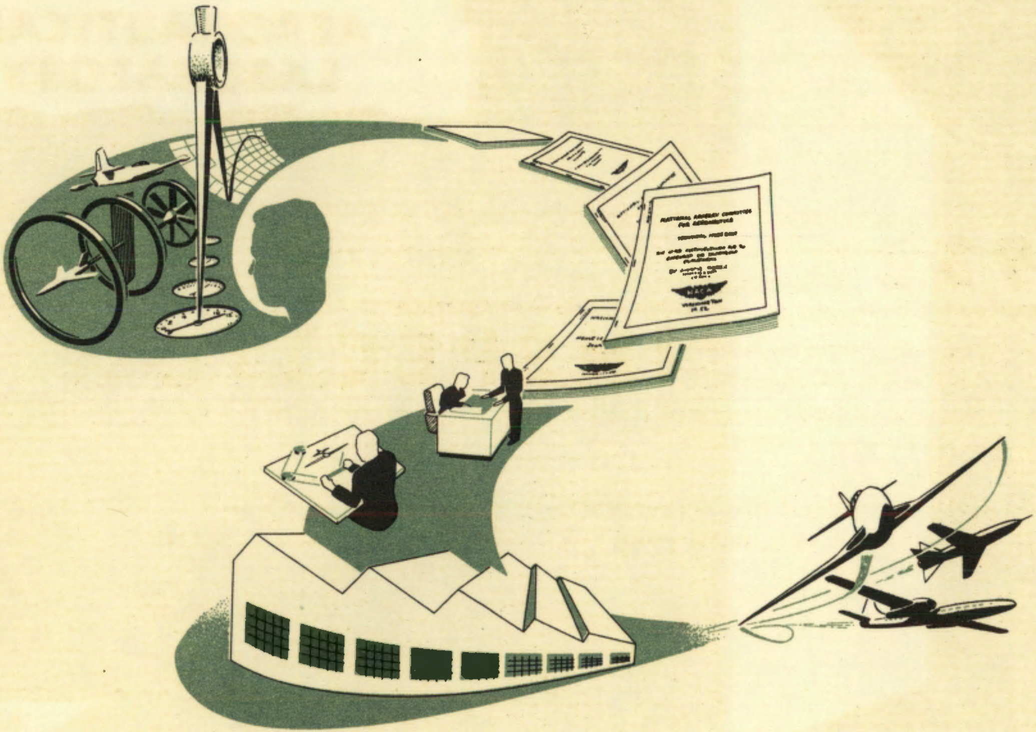
AMES AERONAUTICAL LABORATORY

1952

INSPECTION

NACA

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS



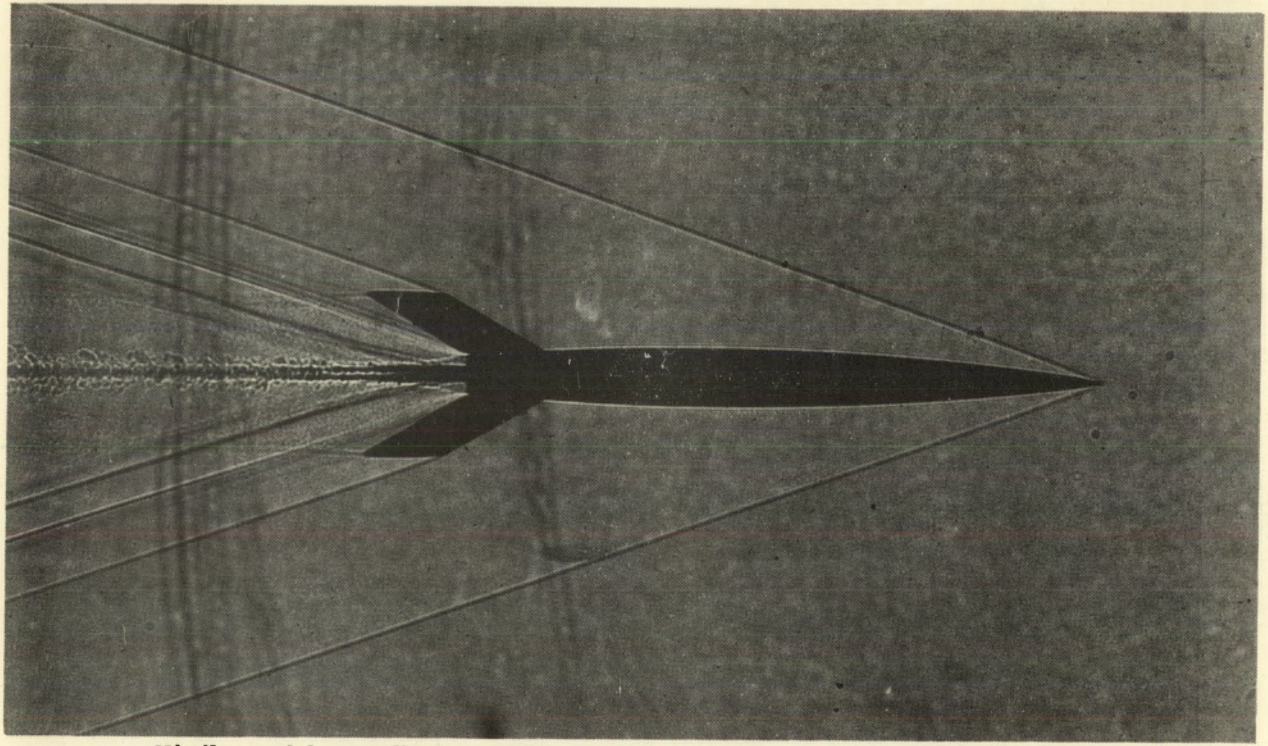
WELCOME . . .

It is a pleasure to welcome you on behalf of the National Advisory Committee for Aeronautics to the 1952 Inspection of the Ames Aeronautical Laboratory. It is our purpose to outline for you the field in which we are working and to summarize progress in certain segments of this field.

The Ames Laboratory is devoted to investigation of aerodynamic phenomena, with emphasis on the problems of high-speed airplanes and missiles. A well integrated research program must consider the interrelation of the various problems in this field as well as structural and propulsion requirements. The changing needs of the military services require constant review and reorientation of research effort. In order that the work of the staff and equipment of NACA laboratories may be most effective, continual cooperation and interchange of ideas with the industry and with the military services are essential.

We are happy to have this opportunity to show you as much of our work as time permits. We hope we can make your visit both profitable and pleasant.

J C Hunsaker
Chairman
National Advisory Committee for Aeronautics



Missile model traveling at 2500 m. p. h. caught by shadowgraph in supersonic free-flight tunnel.

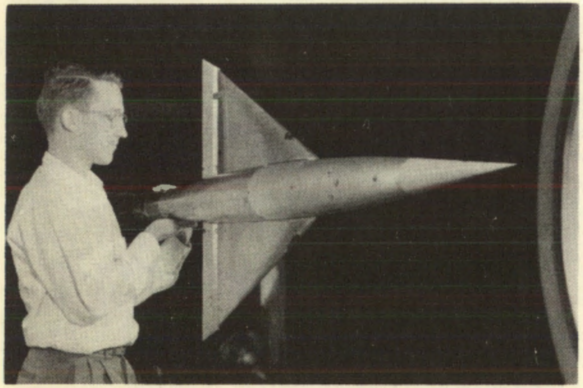
Supersonic flight multiplies aerodynamic problems . . . .

Twelve years ago when the Ames Aeronautical Laboratory was established the principal problems of aerodynamic research were concerned with the performance and static stability of airplanes at subsonic speeds. The field of major interest lay in the effects on airplane characteristics of the compressibility of the air at speeds well below that of sound. Research at supersonic speeds was hardly more than of academic interest and involved a very minor fraction of the total research effort.

In recent years the development of rocket and jet engines has made possible the construction of airplanes to fly at transonic and supersonic speeds. This fact, and the advent of the guided missile, have moved the center of research interest to transonic, supersonic, and hypersonic speeds. Progress in aerodynamics is making flight at these speeds practicable and has contributed more than a little to the high speeds attained.

The increase in speed of airplanes has brought with it a host of new problems. The old problems of performance and static stability are still present; however, in general, they require different solutions. In addition, new problems are involved. Control forces become very large, requiring powered operation of controls. Airplane response to control movements and to gusts is rapid. Oscillations are also rapid, perhaps too rapid for a human pilot to cope with. Hence, automatic stabilization and control may be required. Missiles likewise require automatic stabilization and control. This trend brings into sharp relief the importance of the dynamic characteristics of aircraft as well as the dynamic characteristics of powered and automatic control and stabilization systems; that is, the complete system comprised of aircraft and its control and guidance equipment must be stable both statically and dynamically. If a human pilot is involved in the system, his response time and control capability must be included in the analysis of the system.

In general, the control characteristics of aircraft and guidance systems cannot be plotted as a straight line over their entire useful range. For example, if 10° of control deflection produces 5° of change in trim angle, 20° of control deflection might produce only 8° of change in trim angle. This nonlinear condition does not necessarily



Control flap model in supersonic tunnel.

mean that the system cannot be made satisfactory; however, it greatly complicates the mathematical analysis of such a system and renders component evaluation difficult.

The growing importance of dynamic characteristics has led to the development and exploitation of new techniques for determining such characteristics and for analyzing and synthesizing various combinations of aircraft and control and guidance systems. Emphasis has been placed on the determination of dynamic characteristics of airplanes and models in free flight. Wind-tunnel techniques involving oscillating models have also been developed. Analytical studies utilizing high-speed computing machines have been undertaken.

Intensive theoretical studies guide experimental work at transonic and supersonic speeds and permit generalization of the results. Significant advances in the theoretical field have been made. The development of transonic similarity rules, the prediction of aerodynamic forces in unsteady motion, and the advances in theory of hypersonic flows, that is, flows at very high supersonic speeds, are examples of the progress which has been made.

In addition to the problems of transonic and supersonic flight, the old problem of landing an airplane is still with us. Moreover, with the high wing loadings, thin wing sections, and unconventional plan forms which are required for transonic and supersonic airplanes the problem of obtaining the high maximum lift at low speeds to permit a safe landing is highly aggravated.

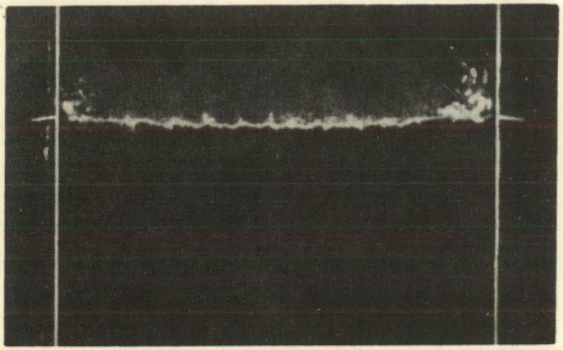
Progress is being made in the development of suitable devices to enable these airplanes to land safely. Such devices consist of the familiar leading-edge slats and trailing-edge flaps in conjunction with "fences" and other devices, and the use of boundary-layer control.

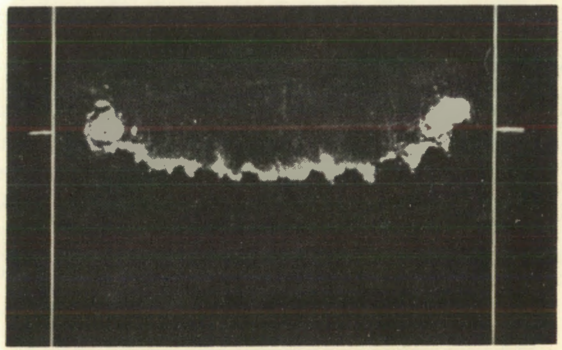
Speed rise affects stability

When flight speeds were considerably below that of sound, various design criteria established through years of experience enabled the designer to obtain good flying qualities in terms of stability and ease of control by the pilot in both steady and maneuvering flight. Now that flight speeds are being projected well beyond that of sound, the designer is confronted with many new difficulties in trying to achieve the desired stability and control characteristics. The old design criteria can no longer be applied.

As an example, let us consider the longitudinal motion of an airplane. In order to balance and control the airplane, in general, a tail surface or trailing-edge flap is required to trim the aircraft as the center of lift moves with respect to the center of gravity. Some movement is normally encountered with change of angle of attack at any given speed. Static stability demands that any increase or decrease in lift be accompanied by a pitching moment which tends to return the airplane to its original flight attitude. At subsonic speeds the center of lift is located on the forward part of the wing, but in going to supersonic speeds it moves aft to the vicinity of the midpoint of the wing. The rearward movement of the center of pressure as the airplane accelerates from subsonic to supersonic speeds produces a larger and larger diving moment. At the same time, the control-surface deflections must be increased, and much larger control forces are required to maintain balanced flight.

The problem of maintaining balanced flight through the transonic speed range is further complicated by a decrease in the effectiveness of the control surface itself. Thus, control deflections for balance become very large, resulting in high drag and therefore reduced aerodynamic efficiency and maneuverability. These large deflections involve large control forces which may be beyond those which the pilot can exert

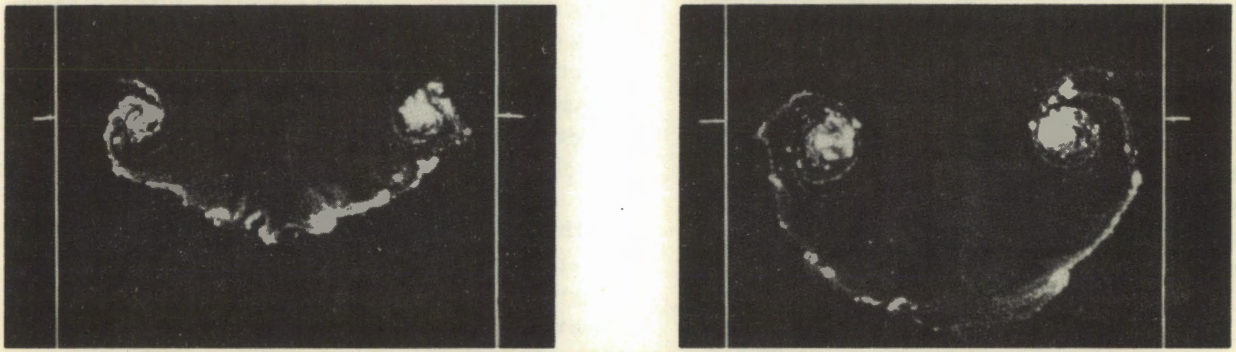




Experimential wing model in tank of water indicates shape of vortex wake.

without the aid of a power-boost system.

In order to cope with the problem of the movement of the center of lift with Mach number, theoretical and experimental research has been directed toward devising means of minimizing the center-of-lift movement as well as to the development of more effective control surfaces for use throughout the speed range. It has been found that wing plan form has a powerful influence on the amount of center-of-pressure movement encountered in passing through the transonic speed range. Control surfaces suitable for use with various wing plan forms on aircraft with tails and on tailless aircraft have been investigated at transonic and supersonic speeds. The effectiveness of balances of various types to reduce control forces on these surfaces are currently under investigation. These developments occupy a large fraction of our present research effort, and considerable progress is being made in the development of effective control surfaces and in reducing the control forces required



Four photos, left to right, show how vortex sheet rolls up behind triangular wing.

at transonic and supersonic speeds.

In the case of an airplane or missile which employs a tail for longitudinal control, the problem of providing adequate stability and control over the speed range is further complicated by the interference of the flow leaving the wing on the flow over the tail surfaces. Due to recent advances in theory, it is now possible to calculate directly the lift on a tail surface and hence its effectiveness if the flow field in which it operates is known. When an aircraft is in flight, the air approaching the lower surface of the wings tends to flow outward around the wing tips and produce a circulatory motion behind the wing. The air leaving the trailing edge of the wing forms a vortex sheet that tends to curl up at the edges and eventually it rolls up into two trailing vortices. These trailing vortices in the wake of the wing affect the entire flow field behind the wing and hence the direction of motion of the air flowing over the tail. The flow field can actually be calculated if the position and strength of the trailing vortices and the shape of the vortex sheet are known.

Theoretical analysis and experiment have shown that the vortex sheet rolls up more rapidly as the wing span is reduced. Hence on supersonic airplanes and missiles where low-aspect-ratio wings are normally employed, it is essential that the distortion of the wake be considered in calculating the flow over the tail surfaces. The accompanying illustrations show graphically the rolling up of the vortex sheet behind a triangular wing which has been plunged into a tank of water. Aluminum powder left by the wing on the surface of the water gives an indication of the shape of the vortex sheet at several stations behind the wing.

Such simple experiments together with theoretical analysis have provided an understanding of the stability characteristics of such complicated cases as missiles with cruciform wings and tails in combined pitch and yaw.

Automatic controls may help

Increased flight speeds involve, in addition to the difficulties in static stability and control noted above, undesirable changes in the dynamic stability of airplanes. This deterioration not only makes an airplane more difficult to fly but reduces the capability of accomplishing missions where precision flight is required. A powerful means of overcoming this difficulty is the use of automatic control and stabilization devices. These devices, in general, employ servo motors to actuate the control surfaces automatically so as to improve the stability and control characteristics of the airplane.

The NACA is presently engaged in extensive research on various types of automatic-control systems for aircraft. In order to gain a better understanding of the basic problems and methods of solution, experiments have been conducted in flight in which a target airplane is tracked by a pursuit airplane. Pursuit airplanes with different dynamic-stability characteristics have been employed. In addition, the dynamic characteristics of the pursuit airplane have been artificially varied by means of automatic servo-actuated devices incorporated in the control system in order that the dynamic characteristics anticipated for future designs of supersonic airplanes may be simulated and the tracking capabilities evaluated.

It has been found that the dynamic characteristics which are to be expected of supersonic airplanes can be greatly improved by artificial stabilization devices, which, while performing their functions, allow the pilot to retain control of the airplane. In order to design properly such automatic-control equipment, information is required about the relationship between an airplane's dynamic characteristics, such as period of oscillation and rate of damping, and the ability of a pilot to track a target. The effect of rough air on the required characteristics of the stabilizing devices

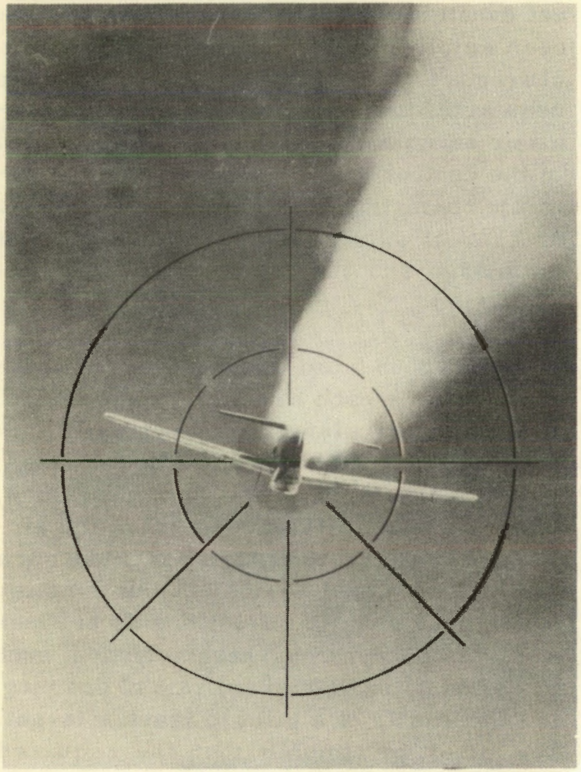
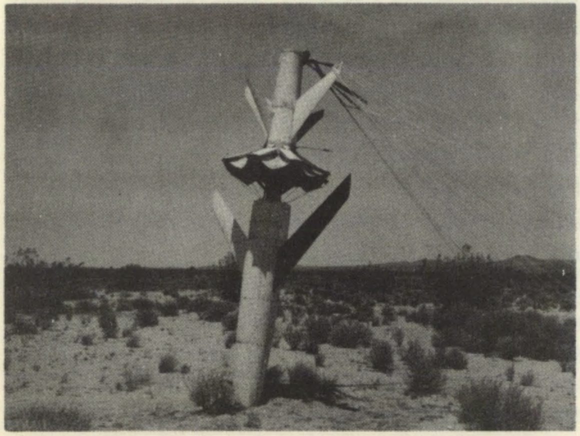


Photo-tracking target plane; note vapor trail.

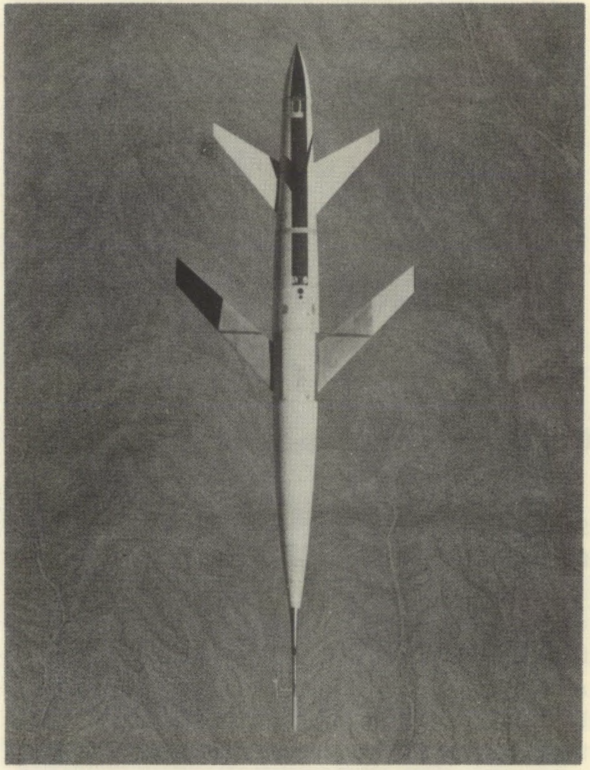
must also be determined. The NACA is currently conducting research in this field by means of actual tracking runs on target airplanes and simulated gunnery runs on fixed targets.

It is becoming more apparent that even such powerful devices to aid the pilot are not sufficient to permit successful accomplishment of many missions involving precision flight. At high flight speeds there is less time available in air combat for the pilot to acquire information, compute mentally his course of action, and then proceed to accomplish his mission. Completely automatic control of the airplane over all or at least a part of its flight plan may be ultimately required. Analytical and flight investigations of completely automatic control and guidance systems have been recently initiated by the NACA to gain fundamental information, particularly with regard to the proper matching of dynamic characteristics of complex automatic-control systems with the airframe and its aerodynamic properties.

It is apparent that many of the problems of automatic control of airplanes are closely related to problems in the design of missile guidance systems. At present, numerous analyses of different combinations of missile airframes and guidance systems are being performed at the Ames and Langley laboratories with the aid of electronic simulators. Flight testing to determine aerodynamic characteristics of the airframes as



Instrumented model recovered, unhurt.



Free-falling transonic research model.

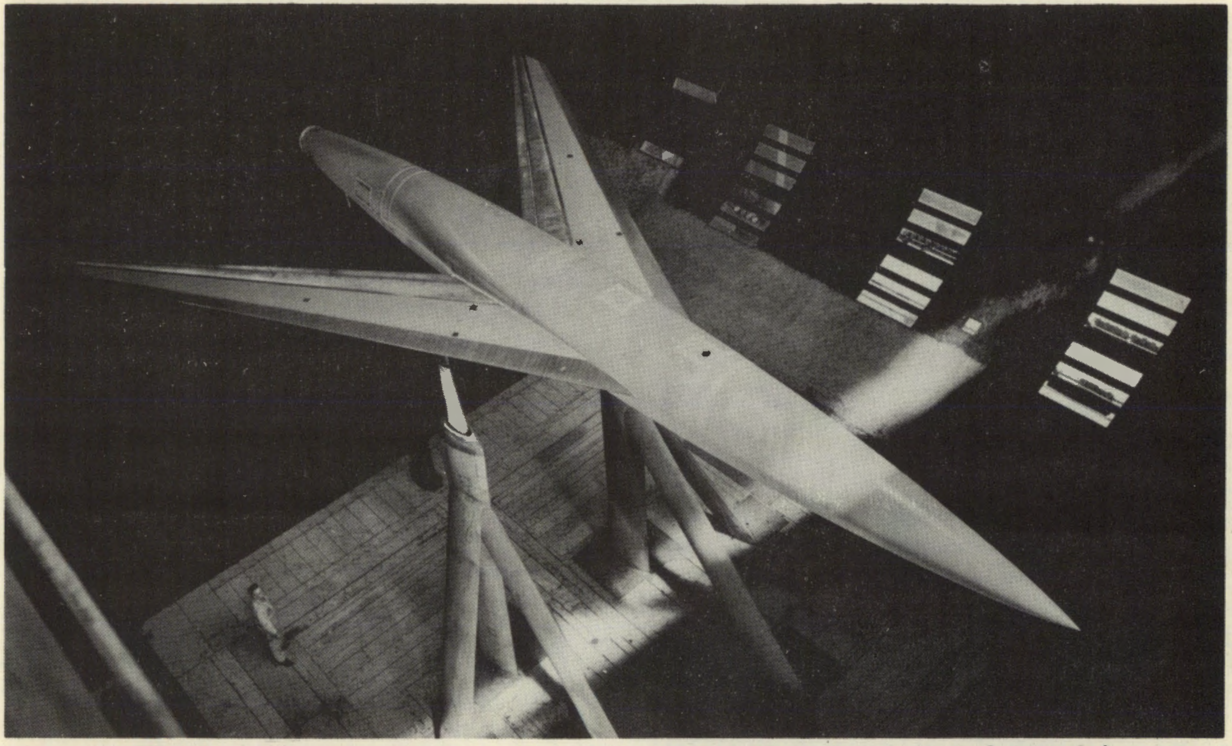
well as to evaluate various guidance systems is also being undertaken by the Pilotless Aircraft Research Division of the Langley Laboratory by means of rocket-propelled models, and the static and dynamic characteristics of a wide range of wings and wing-body combinations are being determined in wind tunnels and by means of experiments where winged bodies are dropped from high altitudes. In this way a wide range of subsonic, transonic, and supersonic speeds is covered.

Safe landing speeds required

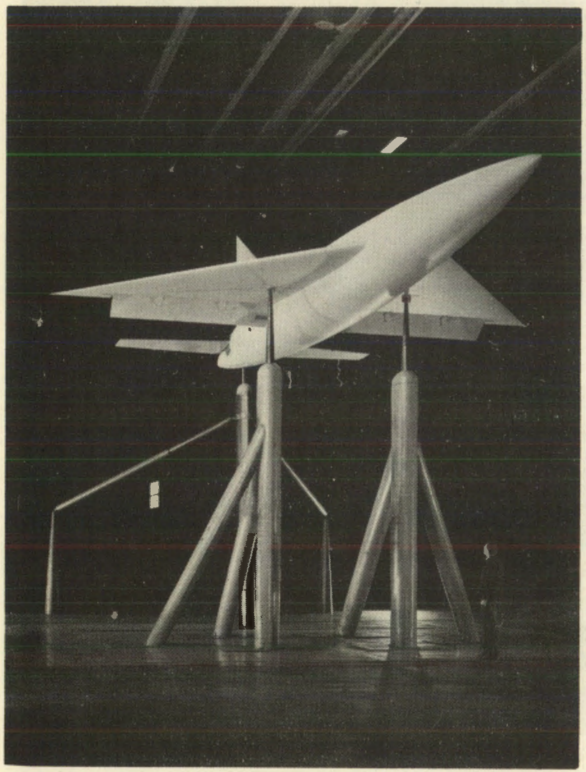
In airplane design the factors which are favorable for high speed are in general unfavorable for obtaining a satisfactory landing speed. The thin low-aspect-ratio wings and the swept-wing and triangular-wing plan forms which are found favorable for transonic and supersonic speeds have undesirably low maximum lifts at the landing condition. In order to attain the desired high speed the wing area must be kept as small as possible, which calls for even greater lift capabilities for landing. Furthermore, triangular wings and low-aspect-ratio wings in general obtain their maximum lift at very high angles of attack. This leads to long landing gears of increased weight and results in poor visibility for the pilot as he approaches the landing.

The problem of increasing the maximum lift capabilities of the wing is not new, but the combination of increased wing loadings and the reduced maximum lift of wings suitable for high-speed flight has intensified the need for more effective devices for increasing the maximum lift. The gains resulting from the use of wing flaps and slats or other modifications to the wing leading edge are no longer sufficient.

Previous research has traced the cause of stalling to the accumulation of slow-moving boundary-layer air over the upper surface of the wing, and it is clear that this air must be dealt with directly if signifi-



Model with porous leading-edge wings for boundary layer control tested in 40 by 80 foot tunnel.



High-lift flaps studied in tunnel at full-scale.

cantly greater lift capabilities are to be obtained.

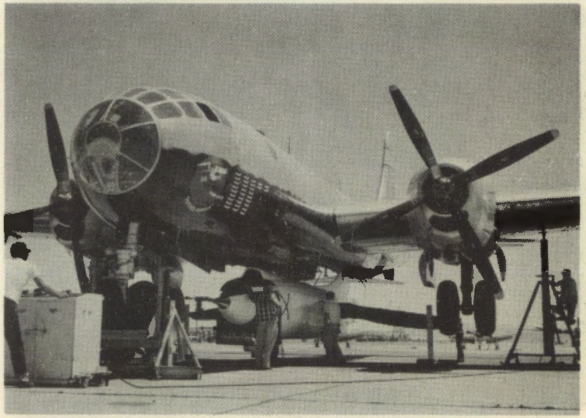
The stalling may be delayed to higher angles of attack in two ways: The slow-moving air can be speeded up, or it can be removed, thus bringing the fast-moving air of the free stream to the surface. Research has demonstrated the validity of these concepts. In the past, the improvement from the application of boundary-layer control for increasing the maximum lift of low-speed airplanes has not been commensurate with the complication involved. For the transonic or supersonic airplane, however, boundary-layer control appears promising and research effort is being directed toward its application.

Boundary-layer control by means of suction applied to slots or porous areas on the wing and re-energizing the boundary layer by means of air blown through slots over the upper surface are among the more promising methods being investigated. The use of boundary-layer control in conjunction with wing flaps or other conventional high-lift devices appears promising for not only increasing the maximum lift but also for decreasing the angle of attack at which the airplane lands. The most suitable arrangement will vary with the type of airplane, and the purpose of NACA's research on boundary-layer control and high-lift devices is to provide information on which the designer can base his selection.

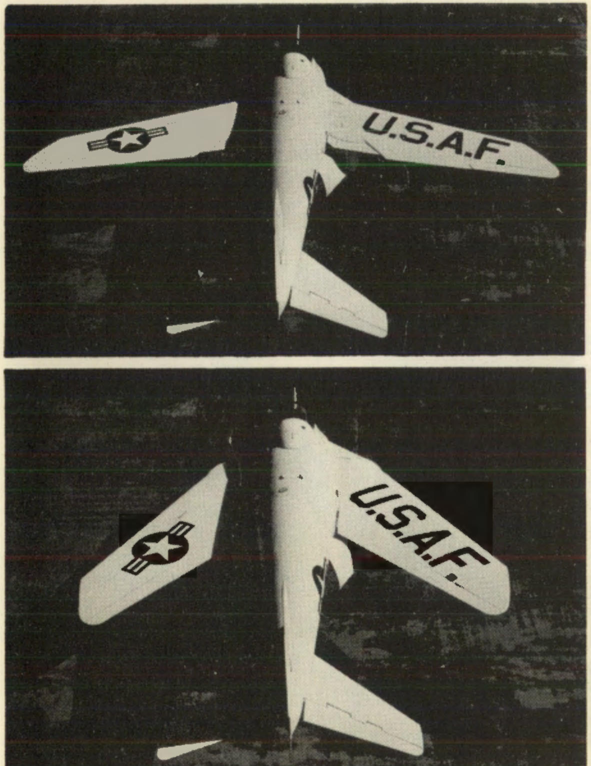
Research airplanes pay off

The research airplane program is the result of a three-way partnership of the aircraft industry, the military services, and the NACA. To further this work, the NACA has established a high-speed flight research station at Edwards Air Force Base on Rodgers Dry Lake in Southern California, a site well suited for high-speed flying. The purpose of the program is to investigate, in actual flight, problems which are anticipated from theoretical and wind-tunnel studies in the transonic and supersonic speed range, and, in addition, to explore any unexpected problems which might arise in connection with the operation of very high-speed airplanes. In pursuing this work, speeds and altitudes far beyond the capabilities of current production airplanes have been explored.

The problems investigated include aerodynamic loads and buffeting, stability and



D-558-I I, being attached to "Mother Ship".

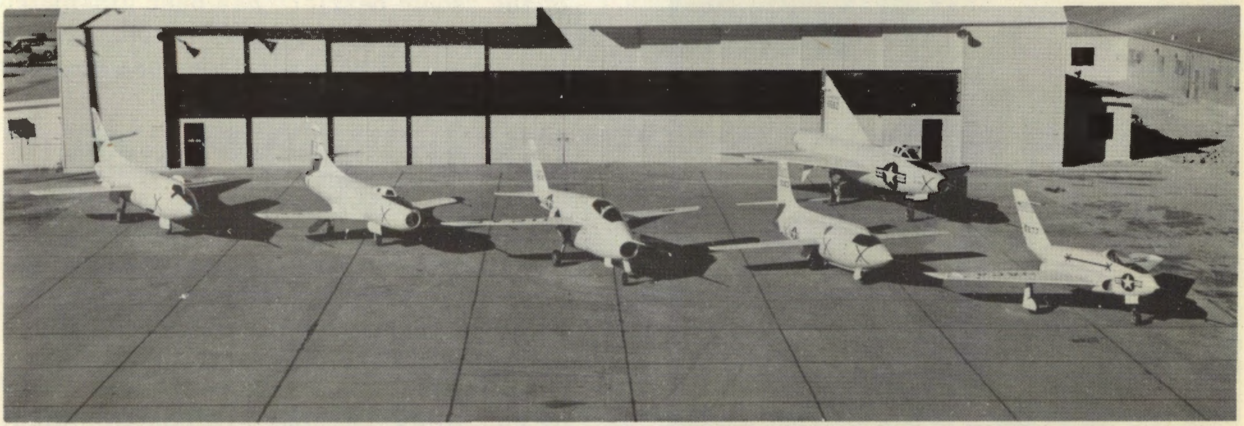


Range of X-5 wing sweep demonstrated.

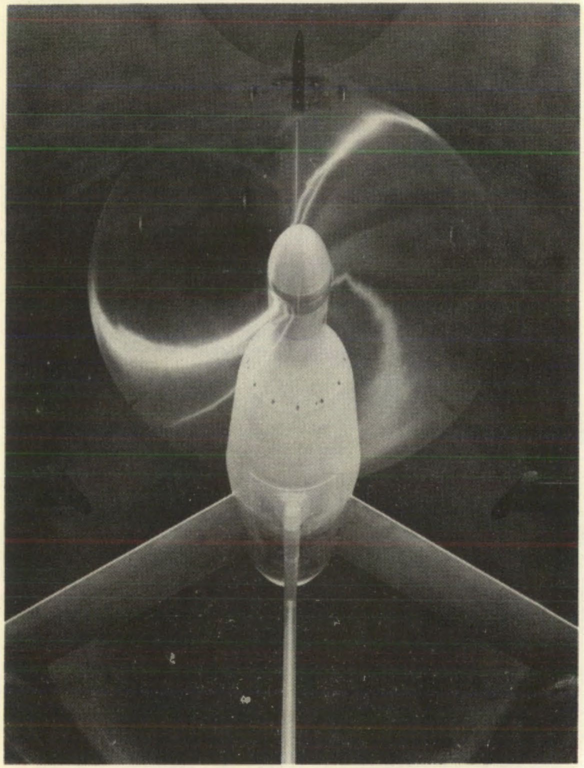
control, the effects of such airplane variables as sweepback and wing plan form, the effects of aerodynamic heating, and the difficulties of landing airplanes designed to fly at high speed. In addition to these direct problems of high-speed flight, the results of this program are of great value in verifying supersonic theory and in checking the validity of data obtained in transonic and supersonic wind tunnels.

The research airplanes have included a wide range of types. Some have been rocket propelled while others have been driven by conventional turbo-jet engines; each has been selected to explore the problems of some particular type. For example, the XF-92A is equipped with a wing of triangular plan form and its flights have given insight into the problems of flying and landing airplanes with this type of wing. Another of the airplane variables which is currently under investigation is the angle of sweepback of the wings. The X-5 airplane was designed for this purpose. The angle of sweep of its wings can be varied from 20° to 60° while the airplane is in flight. The effects of various amounts of sweepback are being investigated throughout the speed range of the airplane and compared with the benefits predicted by theory. The flying qualities and landing characteristics with various angles of sweep are also being determined.

Valuable results are being obtained from the flights of the research airplanes. Security restrictions prevent a detailed report, but certain unclassified benefits may be mentioned here. The stability difficulties and the deterioration of control effectiveness encountered as the airplane passes through the transonic speed range have been thoroughly explored. The flight results have confirmed trends observed in wind-tunnel experiments. Of equal value has been the



Six high-speed research airplanes provide transonic information: left to right, D-558-I I, D558-I, X-5, X-1, X-4 and rear XF-92-A



High-speed prop studied in 12-foot tunnel.

determination of aerodynamic loads at transonic and supersonic speeds, information which is necessary for the design of safe and efficient structures. The airplanes now on the drafting board will reflect in many ways the new aerodynamic information gained.

Another important benefit has been the experience gained by the pilot's participating in this program. Much of the mystery of the "sonic barrier" has been dissipated and the training of pilots for tomorrow's high-speed military airplanes has been put on a rational basis.

Turbo-prop problems studied

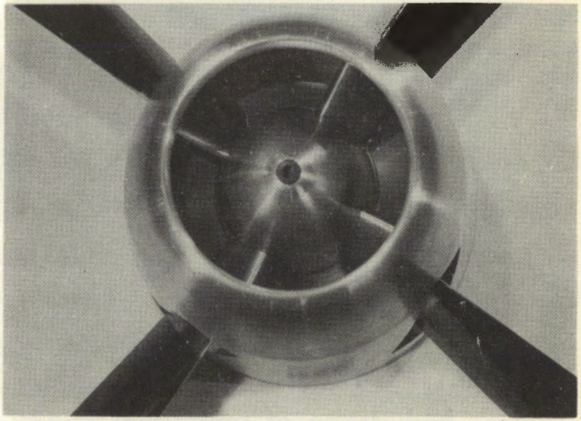
The advent of jet propulsion has resulted in the development of turbo-prop engines five times as powerful as a piston engine. In order to absorb this power with a propeller of reasonable diameter, high rotational speeds are necessary. At the same time, forward speeds of the airplane of 500 or 600 miles per hour are contemplated, which means that a substantial portion of the propeller blades will operate at supersonic speeds relative to the air.

If the structural problems associated with the thin blade sections suitable for these speeds can be solved, the fuel economy of the turbo-prop offers promise for long-range airplanes. The concentration of large power in small-diameter propellers intensifies the effects of the slipstream on the performance and stability of the airplane. These effects are the subject of current investigations and means for improving the efficiency of supersonic propellers are being studied.

The problem of developing efficient inlets for admitting the large quantities of air required by turbo-prop engines is being attacked experimentally. The 1,000-horsepower dynamometer of the Ames 12-foot pressure wind tunnel is one of the NACA facilities being used to study the problems of propellers and air inlets for use with turbo engines.

1600° F. rise at M = 5.

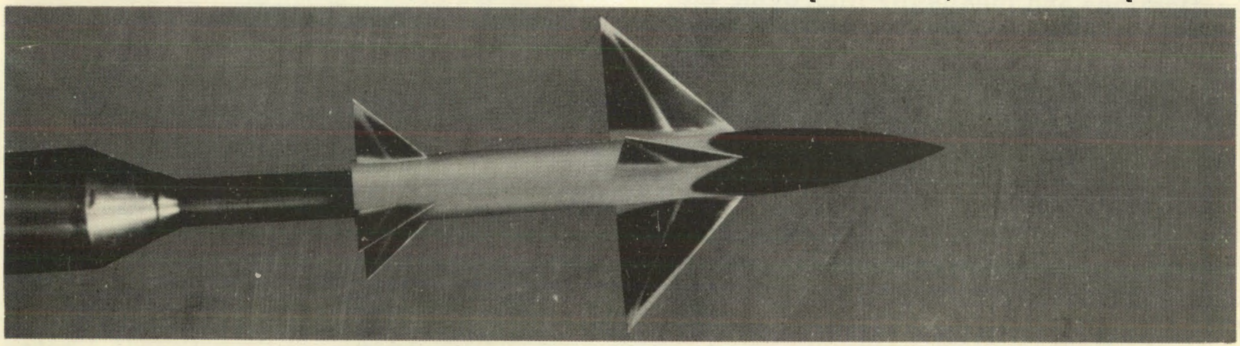
The viscous nature of air produces two effects which become very important at high supersonic speeds. These effects are the friction of the air over the surface of the aircraft, usually termed "skin friction," and the associated rise in temperature of the air called "aerodynamic heating." In order to study these effects, we must look at the thin



Test model of spinner air inlet for turbo-prop.

layer of air known as the "boundary layer" which is next to the surface of the aircraft. The characteristics of this layer determine the amount of skin friction and the rate at which heat is transferred to the skin of the aircraft.

At Mach numbers of 3 or greater the drag due to skin friction can be over one-half the total drag of an aircraft. The temperature rise in the boundary layer at Mach numbers of 3 and 5 are of the order of 600° F and 1600° F, respectively. At the lower temperature, aluminum alloys now used in aircraft construction would lose most of their strength; at the higher temperature, ordinary steels would be greatly weakened. However, this temperature rise does not affect the aircraft instantly since time is required for the heat to flow from the boundary layer into the surface of the aircraft. In any event, if we are to contemplate operating aircraft at these speeds, pilots and cargo must be protected from these temperatures, and the temperature



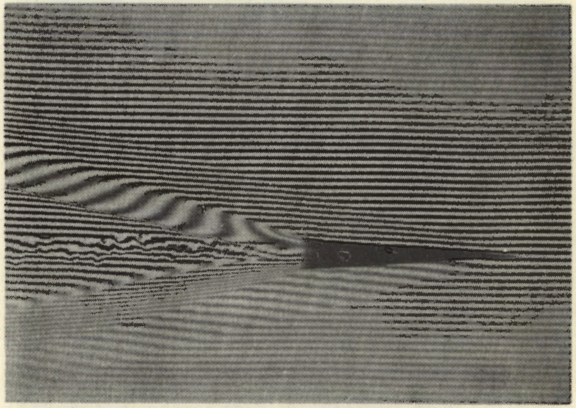
Dark region of luminescent lacquer indicates extent of laminar flow on missile model at Mach number 2.

effect on the structure must also be considered.

The nature of the boundary layer is a critical factor. The smooth laminar boundary layer usually found on the forward portion of a body in flight produces a skin-friction drag that is only about one-sixth as great as that produced by the eddying flow of the turbulent boundary layer usually found on the aft portion. Likewise, the rate of heat transfer from the boundary layer to the surface is much lower for the laminar than for the turbulent boundary layer. Thus it appears that the point of transition of the boundary layer from laminar to turbulent flow should be kept as far aft on the surface of an aircraft as possible.

The NACA is currently engaged in a research program to provide experimental data on skin friction and heat transfer over a wide range of supersonic speeds and to investigate the validity of existing theories for calculating these effects. The factors controlling the transition of the flow from the laminar to the turbulent type of boundary layer are being studied in order that the designer may have means for maintaining the favorable laminar flow over as much of the aircraft as possible.

Present theories regarding skin friction and heat transfer at supersonic speeds agree well with experiment as long as the boundary layer remains laminar. When the



Interferogram at 2800 mph aids theoretical studies.

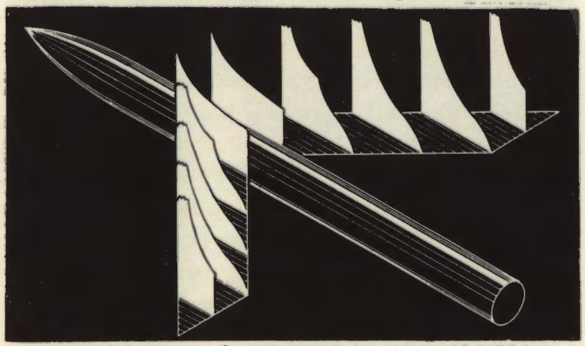
boundary layer becomes turbulent, however, the basic nature of the flow is not well understood and the several theories vary widely in predicting skin friction and heat transfer. The disagreement is very large at high supersonic speeds. Current research is aimed at providing a better understanding of the friction and heat-transfer process in the turbulent boundary layer. It is hoped that the experimental work will either validate one of the existing theories or provide the basis for an improved means of calculating these quantities which are so important in the operation of airplanes and missiles at very high speeds.

Theory guides experiment

Research progress in all the physical sciences has been characterized by the proper blending of experimental and theoretical methods of investigation. Since theory involves a systematic arrangement of the basic variables, it not only provides the means of analyzing and correlating test data but also furnishes an efficient and economical tool to use in prediction. This dual role of theory is particularly apparent in recent investigations of compressible flow in the transonic speed range. One important result of such research has been an essential improvement in the manner of correlating experimental wing characteristics at near sonic speeds.

Significant improvements in methods of predicting the aerodynamic forces on the surfaces of wings flying at subsonic or supersonic speeds have been obtained within the past few years. The extension of such methods to include the interference of wings with fuselages presents a problem of considerable complexity. It has been found, however, that these interference effects can be estimated to a fair degree of accuracy for the slender wing-body shapes common to missiles and some high-speed airplanes. Pressure distributions have been calculated for triangular and swept-back plan forms mounted on cylindrical fuselages. The effect of the section profiles on the pressures has also been predicted. An interesting development of the technique also furnishes the effect on the lift of a horizontal tail surface, in the wake of a wing, for cases in which the vortices form a plane sheet or have rolled up into vortex cores.

Dynamic and structural analyses in the design of modern aircraft have resulted in added demands for information about the response characteristics of wings in unsteady flight throughout a large Mach number range. In conjunction with experimental studies, the Ames Laboratory has carried out a theoretical program of calculating pressure distributions and the variation of wing characteristics under unsteady conditions for triangular wings and two-dimensional wing sections. Solutions are obtained for cases in which the wing undergoes abrupt changes in flight attitude, since from these basic solutions, problems of wings fluttering, entering gusts, or maneuvering can be analyzed. Detailed calculations have indicated the magnitude of the acceleration experienced during gust penetration for rectangular and triangular wings of various weights flying at supersonic speeds. Two-dimensional predictions for both subsonic and supersonic Mach numbers were also obtained.



Wing pressures calculated theoretically.

Recent calculations of wing characteristics have been made more efficient by the development of reciprocal theorems similar to those long known in electricity and magnetism, optics, elasticity, and many other branches of the physical sciences. These theorems enable the determination of many important and useful relations between the aerodynamic forces and moments on wings with the same plan forms but having different twist and camber, or executing different motions. The range of application of these theorems includes unsteady as well as steady motion and applies to subsonic as well as supersonic flight speeds.

Similarly, studies are being made of hypersonic flow where theory is not in the advanced state of development enjoyed by supersonic theory, probably because not as much work has been done in this new speed range. Interestingly enough, however, nonviscous hypersonic flows apparently received serious attention well before correspondingly idealized supersonic flows. In particular, hypersonic flow was studied by Newton whose "impact theory" has been found particularly useful in predicting the pressure acting on bodies of revolution even at speeds corresponding to those at the lower end of the hypersonic range.

More recently, similarity laws for both steady and nonsteady nonviscous hypersonic flows have been developed. These laws are especially useful for correlating the aerodynamic characteristics of related slender shapes operating at different speeds. With the aid of these laws, the indications are that more intelligent experimental and theoretical research programs can be planned, and that the results may be more intelligently interpreted.

Missile problems studied in supersonic tunnel.

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