1- BY 3-FOOT SUPERSONIC WIND TUNNEL

MECHANISM OF SWEEPBACK

Jack N. Neilsen, Edward W. Perkins, or Robert T. Madden

This building houses two supersonic wind tunnels. Behind you is Tunnel No. 1 - a closed-return tunnel equipped with an adjustable nozzle for varying the test Mach number. In front of you is Tunnel No. 2, or the blowdown tunnel, which will be described and demonstrated **later.**

It is our object in this short meeting to discuss a few of the problems associated with the use of sweepback at transonic speeds. Although this is a supersonic research facility, we are emphasizing the transonic speed range because of its current importance and because the transonic and supersonic speed ranges overlap. I will discuss the simple theory of sweepback and point out how sweepback helps to overcome some of the adverse effects of compressibility. The following speakers will discuss various aspects of the problems of airplane performance and stability as related to sweepback. The last speaker will give a brief description of the blowdown tunnel and will demonstrate some favorable effects of sweepback on a wing at a Mach number of 1.2. The material to be covered in these talks is taken from both theoretical results and experimental results obtained from NACA wind tunnels and flight tests.

The possible use of sweepback to increase the aerodynamic efficiency of wings intended to fly at supersonic speeds was first suggested by Bussman at the Volta Congress in Italy in 1935. The wings advocated by Busemann incorporated only moderate angles of sweep for Mach numbers of about 1.5. During World War II, R. T. Jones of the NACA pointed out that substantial gains were to be realized by using sweep angles greater than those advocated by Busemann. Based upon this result of Jones, much work has been done in the past several years toward development of practical swept-back wings.

With the aid of this model (fig. 5(b)), I would now like to explain the theory of sweepback. In its present condition the model has a conventional unswept wing. The velocity of the air relative to the wing is represented by this arrow or vector. The air approaches the wing in a direction which is essentially perpendicular to the leading edge. Consider now the wing rotated about the middle of the root chord, until the sweep angle of the leading edge is about 60° (fig. 5(c)). It is apparent that the air no longer approaches the wing leading edge at right angles. In fact, the air velocity can now be considered to consist of two components; one parallel to the leading edge (represented by this vector) and one perpendicular to the wing leading edge (represented by this vector). The vector diagram shows that the component perpendicular to the leading edge is only about one-half the flight velocity. Now, the simple basis of sweepback is that the forces acting on the wing depend only on the component of velocity perpendicular to the wing leading edge and are not affected by the parallel component. This result is reasonable since air flowing out along the wing toward the tip can produce no appreciable pressures on the wing. We will call the perpendicular component the effective velocity. With the aid of this fundamental concept that we have just discussed, I will point out some of the advantages of sweepback.

The difficulties encountered in flying airplanes with conventional, unswept wing of Mach numbers above 0.8 are well known. At these flight speeds there is a general breakdown in the smooth airflow around the wing. This flow breakdown, known as the shock stall or compressibility burble, is accompanied by large changes in the pressures acting on the wing, which in addition to other detrimental aerodynamic effects, causes large increases in the drag. Consider now an airplane with a wing swept back 60° flying at the same flight Mach number of 0.8. Since as was previously pointed out, the effective velocity, or what is equivalent, the effective Mach number, is much less than 0.8. And since the shock stall occurs only when the effective Mach number reaches or exceeds 0.8, it will not occur for the swept back wing at this flight speed. In fact, the shock stall will be delayed to a much higher flight speed where the effective Mach number, itself, reaches 0.8. Thus sweepback tends to delay the effects of compressibility. It is also noteworthy that while sweepback delays the adverse effects of compressibility to higher flight Mach numbers, it also reduces the severity of these effects when they do occur.

Some of these points are illustrated by this chart (fig. 5(d)) which presents the variation with Mach number of the minimum drag coefficient for the unswept wing and for the wing swept back 60°. For purposes of this discussion, the difference in aspect ratio between the two wings is unimportant. At a flight Mach number of 0.8, the swept-back wing has a lower minimum drag than the unswept wing and its rate of drag increase with Mach number is also much less. The swept wing maintains this advantage of low minimum drag up to a flight Mach number of approximately 1.9. At this flight speed, the effective Mach number for the swept wing is about 0.8, and the effect of compressibility is to increase the minimum drag coefficient in a manner analagous to that for the unswept wing at a flight Mach number of 0.8. Above a flight Mach number of 1.9 the unswept wing has the lower minimum drag. It is apparent that by using sweep angles greater than 60°, we might maintain the advantage of sweep to higher flight Mach numbers. However, because of practical considerations the amount of sweep that can be used is limited.

The next speaker, ______, will discuss some of the problems of airplane performance that are related to sweepback.

PERFORMANCE OF SWEPT-BACK WINGS

Newton Mas, H. J. Walker, or James Summers

In the design of airplanes that are to be used for long range transport or bomber service, the primary criterion for the prediction of performance is the lift-drag ratio, which is a measure of the efficiency of an airplane as a load carrier. This type of airplane should be designed to cruise at a speed and altitude where the maximum possible lift-drag ratio is utilized. In this discussion we will consider the performance of various airplanes which will be assumed to be flying in this optimum condition at all times.

Extensions in top speed with propeller driven airplanes have been attained by the use of higher wing loadings and by increases in available power. However, further substantial increases in maximum speed may be realized by flight at very high altitudes. To indicate the possibilities of flight in the stratosphere, suppose that an airplane flying at about 300 miles per hour at sea level could maintain the same drag and thrust characteristics at higher altitudes and Mach numbers. This chart (fig.5(e)) shows how the flight Mach number could increase with altitude. At a height slightly under 12 miles, the flight Mach number is slightly in excess of 1.5 which corresponds to a speed of 1000 mph. However, the initial assumptions that were made, constancy of drag and thrust characteristics, must be satisfied. The maintenance of thrust at these speeds and altitudes is possible when we consider the use of a turbo-jet engine designed for service under these conditions. The maintenance of low speed drag characteristics, or as are more important, efficient lift-drag ratios, can be accomplished by the use of a sweptback wing similar to that described by the previous speakers. The low-speed wing that is most efficient is the high aspect ratio wing with little or no sweep. Unfortunately, when this type of wing is flown at Mach numbers of 0.80 or greater, it sustains a ten to twenty fold increase in drag with resultant prohibitively low lift-drag ratios, although any attempt to extend the efficient low speed wing into the moderate supersonic speed regime would be impractical. This chart (fig. 5(f)) shows how the required thrust for a 40,000-pound airplane with this unswept wing would vary with Mach number. Actually these values could be materially reduced by using sharp leading edge wings of smaller aspect ratio.

The required thrust for another 40,000-pound airplane with 60° swept-back wings is also included. In this graph, the two airplanes are considered to be flying at the altitude at which their maximum lift-drag ratios occur for each speed. The improvement with sweepback is immediately apparent and the attainment of the values of thrust required by the swept wing transport at very high speeds are not beyond the forseeable future. As was indicated by the previous speaker the straight wing becomes better at Mach numbers of 2 and higher if the sweep is limited to about 60°.

This chart (fig. 5(g)) combines the estimated airplane and propulsive efficiencies and indicates the trends in fuel mileage that can be expected with high speed aircraft. Again the comparison is based on 40,000 pound airplanes at altitudes which allow each airplane to fly at maximum combined efficiency at every speed. Three airplanes are represented; one with the unswept wing and reciprocating engine and propeller combination; the same airplane with a turbo-jet engine installation; and the sweptback wing airplane with a similar turbo-jet engine. At low subsonic speeds the propeller driven airplane is definitely superior because of the low fuel consumption. However, at Mach numbers above 0.8, where both propulsive and wing efficiencies drop radically, flight with this transport would be quite impractical. The values of mileage of the jet-propelled unswept wing airplane at those speeds also drop, but only in the region of poor wing efficiency. These difficulties do not appear when we consider the swept-back wing airplane which continuously maintains relatively high and definitely usable mileages at moderately supersonic speeds.

Using these mileages for a design range of 2000 miles, the 40,000 pound sweptback wing transport, flying at 12 miles altitude, could travel that distance in about two hours with less than 25 percent of its gross weight in fuel, that is, San Francisco to Chicago in less time than it takes to see a double feature movie. It might be pointed out that "ride roughness" is decreased by the use of sweepback which is accompanied by a lower gust factor and that for these configurations the swept wing airplane would be about 1/3 as rough riding as the conventional transport.

Because of the present limitation on usable maximum lift coefficient, due to a longitudinal instability, the landing speed of this plane would be about 190 miles per hour, which is excessively high. This stability problem and others accompanying the use of sweepback will be discussed by Mr. ________________ in the next talk.

STABILITY AND CONTROL CHARACTERISTICS OF SWEPT-BACK WINGS

Arthur Jones, John Sprieter, or
Elliott Katzen

The time required to effect lateral or vertical displacements in a stable airplane equipped with adequate control is essentially the same at subsonic or supersonic speeds. The problem of flying safely at supersonic speeds, therefore, is not one of producing superhuman pilots having phenomenally short reaction time, but one of building airplanes that have stability and control characteristics comparable to what is considered satisfactory in the average aircraft of today. It is also necessary that these characteristics remain as nearly uniform as possible throughout the airplane's entire speed or Mach number range. In this respect we shall endeavor to show that the swept-back wing is decidedly superior to the unswept wing.

The following graphs were prepared from data obtained from the research facilities of the Langley and Ames Laboratories of the NACA. These graphs show the variation with Mach number of some of the basic stability and control factors. You will hear reference to these factors again from both the 12-foot and 16-foot wind tunnel groups, which should be an indication of their significance.

The next chart (fig. 5(h)) shows the variation with Mach number of the center-of-lift location relative to the center of gravity. The center of gravity is represented by this white line. When the center of lift curve lies above the white line it lies forward of the center of gravity, and when the curve lies below the white line the center of lift lies behind or aft of the center of gravity. Now with regard to the longitudinal stability of the airplane, whenever the center of lift is behind the center of gravity, the airplane, after being disturbed, tends to return to its original attitude much in the manner that a weathercock stays lined up with the wind. On the other hand, with the center of lift ahead of the center of gravity, the airplane is unstable. You will note that the variation of the center of lift for the swept-back wing is quite small and regular. On the other hand the variation for the unswept wing is so large and irregular that it will probably require a large horizontal tail to be used in conjunction with the wing to provide longitudinal stability at all speeds.

A factor in the control requirement category is revealed on this same graph which shows the angle of attack required to maintain a constant lift coefficient. The curve for the unswept wing has much the larger and more irregular variation. This means that as changes in speed are made, the longitudinal control will have to be applied frequently and generously in changing the attitude of the airplane to maintain the proper lift and keep the airplane flying straight and level. These frequent control manipulations would impose excessive demands on the pilot of the plane with the unswept wing.

The next chart (fig.5(i)) shows how an important lateral stability parameter, the effective dihedral angle, varies with Mach number. These curves are for wings with no geometric dihedral. Note the reversal of the sign of the parameter for the unswept wing as you proceed from subsonic to supersonic speeds. This indicates that the aileron deflection required to hold wings level in sideslip would reverse in sign somewhere in the transonic range. As the flight research group has pointed out, the pilots consider this aileron reversal as signified by the negative dihedral effect to be a very undesirable situation.

On the adverse side of the argument for swept-back wings it must be admitted that, at present, there is a serious problem that has not been satisfactorily solved. The problem is one of obtaining a lift-drag ratio in the landing attitude that is sufficiently large to keep the sinking speed as well as the forward speed within reasonable limits. This problem is caused by the relatively early tip stall of the swept-back wing. The obvious modifications that might be applied to remedy the situation such as slots or slats, special flaps, or drooped leading-edge devices, tend to alleviate the early tip stall somewhat, but do not provide a completely satisfactory solution to the problem.

In summary, I wish to say that the superiority attributed to the aerodynamic characteristics of the swept-back wing in this series of talks was in no way intended to prove that an airplane with an unswept wing cannot be flown at transonic or supersonic speeds. It is now common knowledge that the XS-1, for instance, has been flown at supersonic speeds. We have merely tried to indicate that the swept-back wing is the more efficient of the two in the transonic and moderately supersonic range. This then is the reason that the swept-back wing must be considered for the supersonic transport airplane even though this plan form may be associated with landing problems far more serious than those that exist for the unswept plan forms. Mr. ______________ will now demonstrate the 1- by 3-foot supersonic wind tunnel.

WIND-TUNNEL DEMONSTRATION

J. Richard Spahr, Robert A. Robinson, or
Joseph Spiegel

As an illustration of some of the principles just described, the beneficial effects of sweepback on the drag of a wing at supersonic speed will be demonstrated in the wind tunnel before you. This wind tunnel is an intermittent-operation tunnel of the so-called "blowdown" type, through which high-pressure air from the adjacent 12-foot pressure tunnel is expanded to the atmosphere. By this process a maximum of about 15 minutes is available for testing. A maximum Reynolds number of 28 million can be reached with a 12-inch model, which corresponds, for example, to a full-scale V-2 missile flying at an altitude of about 70,000 feet and at the same Mach number. The test section of the wind tunnel is 1 foot wide and about 3 feet high, and the Mach number can be varied by means of a flexible nozzle from 1.2 to 3.4, the maximum value being equivalent to about 2600 miles per hour at sea-level conditions.

In order to demonstrate the effects of sweepback on the flow pattern around a wing in supersonic flight, a small wing having variable sweepback is mounted vertically in the test section. The wind tunnel will be operated at a Mach number of 1.2 during which the wing sweepback will be increased from 0° to 45° and then back to 0°. For purposes of the demonstration the schlieren field will be projected onto this display board in order that the flow around the wing can be observed conveniently.

Before the wind tunnel is started, I should like to describe briefly a few of the salient features of the shock-wave pattern which you will observe. As you may know, the schlieren apparatus detects density and hence pressure changes in the flow field. The shock waves which represent sudden pressure increases, appear as dark lines in this schlieren field, and are accompanied by energy losses. Hence, the drag of a wing or body at supersonic speed increases with the intensity of the surrounding shock waves. Consequently, the beneficial effect of sweepback on the drag of this wing can be demonstrated by the decreasing intensity of the shock waves produced by the wing.

A few seconds after the wind tunnel is started, a strong shock wave perpendicular to the tunnel axis will be observed to pass through the test section, followed by the establishment of supersonic flow and the accompanying shock-wave pattern from the wing. These schlieren photographs (fig. 5(j)) of the variable-sweep wing show the effect of sweepback on the wing shock-wave pattern which you will observe in a few moments. With no sweepback a very intense shock wave represented by this solid black region (point to first picture) will be seen ahead of the wing. With the wing swept back, it will be noted that the shock wave is also swept back with an accompanying reduction in its intensity and hence a reduction in the wing drag. (point to second picture)

The schlieren field will now be projected onto this screen for the demonstration. The direction of the air flow is from right to left. Since the noise level of the wind tunnel during operation is quite high, I will not be able to describe the flow at that time. However, I will point to the various features of the flow which I have just described.

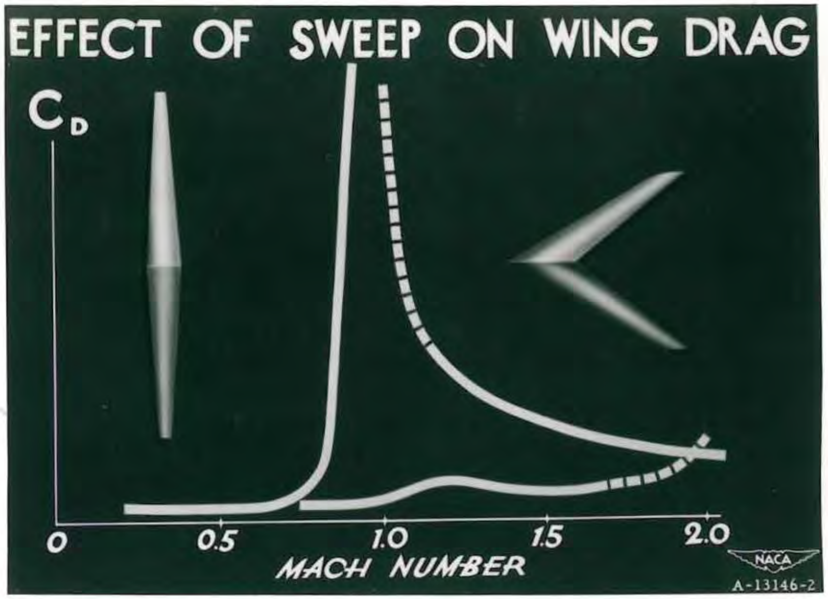
The wind tunnel will now be started.

(a) General view.

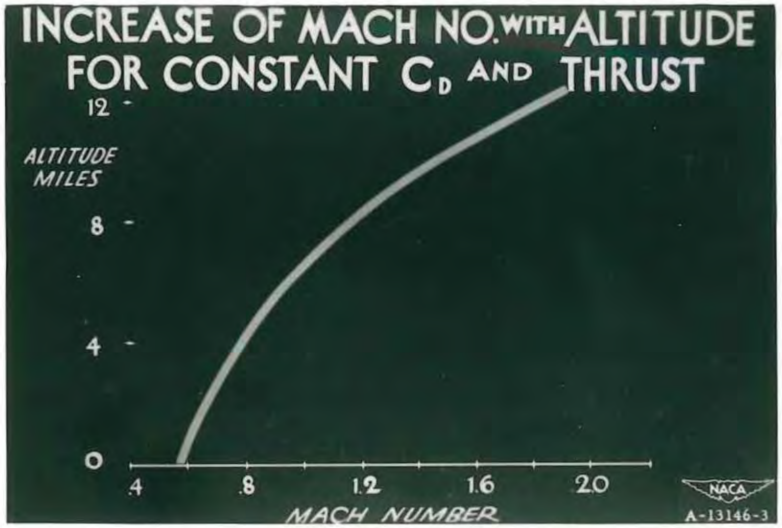
Figure 5.- 1- by 3-foot supersonic wind-tunnel exhibit.

(b) Velocity component on straight wing.

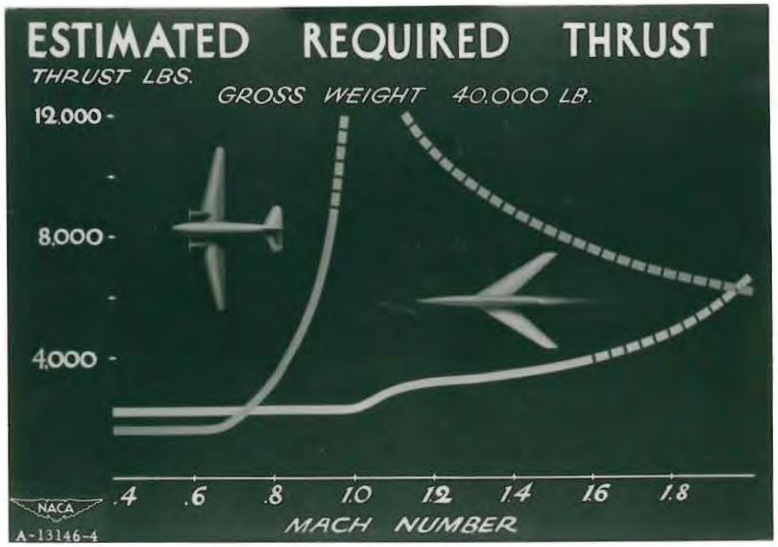
(c) Velocity components on swept-back wing.



(d) First chart.

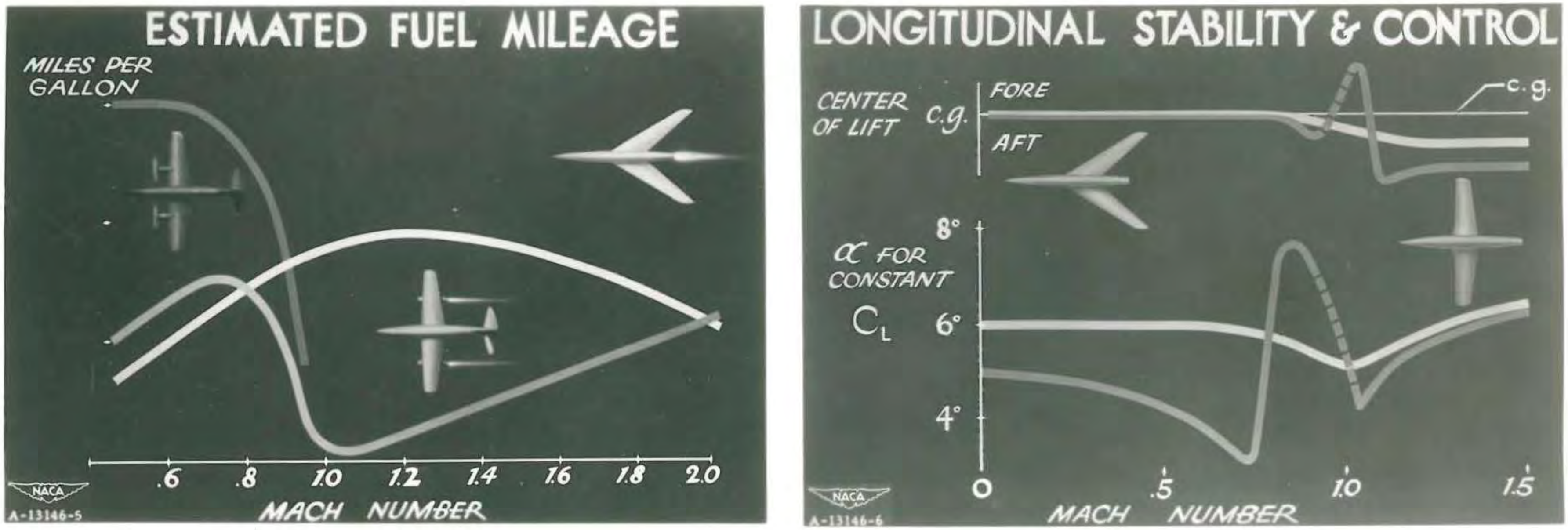


(e) Second chart.



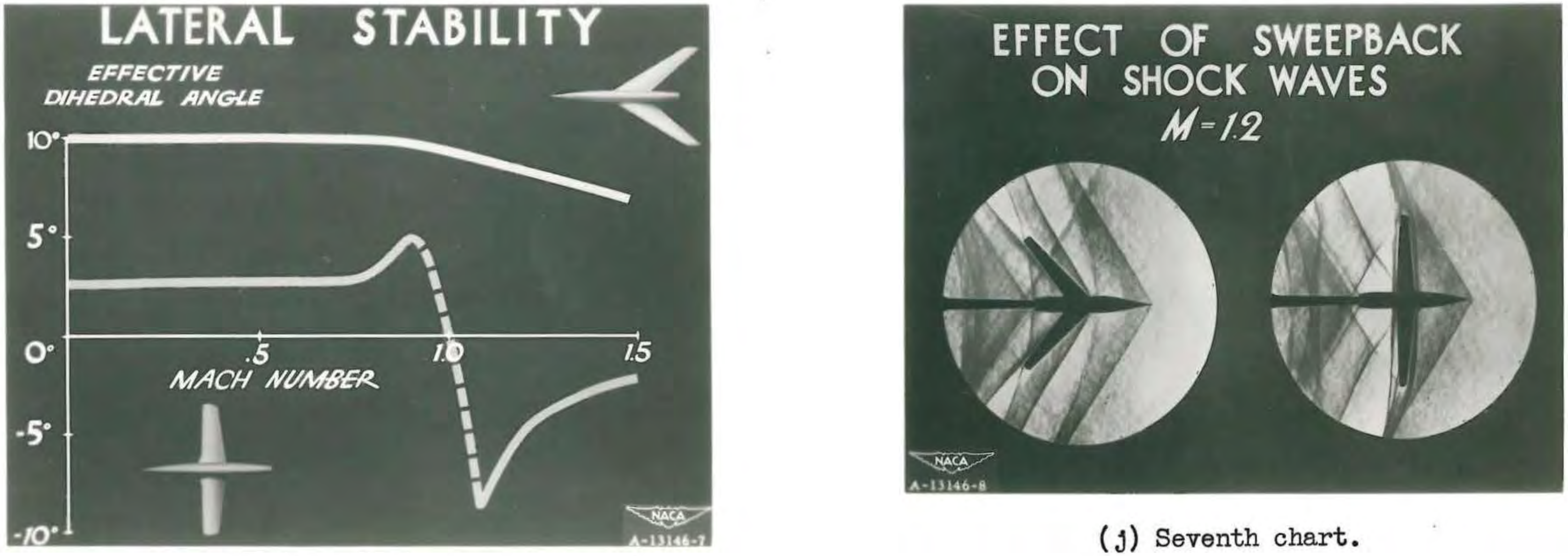
(f) Third chart.

Figure 5.- Continued.



(g) Fourth chart.

(h) Fifth chart.



(j) Seventh chart.

(i) Sixth chart.

Figure 5.- Concluded.