are readily apparent: one, the vortices move downward in equal increments with time and second, the vortex system drifts with the wind while at the same time maintaining the tendency to move downward with time, as in the no-wind case. The vortices form just inboard of the wing tips and remain so spaced, unless disturbed by turbulence or some other factor.

Some elements influencing vortex system intensity, movement and persistence are listed in Figure 5. Thermal and atmospheric wave action of sufficient magnitude can lead to the early disruption of the vortices. On the other hand gentle, moving currents without marked discontinuities are expected to cause little reduction in vortex persistence. Figure 6 illustrates the thermal effects, which can be present over changing terrain, on the vertical position of the vortex wake.

A typical vortex wake location measured aft of the C-5A is shown in Figure 7. The C-5A flew a steady course at 12,500 feet altitude. A probe aircraft located the wake, as shown previously in Figure 3, and radar information was used to establish vertical and longitudinal spacing. No positive explanation of the oscillation is available. Oscillations of this sort might be initiated by the aircraft motions or atmospheric effects as noted before. The vortex wake location extended aft and down with respect to the generating aircraft as expected.

The averages of wake locations behind the C-5A for several test runs are given in Figure 8. It is noted that the wake does tend to level off about 1,000 feet below the flight path of the C-5A for the particular atmospheric conditions existing during these limited tests. The wake remained intact for distances exceeding 10 nautical miles behind the C-5A.

(9)

The roll response of three aircraft (DC-9, Cessna 210, Lear Jet) on encountering the C-5A wake at various distances astern are shown in Figure 9. The weight spread of these aircraft extended from about 70,000 pounds to about 3,000 pounds. The roll response was achieved despite the efforts of the pilot to counter the imposed bank angle. Obviously upsets of this type could be hazardous. A practical limit of  $30^{\circ}$  bank angle was set (8) and noted on the Figure, assuming this bank angle would be about all a pilot would want to contend with, especially in holding patterns, during approach to landing and shortly after takeoff.

Information from Figures 8 and 9 and reference 8 was used to derive the envelopes of vortex vertical locations aft of a large transport aircraft shown in Figure 10. Pilots could possibly encounter large load factors, bank angles, and roll rates in the shaded area. Turbulence could shrink these areas, as could aircraft which generate vortices of less intensity. As we saw in Figure 7 the vortex trail is often distorted and its exact location unknown. More recent tests with the C-5A revealed wake locations at still other locations within the cross hatched area, some nearly on the flight path, verifying the avoid area noted on Figure 10. The lateral displacement envelope shown in the Figure accounts for vortex drift under various wind conditions, as described in Figure 4 and discussed in Reference 8. An airplane entering the shaded areas would not necessarily encounter a vortex because of their respective locations, but pilots should avoid the area to the extent possible.

Previous mention was made of the loads factors which an airplane could experience when traversing the vortices along a line through the vortex centers. An illustration of this flight path and typical load factors is given in Figure 11. It is to be noted that there is a marked reduction in imposed load factor when the aircraft is but a short distance ( $\sim 25$  feet) above or below the line through the vortex centers. In other words, to experience high load factors it is necessary to pass close to at least one of the vortex cores.

Calculated vertical load factors (5) imposed on a light aircraft crossing the wake of a heavy transport aircraft (180,000 pounds), perpendicular to the flight path and along a line through the vortex centers are shown in Figure 12. Two important facts should be pointed out, the first is that relatively high load factors can be reached and the second is that elevator motion, initiated by the pilot to counter initial upwash of the vortex, compounded the hazard. Ultimate load factors were reached with elevator motion.

Load factors measured during flight tests are shown by the cross hatched areas in Figure 12. The load factors measured on a T-33 aircraft and a U-3A (Cessna 310) aircraft during penetration of wakes from

large aircraft, are of a preliminary nature. The large aircraft were not at maximum weights and the exact location of the penetrating aircraft relative to the center of the wake is not known. The point is that measured load factors are about what was expected. It appears probable that even higher load factors could be experienced when light aircraft encounter the wake of heavier laden large transport aircraft under more adverse conditions. The penetrating aircraft in each of these incidents was relatively close behind the heavier aircraft generating the wake--about 1.5 miles or about 30 seconds after passage.

The expected movement and persistence of vortices shed by large aircraft at altitudes above 1,000 feet were shown in Figure 10 to occupy parts of a certain volume of air aft and below the flight path, dependent upon the directions of the crosswind. This is important information for following-aircraft pilots to keep in mind. Yet it is still another matter to make use of the information in practical situations. Vortex trails as might be seen by the pilot of a light airplane is shown in the sketch of Figure 13. The large transport aircraft shown through the windshield are approximately 2 miles in the distance.

The one aircraft shown climbing up and away has left a vortex trail outlined by engine exhaust smoke. Since the vortex at this point of encounter is only about 30 seconds old, it would be wise to stay clear, preferably up wind, above or well below the smoke trail. Avoidance may be still more difficult in the future as engine smoke emission is eliminated.

The other vortex trail situation illustrated in Figure 13 is of a large transport aircraft crossing from right to left at about two miles distant. In this case, the vortex trail is not usually made visible by engine smoke, although condensation trails, at times, mark the vortices. The 1,000 ft. increment below the crossing point is shown. Aircraft in this situation should cross 1,000 feet or more below or above the flight path of the large aircraft. The importance of the light plane pilot "to read" the flight path of the heavier aircraft is apparent.

Some pilots have noticed an apparent rooster tail of exhaust smoke behind aircraft on the approach path. A question arose as to whether or not this indicated an initial upward movement of the trailing vortex system, quite the opposite to the initial downward movement shown in the sketch of Figure 4. Based on my observations the situation can be described as shown in Figure 14. The high speed exhaust plume initially trails aft, expanding somewhat, along the approach path. The high speed exhaust slows down rapidly and then comes under noticeable influence of the downwash field behind the aircraft, eventually becoming wrapped up in the trailing vortex system.

Vortex system movement near the ground is illustrated in Figure 15. In the sketch on the left a vortex system is shown to move downward and drift with the wind as discussed before. Obviously if the aircraft is closer than 1,000 feet above ground level, as shown in the sketch on the right, the vortex system comes in close proximity to the ground and is markedly influenced by this additional factor. In the sketch at the right, vortex movement is shown for the no wind case (solid lines). Here the vortices move downward until about a wing span distance from the ground, at which time they respond to the influence of the ground-plane and start to move outward, at a height of about a wing semispan above the ground.

In the wind case (dashed lines) the vortices are influenced by the ground plane as mentioned before and also move with the added velocity vector of the wind. Vortices in the vicinity of the ground are known to exist for periods of 2 or more minutes, under some situations, and become a source of concern to following aircraft and aircraft using other intersecting and parallel runways. The real hazards related to this condition are under investigation, making use of aircraft flybys and instrumented towers. It is expected that information obtained by the Federal Aviation Administration and the NASA will soon permit an analysis to be made of the factors contributing to the maximum movement and persistence of vortices in the runway area.

Despite the lack of knowledge of some details on vortex influence near the ground we do know enough to suggest a technique to avoid vortex encounters along the approach path. Light aircraft, using the instrument landing system (ILS) and visual approach slope indicator (VASI) (at airfields used by large heavy aircraft), should stay on the high side of the glide slope and to the up wind side as shown at the bottom of Figure 16. Smaller, slower aircraft are sometimes routed in airport traffic at a lower altitude and in tighter patterns than the larger faster aircraft (top of Figure 16). If the light plane pilot is faced with this situation while turning from the downwind leg to the base leg it is essential that he remain above the flight path of the larger aircraft if at all possible. Many of the vortex accidents seem to be caused when the light aircraft approaches the airport on final leg at a lower altitude than the preceding aircraft(2). In addition, should the large aircraft execute a missed approach, special precautions should be exercised by the following aircraft as can be surmised from previous discussions.

It was noted earlier (Figure 10) that vortices should be avoided in air space up to 10 nautical miles behind very large aircraft. Hence at least from the outer marker to the airport, as shown in Figure 16, the pilot should be particularly conscious of the vortex hazard--where altitude decreases from approximately 1500 feet to touch down and an upset would be unnerving to say the least. For similar reasons following aircraft should remain above the takeoff flight path and/or to the windward of large aircraft (8) to avoid vortex encounters.

The data gathered from vortex measurement programs underway are expected to be instrumental in the establishment of the probabilities of vortex travel and persistence under the varied conditions which might actually exist. To assist in this evaluation of the potential hazards it seems that a good bit of additional pertinent data could be provided by pilots of aircraft experiencing a vortex-caused incident. It is suggested that consideration be given to soliciting help from pilots, in a manner similar to the reporting procedure now used for near midair collisions, as illustrated in Figure 17. These data would represent actual situations and analysis might highlight the principal factors which contribute to known hazardous conditions.

### 3.2 Vortex Attenuation/Elimination

An exciting phase of the trailing vortex research was born when it became apparent that the vortex system of large transport aircraft could well have significant bearing on the design and optimum use of airfields. This placed a demand on the researchers to probe the very spawning ground of early vortex flow in the periphery in a manner not before accomplished, with the aim of possibly uncovering a triggering mechanism that could be exploited in the development of a practical way to eliminate the vortical flow at the wing and, even more important, far down stream. This detailed research is also expected to uncover candidate schemes to promote either early break up of the vortex system or alternation of the flow to eliminate unfavorable characteristics of concern to following aircraft. Either of these solutions would be an acceptable means to remove all of the elements of the trailing vortex problem; the hazards, the economic penalties, and the passenger discomfort.

Those concerned with the research have considered several different basic ideas that might warrant further study. Figure 18 lists these ideas. Closely related to any successes in the wind tunnel or water channel will be the flight test phase both to verify the model tests and evaluate the scheme as a practical way to solve the problem.

Some work has been done on the effect of an engine located at the wing tip (13) and further tunnel work is planned to investigate the use of an engine with rotational jet exhaust flow counter to the normal vortex flow expected at the wing tip. The effect of a hot jet flow on vortex intensity and persistence may also be documented.

Different wing tip shapes to alter the vortex flow have already been looked at especially as they relate to the helicopter blade tip vortex as a noise source, but new tip alterations still appear attractive and will be tested in the wind tunnel. Tip modification, if successful, would suggest the possibility of an economic retrofit for the current fleet of large aircraft.

Detailed measurements of velocity distributions are being made of the vortical flow generated at the tip of a rectangular wing (14). Future analysis and understanding of the vortex flow and structure are expected to provide baseline information from which we can extract ideas to stimulate possible attenuation/elimination experiments.

Other wind tunnel developmental work (15) showed that a small vertical panel (see Figure 19) mounted on the wing upper surface near the tip significantly reduced the vortex tangential velocities. Subsequent flight tests with the panel mounted on one wing of the NASA CV-990 indicated that less dramatic changes were made in the vortex system 1.5 to 5.0 miles down stream. It is difficult to determine the true merits of the panel at this time although some benefits were realized by the penetrating aircraft (Lear Jet) in the form of less roll acceleration and less roll control needed to counter the vortex induced roll. Some lift and drag penalties were also apparent from the model studies.

One question is often raised in regard to the vortex problem with respect to new type aircraft being considered for future use as the STOL vehicles and the supersonic transports. NASA scientists working in the areas of new experimental aircraft development are aware of the trailing vortex problem and hopefully will consider this aspect to the extent possible in the development of the vehicle and in plans for its operation in the air traffic system. Examples of new aircraft types are shown in Figures 20, 21 and 22. The very fact that these aircraft have unusual features, compared to aircraft in current use, raise questions concerning the possible unusual aspects that might show up in vortex intensity and persistence.

Results from this program are eagerly awaited. Benefits might also be realized in more efficient wing and helicopter blade design by improving flow in the tip region.

### 3.3 Measurement Techniques

Various trailing vortex measurement techniques for use in the wind tunnel, during flight test at high altitudes and near the ground, and to monitor the airport vicinity are listed in Figure 23.

There will be no attempt to describe in detail most of the techniques listed because their physical principles involved are well known. Some information on use of the hot wire anemometer is given in ref (14). Development of the laser Doppler velocimeter for use in the wind tunnel is described in ref (16, 17 & 18). Flow visualization techniques in the wind tunnel include use of tuft grids (15) and smoke (19).

In flight tests far from the ground several aircraft are used, depending upon the type measurements made. In the tests carried out by the Flight Research Center (11, 12) the probe aircraft generally carried instruments to record airspeed, altitude, normal acceleration, longitudinal acceleration, transverse acceleration, pitch velocity, roll velocity, yaw velocity, bank angle, angle of attack, angle of sideslip, lateral-control wheel positions, and aileron positions. A Langley Research Center probe aircraft carries instruments that record data which permits computation of the three velocity components. This information is very useful and gives a precise picture of vortex characteristics and enables a determination to be made of the possible effects of the vortical winds on other probe aircraft.

Flight tests near the ground make use of instrumented towers with bi-vane anemometers, and smoke visualization with photographic coverage. This is an acceptable way to study many of the vortex system characteristics near the ground. One drawback of the instrumented tower is the effect it has both on the atmospheric flow field and, often times, the dramatic reaction of the vortex trails when passing the tower. Then too, the stationary nature of the tower, and often its height limitation and spacing of sensors, encourages efforts to develop and improve the system. If data are needed on vortex life, the array of towers down wind of the tower nearest the airplane raises serious questions as to the validity of the data.

These factors that limit, somewhat, the use of the tower as an instrument platform prompted us to explore and develop means to remotely sense the vortex winds, without having the sensor and instrument tower disturb the flow. The feasibility of using a laser Doppler velocimeter to perform these measurements has been demonstrated (20) with a one-dimensional unit, supported by other efforts reported in references 21-26.

A test facility, subsequently used to assess the characteristics of the laser system, is shown in Figure 24 and a comparison of wind measurements using a cup anemometer and a laser Doppler velocimeter is shown in Figure 25. The instrument makes use of a 20 watt carbon dioxide laser to send a focused beam to a selected point in the atmosphere. The particulate matter in the sensitive volume back scatters some of the laser light. A frequency analyzer determines the Doppler shift in light frequency caused by the velocity of the particulate matter, which is a measure of the wind velocity component along the laser beam within the sensitive volume.

A conceptual design study is underway to consider applications of the laser Doppler velocimeter to low altitude vortex research as illustrated in Figure 26. The instrument would have the ability to search a known plane, which the test aircraft would have penetrated, and measure the three components of wind velocity from the Doppler shift

recorded in each of the three field units. For more refined and detailed measurements, the measurement grid could be reduced and allowed to follow the vortex drift. Breadboard instruments will be used within the next few months to develop techniques useful for the low-altitude vortex research measurement system. This system is expected to have possible applications as an airport trailing vortex warning system as depicted in Figure 27. A design study is underway to define the system specifications to meet the airport applications. Should this system concept be used at airports, the measured vortex data intensity and location would appear to be readily adaptable for the development of airport system avoidance procedures. This system might be particularly useful if elimination of the trailing vortices is not achieved by practical means.

A parallel effort is being made using an argon laser of from 5 to 100 watts. This instrument is planned for use only as a diagnostic tool for research work. An argon laser is hazardous and its use will be carefully controlled. Argon has a wave length of  $\frac{1}{2}$  micron (versus 10.6 microns for carbon dioxide) and very fine scale measurements of vortex velocity fields will be made. An ability to remotely measure atmospheric winds will have other applications, as measuring vertical wind profiles and low level wind shears, and justifies a strong developmental effort.

#### 4. CONCLUSIONS

NASA has a comprehensive effort underway including flight tests, wind tunnel tests, and instrument development to achieve a better understanding of aircraft trailing vortex formation and persistence behind large transport aircraft and concurrently, other studies will evaluate several different concepts on ways to either prevent the trailing vortices from forming or induce early dissipation of dangerous velocities.

Recent flight tests have provided valuable information needed to establish adequate spacing behind large aircraft to prevent hazardous situations from occurring. Additional tests are scheduled to measure the velocity distributions in wakes at various distances down stream of large aircraft, both near the ground and at the cruise/holding pattern altitudes.

Recent research results give hope that the operational hazards and economic penalties related to trailing vortices might be reduced or eliminated in the future by aerodynamic design. In addition, techniques to locate and measure the trailing vortex velocities for use in research programs and for use as an airport monitor are under development.

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G. E. Krier  
G. H. Robinson

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R. P. Bielat  
J. P. Campbell  
D. R. Croom  
R. E. Dunham, Jr.  
R. E. Kuhn  
L. E. Mauldin, III  
W. C. Sleeman, Jr.  
R. T. Whitcomb  
J. A. Zalovcik

### Marshall Space Flight Center

W. K. Dahm  
R. M. Huffaker  
I. P. Jones  
E. A. Weaver

### NASA Headquarters

M. T. Charak  
R. J. Wasicko

IN-FLIGHT HAZARDS OF TRAILING VORTICES  
TO ENCOUNTERING AIRCRAFT

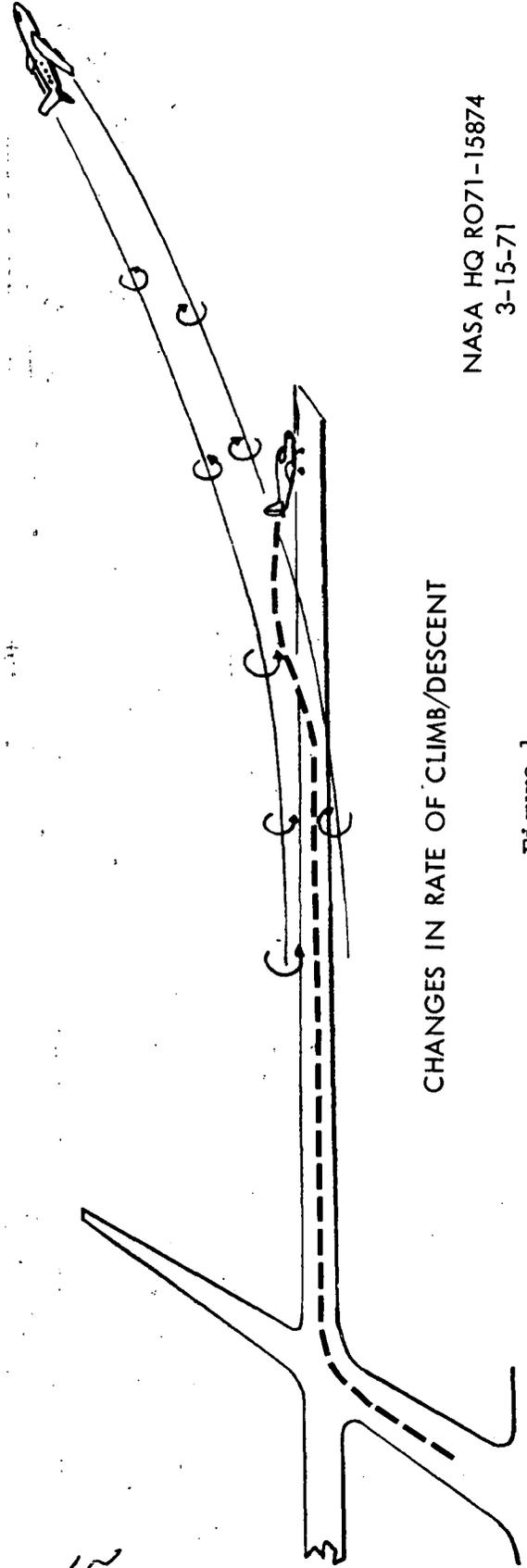
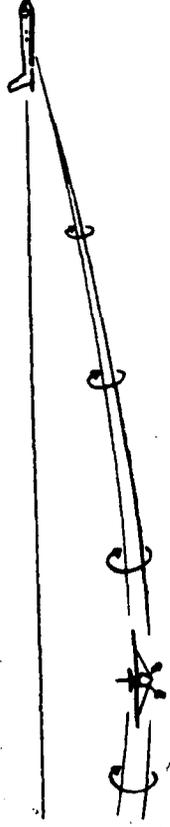
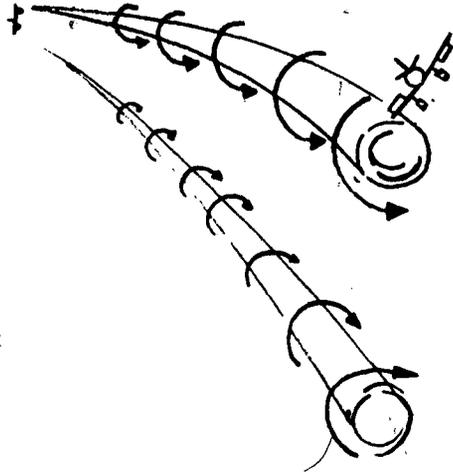
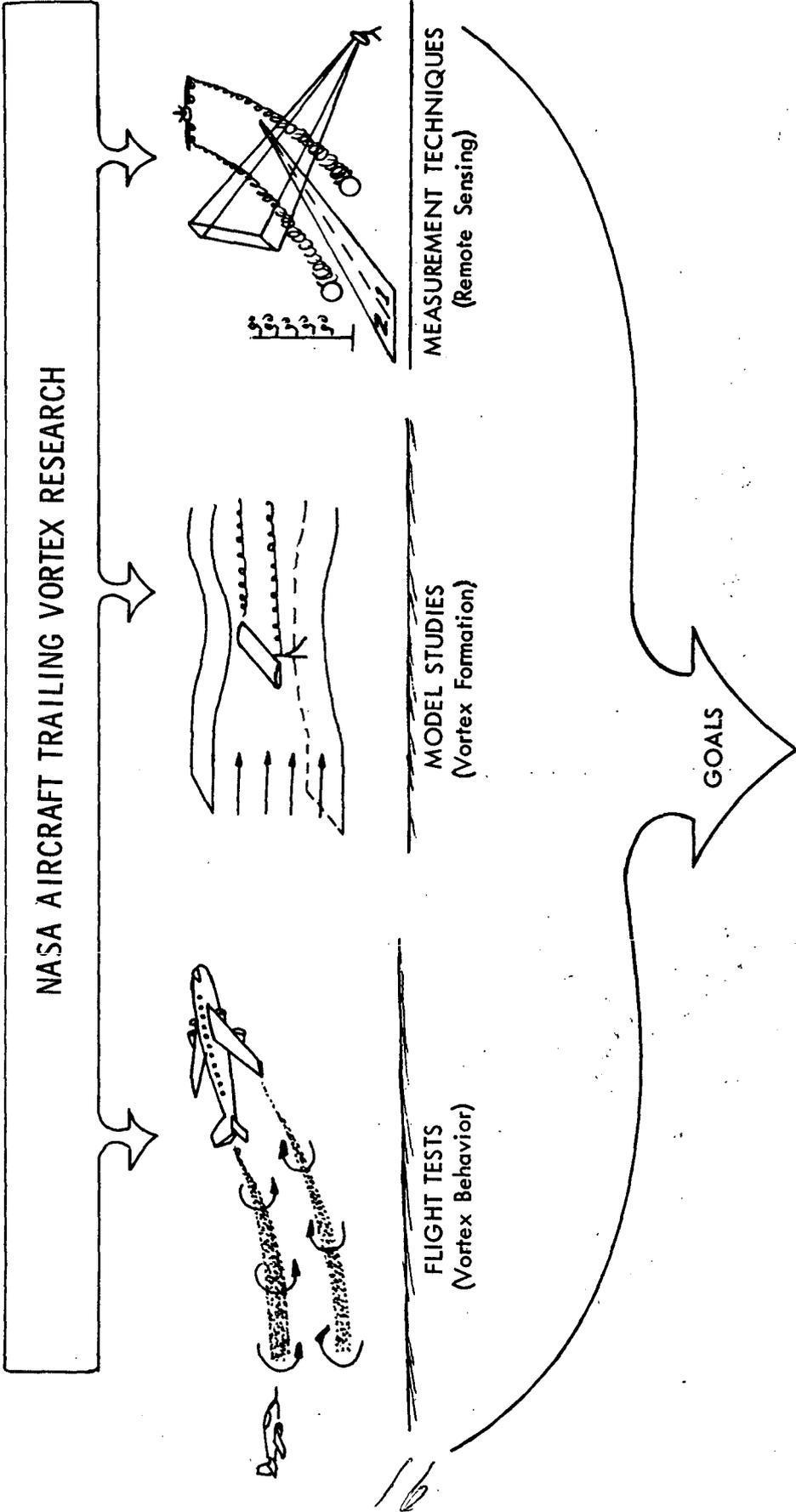


Figure 1

NASA HQ RO71-15874  
3-15-71



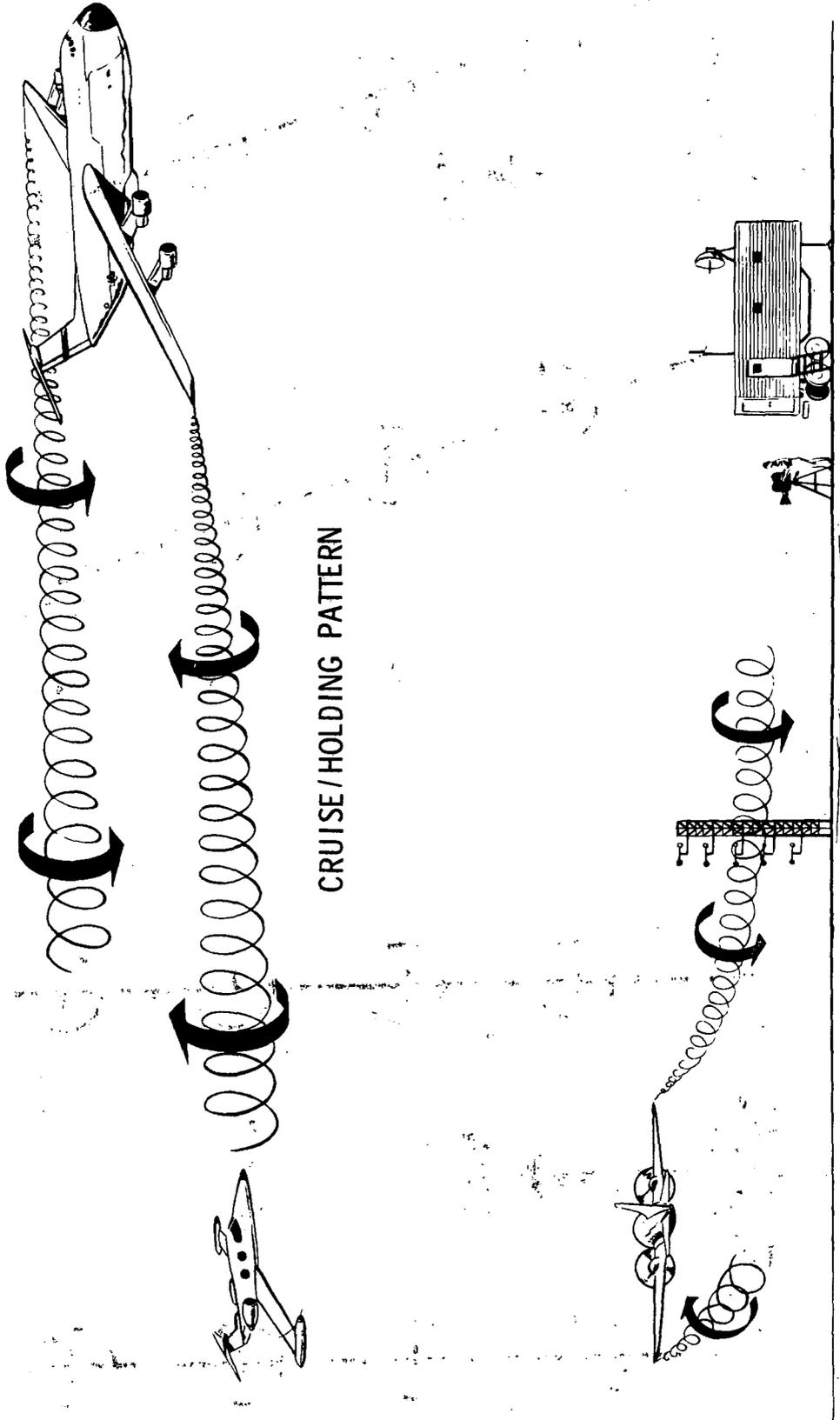
ELIMINATION OF HAZARD POTENTIAL

NEAR TERM  
SYSTEM AVOIDANCE PROCEDURES

FINAL

Figure 2

# AIRCRAFT TRAILING VORTEX RESEARCH



AIRPORT AREA

NASA RO71-3515  
2-22-71

Figure 3

# VORTEX-SYSTEM MOVEMENT

(NO GROUND EFFECT)

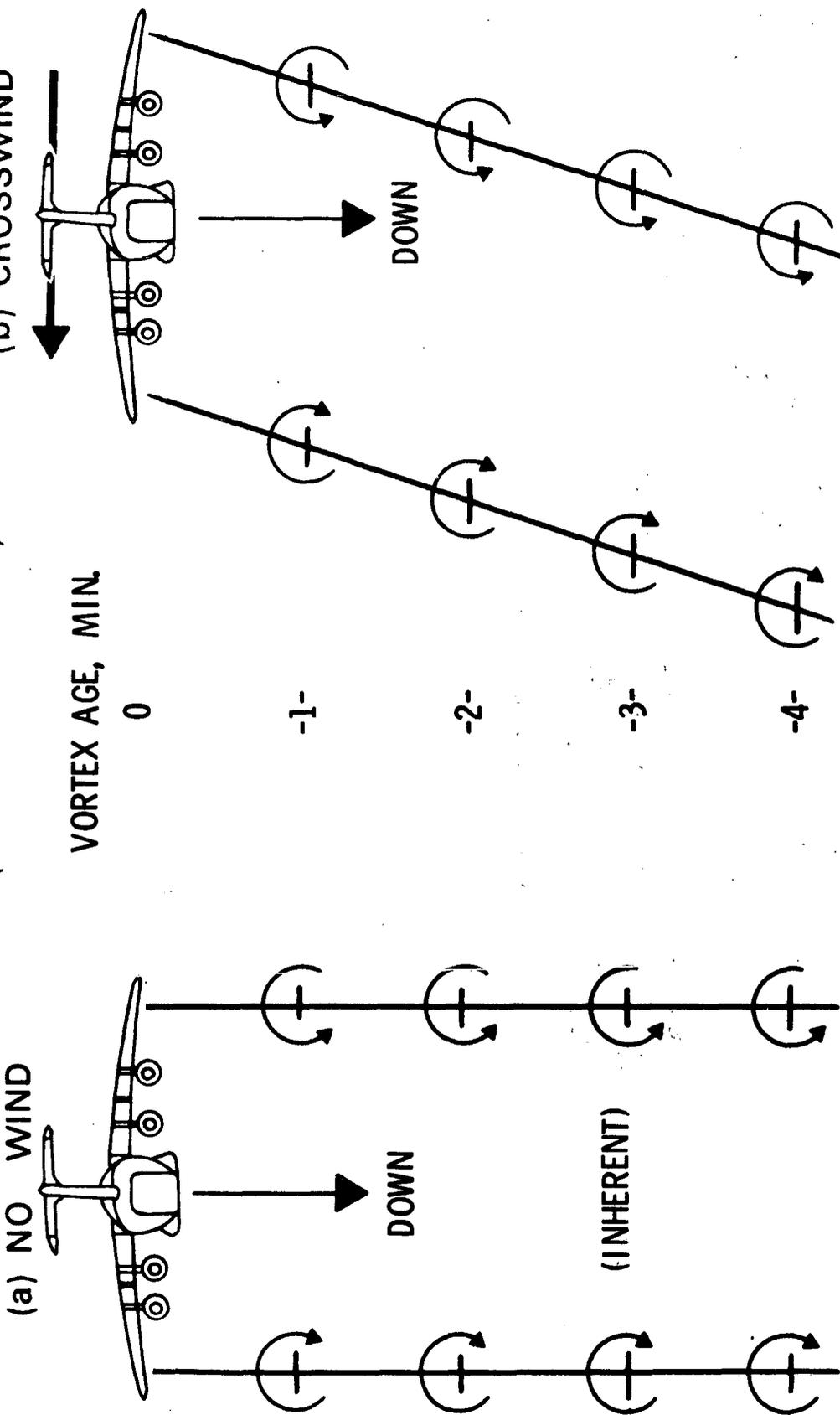


Figure 4

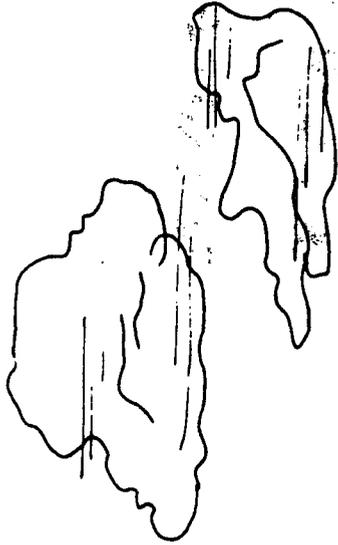
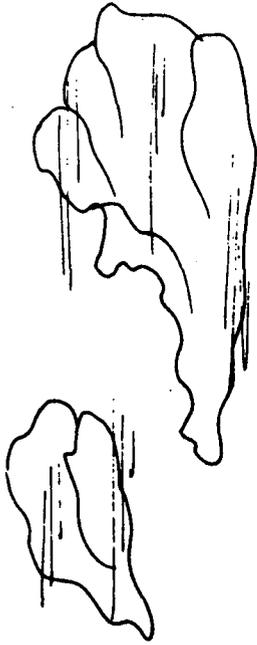
NASA HQ RA68-15857  
Rev. 9-22-70

# ELEMENTS INFLUENCING VORTEX SYSTEM INTENSITY, MOVEMENT AND PERSISTENCE

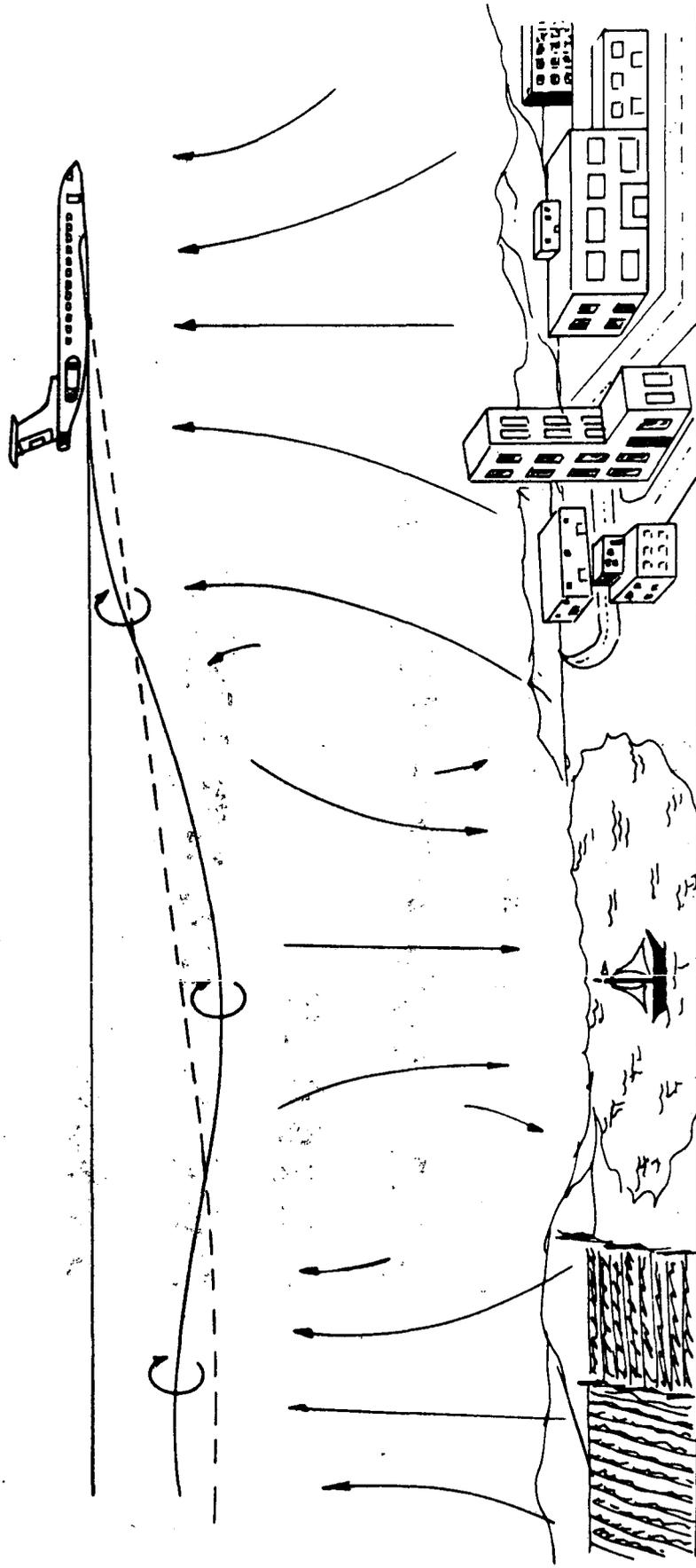
- AIRCRAFT TYPE, WEIGHT, CONFIGURATION, SPEED
- CHANGE OF FLIGHT PATH, MANEUVERS
- AIR DENSITY
- WIND INTENSITY, FLOW DIRECTION
- TURBULENCE
- PRECIPITATION
- GROUND PROXIMITY

19

# THERMAL EFFECTS ON VERTICAL POSITION OF VORTEX WAKE



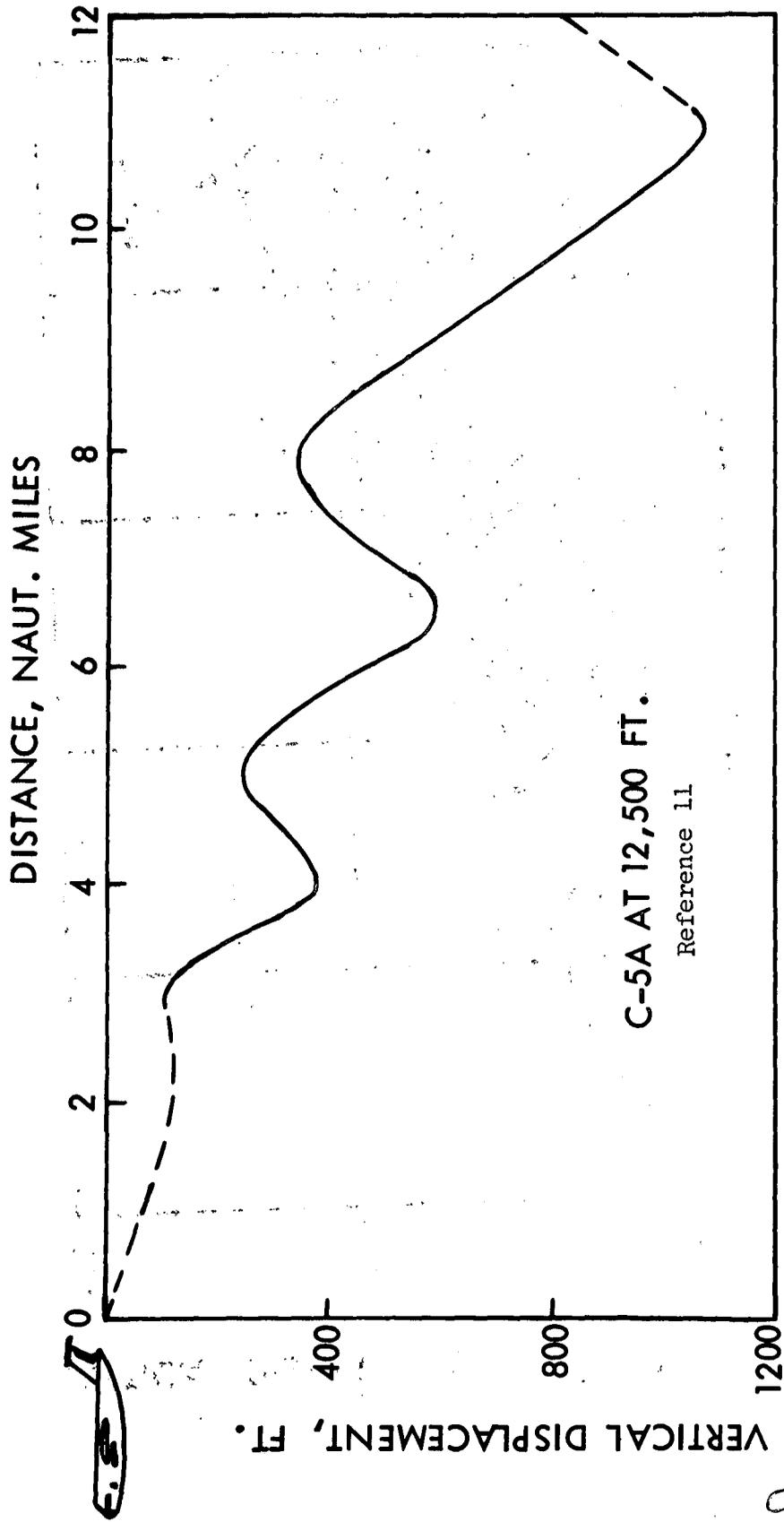
20



NASA HQ RA71-15211  
9-22-70

Figure 6

# TYPICAL VORTEX WAKE LOCATION AFT OF THE C-5A



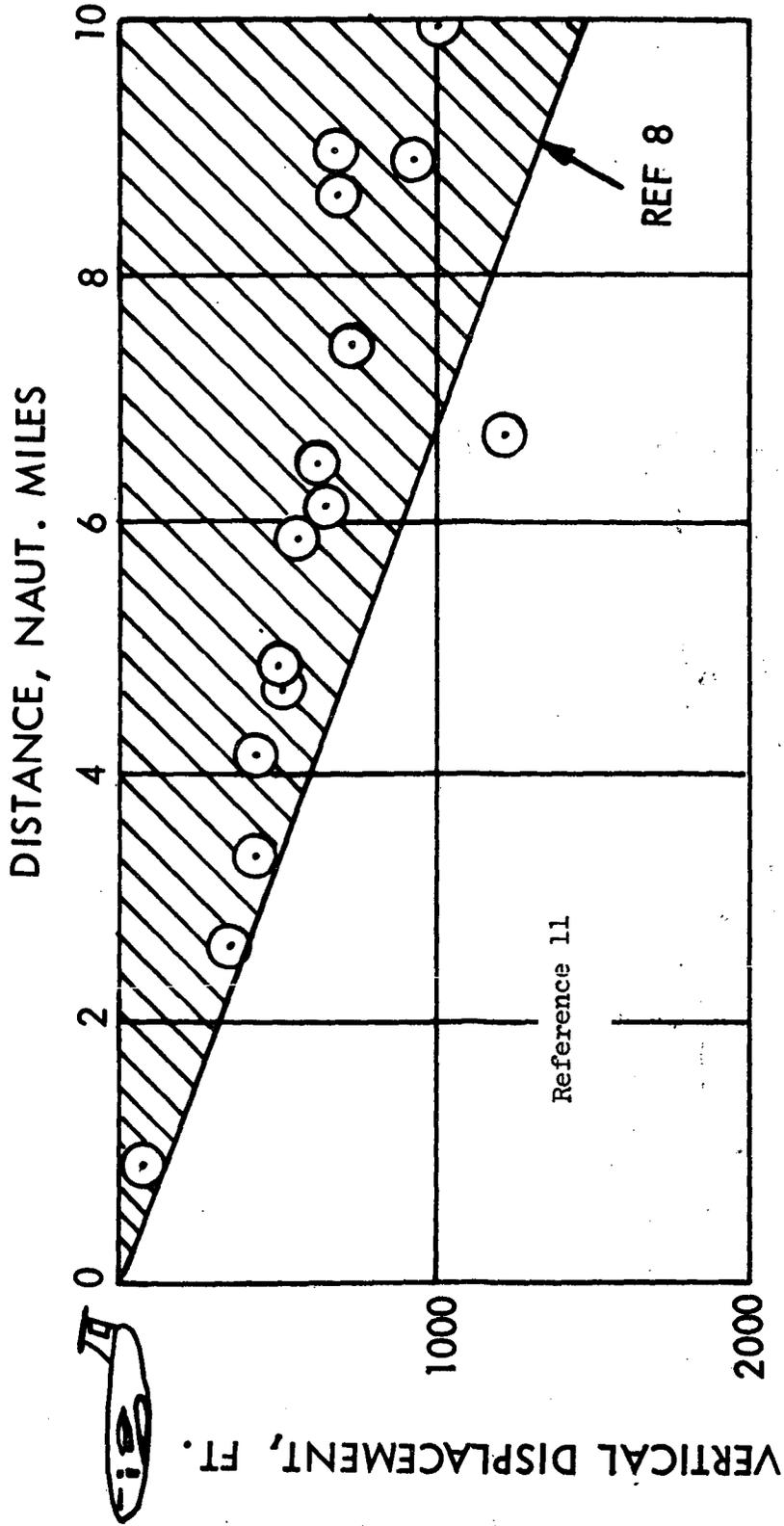
NASA HQ RA71-15206  
9-22-70

Figure 7

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# VERTICAL LOCATION OF VORTEX WAKE AFT OF THE C-5A

22



NASA HQ RA71-15205  
9-22-70

Figure 8

# MAXIMUM ROLL RESPONSE OF TEST AIRCRAFT IN THE C-5A WAKE

——— DC-9  
 - - - CESSNA 210  
 - - - LEAR JET

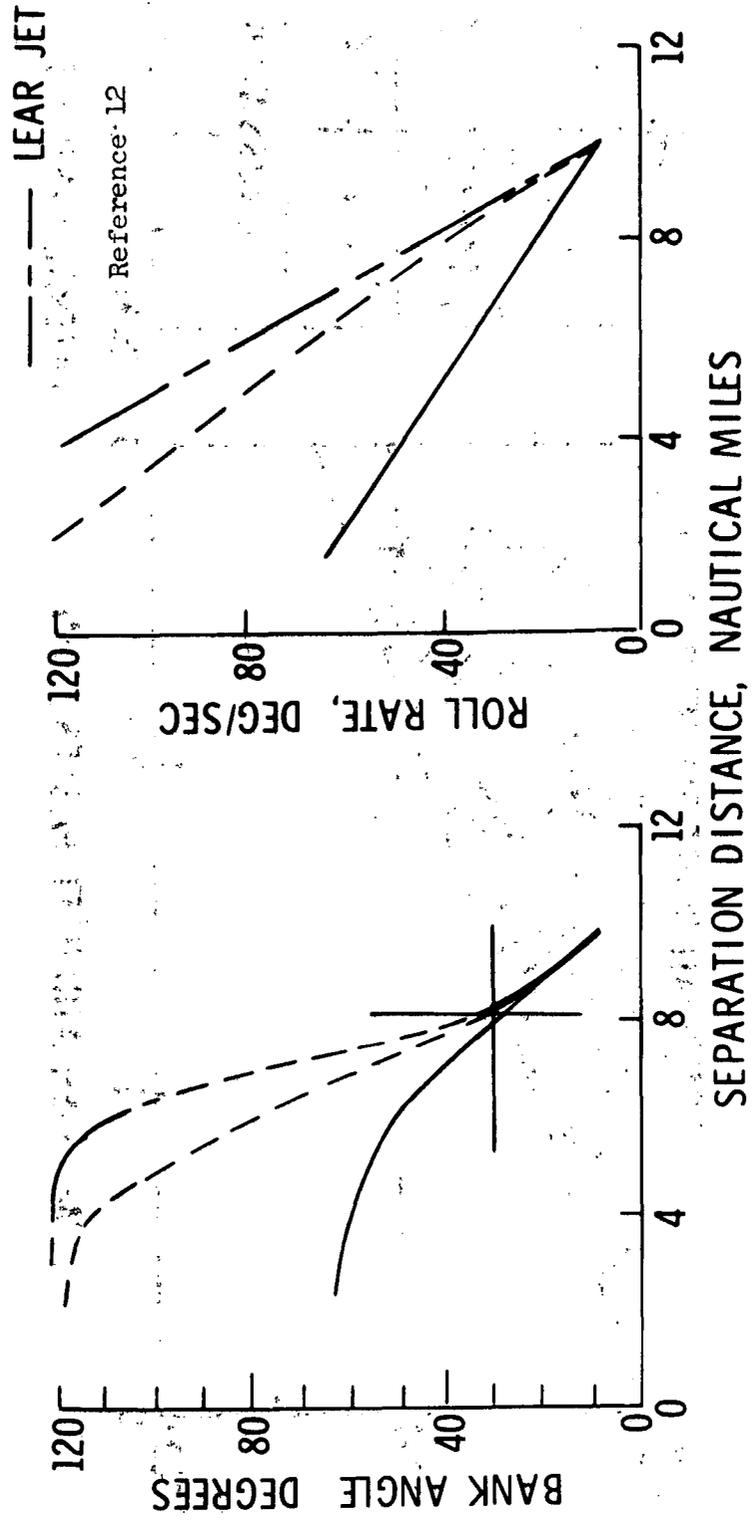
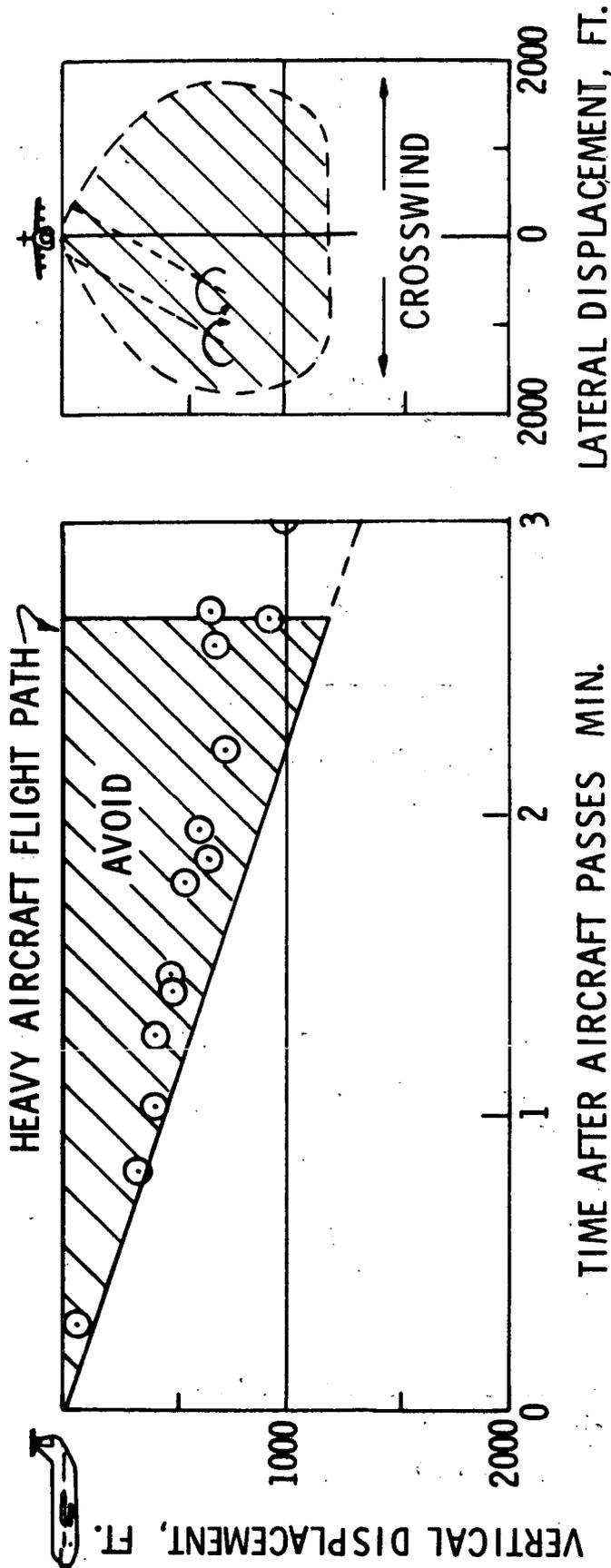


Figure 9

23

# SUGGESTED ENVELOPE OF VORTEX VERTICAL LOCATION FOR OPERATIONAL USE

(No Ground Effect)



UP TO 10 NAUTICAL MILES

Figure 10

24

# LOAD FACTORS ON AIRPLANE TRAVERSING

## TRAILING VORTICES

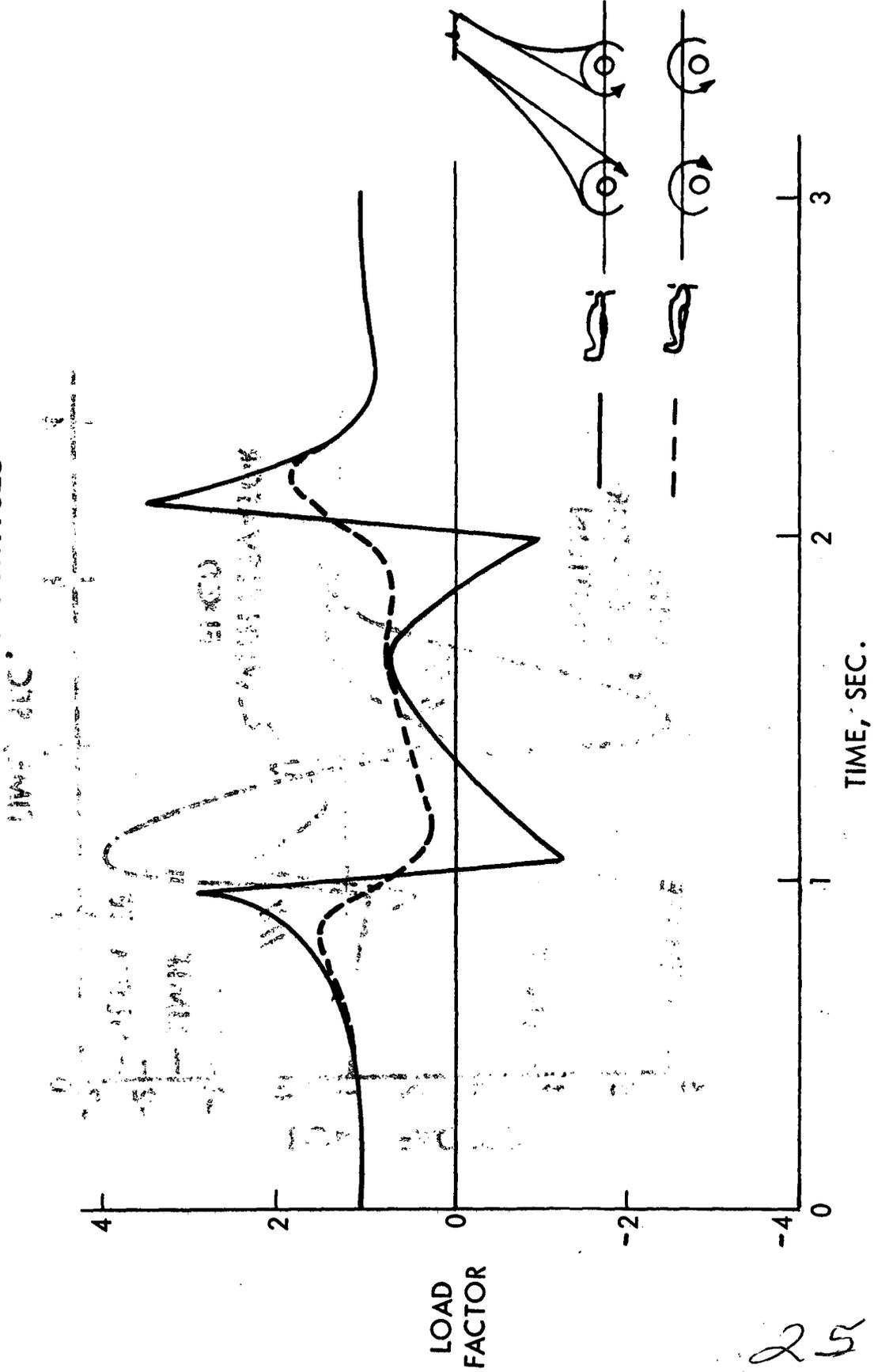
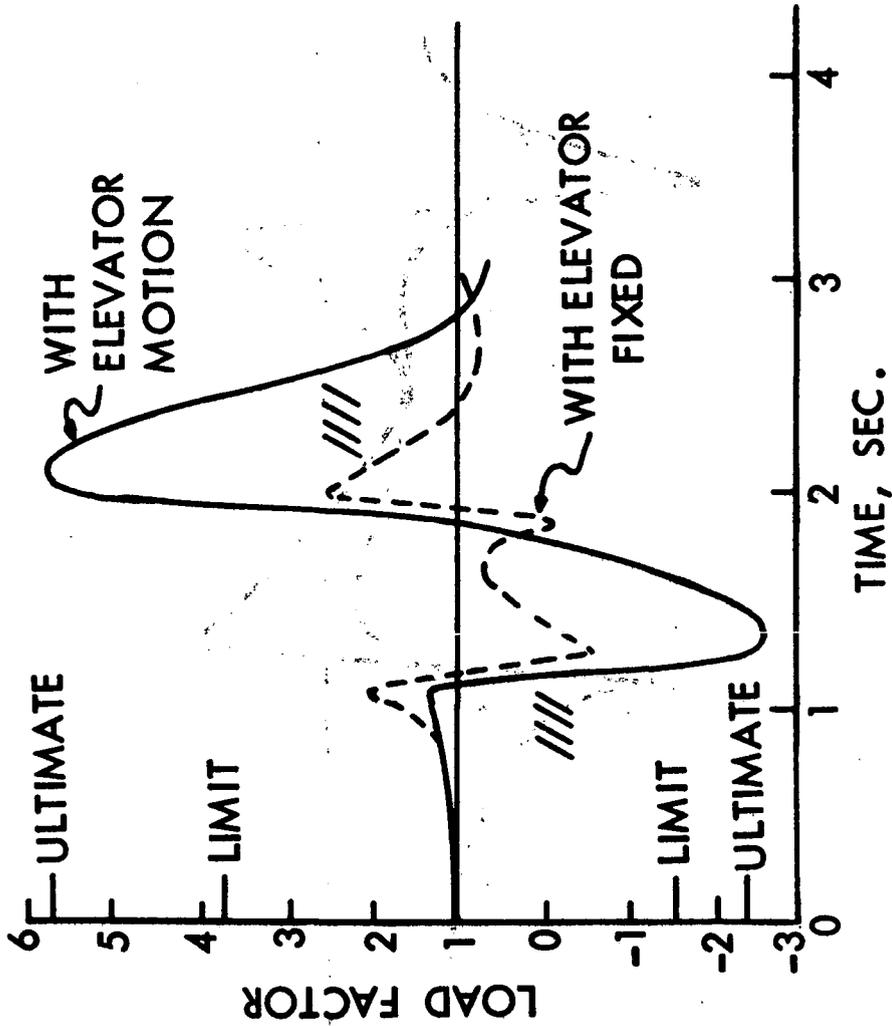


Figure 11

25

# VERTICAL LOADS IMPOSED ON LIGHT AIRCRAFT CROSSING THE WAKE OF HEAVY TRANSPORT



NASA HQ RA71-15204

9-22-70

Figure 12

# COCKPIT VIEW OF VORTEX TRAILS

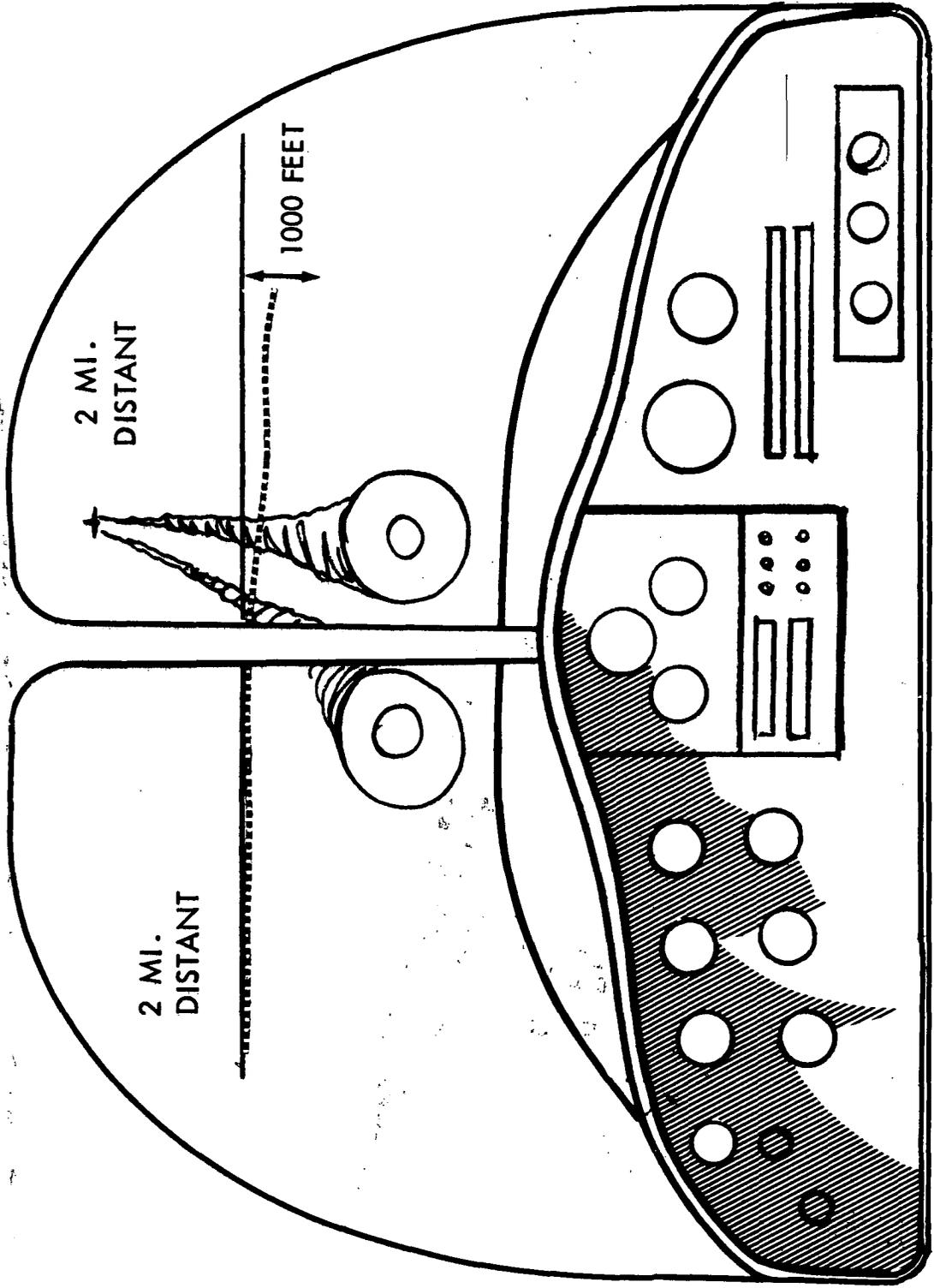


Figure 13

NASA HQ R071-15873

3-15-71

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EXHAUST PLUME ON APPROACH PATH  
(Apparent Rooster Tail)

28

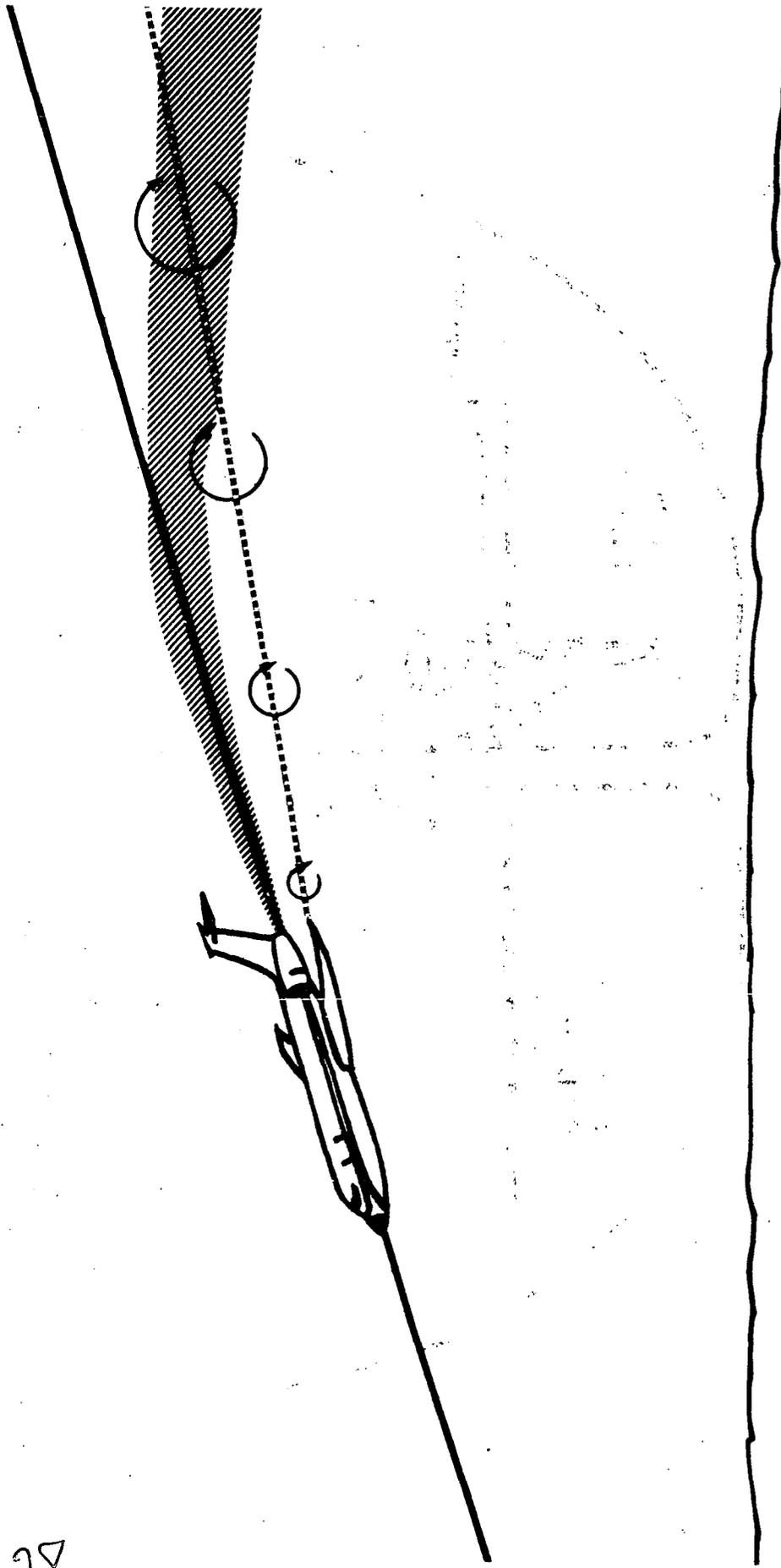
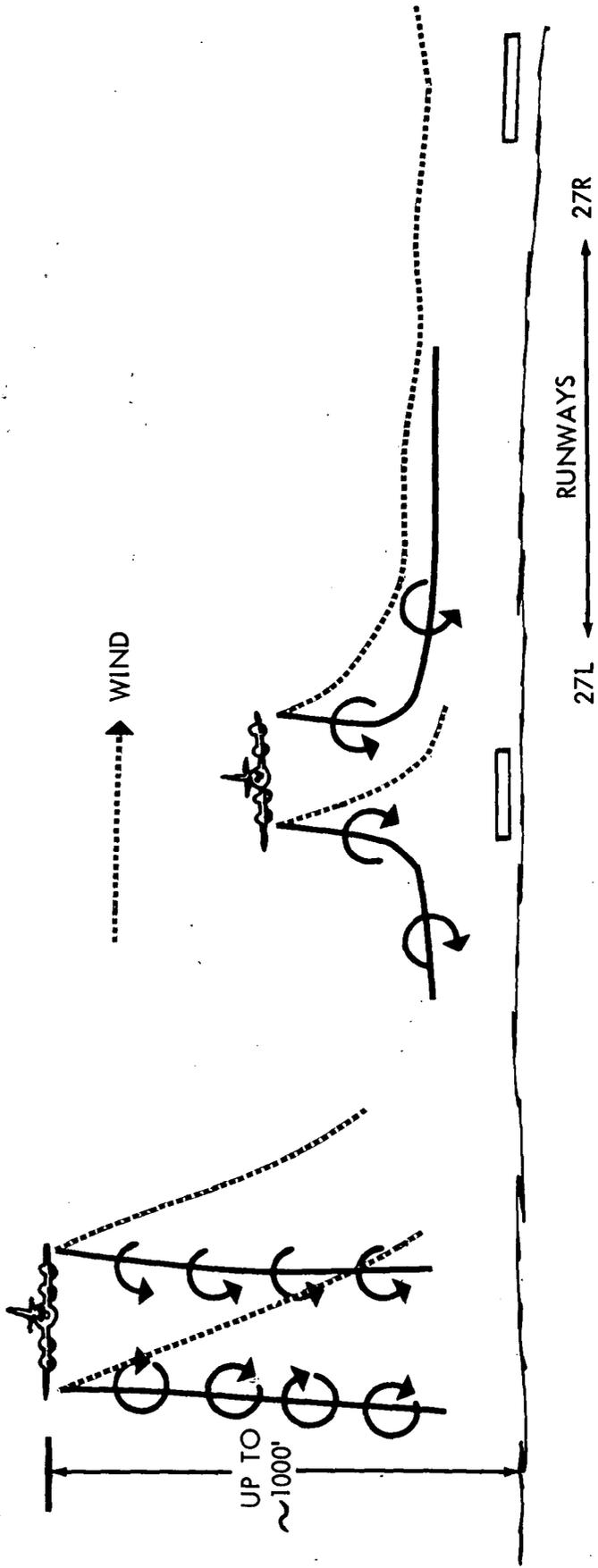


Figure 14

NASA HQ RO71-15870  
3-15-71

VORTEX-SYSTEM MOVEMENT NEAR THE GROUND

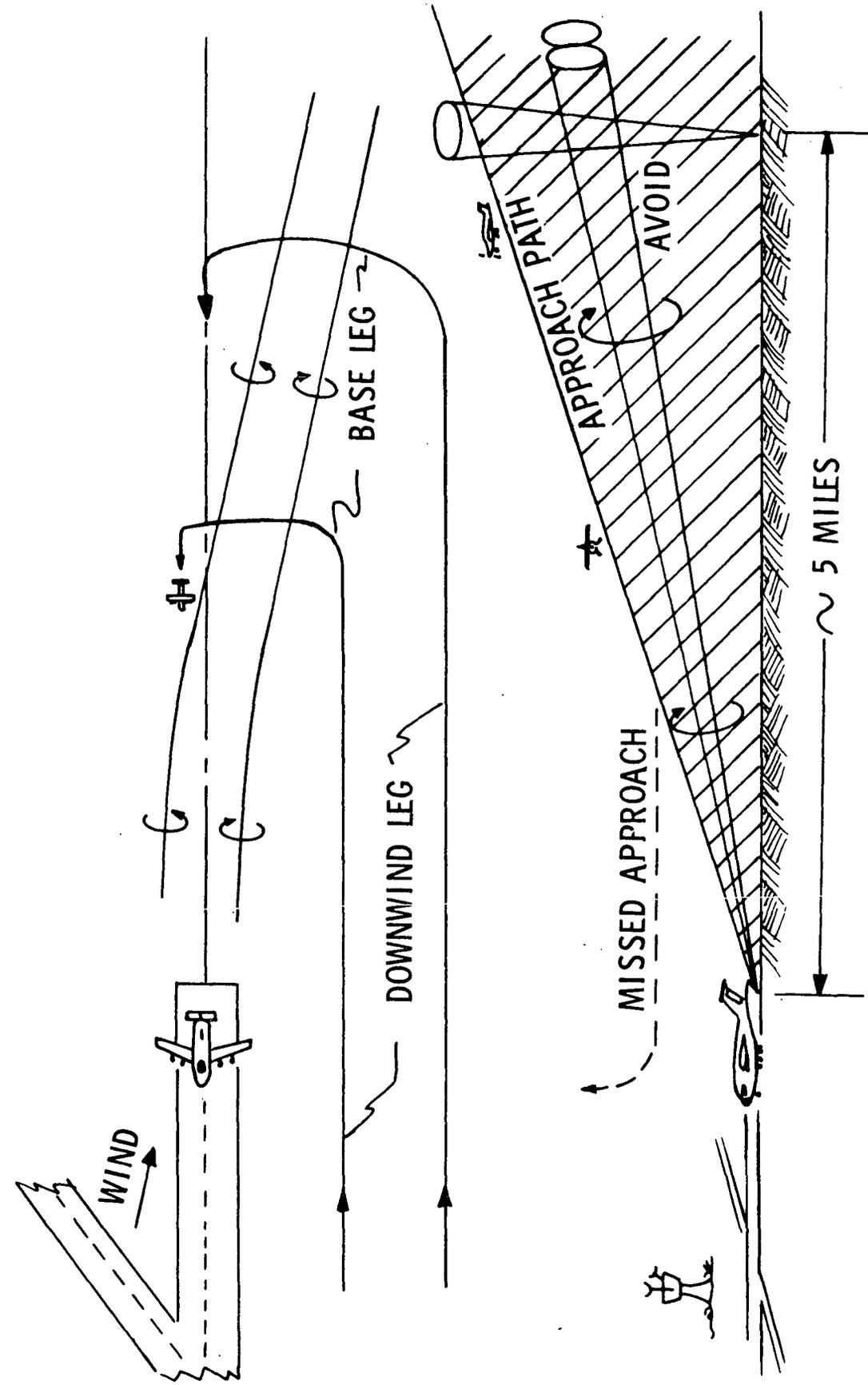
— NO WIND  
- - - WIND



NASA HQ R071-15878  
3-15-71

Figure 15

# VORTEX AVOIDANCE ALONG APPROACH PATH



30

Figure 16

## PILOT REPORTS OF

### WAKE TURBULENCE INCIDENTS

- (1) TIME OF INCIDENT
- (2) LOCATION AND ALTITUDE
- (3) REPORTING AIRCRAFT'S TYPE
- (4) OTHER AIRCRAFTS TYPE
- (5) WEATHER CONDITIONS
- (6) APPROXIMATE COURSES OF BOTH AIRCRAFT
- (7) SEPARATION DISTANCE AT TIME OF INCIDENT
- (8) AIRCRAFT REACTION

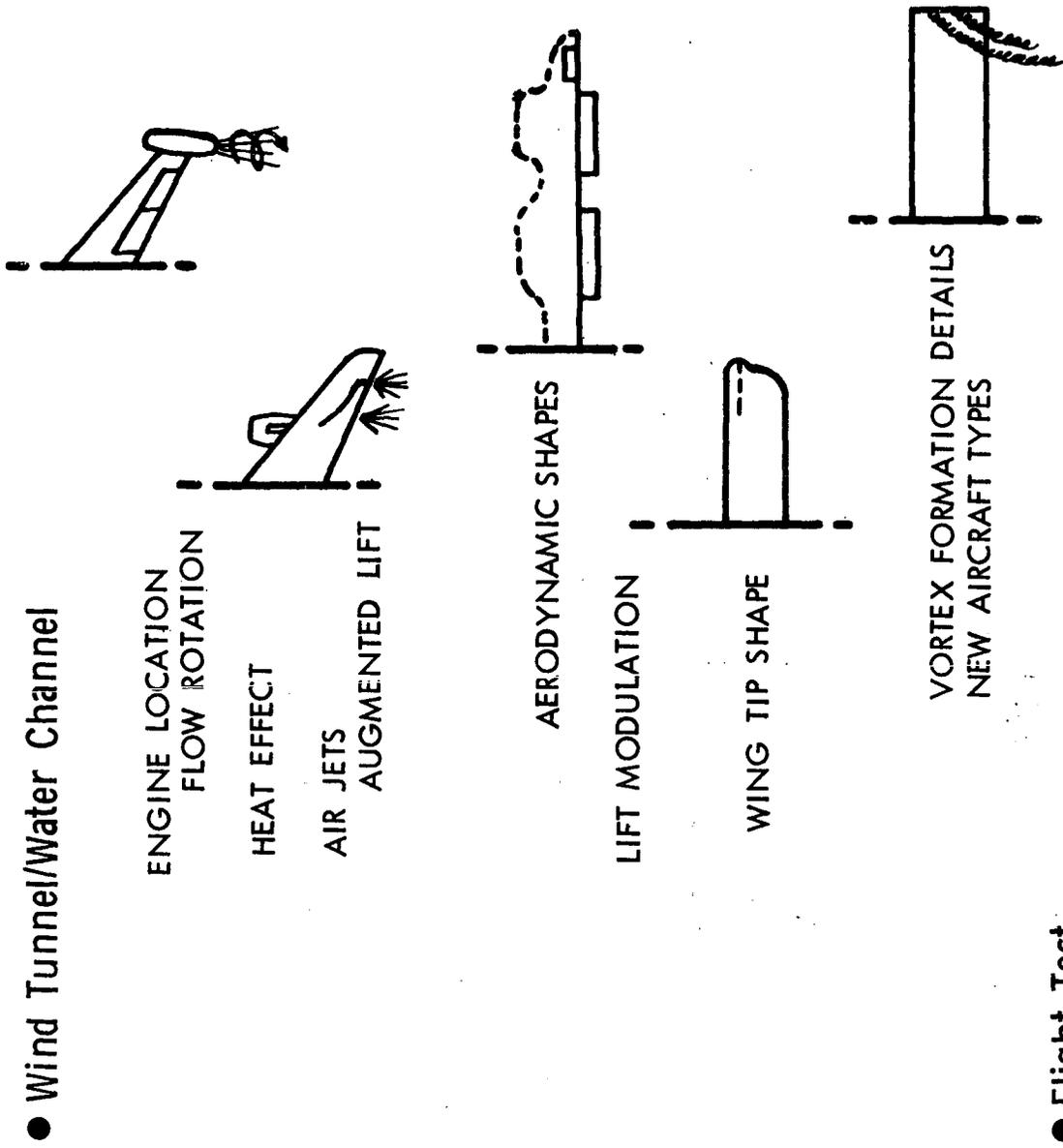
(Similar to Reporting Procedure for Near Midair Collision)  
AIRMAN'S INFORMATION MANUAL

Figure 17

NASA HQ RO71-15869  
3-15-71

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# VORTEX REDUCTION/ELIMINATION RESEARCH

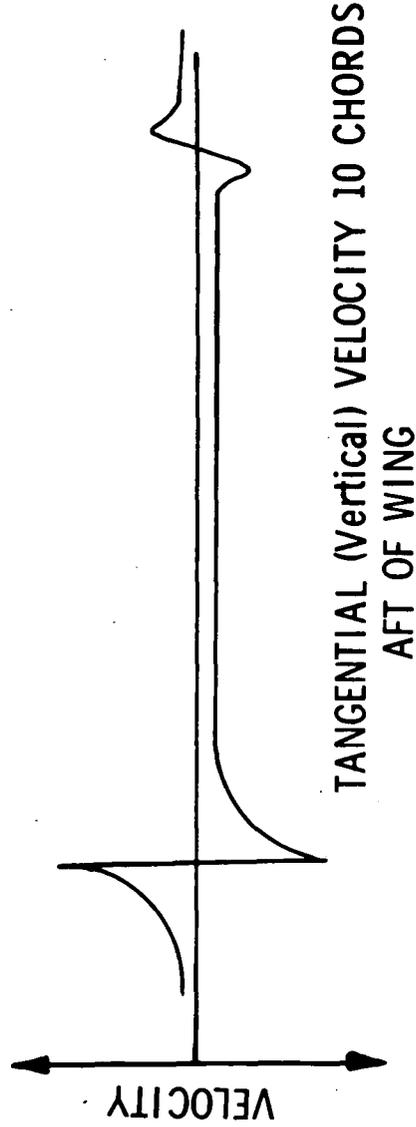
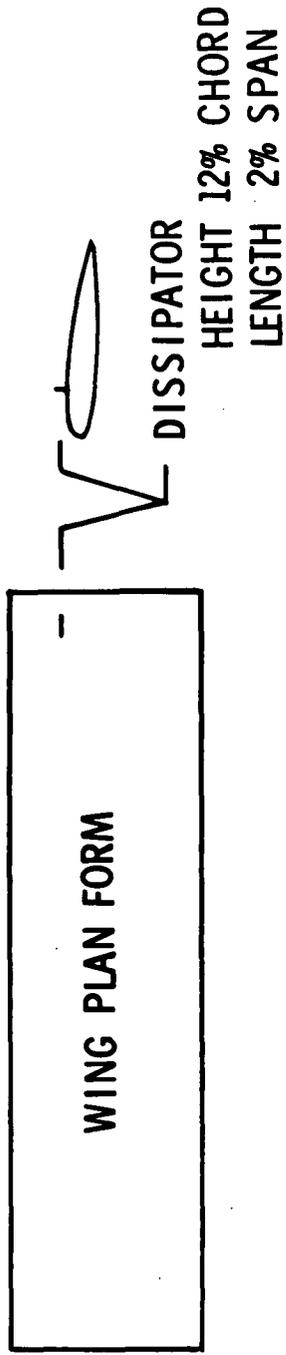


- Flight Test
- VERIFICATION
- EVALUATION

Figure 18

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# VORTEX DISSIPATION RESEARCH (Wind Tunnel Measurements)



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Figure 19

# AUGMENTOR WING CONCEPT

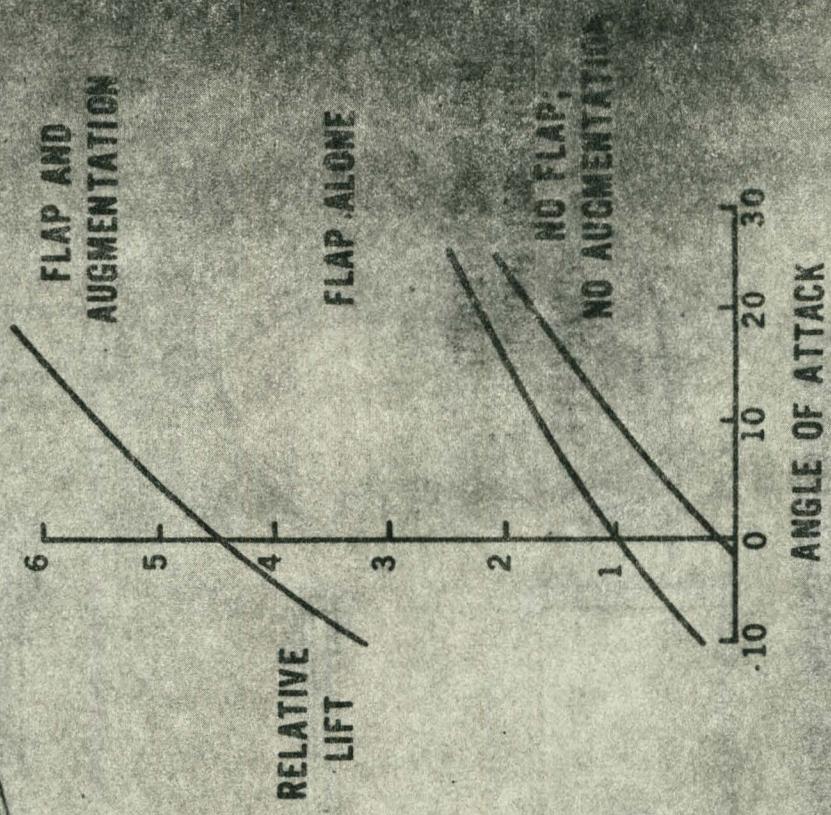
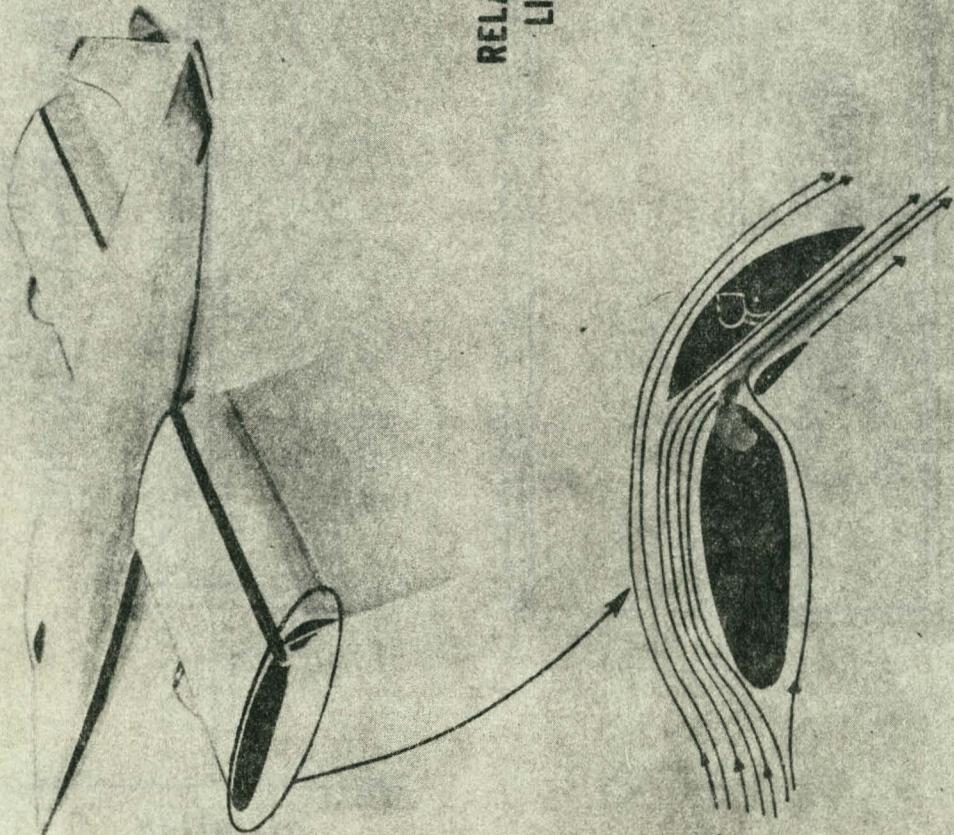
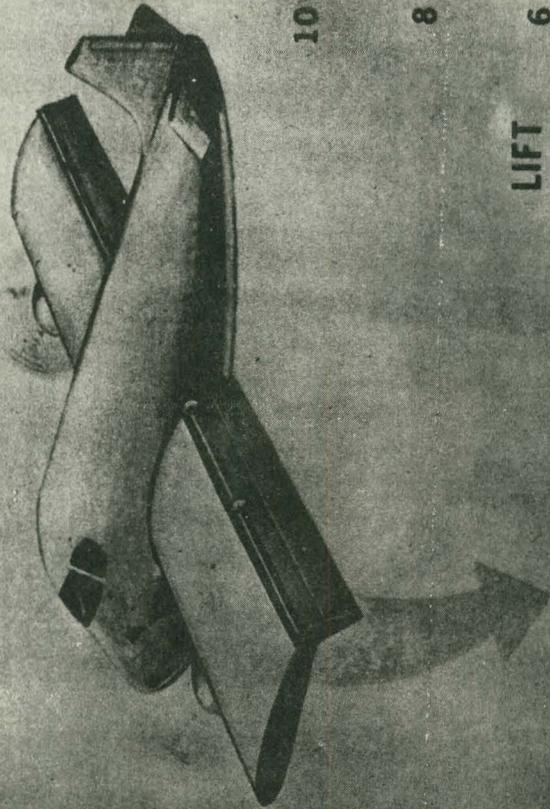


Figure 20

34

# ROTATING CYLINDER FLAP



FLAP DEFLECTION =  $60^\circ$   
 AIRSPEED = 45 MILES PER HOUR

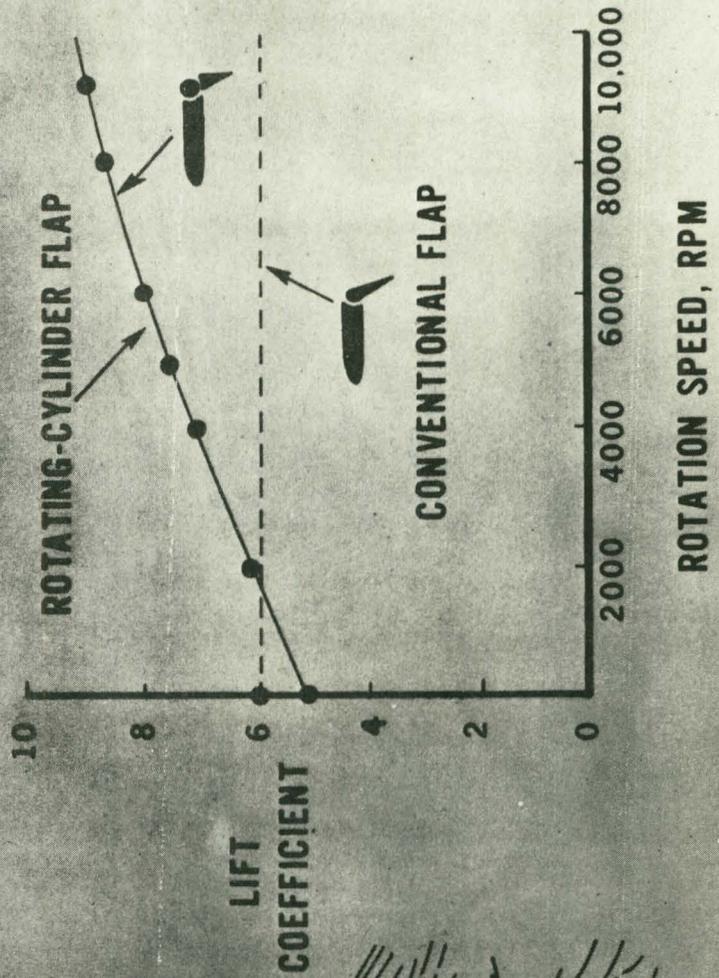
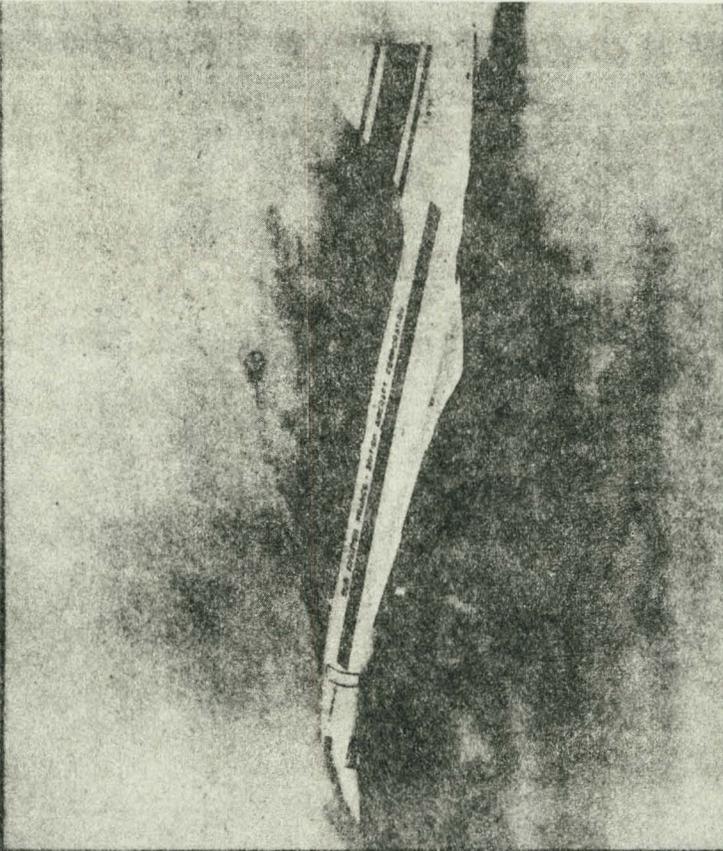


Figure 21

35

CONCORDE SST



BOEING SST

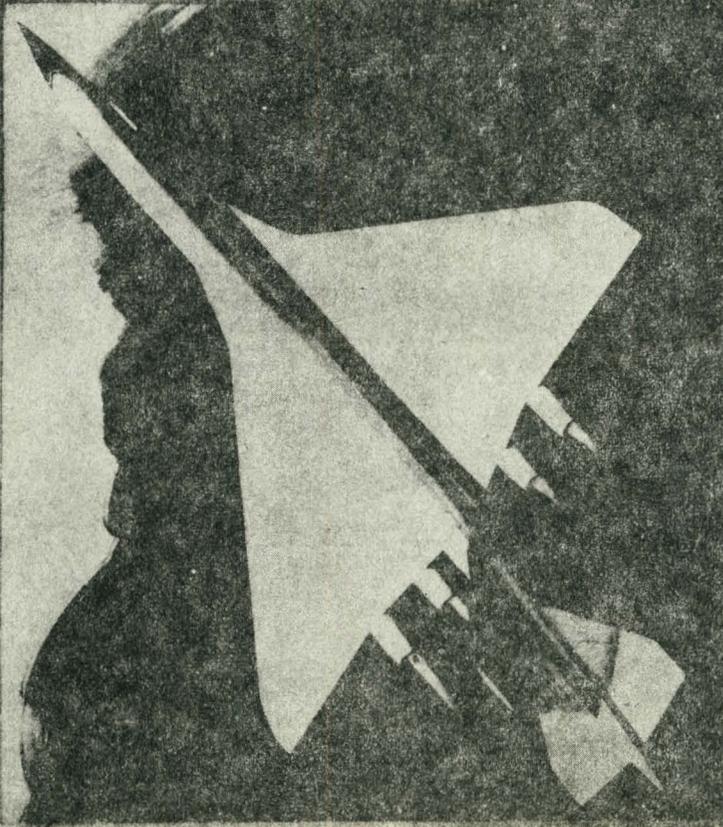


Figure 22

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# VORTICAL WIND MEASUREMENT

## TECHNIQUES

- Wind Tunnel

HOT WIRE ANEMOMETER  
FLOW VISUALIZATION  
PRESSURE TRANSDUCERS  
LASER DOPPLER VELOCIMETER

- Flight Test

FAR FROM THE GROUND  
INSTRUMENTED AIRCRAFT

NEAR THE GROUND  
INSTRUMENTED TOWERS  
FLOW VISUALIZATION  
LASER DOPPLER VELOCIMETER

- Airport Monitor

LASER DOPPLER VELOCIMETER

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Figure 23

LASER DOPPLER VELOCIMETER TEST FACILITY

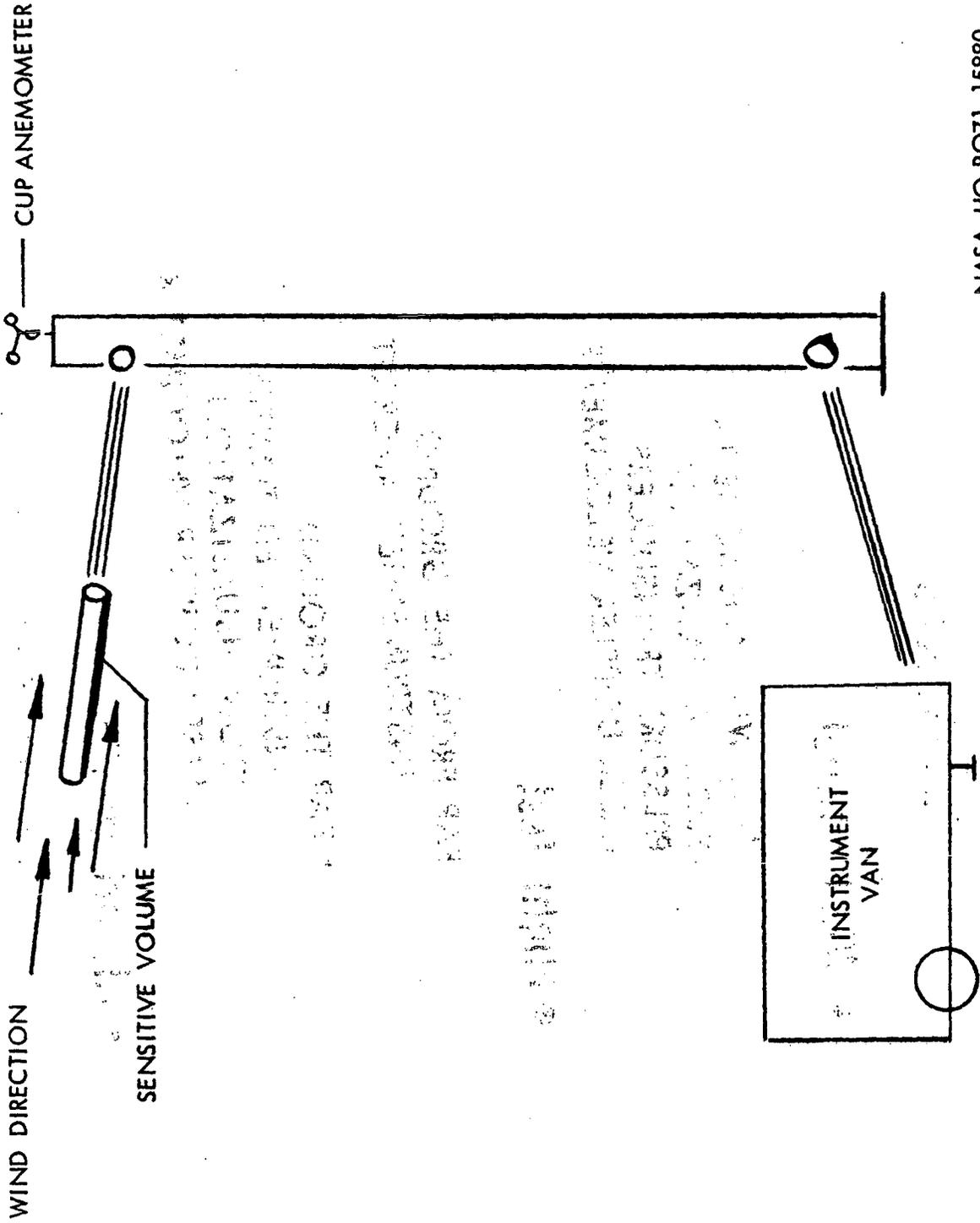


Figure 24

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3-15-71

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# COMPARISON OF WIND MEASUREMENTS

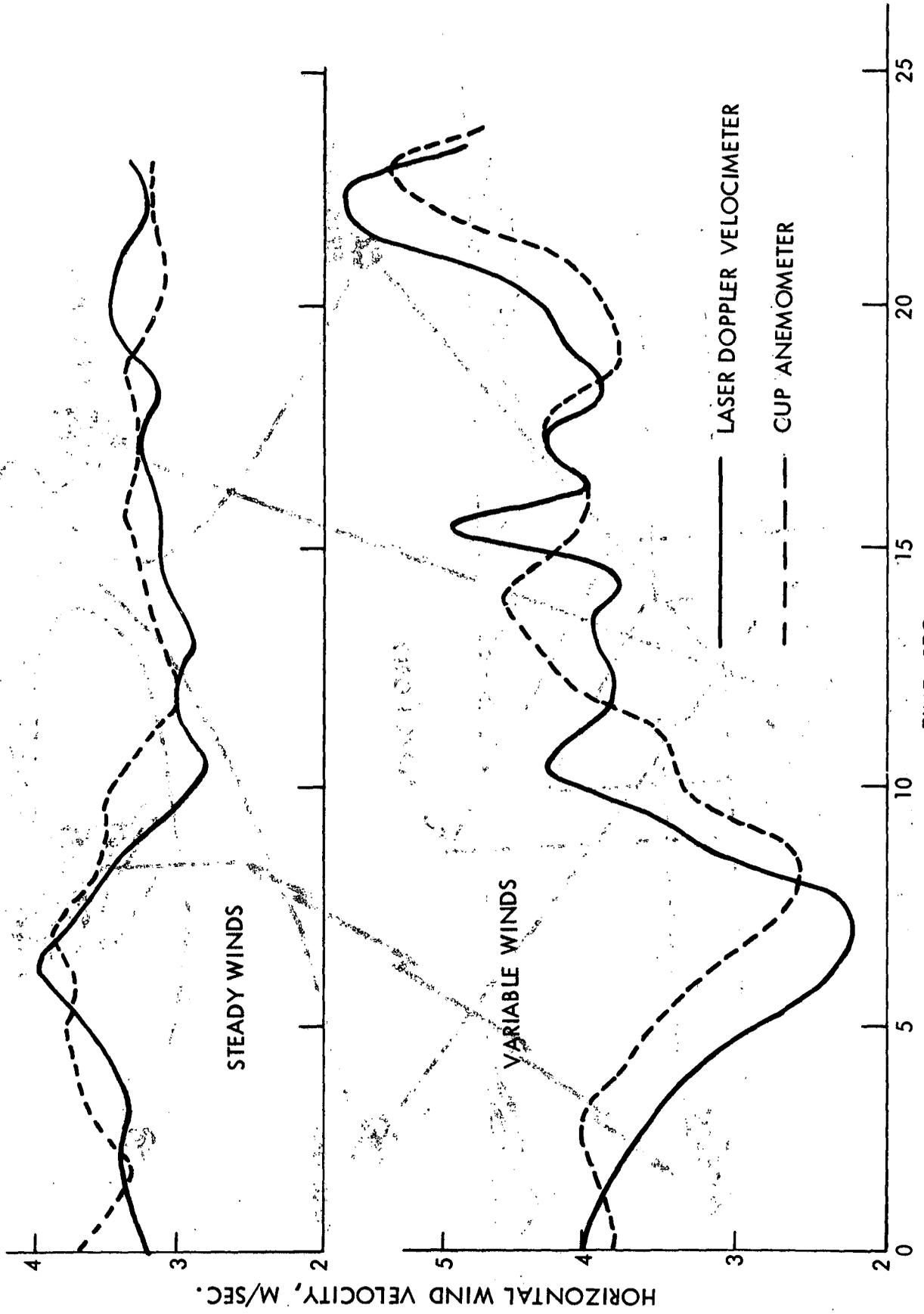
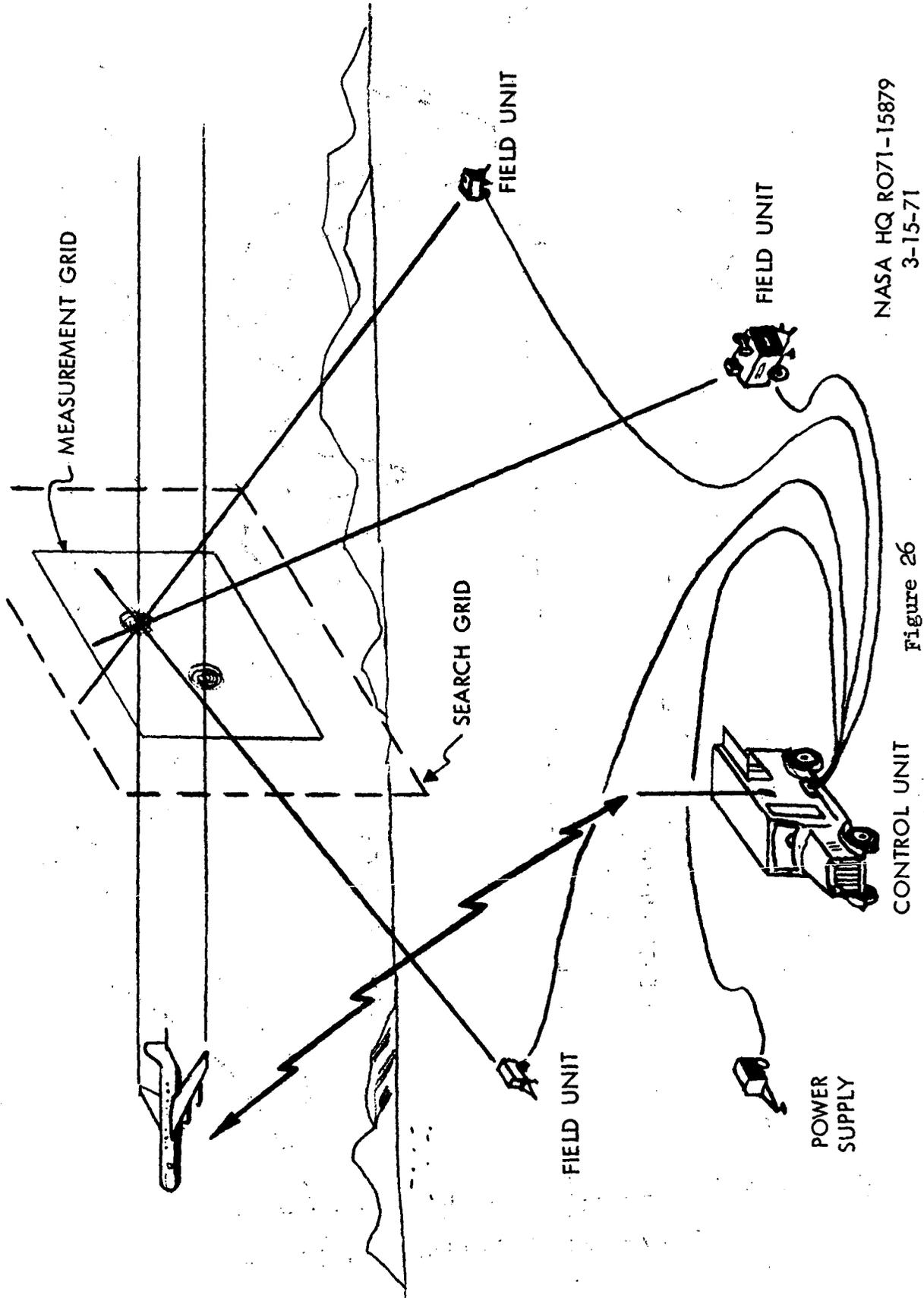


Figure 25

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LOW-ALTITUDE VORTEX RESEARCH  
MEASUREMENT - SYSTEM STUDY



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3-15-71

Figure 26

CONTROL UNIT

HD

# AIRPORT TRAILING-VORTEX WARNING SYSTEM

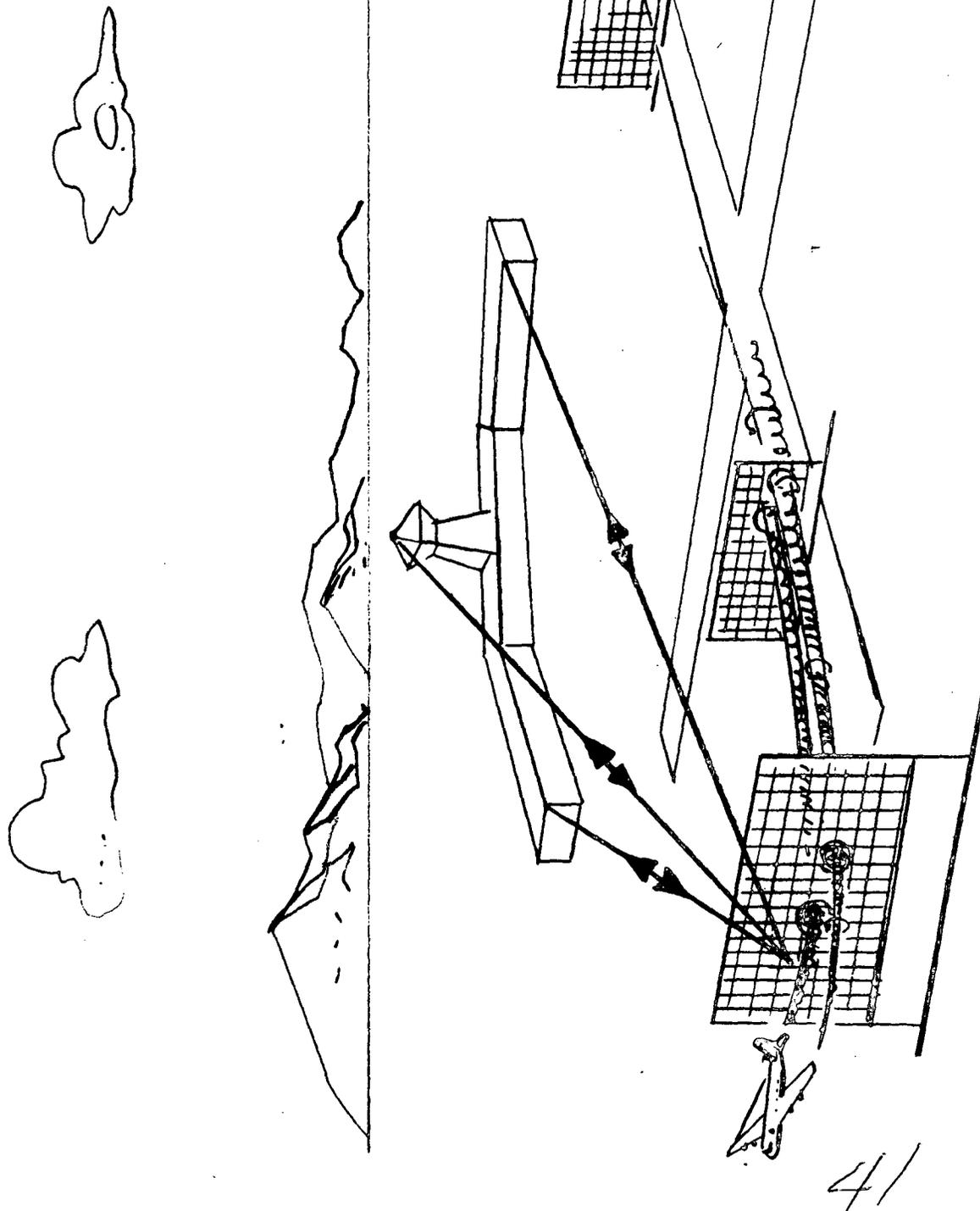


Figure 27

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3-15-71