FLIGHT TESTS OF THE UNITED AIR LINES STALL WARNING SYSTEM

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FLIGHT TESTS OF THE UNITED AIR LINES STALL WARNING SYSTEM

SUMMARY

This report presents the results of tests carried out by the Civil Aeronautics Administration on the United Air Lines airplane stall warning system installed on a Boeing 247-D airplane These tests were made possible through the cooperation of United Air Lines, Inc The stall warning system installation on the Boeing 247-D includes four stall detector units and a warning indicator The detector units are mounted on the upper surface of the left wing in the region of the trailing edge and are distributed spanwise from the outboard side of the nacelle to the wing tip The units contain diaphragm switches which are adjusted to respond in sequence as the stall is approached Each unit is electrically connected to a corresponding signal light on the warning indicator which is mounted on the pilot's instrument panel The warning lights indicate to the pilot the progress of the stall over the wing as the angle of attack is increased This system operates when a decrease in the negative pressure on the stall detector units, caused by a change in the air flow over the upper surface of the wing, reduces the pressure differential on the diaphragm

The stall warning system was tested in stalls performed both with and without simulated ice applied to the leading edges of the wings The effect of throttle setting and landing gear position on the system also was investigated

The warning margins, which are the differences between the warning speeds, (V_W), and the stalling speeds, (V_S), are expressed as a ratio (V_W/V_S) The analysis of the data is based on the deviation of these ratios, for the various flight conditions, from the ratio obtained when the stall detector units were adjusted to give a satisfactory progressive warning during a level stall and with the wings free from simulated ice The results of these tests indicate that for the non-icing conditions the warning margins are ample, however, there is an undesirable variation in these margins for the different flight conditions tested

The application of increasing amounts of simulated ice resulted in relatively little increase in the warning speeds but caused a marked increase in the stalling speeds This caused the warning margins to diminish progressively until an unacceptable value resulted for the severest icing condition tested This is disturbing, particularly when it is remembered that the quantity of natural ice formation on an airplane may well exceed that of the simulated ice which was applied for flight test purposes It is entirely possible that the development of a stall warning indicator which will function adequately during all icing conditions may have to depend on the complete deicing of the wings Recently developed wing deicing methods have proved most effective

The results of the data have indicated the desirability of continued development to explore the influence of various stall detector housing contours on the air flow and to conduct tests involving switch arrangements other than those of the diaphragm type It is believed that further research will result in the development of an instrument that will provide reasonably constant warning margins under non-icing conditions Furthermore, continued research also may result in the development of an instrument that will function even when ice has accumulated on the wings

INTRODUCTION

The need for a practical device to warn the pilot of the impending stall has been recognized since the invention of the airplane Stall accidents have caused as many deaths as all other accidents combined, and in the majority of the cases they might have been avoided if a positive and early warning had been provided

In view of the foregoing and as a result of numerous requests from other government agencies and from the aircraft industry, the Civil Aeronautics Administration has undertaken a program for the development of stall warning indicators This involves two major types (a) a device that will function under all conditions of flight except when ice has accumulated on the wings, and (b) a device that will function even with ice on the wings Type (a) is considered suitable for personal type aircraft since only 1 percent of their stall accidents involved icing Where air carrier type aircraft are concerned, stall accidents generally are associated with icing and a universally applicable type of stall warning indicator is required

For any particular airfoil section the stall occurs at a certain critical angle of attack The accretion of ice on the wings of an airplane changes the airfoil section and causes the airplane to stall at smaller angles Wind tunnel and flight tests in which streamers or "tufts" were attached to the upper surface of the wings indicated that the actual stall is preceded by a change in the character of the air flow on the upper surface of the wing, even when simulated ice was applied to the leading edges of the wings This change first appears in the vicinity of the trailing edge It was felt that an instrument, actuated by the changing air flow when the angle of attack is increased, would provide a warning of the impending stall

An instrument of this general nature was tested by the National Advisory Committee for Aeronautics in 1937 and was further developed by United Air Lines, Inc , during the years 1940 to 1943 With the thought that further flight testing on the part of the CAA would expedite this development, the cooperation of United Air Lines, Inc was obtained, and in March 1943 the stall warning system was installed in the Technical Development Division's Boeing 247-D airplane Extensive flight tests were conducted by the Civil Aeronautics Administration and U A L personnel at the Technical Development Division's Experimental Station at Indianapolis, Ind This report covers those flight tests

GENERAL DISCUSSION OF THE STALL

During normal flight the air flow over the upper surface of the wing is smooth and essentially laminar with a thin layer of turbulence (the boundary layer) next to the surface If the speed of the airplane is reduced, the angle of attack must be increased in order to obtain sufficient lift to support the airplane. As the angle of attack is increased it becomes increasingly difficult for the air flow to follow the upper contour of the wing and the boundary layer begins to thicken Further increases in the angle of attack cause the air streamlines to separate from the aft portion of the wing and to become generally turbulent The part of the wing where the air flow has become turbulent experiences a change in pressure and it no longer contributes to the lift The wing has then become partially stalled Any additional increases in the angle of attack cause the turbulence to spread forward and spanwise over the wing until there is an insufficient lift to support the airplane The airplane has then reached its stalling angle and falls, often resulting in a spin.

It is practically impossible to predict just where natural ice will accumulate on the wings or what its contour will be The amount and type of ice accumulated depend upon the severity of the icing conditions and the length of time that the airplane continues to fly under these conditions The precise effect of ice accretion on the aerodynamic characteristics of the wing cannot accurately be predicted Generally, the maximum lift coefficient and the angle of attack at which the stall occurs is markedly reduced and higher speeds are necessary to avoid stalling The accretion of ice may also cause the stall to occur almost immediately after the initial appearance of turbulence on the upper surface of the wing It is therefore essential to detect any change in the air flow as early as possible if an adequate warning margin is to be obtained.

DESCRIPTION OF TEST SETUP

The United Air Lines airplane stall warning system as installed on the Boeing 247-D airplane comprises four stall detector units and a warning indicator

The Stall Detector Unit

The stall detector unit shown in figures 1 and 2 is made of aluminum alloy and consists of a housing and a case containing a diaphragm switch arrangement The housing and the case are attached on opposite sides of a 3-inch diameter mounting plate The housing projects above the wing and the case is submerged within the wing

The housing is in the form of a streamlined blister and is 2-1/4 inches long, 1 inch wide, and 1/2 inch high A louvered opening in the top of the housing serves to transmit pressure changes from the upper exterior of the wing to the interior of the housing A small tube or standpipe further transmits those pressure changes to one side of the diaphragm case The other side of the case communicates with the interior of the wing by means of a static opening To provide drainage for any water that might enter the housing through the louver, a small tube is attached to the bottom of the mounting plate near the rear of the housing and opens to the interior of the wing

The case containing the diaphragm is 2-1/8 inches in diameter and about 3/8 of an inch in width The diaphragm is composed of a rubber impregnated silk material and has an effective diameter of 1-5/8 inches Thin metal plates, electrically connected, are mounted on either side of the diaphragm

In normal flight there is a negative pressure or suction existing on the upper exterior of the wing that holds the diaphragm to one side of the case against the pressure of a small leaf spring that incorporates an electrical contact The spring contact bears against the diaphragm plate and the spring pressure is regulated by a screw which is adjustable from the outside of the case. As the stall is approached, the general air turbulence and the aerodynamic effects produced by the housing contour combine to reduce the negative pressure to a point where the spring forces the diaphragm to move until the metal plate touches a contact which extends through but is insulated from the case. The electrical circuit is then made from the case through the leaf spring to the plates on the metal diaphragm and finally to the insulated contact This connects the airplane's battery directly to the lights on the warning indicator The diaphragm contacts of each stall detector unit carry 0 20 amperes at 12 volts

Location of the Stall Detector Units

The location of the stall detector units is determined by the progress of the stall over the wing as visualized through the action of tufts or streamers distributed over the entire upper surface of one wing In normal flight the tufts are directed rearward and are fairly steady due to the laminar flow of the air However, when the wing is stalled, the turbulent action of the air causes the tufts to oscillate violently

Motion pictures of tuft action on a Boeing 247-D airplane during level stalls with power off and power on were taken by United Air Lines, Inc These pictures showed that turbulence begins at the inboard end of the trailing edge next to the fuselage when the power is off As the angle of attack is increased the turbulent action progresses diagonally over the wing forward to the leading edge and outward to the wing tip This progress is illustrated in figure 3 When the stall is approached with the power on, the progression is similar but originates outside the propeller slipstream, as shown in figure 4

In order to obtain a progressive warning when approaching the stall, the stall detector units are located on the upper surface of the left wing near the trailing edge and are distributed spanwise from the outboard side of the nacelle to the wing tip Units on one wing only were found to be sufficient Their location, together with a wiring diagram, is shown in figure 5

The Warning Indicator

The warning indicator shown in figure 6 consists of a group of four lights arranged in a semicircle and mounted on a standard 2-3/4-inch diameter instrument case The lights are numbered 1 through 4 to correspond with the stall detector units Each light is covered with an amber-colored jewel to prevent undue glare The light bulbs are General Electric Mazda, single contact bayonet base, rated at 0 20 amperes at 12 to 16 volts

The indicator is provided with a cover plate which contains eight circular holes on its face For daylight operation the cover plate allows four 1/2-inch diameter holes to register with the lights For night operations the plate is rotated to permit four 1/16-inch diameter holes to register with the lights Thus the apparent intensity of the lights is reduced during night operation It was found that this lighting arrangement did not adversely affect the pilot's vision A test push button is installed on the face of the indicator behind the cover plate to determine whether the warning lights are functioning The cover plate incorporates a cam which pushes the button when the plate is rotated The warning indicator is mounted on the airplane's instrument panel directly in front of the pilot

Installation of the Stall Warning System

A hole 3 inches in diameter is cut in the wing skin at each of the stall detector unit locations The hole is reinforced with a ring which is riveted to the skin The stall detector unit is mounted on the reinforcement ring by means of screws through the mounting plate Stall detector unit No 1 installed on the Boeing 247-D wing is shown in figure 7

A single wire leads from each stall detector unit to a corresponding light on the warning indicator Number 22 General Electric Flameproof wires are used to connect the detector units to the warning lights The wires are enclosed in a single cable which is routed through the wing Each stall detector unit and light are a separate circuit and the complete installation operates on a 12-to 16-volt, direct-current, ground return system

Operation of the Stall Warning System

When the airplane is ready to take off, all the warning lights are indicating because the force of each leaf spring bearing against the diaphragm maintains a closed circuit As the airplane accelerates during the take-off, the air flow over the wing creates a suction at the opening of the wing detector which is transmitted to the diaphragm When the force of the suction becomes greater than that of the leaf spring, the diaphragm is deflected away from the insulated terminal and the light to which the detector unit is connected is extinguished This diaphragm action is illustrated in figure 8. As the take-off continues, each light is extinguished progressively and in sequence depending upon the location of each stall detector unit and upon the adjustment of the leaf spring

When the angle of attack is increased when approaching the stall or when landing, the pressure differential on each diaphragm is reduced When the force of the suction acting on each diaphragm becomes less than that of the leaf spring, the circuit is closed, as shown in figure 9, and a warning is given by the light on the warning indicator As the stall advances over the wing, due to a further increase in the angle of attack, a progressive warning is obtained from the lights on the warning indicator.

TEST PROCEDURE

Preliminary flight tests were conducted in order to adjust the leaf springs on the stall detector units It was the purpose of these adjustments to obtain a uniformly progressive warning when the airplane approached the stall with the wings level and the landing gear retracted It was also desired to obtain an initial warning at approximately 25 m p h above the stalling speed for No 1 warning light, a 20 m p h margin for No. 2 warning light, a 15 m p h margin for No 3 light, and a 10 m p h margin for No 4 light Time did not permit the opportunity to obtain a precise adjustment for the warning margins listed above, however, the final warning margins which prevailed at this particular flight condition were considered satisfactory as a basis for comparing the warnings given at other flight conditions

Flight tests were then conducted to determine the effectiveness of the U A L stall warning system when approaching the stall from various flight attitudes under different power settings and with retracted and extended landing gear positions. A description of the flight conditions are given in table 1

Table I

STALL TYPES

Stall Type	Flight Condition	Power Setting	Landing Gear Position
1	Level	On	Retracted
2	Level	Off	Retracted
3	Level	On	Extended
4	Level	Off	Extended
5	Left turn 30° bank	On	Retracted
6	Right turn 30° bank	On	Retracted
7	Landing	On	Extended

A level stall is one in which the nose is pulled up gradually with the wings level, a turn stall occurs when the airplane is banked in a turn All power stalls were performed with partial power at a manifold pressure of 14 inches Hg and a corresponding propeller speed of 1950 r p m The flight tests were conducted at altitudes between 3,000 and 4,500 feet

To determine the ability of the stall warning system to give adequate warnings when the normal stalling speed of the airplane is raised by the accretion of ice on the wings, flight tests were conducted with simulated ice applied to the leading edges of both wings The simulated ice consisted of a mixture of sawdust and dope which was applied to the wings in a plastic condition and which dried to form a tenacious mass resembling rime ice The simulated ice was applied in increasing amounts described in table 2, and each of the stall types listed in table 1 was repeated for every icing condition

Table II

ICE CONDITIONS

Ice Condition	Description
A	No ice
B	1/2-inch ice from outboard side of nacelles to points midway on each wing (figures 10 and 11)
C	1/2-inch ice from outboard side of nacelles to wing tips
D	1-1/2-inch ice from outboard side of nacelles to points midway on each wing and 1/2-inch ice from midpoints to wing tips
E	1-1/2-inch ice from outboard side of nacelles to wing tips (figures 12 and 13)

During each stall the copilot observed the sequence of the warning indications and the corresponding indicated air speed at which each warning light indicated An observer located at the cabin doorway recorded these indications as the copilot called out the readings The air speed at which the nose of the airplane began to drop was recorded as the stalling speed

RESULTS OF FLIGHT TESTS

Because of the continual movement of the pointer on the air-speed indicator as the speed of the airplane decreased when approaching the stall, and because the indicator dial was calibrated in increments of 5 m p h , it is estimated that an error of ±2 m p h in recording the data exists Since the pertinent quantity for evaluating the merits of a stall warning indicator is the difference between the air speed at which the warning is given and the stalling speed of the airplane, the total error is approximately ±4 m p h The extent to which the results are reproducible is not known because time did not permit an opportunity for the repetition of the individual tests However, the warning speeds in stall type No 7 are comparable with the warning speeds for stall type No 3

The warning and stalling speeds for all the flight tests have been tabulated and are shown in table 3 The warning margins, which are the differences between the initial warning speed V_W and the stalling speed V_S are given as the ratios V_W/V_S The data are also presented graphically in figure 14 The graphs show the speed at which each light indicated when approaching the stall and the stalling speeds for all flight conditions tested The sequence of the four warnings for each test condition is determined by the value of the warning speed indicated by each warning light shown in figure 14 The initial warning is given by the particular light indicating at the maximum warning speed shown, and the final warning is given by the light that indicated during the minimum warning speed

Table III

WARNING CHARACTERISTICS - STALL DETECTOR UNITS

Stall Type 1 Level - Power On - Landing Gear Retracted

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	82	79	78	64	56	82	26	1 46
B	78	80	73	62	60	80	20	1 33
C	79	86	86	75	72	86	14	1 20
D	79	89	88	72	70	89	19	1 27
E	80	92	90	76	71	92	21	1 30

Stall Type 2 Level - Power Off - Landing Gear Retracted

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	80	79	79	65	55	80	25	1 45
B	79	80	79	65	59	80	21	1 36
C	80	90	83	72	70	90	20	1 29
D	79	90	86	72	71	90	19	1 27
E	80	90	89	79	76	90	14	1 18

Stall Type 3 Level - Power On - Landing Gear Extended

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	100	90	94	80	61	100	39	1 64
B	89	92	92	75	70	92	22	1 31
C	86	92	95	83	81	95	14	1 17
D	87	94	95	83	82	95	13	1 16
E	92	98	100	94	90	100	10	1 11

Stall Type 4 Level - Power Off - Landing Gear Extended

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	95	89	90	76	61	95	34	1 56
B	88	91	93	72	70	93	23	1 33
C	89	93	97	84	82	97	15	1 18
D	92	95	95	87	85	95	10	1 12
E	95	96	100	96	95	100	5	1 05

Stall Type 5 Left Turn - 30° Bank - Power On - Landing Gear Retracted

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	82	88	87	65	65	88	23	1 35
B	82	80	73	72	72	82	10	1 14
C	80	88	89	70	69	89	20	1 29
D	76	86	85	72	71	86	15	1 21
E	80	89	90	75	73	90	17	1 23

Stall Type 6 Right Turn - 30° Bank - Power On - Landing Gear Extended

Ice Condition	Stall Detector Unit Warning Speed				Stall Speed V_s	Initial Warning Speed V_w	Initial Warning Margin $V_w - V_s$	Initial Warning Margin V_w/V_s
	No 1	No 2	No 3	No 4				
A	82	75	75	70	62	82	20	1 32
B	78	84	75	66	66	84	18	1 27
C	80	82	76	72	70	82	12	1 17
D	79	85	78	75	75	85	10	1 13
E	76	87	80	72	71	87	16	1 23

Stall Type 7 Landing - Power On Landing Gear Extended

Ice Condition	Stall Detector Unit Warning Speed				Initial Warning Speed V_w
	No 1	No.2	No 3	No 4	
A	86	89	92	70	92
B	89	90	92	79	92
C	92	92	90	90	92
D	92	96	96	79	96
E	95	101	100	89	101

DISCUSSION OF THE RESULTS

From an inspection of table 3 it is noted that positive initial warning margins are provided by the stall warning system when approaching the stall during the non-icing conditions The table shows a variation in the margins V_W/V_S from 1 32 to 1 64 for all the stall types performed when the wings are free from simulated ice

The application of ice to the leading edges of the wings reduces the warning margins For stall type No 4 and with 1-1/2 inches of ice on the wings, the margin is reduced to a minimum of 1 05 The effect of applying increasing amounts of ice to the wings is clearly shown in figure 14 Simulated ice on the wings caused the stalling speeds to increase appreciably but had little effect on the stall detector units, causing the warning speeds to increase slightly The warning margins were reduced as a result of this condition Actual icing conditions could well result in more ice than was simulated for flight test purposes, and if the progress discussed above were to continue, the stall would occur before the warning was obtained

It will also be noted in table 3 that extending the landing gear in level flight causes an increase in the stalling speeds This increase is noted when comparing the stalls performed in turns with those performed in level flight The approximate similarity existing in the warning margins for the two power settings when stalling under the same icing conditions indicates that power variation does not influence the stall warning system appreciably

It should be remembered that all the flight tests involved only one chordwise location and one leaf spring adjustment for each stall detector unit Tuft test results indicate that moving the stall detector units forward in the direction of the leading edge would cause them to operate at lower air speeds which would naturally reduce the warning margins Reducing the initial pressure of the leaf springs on the detector units would have the same effect The general operating characteristics, however, would not be expected to change appreciably due to moderate changes in the chordwise location and the spring adjustments

Although positive warning margins were given by the stall warning system in all the stalls performed when the wings were free from ice accretion, the wide variation in the margins is believed to be undesirable It is felt that a warning which is given too early will eventually be disregarded by the pilots. On the other hand, a warning which is given very close to the actual stall, as experienced during the severest icing condition tested, is considered dangerous. A value for V_W/V_S of 1 25 to 1 30 has been suggested as a satisfactory margin

CONCLUSIONS

The flight tests of the U A L airplane stall warning system on the Boeing 247-D airplane indicate that there is considerable promise for the development of an instrument of this general type which will provide reasonably uniform and adequate warning margins when there is no ice on the wings of the airplane

Results of the flight tests on this stall warning system indicate that increasing applications of simulated ice reduces the warning margins, but are not indicative that the development of an instrument which will give satisfactory warnings during this condition is unfeasible

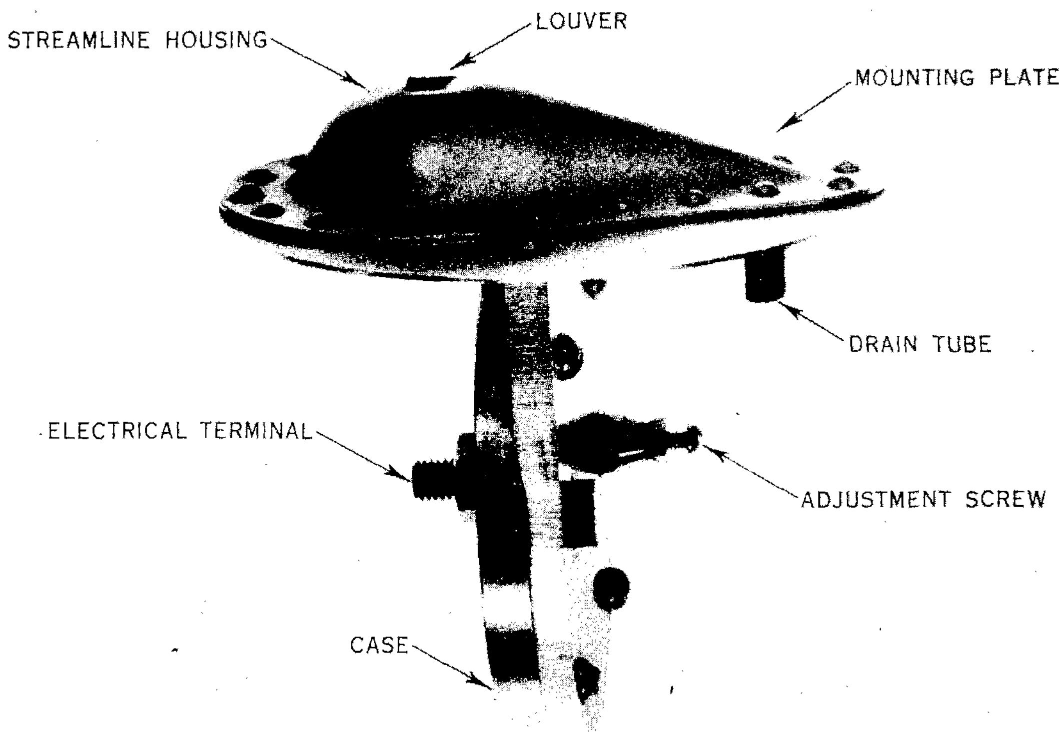


Figure 1. Stall Detector Unit - Assembled.

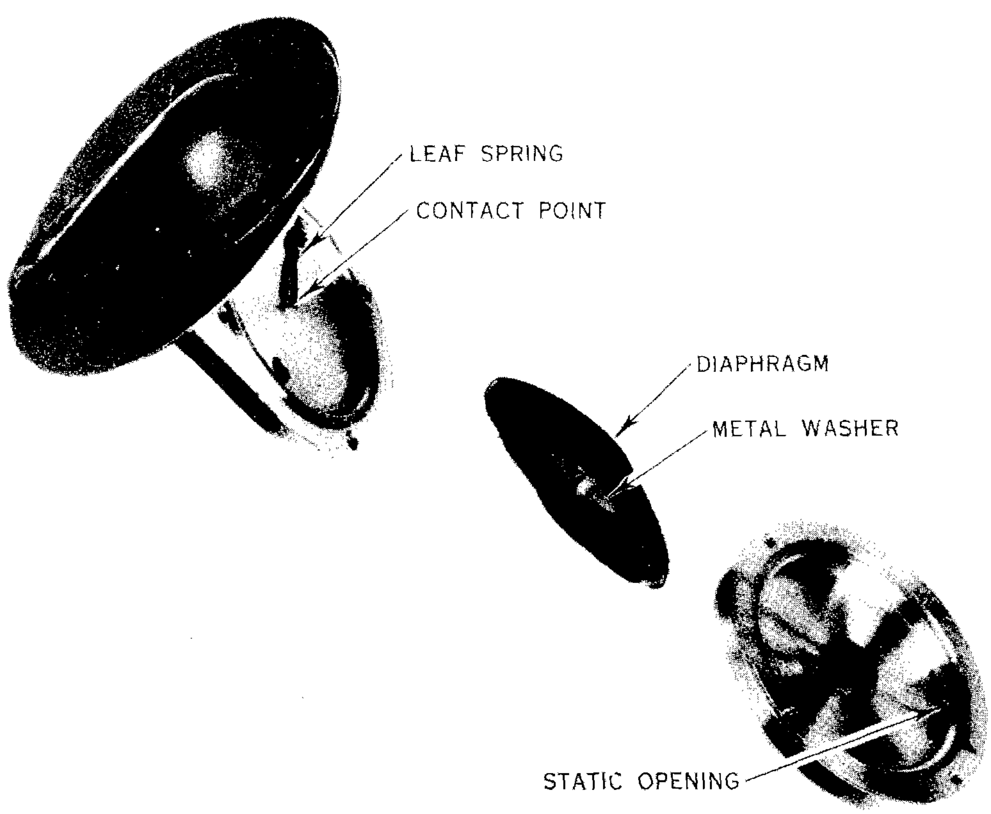


Figure 2. Stall Detector Unit - Unassembled.

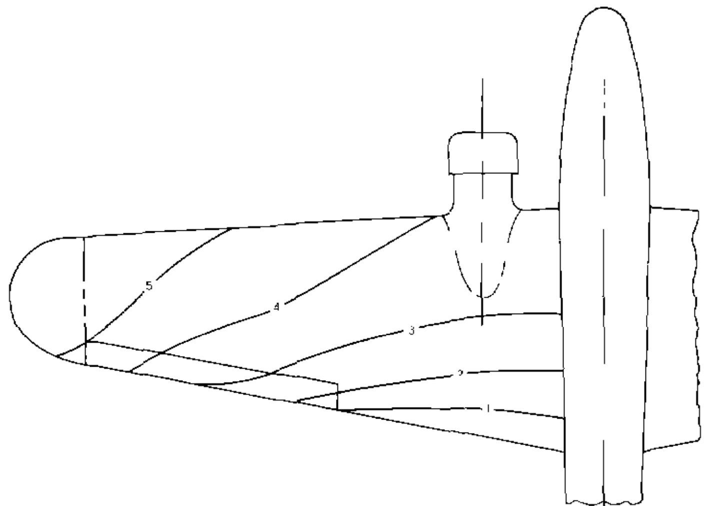


Figure 3 Stall Progression on Boeing 247 D Wing Power Off

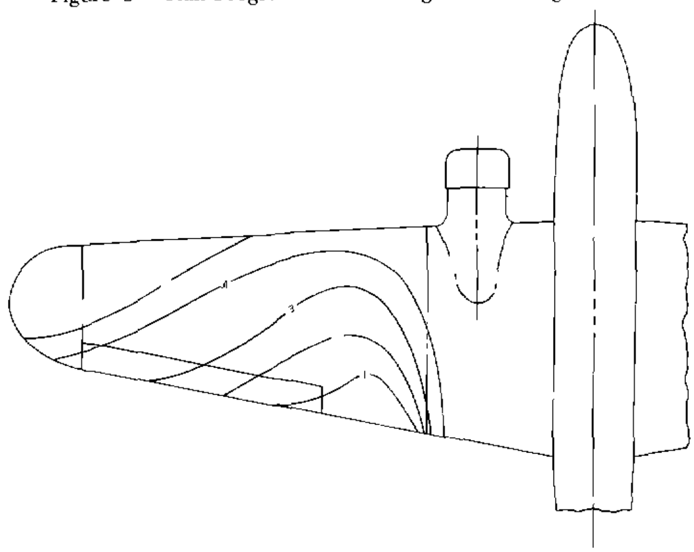


Figure 4 Stall Progression on Boeing 247 D Wing - Power On

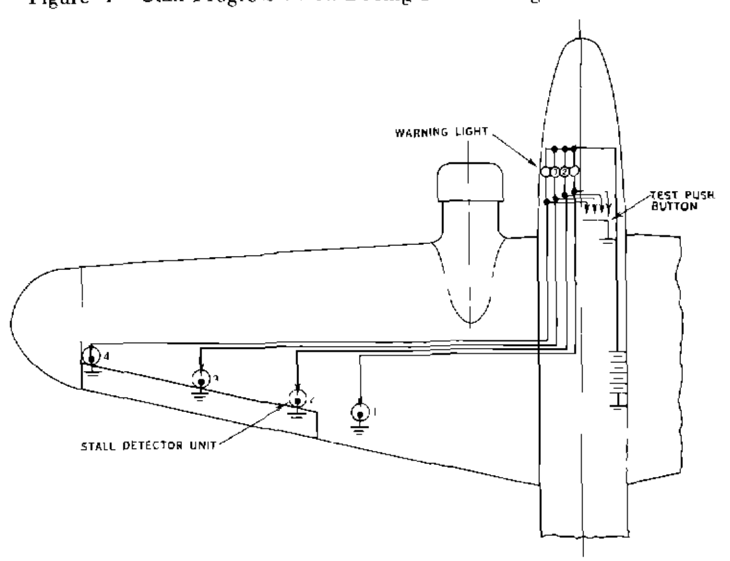


Figure 5 Installation of U A L Airplane Stall Warning System on Boeing 247 D Airplane

Figure 6. Warning Indicator.

Figure 7. Stall Detector Unit No. 1 Installed on Boeing 247-D Airplane Wing.

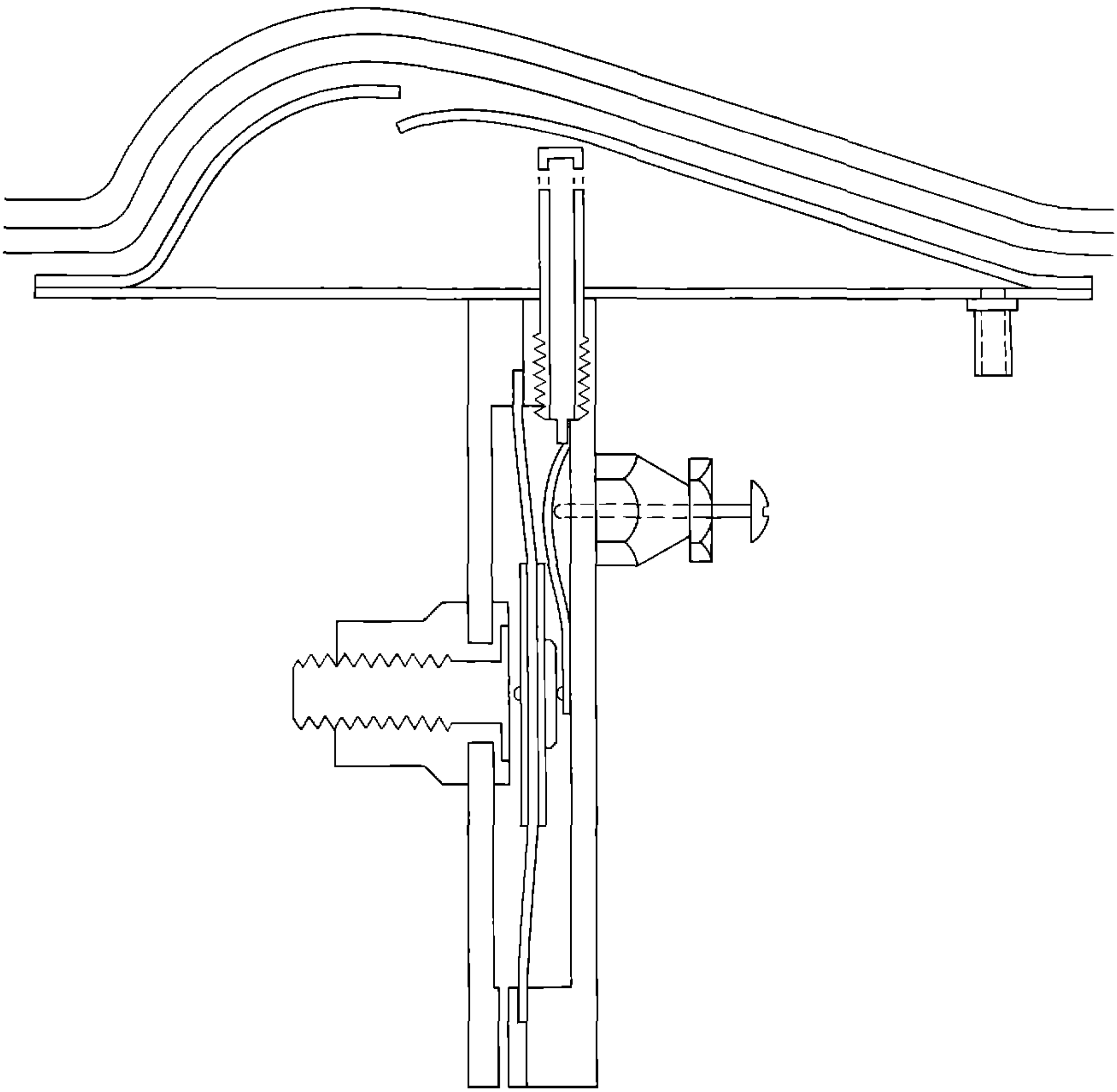


Figure 8 Stall Detector Unit Open Circuit

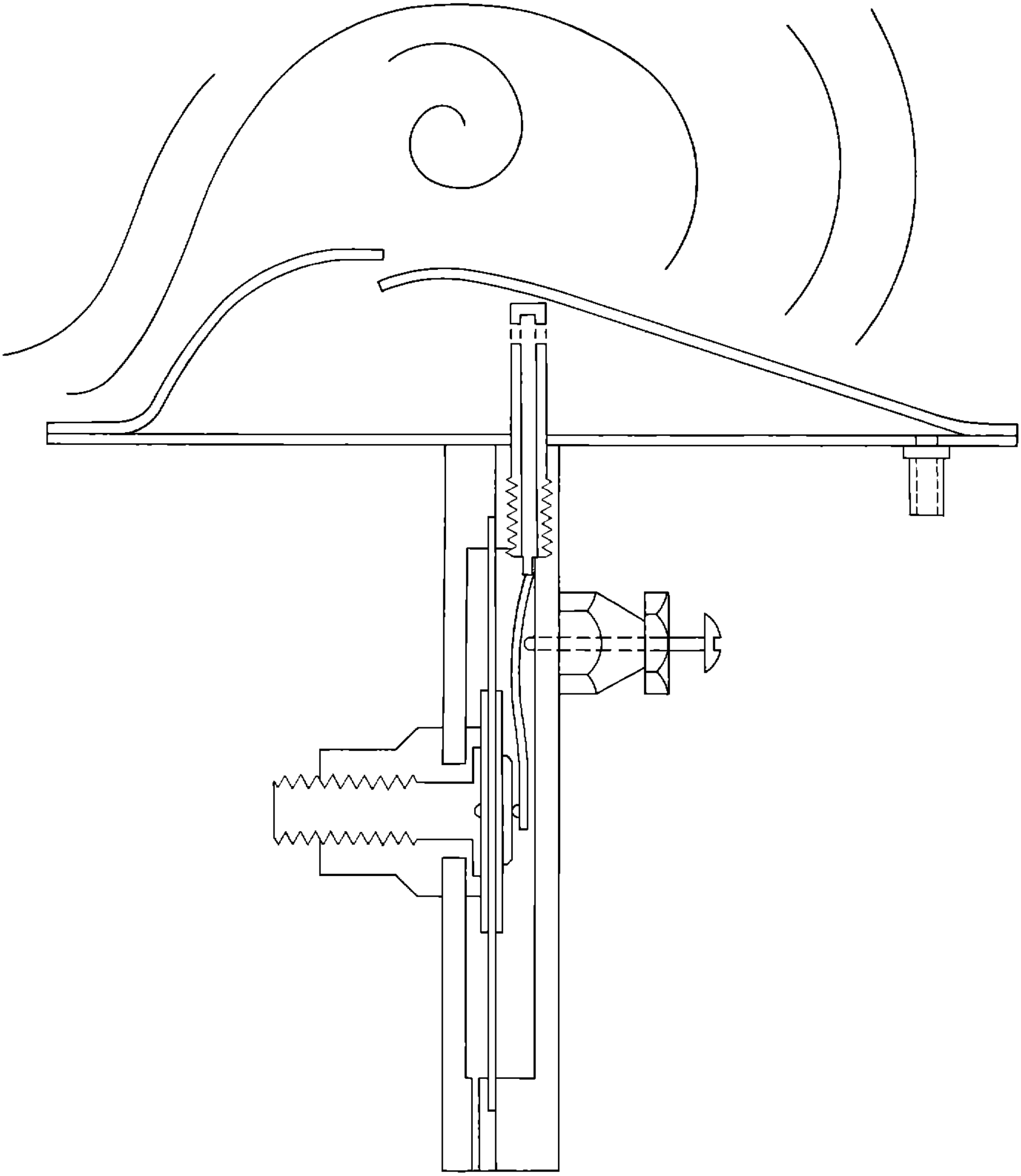


Figure 9 Stall Detector Unit Closed Circuit

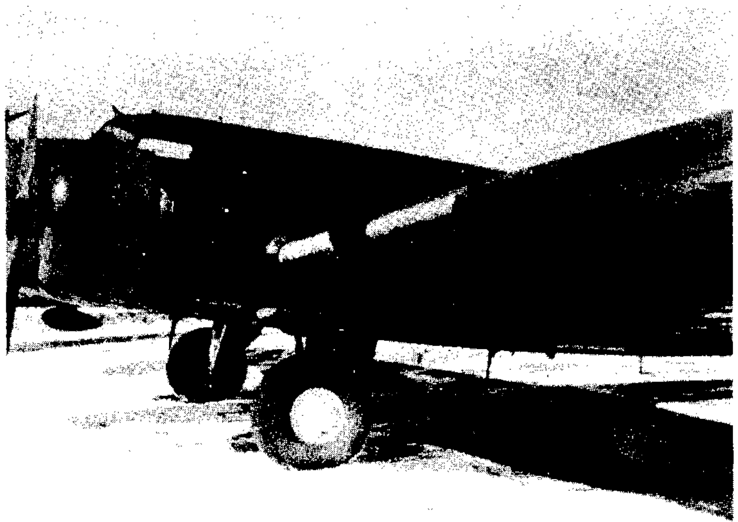


Figure 10. One-Half Inch Simulated Ice on Leading Edge of Boeing 247-D Airplane Wing.

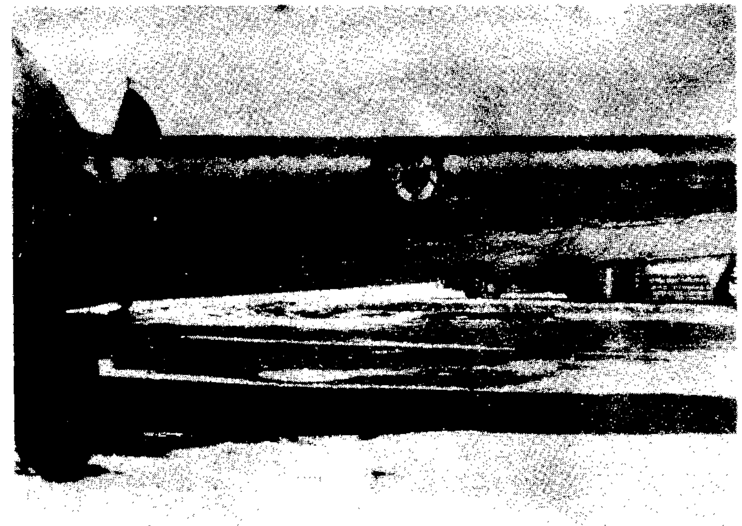


Figure 11. One-Half Inch Simulated Ice on Leading Edge of Boeing 247-D Airplane Wing.

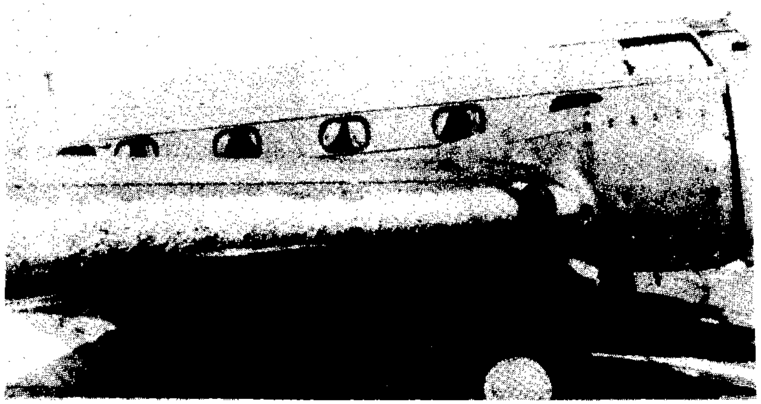
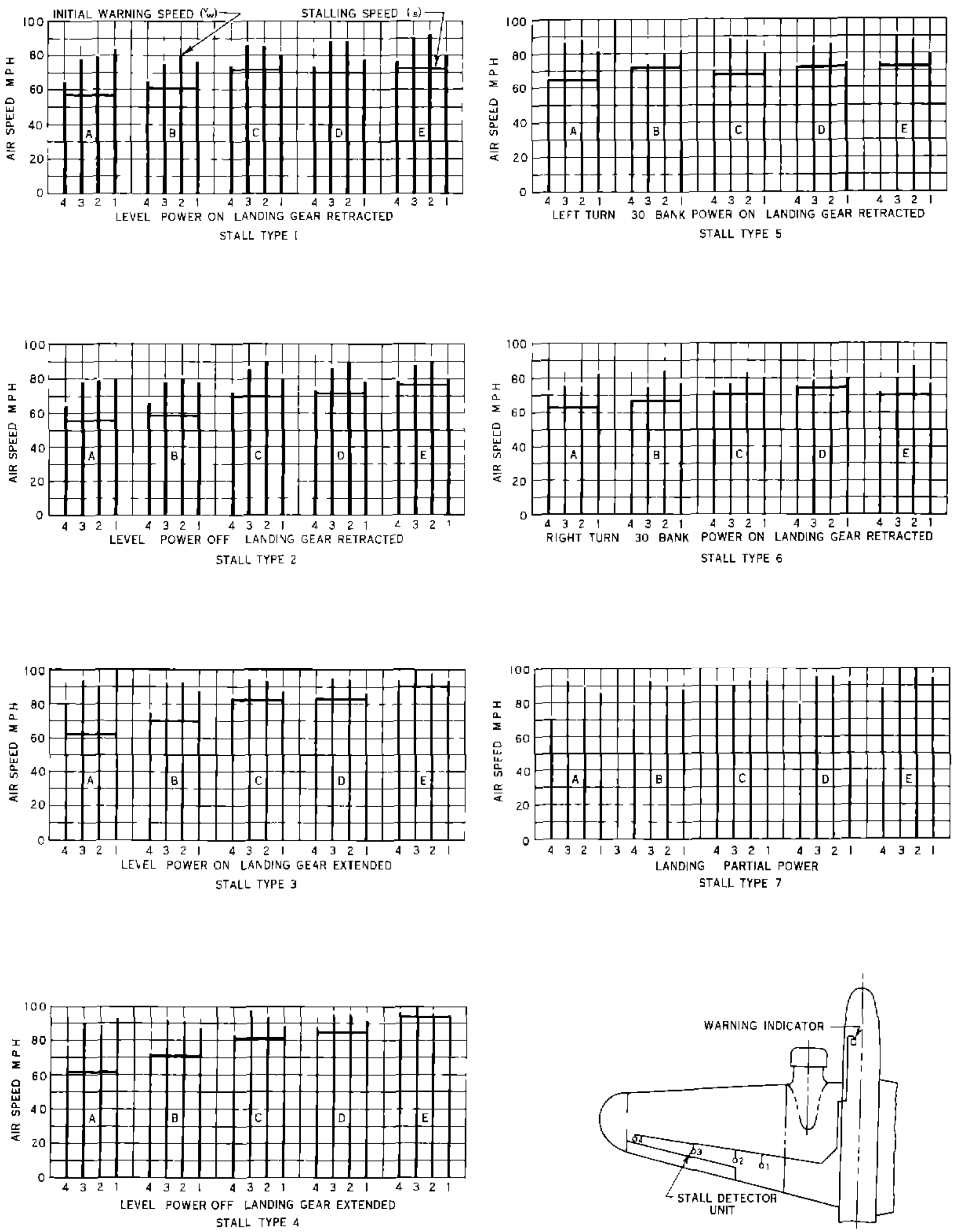


Figure 12. One and One-Half Inch Simulated Ice on Leading Edge of Boeing 247-D Airplane Wing.

Figure 13. One and One-Half Inch Simulated Ice on Leading Edge of Boeing 247-D Airplane Wing.



ICE CONDITIONS A TO E — SEE TABLE 2

Figure 14 Warning Characteristics Stall Detector Units