A Review of Facilities and Test Techniques Used in Low-Speed Flight

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INTRODUCTION

New classes of aircraft being developed require new and improved flight test facilities and techniques. The high cost of designing novel transport aircraft, in particular a supersonic transport, makes it essential to be able to predict flight characteristics accurately. And safety is a major consideration, especially in flight testing new VTOL designs. For these reasons a number of new facilities have been developed to support flight test programs, and new flight test techniques have been devised to help explore problem areas. This paper will discuss how these facilities and techniques have been applied. The relative merits and limitations of each facility and technique will be pointed out, and future needs will be discussed.

Many phases of flight testing are normally involved in developing a new aircraft; however, this paper will deal with facilities and test techniques for studying only low-speed problems of handling qualities, stability and control, and performance.

The material for this paper has been gathered from flight tests made by the NASA, other research organizations, and various aircraft companies. The discussion is divided into two parts, the first dealing with flight test facilities, and the second, flight test techniques. A common problem has been chosen to illustrate the interrelationship between facilities, and the relative merits and limitations of each.

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FLIGHT TEST FACILITIES

In recent years a number of new facilities have been employed to aid the development of new types of aircraft. Among these are:

- Piloted ground-based simulators
- Ground-test rigs
- Flying-test rigs
- Variable-stability aircraft

In the following discussion, examples are given to show how these facilities are used in studying control power requirements in low-speed flight.

Piloted Ground-Based Simulators

A number of simulators used in V/STOL research are reviewed in reference 1. The piloted simulator has become a valuable aid in flight test programs. For example, in an attempt to reduce the roll control power in hovering VTOL aircraft, it was planned to install a movable vane in the engine exhaust to vector the thrust, thereby producing sideward translation without banking the aircraft. We needed to know (1) how to control the vane from the cockpit (i.e., by a thumb controller or by the stick deflection), and (2) how much to deflect the vane for satisfactory maneuvering. To answer these questions a piloted simulator study was conducted on the NASA-Ames six-degree-of-freedom motion simulator (fig. 1). The cab of this simulator is free to travel within a cube approximately 18 feet on a side and with angular motion capability of ±45° about all axes. According to pilots' comments, the overall motion capabilities of the simulator closely corresponded to actual hovering flight.

[redacted]

The results of the simulator study in which three methods of control were used are presented in figure 2. Two points can be observed: (1) The vane improved (lower number) pilot rating; (2) programing the vane as a function of bank angle was not as desirable as actuating the vane by a thumb controller on top of the stick. Both bang-bang and proportional controller methods were evaluated for possible flight application. The simulator tests indicated that a lateral acceleration of approximately 0.10 g would be the maximum desired for rapidly positioning a VTOL aircraft. In addition, attitude stabilization in roll was desired to reduce the effects of inadvertent upsets caused either by the pilot or by gusts.

Flight tests with the vane on the X-14A VTOL aircraft (fig. 3) have borne out trends shown by the simulator. The flight tests also emphasized the need for attitude stabilization when the vane is used for control. The thumb controller method of regulating the vane, established by the 6° simulator studies, was adequate and remained essentially unchanged for the flight program.

In summary, the foregoing is only one of many examples of the vital support of flight research provided by simulators. It is expected that the piloted simulator will become more valuable in flight research in the future. Indications are that cab motion contributes significantly to the realism of the simulation, thereby producing more accurate results, which in turn, can simplify research, increase safety, and reduce the amount of actual flight time required to prove a new design. Even when sophisticated, multimotion piloted simulators are used, experience has shown the need for flight validation.

Ground-Based Test Rigs

Ground-based test rigs have recently become popular with the advent of VTOL aircraft. They are used

To provide a functional check of the control systems used in hovering flight including SAS failure and engine out.

To study ingestion and recirculation problems due to engine exhaust or lift system.

To measure hover performance in and out of ground effect.

To check engine operation, calibration of various equipment, and initial pilot familiarization.

An example of the use of a ground-based test rig for checking control systems is given for the XV-5A fan-in-wing VTOL aircraft shown mounted on the NASA Ames Research Center adjustable height test rig in figure 4. Before flight the aircraft was tested on the stand at various heights above the ground. These tests revealed that close to the ground, an erratic rolling oscillation was produced by recirculation of the nose fan exhaust. The XV-5A aircraft is controlled laterally by means of louvers at the wing fan exit which close off the fan exhaust differentially to produce a rolling moment. Measurements of the available control moment indicated that lateral control would be only marginal. Subsequent checks indicated that the control system mechanism deflected under dynamic pressure from the fan exhaust. Therefore, a more rigid system was installed before flight tests were begun. The flight tests confirmed the unsteady flow behavior in ground effect; but the difficulty of operating in this region had been alleviated by making the roll control power adequate and by use of attitude stabilization.

The foregoing was an example of a ground test rig adjustable only in height. More sophisticated ground-based rigs with more motion freedom have been used, particularly in West Germany. The rig shown in figure 5 for testing the VJ-101-X2 is a telescope type with a mounting capable of angular freedom in roll, pitch, and yaw. It is desirable, of course, to mount the pivot as close to the center of gravity of the aircraft as possible to avoid large static moments when the aircraft is tipped. The maximum free movement, which is restricted by cable, is $\pm 25^{\circ}$ in pitch and roll and $\pm 8^{\circ}$ in yaw. It is possible to "fly" the aircraft on the telescope and this is done subsequent to any changes or maintenance performed on the control system including the SAS (stability augmentation system). By this means it is possible to check such items as the time constants of the control system (thrust modulation is used for pitch and roll), hardover failures in the SAS, the effect of one engine thrust loss, and the difficulty of flying as the system fails progressively from an attitude command, to a rate damped, and finally an acceleration system. It is ironic that the VJ-101-X1 was not checked on the telescope prior to the loss of that aircraft. The crash resulted from a yaw gyro which was installed with the wrong polarity. The flight was made as a conventional flight with no hovering intended; however, the yaw gyro which in conventional flight serves as a yaw damper, caused a divergent Dutch roll oscillation.

In summary, ground test rigs have been extremely useful not only for examining potential control problems for hovering flight, but also for checking the functioning of the entire aircraft in a partial-flight environment. Because of their inherent limited motion capabilities, however, this type of equipment cannot be used for determining the desired values of control power needed for hovering. The ground test rig needs to continue to grow in sophistication as VTOL aircraft become more complex.

Flying Test Rigs

Airborne test rigs were first used in the 1950's; the Rolls-Royce Flying Bedstead in the U.K. and the Coleopter in France proved the practicability of attitude control for VTOL flight. Recently, the airborne test rig has been used (1) as a flying simulator in the development of hover and low-speed handling qualities requirements, and (2) as a test bed for the propulsion and control systems hardware which will ultimately be installed in a specific aircraft.

An example of the former is the North American FS-1 "Hoverbuggy" shown in figure 6. This vehicle has a cruciform shape, has a 22-foot span, and is powered by two GE-YJ-85-1 turbojet engines. Its gross weight at take-off is approximately 3,400 lb. Compressor bleed air is ducted to the cruciform extremities for a continuous flow reaction control system. An electronic package provides variable stability and control features which allow control power, control sensitivity, rate damping, and attitude stabilization to be studied systematically in a real world environment.

Tests to determine hover and low-speed control power requirements for various control systems have just recently been completed at North American Aviation. Since the FS-1 has essentially no aerodynamic surfaces (pilots report essentially neutral stability about all axes), it has been suggested that this type of vehicle could be used to define control power requirements for maneuvering. Much larger multiengined rigs of this type have been proposed to help answer the controversial question of the effect of aircraft size and inertia on control power requirements. Initial results with the FS-1 rig indicate that it can be very useful as a flying simulator for comparing the effect of various control system parameters on a specific maneuvering task. Its small size, however, limits its usefulness for settling the aircraft size-control power question for at least two reasons: First, it does not take into account the control requirements for offsetting the effects of upsets and gusts acting on the aerodynamic surfaces, and second, even though inertia can be increased by adding weights, there are unknown effects of angular acceleration on the pilot. Since the pilot is usually displaced farther from the c.g. as aircraft grow in size, the amount of control power desired for pitch and yaw will undoubtedly be influenced by this factor. The roll axis, which has been of greatest interest from the designers standpoint, would be influenced to a lesser extent since the pilot is usually located close to the roll axis regardless of aircraft size. Exceptions to this occur in specialized aircraft, such as the Sikorsky S-64 where the pilot is relatively far below the c.g.

An example of a more sophisticated airborne test rig is the DO-31 described in reference 2. It is typical of those used in West Germany for developing such aircraft as the VJ-101, DO-31, and VAK 191B. It is large (fig. 7) and is used essentially for research on the control systems hardware and the propulsion system which ultimately will be installed on the actual aircraft. The systems tested on this rig will have encountered the real life environment of noise and vibration in free flight, and such items as control system gains and time constants will have been adjusted for optimum performance. Both the VJ-101 and DO-31 test rigs have proved to be extremely valuable in the development of the actual aircraft. These rigs, particularly the DO-31 rig, have broader potential uses for research on control-systems requirements for a large jet VTOL transport. The DO-31 rig is in essence an aerodynamic duplication of the flight vehicle and would have realistic trim, upset, and ground effect disturbances typical of a large jet-lift transport.

In summary, airborne test rigs are valuable mainly for assisting in the development of complex VTOL aircraft. Because of safety considerations, however, they are limited in their capability, as are aircraft, to investigate control requirements in areas of low control power, hardover SAS failures, and engine failures. These requirements are best investigated on a multimotion, ground-based, piloted simulator. The upper limits of hovering flight (i.e., the transition to aerodynamic flight from engine-supported flight) also cannot be studied with airborne test rigs.

Variable-Stability Aircraft

This type of aircraft has been used in varying degrees of sophistication for many years, contributing strongly to the establishment of handling qualities criteria. Recently, new generations of transport aircraft have created new low-speed problems. Included are the landing approach characteristics of the supersonic transport with a wing plan form designed primarily for high speed, and very large, high inertia subsonic transports, such as the Boeing 747 and the Lockheed C5-A. The handling qualities of these new aircraft are expected to be quite different from those of present airplanes, and existing specifications for military aircraft can serve only as a general guide. Some requirements, such as dynamic longitudinal stability, which has been based chiefly on fighter experience have been unduly restrictive; others have not been restrictive enough.

Examples of variable-stability aircraft used for examining low-speed problems of large aircraft are the Cornell B-26 aircraft,[3] the Lockheed Jetstar,[4] and the Boeing 367-80 (707 prototype).[5] These variable stability aircraft differ in type and size, ranging from the propeller driven B-26 of 35,000 lb gross weight to the jet transport 707 of 175,000 lb. The question naturally arises as to the validity of the results when a small aircraft is used to simulate the low-frequency longitudinal dynamics of a large high inertia SST or C-5A type aircraft. The small aircraft must be forced to a much lower frequency than its natural frequency, and providing a valid long period response is tied-in with the type of variable-stability system used.

Variable-stability systems have been mechanized by either: (1) a response feedback, or (2) a model-controlled system. With the response feedback technique the aircraft response variables are sent as commands to control surface actuators. Thus the aircraft's aerodynamic stability parameters can be changed artificially by generating forces and moments proportional to the aircraft responses. The model-controlled technique uses an on-board computer programed to simulate the model aircraft's aerodynamic parameters. In effect, the pilot flies the model, and the feedback loops force the airplane responses to match those of the model.

There are limitations in the use of each variable-stability technique. The response feedback system, although the earliest in use, has limitations which include (1) accurate knowledge of the basic aircraft's aerodynamic characteristics, and (2) frequent in-flight calibration to check the values of the aerodynamic parameters being simulated. The process for evaluating the aerodynamic parameters from the aircraft responses is tedious and in certain cases inherently inaccurate, although an analog computer can relieve this somewhat. In simulating the large inertia, long period SST, for example, the gains of the response feedback system must be maintained with great accuracy to cancel the basic aircraft's short period as gross weight and c.g. change due to fuel use. The model-following technique on the other hand for simulating the short period modes requires higher feedback gains to keep the errors between the basic aircraft response and the model output small. Using high gains is limited, however, by system noise, instabilities, and nonlinearities. In addition, in applying the model-following system to a flexible aircraft, the gains must be limited to avoid exciting structural modes. Limiting the gains would, of course, reduce the accuracy of the simulation.

Another aspect of using variable-stability aircraft in flight simulation has to do with cost. Large aircraft with complex systems are inherently expensive to operate and one must limit the number of flight hours devoted to a program. Ames Research Center has taken the view that flight simulation must be complemented largely by ground-based simulation. The ground-based studies can cover a broader range of parameters including those in the "unsafe for flight" areas such as failures (augmentation, hardover, etc.). The flight simulator then is used to validate the trends established by the ground-based tests.

An example of the use of this approach is given in reference 6 where the Boeing 367-80 was used to study the longitudinal control requirements for a large aircraft such as the C5-A. The results in figure 8 illustrate the point that the ground-based simulator results covered a broad range of pitching moments due to angle of attack and the flight test points served as validation of the trends established by ground-based simulators. The lack of flight test points in the region of low stability (long periods) reflects the difficulty of operation in this area.

Variable-stability aircraft have proved valuable in aiding the development of new aircraft designs but they are limited in their capability to define the effects of aircraft size including the aerodynamic parameters peculiar to large aircraft and the effect of pilot position. Small variable-stability aircraft, in particular, fail to produce realistic translational accelerations and again one must look to ground-based simulators to study this effect.

FLIGHT TEST TECHNIQUES

Various flight test techniques have been devised for exploring specialized flight problems, such as

Measuring hover control power for VTOL aircraft.

Measuring the ground effect on delta winged aircraft.

Studying stalling behavior.

Studying recirculation and ingestion.

In the following paragraphs the relative merits of various testing techniques are discussed with the objective of indicating required refinements and future needs.

Measurements of Control Power in Hover

The amount of control power needed to hover VTOL aircraft has been controversial. VTOL aircraft are particularly sensitive to control power requirements because there is usually a direct trade between performance and the amount of control power needed to hover. Of interest here are the flight test techniques used to measure control power. Control power can be evaluated by (1) measuring attitude changes directly with an attitude gyro, (2) integrating angular rate, and (3) measuring angular accelerati . It is important to include all methods since angular acceleration measurements will give only the moment available and not include the effects of time constant. Of the various techniques used to measure angular acceleration, the control reversal method illustrated in figure 9 is preferred. For measurements of rolling acceleration the aircraft is initially banked in a direction opposite to that for the measured responses to assure that the lateral control input is constant at the time angular acceleration is measured, and to reach high angular accelerations at smaller bank angles. A chain stop is usually used at the stick grip to aid in holding control inputs constant and to provide a means of obtaining prescribed partial control positions.

Even with the reversal technique large bank angles can occur for high response systems and the use of the chain stop on the control stick can make control power measurements somewhat hazardous when hovering near the ground. Ames therefore has measured control power values on the X-14A VTOL aircraft at approximately 2,000 feet above the ground. Another advantage of hovering at altitude is that a conventional take-off can be made thereby allowing a new hover control system to be checked in an environment where SAS or hardover failures are not catastrophic. Hovering at altitude has limitations, however. Without good position information, it is difficult to avoid sideward or fore and aft translation. This not only affects the accuracy of the control power measurements, but in a number of cases, has resulted in upsets for the X-14A aircraft when too large sideward or backward velocities were reached inadvertently. Large and higher wing loading aircraft would have to be hovered at higher altitudes to afford safe recovery from possible upsets. This would, of course, be unattractive from performance aspects.

Measurement of Ground Effect

The effect of ground proximity on the lift and pitching-moment characteristics of low-aspect-ratio wings is a significant design consideration for take-off and landing. The increase in lift due to ground effect is beneficial in reducing ground roll for these wings; however, pitching-moment changes may adversely affect the pilot's precision of control in a landing flare or rotation in take-off. Further, it is important to measure ground effect precisely on existing low-aspect-ratio designs in order to compare with wind-tunnel results and theory.

Two flight test techniques have been developed for measuring ground effect. One method[7] is to make level "fly-by" runs at various heights above the ground and at various speeds. This method relies upon on-board measurements of aircraft acceleration, thrust, and attitude for calculating lift and drag. A special camera (Lockheed Location Orientation Recording Instrument (LORI)) facing downward from the under surface of the fuselage measures aircraft height, rate of change in height, ground speed, and pitch attitude.

The "fly-by" method has two inherent deficiencies. First, it requires a large number of passes, one for each height and airspeed of interest; second, repeatability is poor because of inaccuracies in measuring such items as angle of attack and thrust. Interpreting the data from the camera is time consuming and tedious.

Another technique for measuring ground effect is the external tracking of the aircraft while it makes a steady descent at a constant angle of attack and power setting. Ground effect will cause the aircraft to flare, the change in drag will cause a change in speed, and the change in pitching moment will require longitudinal control to hold a constant angle of attack. Results of using this technique to test the B-70 are shown in figure 10 and are reported in reference 8. The results obtained with this method show a nonlinear variation of C_L with ground proximity.

Although this method holds promise of improved accuracy because it does not require on-board measurements, it has a number of limitations. First, the initial sink rate and power setting must be established carefully with no wind, and thermal effects of the atmosphere must be small so that the aircraft can maintain an equilibrium glide slope. Second, the pilot must maintain a constant angle of attack usually from an indicator which may be difficult to track and may have a flow induced error as a function of ground height. The data reduction is again tedious and subject to the usual errors in reading the aircraft's position and attitude on each film.

In summary, experience has shown that both methods lack repeatability and are greatly subject to the effects of atmospheric turbulence and to pilot proficiency in performing the required maneuvers. Improvements are needed in data reduction and more experience is needed, particularly with higher aspect ratio aircraft, to prove the techniques.

Studies of Stalling Behavior

A primary consideration in the design of new aircraft is stall behavior. New aircraft designs, such as the T-tail and supersonic transports, have reemphasized the stall problem. The wing plan form of the Concorde SST was designed primarily for low drag at high speed; however, tests have shown that its high lift characteristics at low speed are better than those of plan forms of low aspect ratio. Studies of this type of wing, the Ogee[9] on the F5-D aircraft, revealed that the high lift benefits result from a stable vortex flow which is associated with the sharp, highly swept leading edge. Although this plan form had relatively high lift, its stalling behavior was manifested by a pitch up and small amplitude rolling motion.

To obtain a better understanding of the stall behavior, the flow separation pattern on the wing was examined by two flight test techniques. One technique was the well-known method of tufting the upper wing surface with nylon; the other consisted in observing the condensation trails of the vortex. The changes in location of the vortex were visible in all but the driest air. Photographs (figs. 11 and 12) show that in steady flight, the vortex core passes above the leading edge and at a sweep angle higher than the wing.

It is of interest to correlate the location of the vortex with sketches of tuft patterns, such as those shown in figure 13. The sketches, derived from the photographs taken by the tail mounted camera, show an increase in unsteady flow as angle of attack increases. The tuft patterns indicate that flow separation occurs on the wing tips outboard of the vortex core. At an angle of attack of 15° the F5-D airplane exhibits a lateral oscillation, and as angle of attack increases further, a mild pitch up.

It was considered possible also that the vortex affected the flow over the vertical tail which, in turn, improved the lateral-directional behavior over that of the original aircraft. The pilot of the chase aircraft observed that during flights in this high angle-of-attack region, the vortex appeared to be high off the wing and to flow to an area near the tail.

Another means of observing the vortex without relying on the condensation was used by the RAE, Bedford, U.K. on the HP115 slender delta-wing research aircraft. They used a smoke generator to emit smoke at the leading edge of the wing at the junction of the fuselage. The smoke entrained in the vortex could easily be observed.

Studies of Recirculation and Ingestion

Several V/STOL aircraft have encountered unsteady flight behavior when operating at low airspeeds in close proximity to the ground. Reference 10 describes the unsteady flight behavior of the XC-142 tilt wing aircraft in the landing approach at speeds of the order of 25 knots. This unsteady behavior was characterized by a strong loss of lift and weakened directional and lateral controllability; it was attributed to flow splitting where the deflected propeller slipstream begins to precede the aircraft, and limited aircraft performance capabilities to wing angles of 35°. A similar type of unsteady flight behavior had been noted on the Ryan VZ-3 deflected slipstream aircraft.[11] Although this ground effect phenomenon was predicted, having shown up in wind-tunnel tests, it is difficult to establish the limitation of low-speed operation, in fact, the XC-142 aircraft was damaged in attempting to do so.

In order to gain a better understanding of the flow characteristics in ground effect, and thereby attempt to predict the aircraft behavior, pictorial studies were made with the Ryan VZ-3 deflected slipstream aircraft. The results, shown in figure 14, were obtained by dusting the runway with Ansul fire extinguishing powder and flying over at a constant altitude and airspeed. In figure 14(a), the velocity of the aircraft exceeds the velocity of the recirculated slipstream and the disturbed area, shown by the dust cloud, proceeds somewhat ahead of the recirculated slipstream regardless of proximity to the ground. In figure 14(c) the aircraft entered the ground effect at too low an airspeed to prevent a landing even though power was applied as rapidly as possible. The results show that as airspeed is decreased the deflected slipstream is recirculated through the propeller disc as turbulent air, causing a partial loss in thrust and turning effectiveness. By flying over the Ansul powder at gradually reduced airspeeds, it would be possible to predict when the recirculated flow would affect the lift of the aircraft.

Jet lift VTOL aircraft have also encountered ground effect problems; both induced flow effects, similar to recirculation problems for propeller aircraft, and ingestion effects in which the engine exhaust enters the engine inlet. The X-14A was flown over Ansul powder in an attempt to study flow patterns, but the high velocity of the jet exhaust dispersed the powder too rapidly and flow patterns were not visible. A heavier substance, crushed nut shells, commonly used for cleaning compressor blades of turbojet engines, was tried also without success. Injecting Corvis oil into the tail pipe has been successful for flow visualization in a study of in-flight thrust reverser operation. When this was tried on the X-14A in hover, the aircraft was immediately engulfed in a cloud of smoke and flow patterns were not discernible. By intermittently injecting discrete amounts of oil into the tail pipe, some improvement was noted, however, the flow patterns were still unclear. The best picture of flow patterns for jet aircraft has been obtained over a wet runway.

In summary, an improved testing technique is needed to explore more safely STOL limitations of V/STOL aircraft. Flow visualization methods are not a good solution because they have not proved successful for all types of aircraft.

CONCLUDING REMARKS

Novel aircraft configurations introduce new types of stability and control and handling qualities problems making it more difficult to accurately predict flight characteristics and assure safety of flight. A variety of test facilities have been shown to be necessary to aid in solving problems. For example, multi-motion piloted simulators cannot by themselves completely answer all questions; therefore flight validation is necessary. While considerable progress has been made, existing facilities and test techniques will not be adequate as new aircraft grow in complexity and cost; therefore continued emphasis must be placed on further improvements and refinements.

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FIGURE LEGENDS

Figure 1.- View of six-degree-of-freedom motion simulator.

Figure 2.- Effect of lateral acceleration vane on control power.

Figure 3.- Vane installation on X-14A VTOL aircraft.

Figure 4.- View of XV-5A VTOL aircraft mounted on the Ames ground test rig.

Figure 5.- View of VJ-101 VTOL aircraft mounted on EWR ground test rig.

Figure 6.- View of the North American flying test rig.

Figure 7.- View of DO-31 flying test rig mounted on Dornier ground test rig.

Figure 8.- Pilot rating of static stability showing correlation of flight and ground based simulator results.

Figure 9.- Time history showing technique for measuring lateral response; δ_a = aileron deflection; φ = bank angle; p = rolling angular velocity; $\dot{\varphi}$ = rolling velocity.

Figure 10.- Ground effect results obtained with constant angle of attack approach method.

Figure 11.- View of the F5-D in flight showing vortex and tuft pattern.

Figure 12.- View of F5-D in flight showing vertical location of vortex.

Figure 13.- Wing tuft flow patterns from F5-D aircraft.

Figure 14.- Pictorial indication of slipstream recirculation of Ryan VZ-3RY deflected-slipstream test vehicle with flap deflected 65°; surface wind calm. (a) 24 knots; 1.8 propeller diameters above ground; power for level flight; out of ground effect. (b) 8 knots; 1.8 propeller diameters above ground; maximum power; out of ground effect. (c) 8 knots; 1 propeller diameter above ground; maximum power; in ground effect.

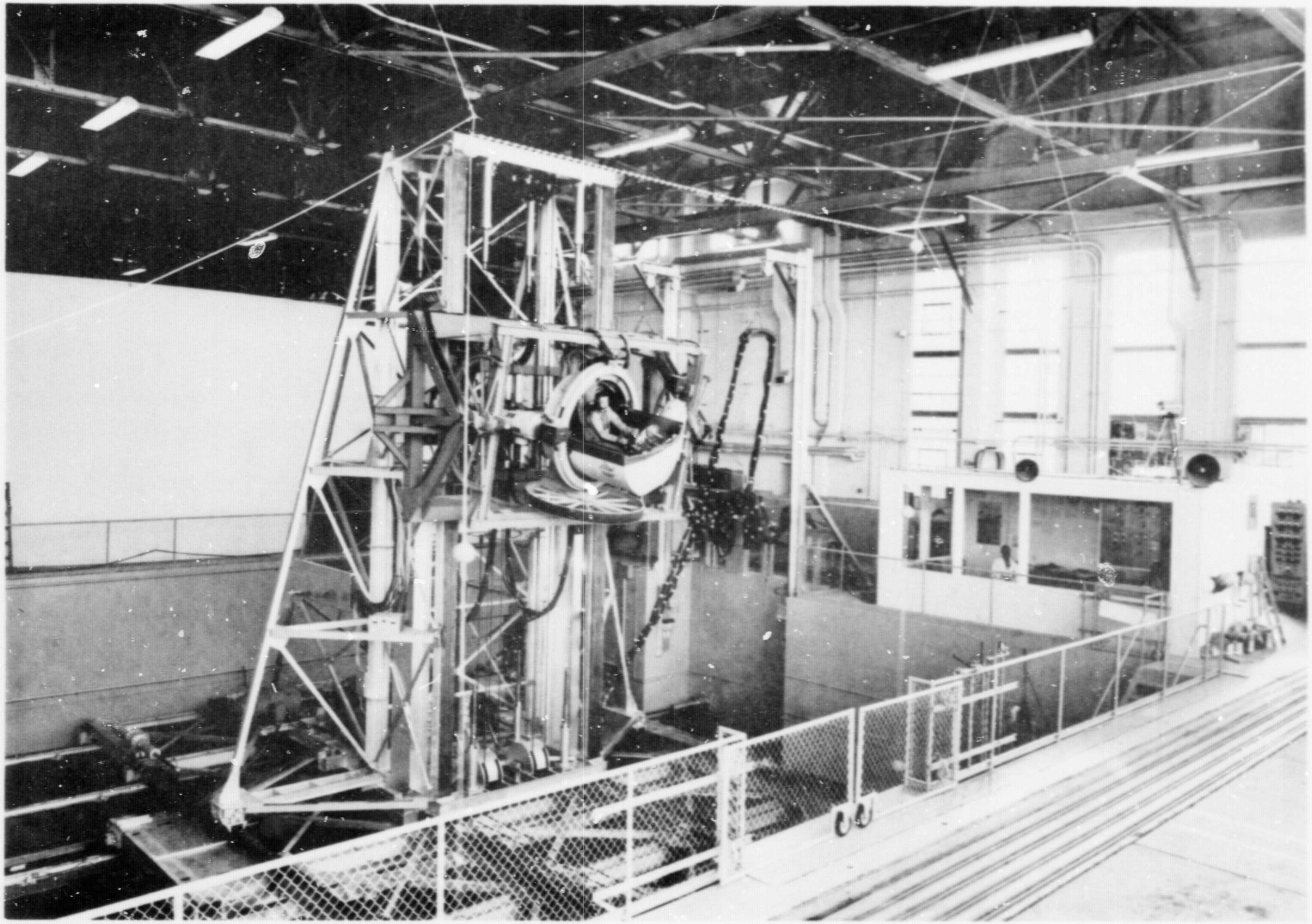

Fig. 1

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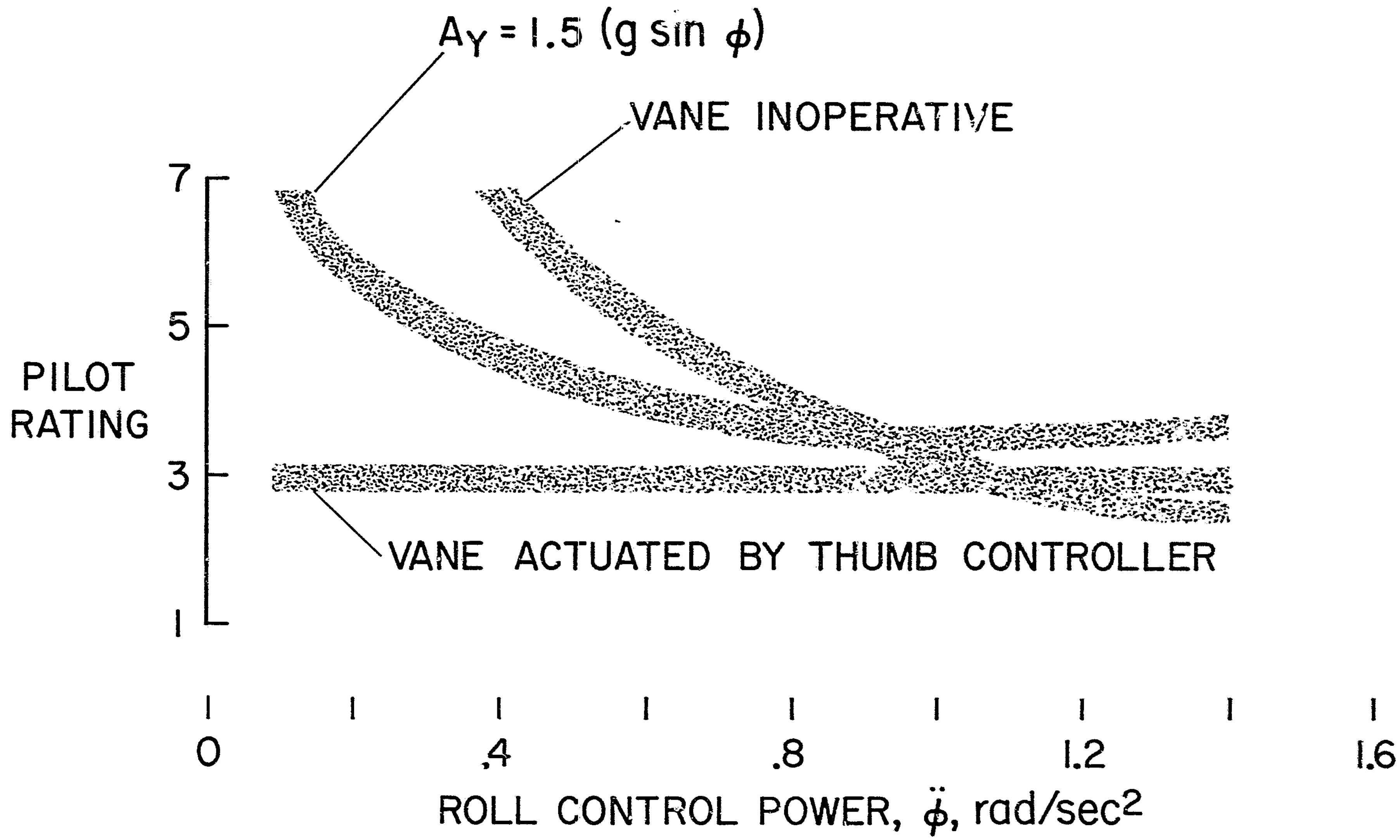

A_Y = 1.5 (g sin φ)
VANE INOPERATIVE
7
5
3
1
PILOT RATING
VANE ACTUATED BY THUMB CONTROLLER
0
.4
.8
1.2
1.6
ROLL CONTROL POWER, φ̈, rad/sec2

Fig. 2

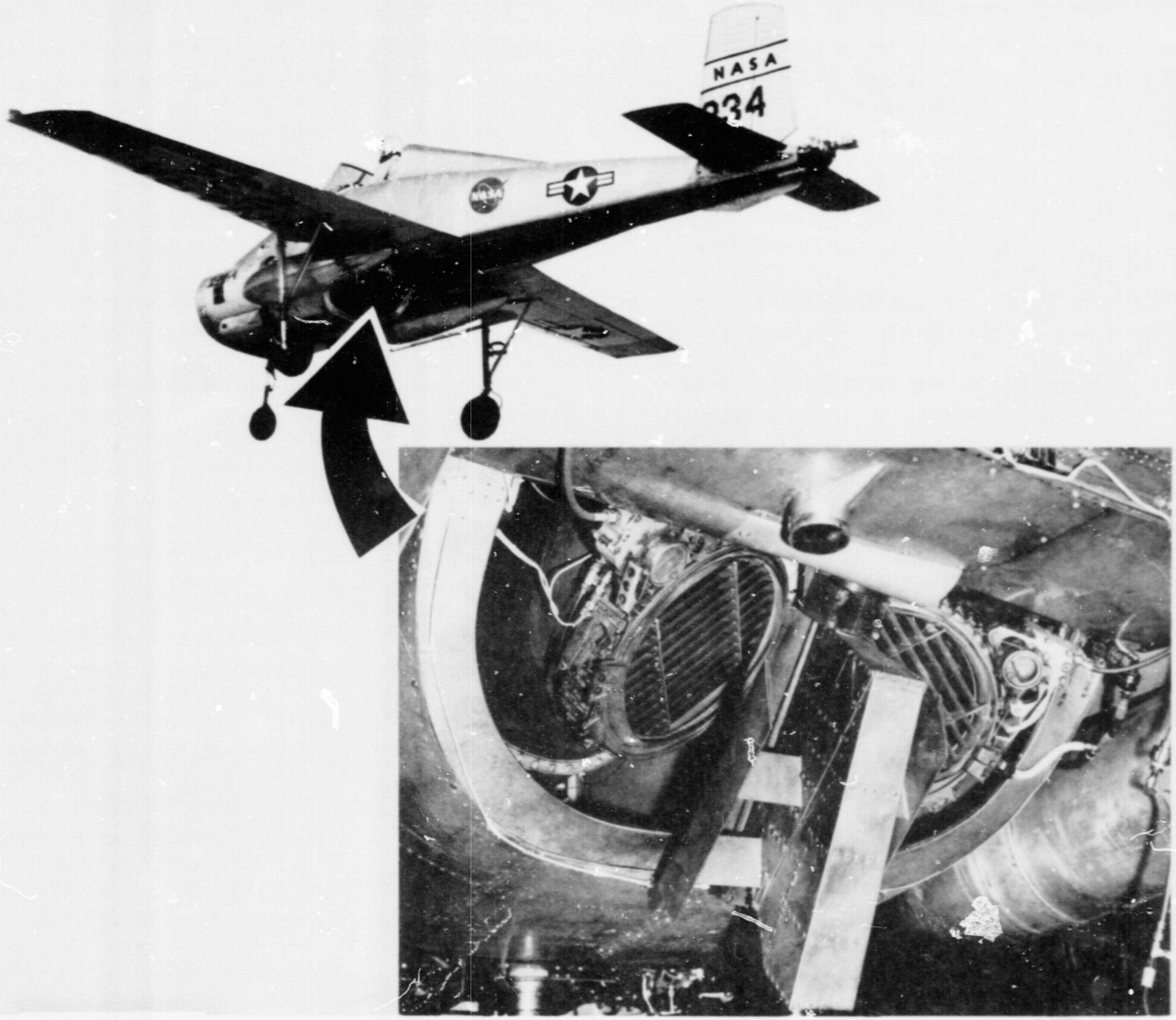

Fig. 3

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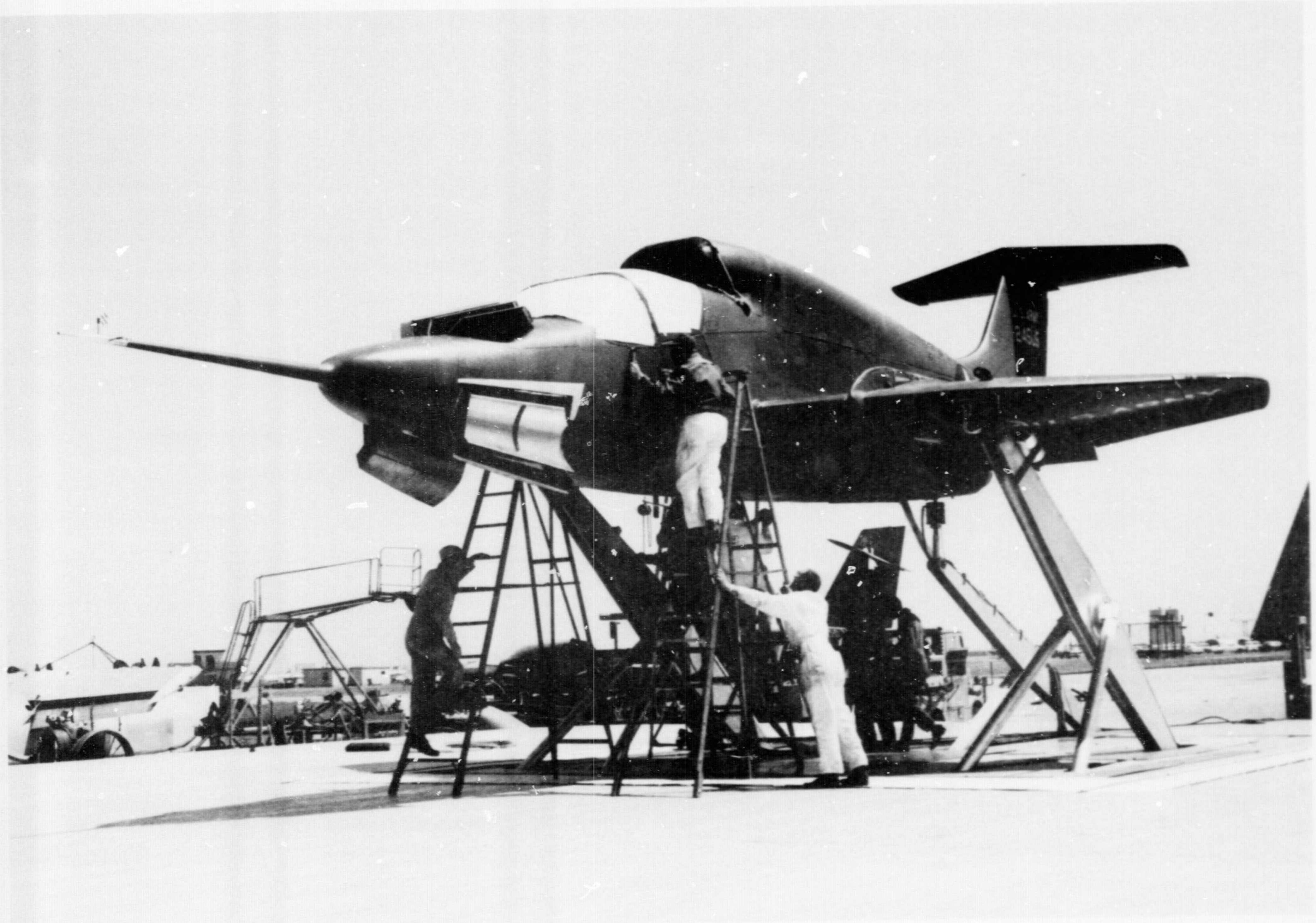

Fig. 4

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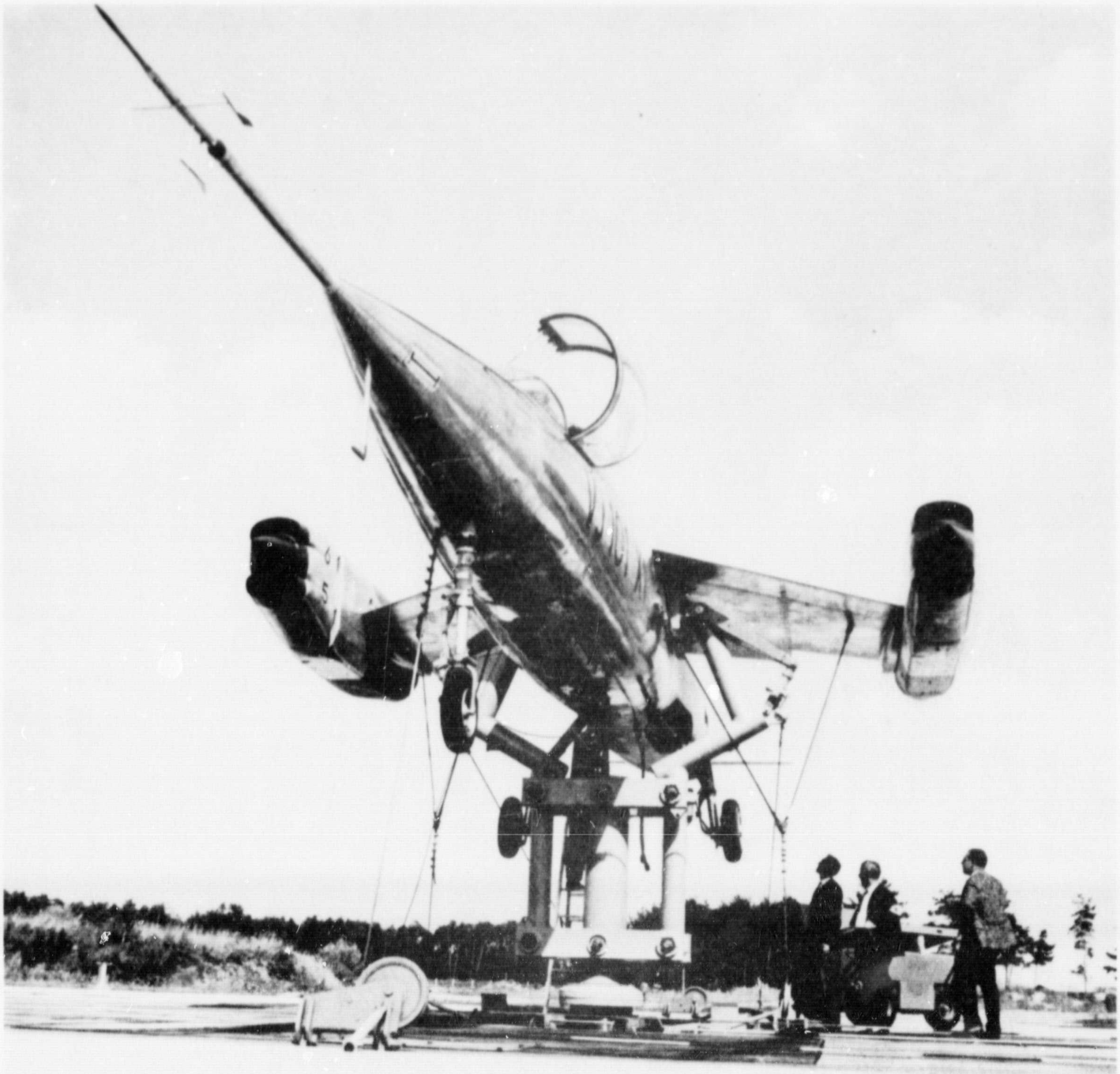

Fig. 5

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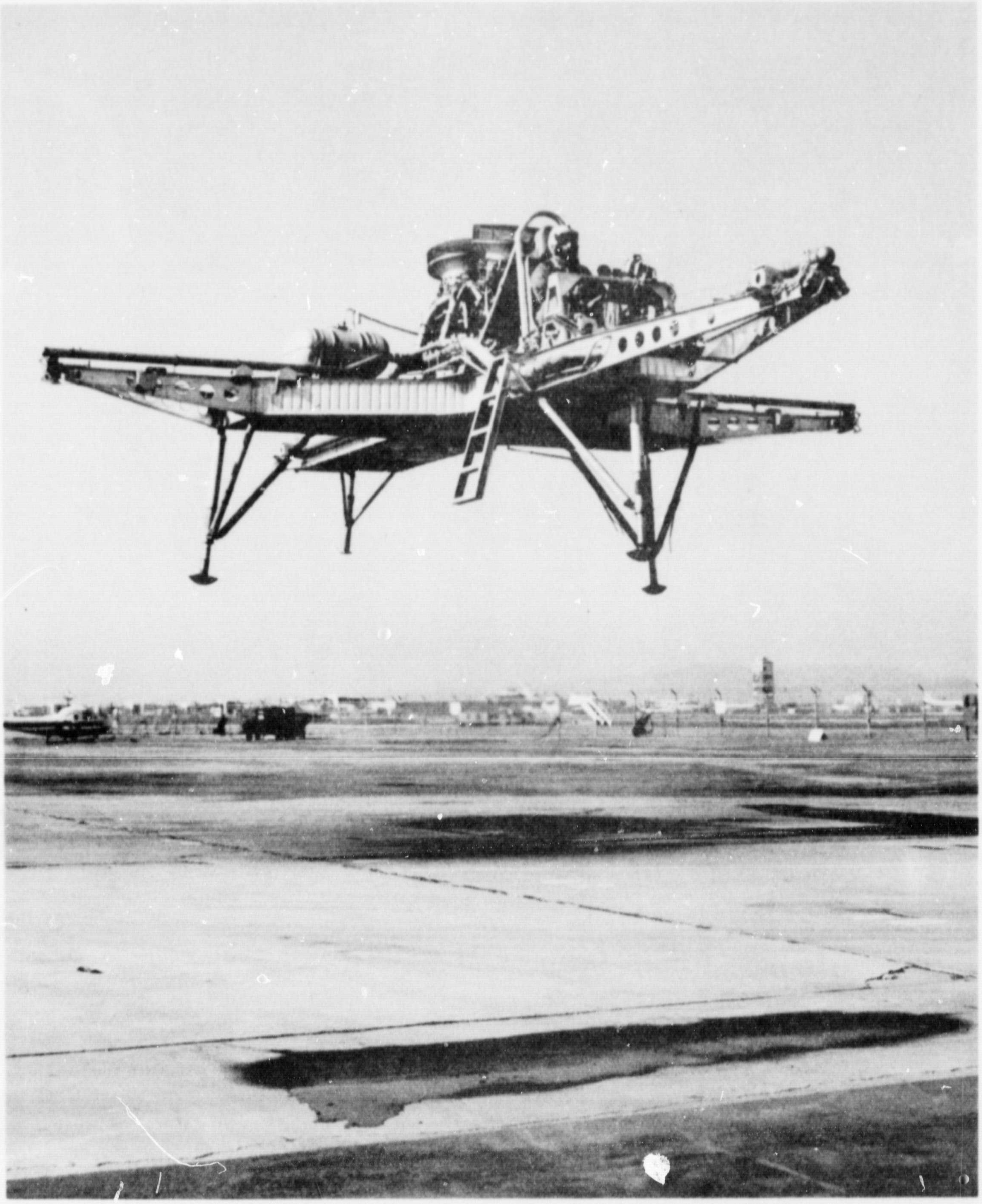

Fig. 6

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Fig. 7

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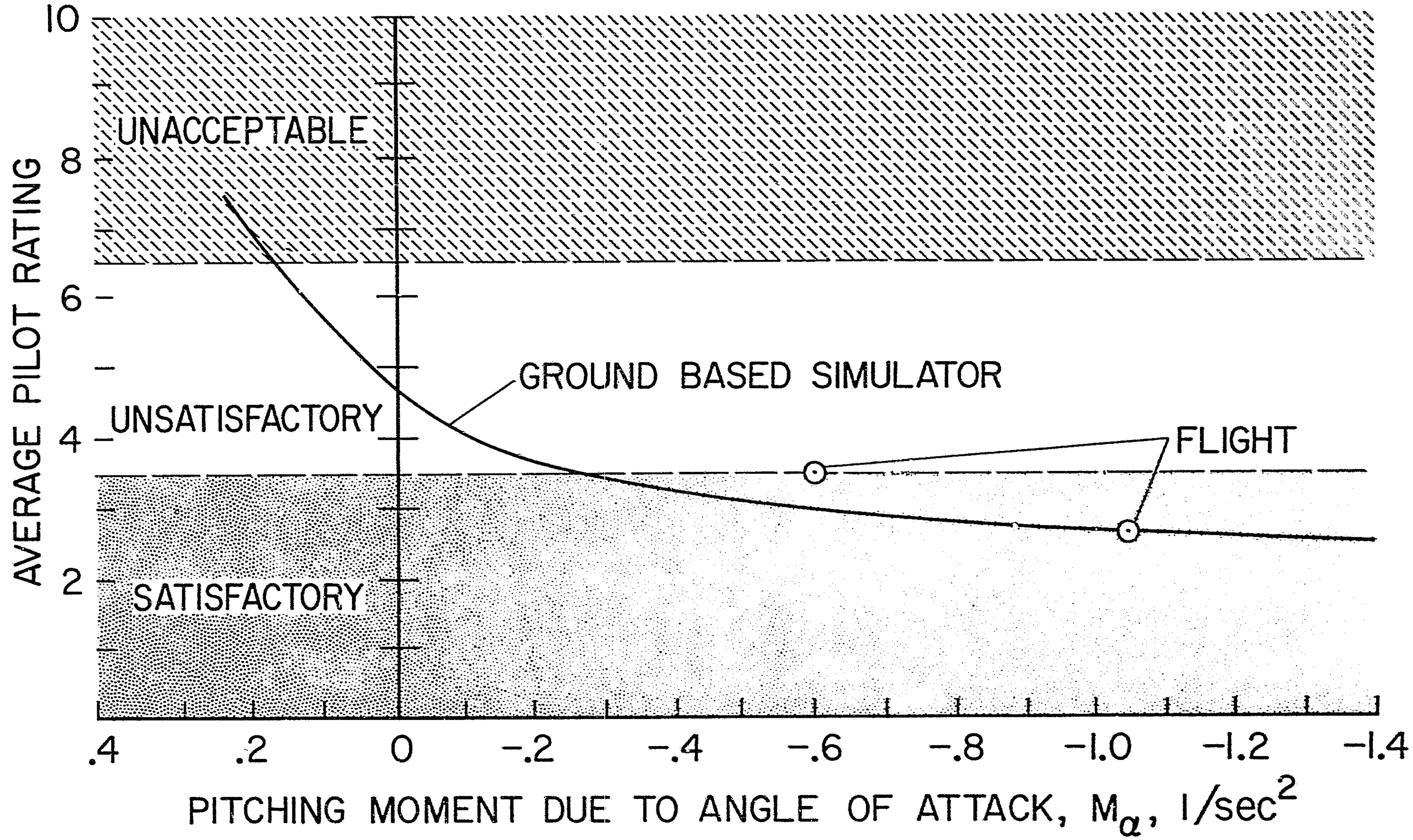
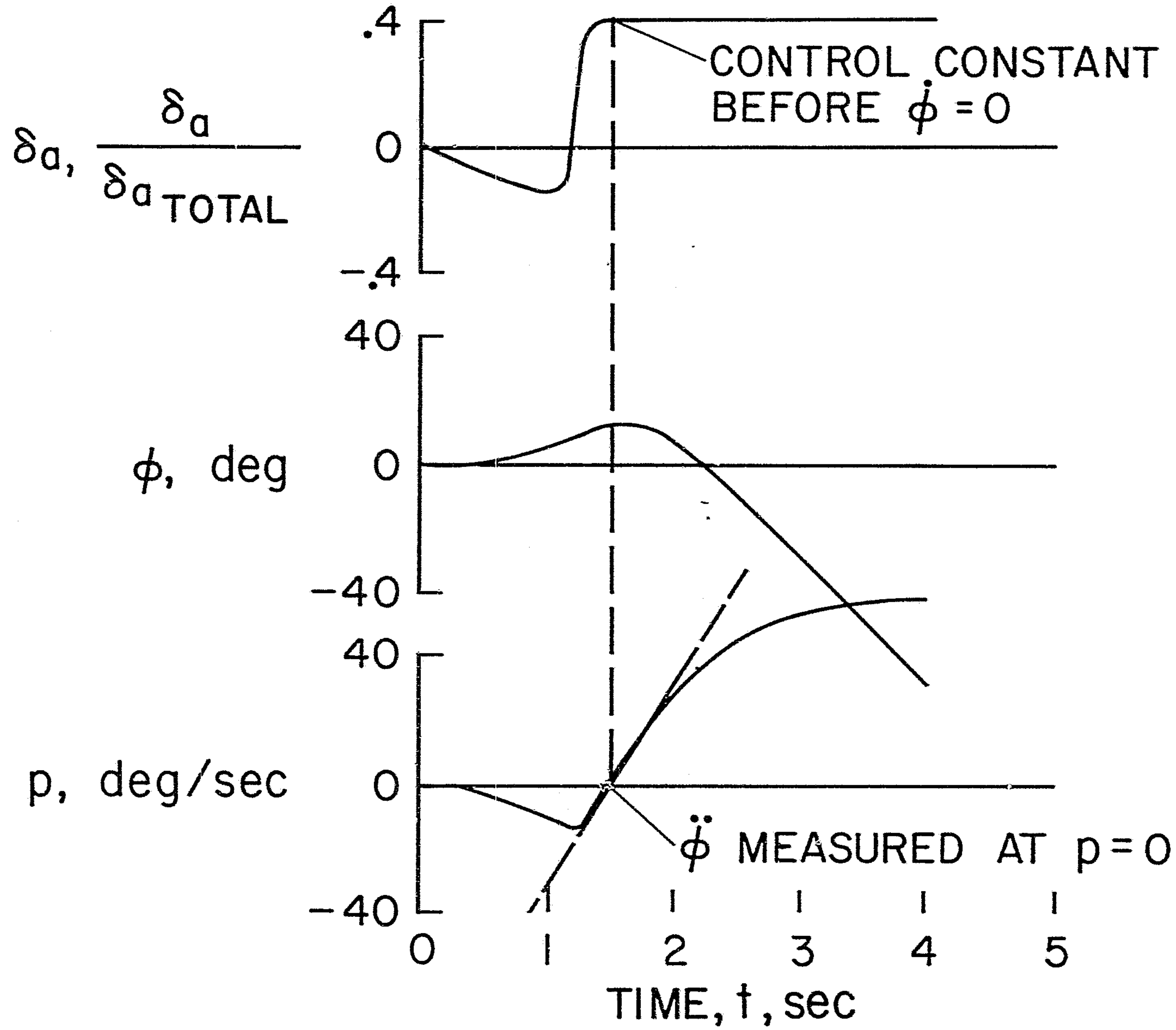


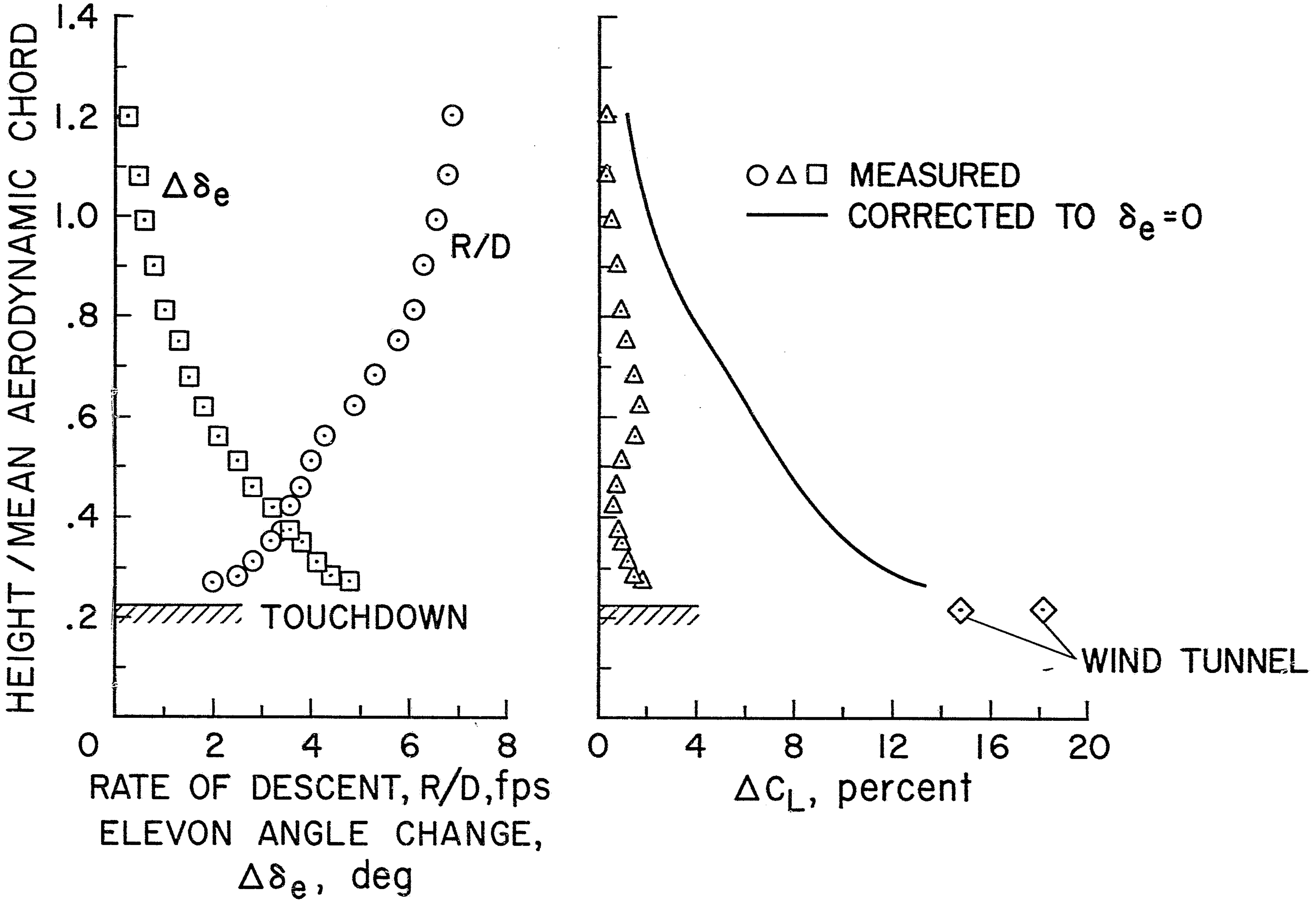
10
8
6
4
2
AVERAGE PILOT RATING
UNACCEPTABLE
UNSATISFACTORY
SATISFACTORY
GROUND BASED SIMULATOR
FLIGHT
.4
.2
0
−.2
−.4
−.6
−.8
−1.0
−1.2
−1.4
PITCHING MOMENT DUE TO ANGLE OF ATTACK, M_α, 1/sec^2

Fig. 8



$\delta_a, \frac{\delta_a}{\delta_{a_{TOTAL}}}$
.4
0
-.4
CONTROL CONSTANT BEFORE $\dot{\phi}=0$
ϕ, deg
40
0
-40
p, deg/sec
40
0
-40
$\ddot{\phi}$ MEASURED AT p=0
0
1
2
3
4
5
TIME, t, sec

Fig. 9



HEIGHT / MEAN AERODYNAMIC CHORD
1.4
1.2
1.0
.8
.6
.4
.2
$\Delta\delta_e$
R/D
TOUCHDOWN
0
2
4
6
8
RATE OF DESCENT, R/D, fps
ELEVON ANGLE CHANGE,
$\Delta\delta_e$, deg
MEASURED
CORRECTED TO $\delta_e = 0$
WIND TUNNEL
0
4
8
12
16
20
ΔC_L, percent

Fig. 10

Fig. 11

A-33500-3

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Fig. 12

A-33500-1

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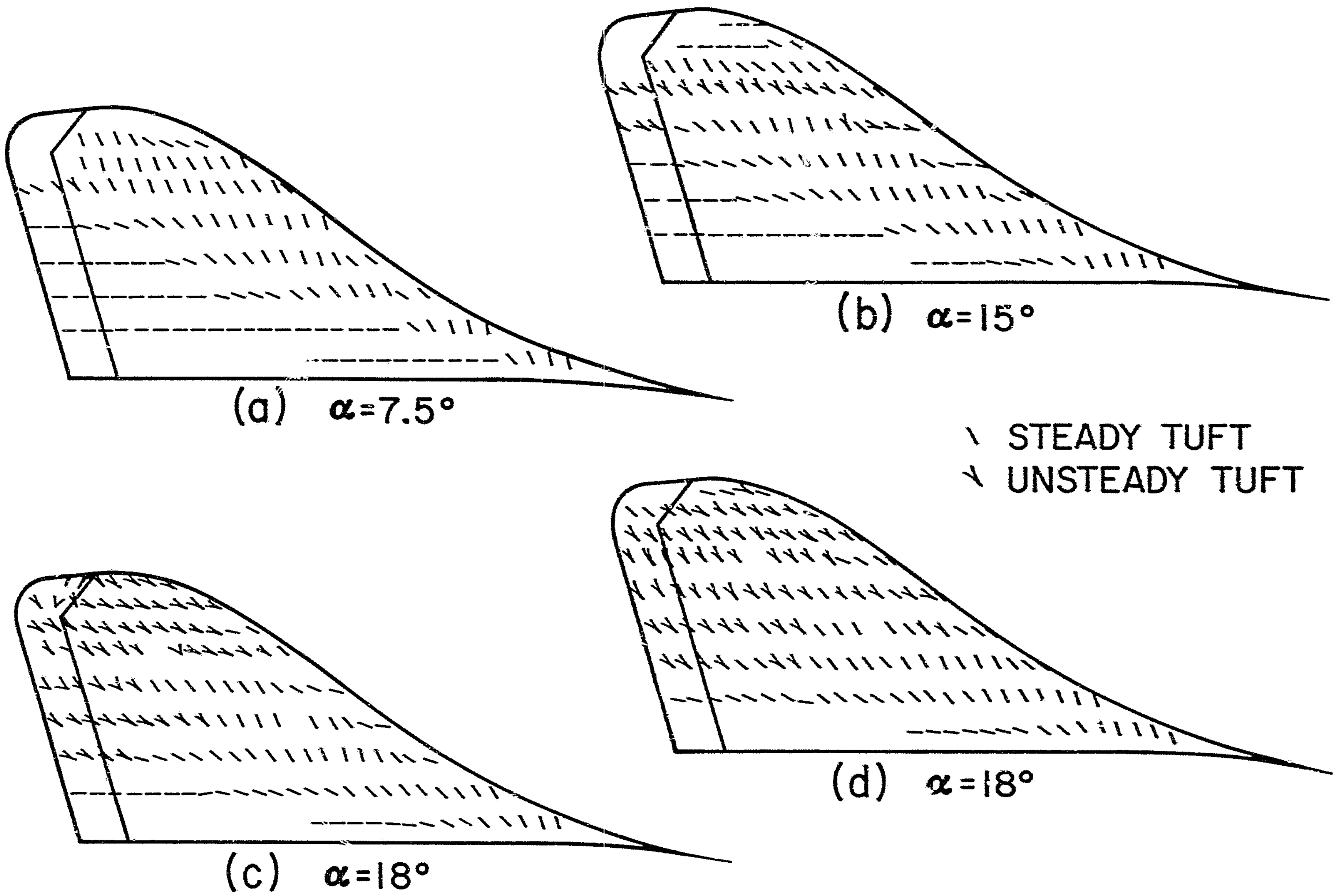
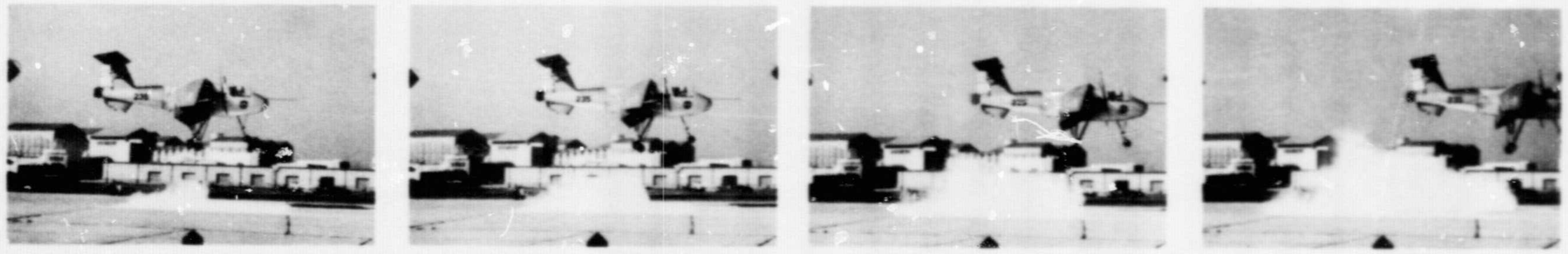
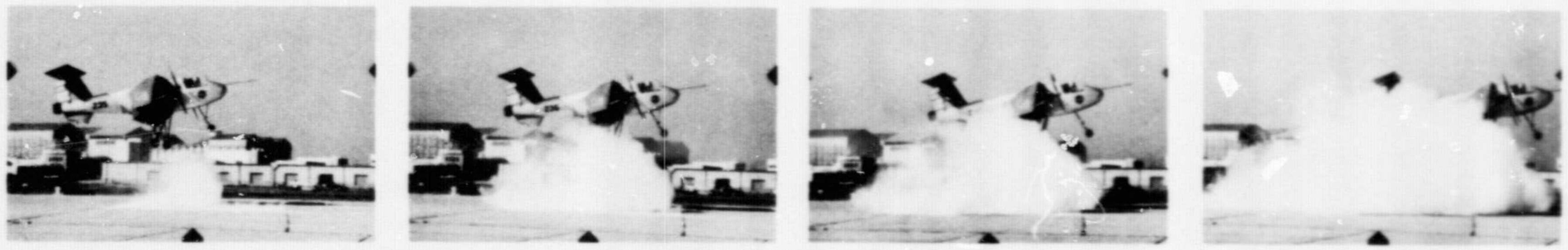


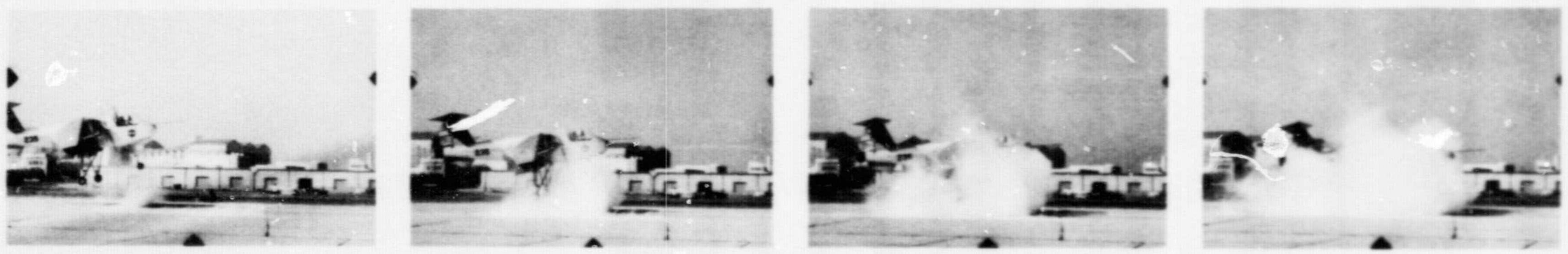
Fig. 13



(a) 24 knots; 1.8 PROPELLER DIAMETERS ABOVE GROUND; POWER FOR LEVEL FLIGHT; OUT OF GROUND EFFECT



(b) 8 knots; 1.8 PROPELLER DIAMETERS ABOVE GROUND; MAXIMUM POWER; OUT OF GROUND EFFECT



(c) 8 knots; 1.0 PROPELLER DIAMETER ABOVE GROUND; MAXIMUM POWER; IN GROUND EFFECT

Fig. 14

A-_0240

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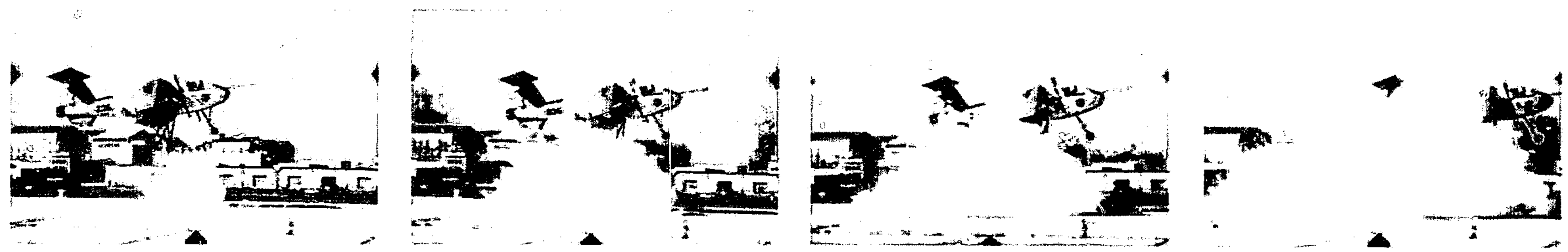
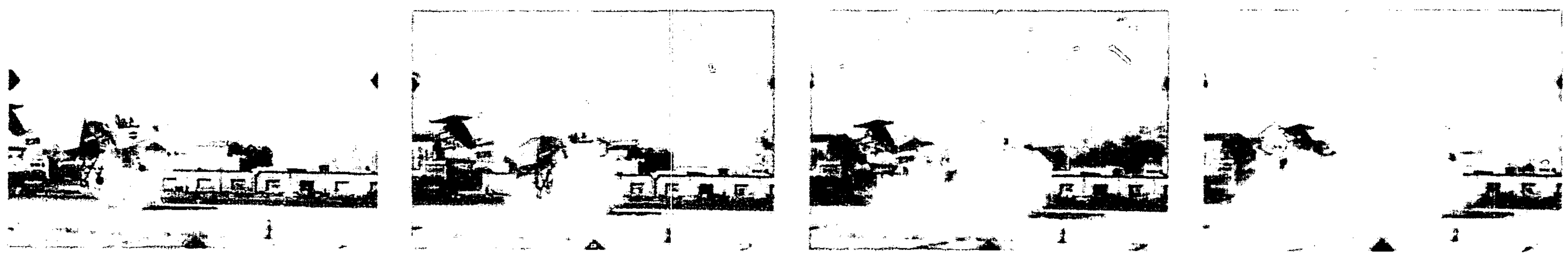
(a) 24 knots; 1.8 PROPELLER DIAMETERS ABOVE GROUND; POWER FOR LEVEL FLIGHT; OUT OF GROUND EFFECT



(b) 8 knots; 1.8 PROPELLER DIAMETERS ABOVE GROUND; MAXIMUM POWER; OUT OF GROUND EFFECT



(c) 8 knots; 1.0 PROPELLER DIAMETER ABOVE GROUND; MAXIMUM POWER; IN GROUND EFFECT

Fig. 14

A-30240