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SOME AERODYNAMIC DISCOVERIES AND RELATED NACA/NASA RESEARCH PROGRAMS FOLLOWING WORLD WAR II

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SUMMARY

During the World War II time period, NACA test facilities were heavily committed to investigations of airplanes related to the war effort. Much of the work was directed toward the improvement of existing airplanes but work was also being done on new designs. At one time in July 1944, 78 different models of airplanes were being investigated by NACA, most of them at the Langley Memorial Aeronautical Laboratory (now Langley Research Center). Spin tests were made in the Langley spin tunnel on 120 different models. The atmospheric wind tunnel (AWT) tested 36 military aircraft for stability, control, and performance characteristics. In the post World War II period, an essentially new era of aerodynamic research began that was spawned by the lessons learned from air warfare and by some advances revealed from foreign technology, principally in the development of jet propulsion and the advent of high-speed flight.

INTRODUCTION

In 1938, the growing menace of a military buildup in Germany was obvious except to those who would not see it. President Roosevelt asked Congress for a major increase in defense appropriations, mostly for Naval strength, and got it. In early 1939, Roosevelt told Congress that U.S. air strength was "utterly inadequate." At that time, the official strength included 1700 airplanes of which only 800 were considered first-line and these were primarily outdated Douglas B-18A's, Northrop A-17A's, and Curtiss P36A's. A mere 23 Boeing B-17's were on hand. In comparison, the Royal Air Force had 2000 first-line airplanes, and the German Luftwaffe had at least 4000 airplanes. The U.S. Congress was asked to approve a massive investment in defense and did pass legislation (as it turned out, wisely) to strengthen the military with authorization that included a buildup to 5500 airplanes. This marked a change in U.S. policy away from isolationism, away from the concept of disarmament, and toward rearmament.

The growth of total military power, including air power, with the rise of the Hitler German government was alarming to some observers. While the western world was puzzling and debating the thoroughness with which Germany was building up her military might, another unusually large military buildup was going on almost unnoticed on the relatively small islands of Japan. The Japanese Air Force included about 2100 airplanes in 1937 and, in the late 1930's, Japan was building two aircraft carriers yearly.

The German might was unleashed in Europe in September 1939 and much U.S. equipment was sent to aid England and France. In a surprise move in December 1941, Japan unleashed its power at Pearl Harbor and the U.S., with depleted forces, was drawn into war. In both cases--Germany and Japan--the fighting followed a period of expansionism and a period of negotiation. From the German and Japanese ventures, at least two nontechnical lessons should be noted as related to warfare:

- One should view with suspicion and caution those countries engaged in an inordinate military buildup while, at the same time, expanding and negotiating.

- One should avoid mental lapses or physical weaknesses that might be construed as susceptibility to a surprise attack.

The war revealed many technical lessons relative to some needs for airpower efficiency. Some important needs, for example, were:

- Agility for air superiority fighters
- Long range for escort fighters
- Long range bombers
- Large payload capability for fighters and bombers
- Speed for rapid, surprise, air intercept
- Speed for disengagement in air combat
- Operational capability at substandard bases
- Guided missiles for air defense
- Guided missiles for long-range strike

Some of the discoveries made and lessons learned in carrying out research programs intended to meet these needs will be discussed. Additional background material is listed in the bibliography.

DISCUSSIONS

German scientists, under the pressure of war and with innate technical capability, were making giant strides in advancing the state of the art in air power developments in areas such as propulsion, compressible flow, supersonic aerodynamics, and missile design. The impact of some of the wartime technology subsequently had an influence on U.S. research and development.

Propulsion

Between World War I and World War II, airplane speeds steadily increased. During World War II, speeds became limited for propeller-driven aircraft and the development of reaction-propelled airplanes that would lead to supersonic flight began to take place in many countries. Developments in Germany are of particular interest. Erich Warsitz made a series of successful flights with the first rocket-powered Heinkel 112 in 1937. This led to the development of a small, rocket-powered fighter, the Heinkel 176--but with the outbreak of war, the project was shelved after several successful flights. It was only near the end of the war that rocket-powered airplanes such as Lippisch's Me 163 made a dramatic, though limited, comeback. Unknown until after World War II, Warsitz had flown the first jet-propelled airplane, the Heinkel He-178 with a Hans von Ohain designed engine, in Germany on August 27, 1939. Some German jet-propelled fighters, such as the Me-262 twin-engined airplane, also saw limited service near the end of the war. The use of jet propulsion was boosted by the work of Frank Whittle in Britain, who began his work in 1930 at the age of 23, and finally saw the Gloster E28/39 fly with one of his engines on May 15, 1941. By the summer of 1944, the Gloster Meteor twin-engine jet fighter was in service.

The first American jet-propelled airplane, the Bell P-59 Airacomet powered by two General Electric engines, was under secret development in the early 1940's, and was first flown on October 1, 1942. The G.E. engine was an American version of the Whittle engine.

The first true American operational jet fighter was the Lockheed P-80 Shooting Star, although it did not fly until January 8, 1944. The P-80, however, did not enter combat service during World War II. After the establishment of the United States Air Force as a separate service (July 26, 1947), aircraft disignations were changed. The P-80 officially became the F-80 on June 11, 1948. The F-80C did see combat service in the Korean War and, even though the airplane's performance was somewhat disappointing, an F-80C destroyed a MiG-15 on November 8, 1950 in what was believed to be the first conclusive air combat between jet fighters.

Early Problem Areas

Compressibility.- Jet airplanes that pushed to the border of sonic flight were limited by the onset of compressibility effects, a new major problem of high-speed flight, resulting from the fact that air is compressible such that, when a given shape moves through the air at increasing speeds, a point can be reached where the compressed air creates a drag in excess of the thrust and changes in pressure distribution occur that cause stability and control problems. Some of these effects had been experienced by high-speed propeller-driven airplanes such as the North American P-51 Mustang and the Lockheed P-38 Lightning. One problem was the phenomena of "tucking under" characterized by a severe nose-down tendency at high speeds with an attendant decrease in the control power required to effect a normal recovery. "Wing dropping" was another phenomena characterized by an unwanted roll tendency, apparently induced by spanloading changes caused by asymmetry and further aggravated by a decrease in aileron effectiveness necessary for corrective action.

While in-house studies of high-speed flight problems were progressing, an interest in foreign technology began at NACA-Langley shortly after World War II (1946) when many documents, particularly German and some Italian, became available for study. In addition, the German scientist, Adolf Busemann, and the Italian scientist, Antonio Ferri, worked for some time at Langley. Information from these sources was used as a partial guide to NACA research studies of the 1940's in many fields including compressible flow, supersonic aerodynamics, high-speed airplane configurations, and missiles.

Conventional wind tunnels of the mid-1940's were not able to test near a Mach number of 1 ($M = 1$) because of the same compressiblity and shock wave effects that airplanes were beginning to experience. In the case of the wind tunnel, the presence of the tunnel walls resulted in reflected shocks that disrupted the tunnel flow. Alternate methods used in the early 1940's for obtaining transonic data included free-fall drop models; the wing-flow and transonic-bump techniques; and free-flight, rocket-propelled modes. The transonic bump (fig. 1) utilized a semispan model mounted on a curved surface over which the locally induced velocities exceeded $M = 1$. The same principle was used with the wing-flow technique. These techniques were soon to be followed by the X-series of flight research airplanes. In addition, the slotted-throat transonic tunnel was being developed under the direction of John Stack. In December 1949, the converted 8-foot transonic tunnel was operated at NACA-Langley, followed a year later by the 16-foot transonic tunnel.

Through the use of the newly developed test techniques, along with the existing subsonic and supersonic wind tunnels, a storehouse of data was soon being produced to aid in the development of a rapidly emerging generation of new airplanes. A large data base for the aerodynamic characteristics of supersonic airplanes and missiles was begun when the Langley 4- by 4-foot supersonic pressure tunnel became operational in 1948 and was expanded when the Unitary plan wind tunnel became operational in 1956.

Transonic drag and lift.- Transonic drag and lift characteristics obtained from early free-flight rocket-propelled models and determined by the transonic-bump technique indicated the desirability of using more slender bodies to obtain a marked reduction in the transonic drag rise. Increasing the wing-sweep angle was also shown to be an effective means for reducing the drag rise, and reducing the value of thickness-to-chord ratio, t/c, for airfoil sections progressively reduced the drag rise and increased the lifting effectiveness. The design trends that began to emerge for supersonic airplanes thus began to show the use of swept wings, thinner wing sections, and long slender bodies. In addition, there was a tendency for the center of gravity to move rearward because of the location of jet engines near the rear. These design trends for achieving supersonic flight were, in some cases, to become contributors to stability problems.

Area distribution.- Since it was clear that compressibility and shock-induced phenomena were a function of the amount of disturbance imparted to the surrounding air, the thought of lessening the disturbance became important. Through the efforts of Dr. Richard T. Whitcomb and others working with some thoughts from A. Busemann, the concept of the transonic area rule was developed in the early 1950's which stated that the cross-sectional area of an airplane should vary as gently as possible from the front to the back with the ideal equivalent body being as nearly parabolic and as slender as possible. The concept did prove to be correct and a major aid to overcoming the drag rise was available. Later developments of the "supersonic area rule" were devised for reducing the supersonic wave drag. The application of the smooth area distribution techniques continues to be a valuable tool in the design of supersonic airplanes.

Downwash characteristics.- Another aerodynamic change observed from early transonic-bump tests for aft-tail airplanes was the gradual reduction in the effective downwash at the tail with increasing M and, often, the appearance of an upwash at supersonic speeds. Some design trends that have been partly influenced by the downwash characteristics are the tailless designs and canard designs. The vertical location of the horizontal tail with respect to the wing also became a design trade factor from a stability as well as a structural standpoint.

Longitudinal stability.- The longitudinal stability for a typical aft-tail supersonic configuration resulted in a characteristic increase in stability through the transonic range. The primary problem to be faced as a result of the increased longitudinal stability was the increased control power required to provide for trimming which, in turn, reduced the ability to maneuver. This problem lead to the use of all-moving horizontal tails for pitch control to replace the long standing, conventional elevator. When large deflections of an aft-tail became necessary for trimming, an added impetus was given to configuration shaping designed to reduce excessive longitudinal stability.

Additional supersonic longitudinal stability problems at high angles of attack were related to the geometric characteristics of some airplanes. The location of aft-tails relative to the wing wake sometimes resulted in a sharp pitch-up tendency. The pitch-up tendency was generally aggravated by aft center-of-gravity locations that accompanied rear engine designs and promoted a more severe destabilizing effect from the lift of the long, slender forebodies with increasing angle of attack.

Directional stability.- While the longitudinal traits of supersonic designs initially produced a problem of too much stability, the directional traits of the early designs produced a problem of insufficient stability. The initial problem with directional stability at supersonic speeds occurs when the level of instability for the wing body is large (generally due to aft center of gravity) and the lift-curve slope of the vertical tail decreases to the point where most of the tail contribution is required to offset the instability of the wing body and little tail contribution remains to provide positive stability for the complete airplane. The problems of directional stability may be further aggravated with increasing angle of attack by vortex flows which may cause an adverse sidewash at the vertical tail.

Control effectiveness.- The general problem of control effectiveness at high speed that led to the use of the all-moving tail for pitch control has been mentioned. A roll-control problem with conventional aileron control was also discovered near the transonic range, that often resulted in a complete loss, or even reversal, of roll control. However, differential deflection of the all-moving horizontal tail was adopted as an effective way of dramatically increasing the roll-control power.

Lateral characteristics.- Another aerodynamic trend found to be related to supersonic flight was the variation of effective dihedral with angle of attack and Mach number which indicated changes from a negative value (positive effective dihedral) to zero or slightly positive values (negative effective dihedral) when the wing leading edge becomes sonic. Such a characteristic results in changes in the roll-to-yaw ratio as a function of Mach number and causes significant changes in the dynamic directional stability.

Dynamic pressure fields.- Another significant characteristic of supersonic aerodynamics noted was the change in local dynamic pressure fields, q, for a lifting surface. In the upper-surface flow field (expansion), the local q is substantially reduced whereas the lower surface flow field (compression) shows a significant increase in local q. Not only do these q changes affect the lifting surface itself but also the characteristics of any other part of a vehicle located in the flow fields induced downstream. The effectiveness of an aft tail, for example, could be seriously impaired if located in the upper-surface flow field or considerably enhanced if located in the lower-surface flow field.

Airframe Considerations

Swept wings.- At the end of World War II, the work of German scientists on the use of wing sweep for achieving higher flight speeds became available. An example is the work of Dr. Adolf Betz on airfoil theory published in 1935. The basic theory for swept and yawed wings as developed by Betz is based on the concept that only the component of velocity normal to the wing leading edge determines the chordwise pressure distribution. Thus, by increasing the sweep angle, the normal component of flow is reduced and the critical Mach number at which the drag rise due to compressibility is increased. Wind-tunnel tests and theoretical studies of swept and yawed wings (including swept-forward wings and strakes on swept wings) were underway at NACA in the mid-1940's. One of many swept-wing models studied in the Langley

300-mph 7- by 10-foot tunnel is shown in figure 2. In addition to the data produced on basic wing sweep, some results were also obtained on the effects of wing-root strakes as shown in the figure. One of the forward-sweep study models is shown in figure 3. The use of wing sweep was to have a pronounced effect on the design of airplanes and missiles for years to come. The first operational swept-wing fighter in the U.S. was the jet-propelled P-86 which first flew on October 1, 1947. The airplane began its life in 1944 as a straight-wing Navy jet (XFJ-1 Fury). As swept-wing data became available, the design evolved to the 35-degree swept-wing airplane.

Delta wings.- The delta planform offered another approach to increased speed through the use of a highly-swept leading edge and the achievement of a low-thickness ratio. It was also throught that some of the stability problems associated with aft-tail designs could be avoided by the use of tailless delta-wing designs. The concept has an origin traceable to Germany where Dr. A. Lippisch developed the tailless Me 163 Komet rocket airplane and did research work on delta-wing designs. Lippisch continued his work with the U.S. Air Force following the war, and working in cooperation with Convair, the tailless delta-wing XF-92A was conceived and first flew on June 8, 1948. Many other delta-wing type aircraft were subsequently developed and this configuration was destined to leave its mark on aircraft design history.

Trapezoidal wings.- Still another approach for high speed was through the use of razor-sharp, thin, low-aspect-ratio wings. A classic example was the F-104. While achieving low-drag and high-speed potential, some stability problems and load-carrying limitations occurred and the basic concept was not to become a hallmark of airplane design.

Variable sweep.- U.S. studies in the late 1940's by the Bell Company, based partly on German data from the Messerschmitt P-1101, suggested the possibility of combining the low-speed advantages of low sweep with the high-speed advantages of high sweep into one airframe having a variable wing-sweep capability. The concept resulted in the X-5 variable-sweep research airplane that partly lead the way to aircraft such as the F-111, B-1, and the F-14. In addition, many other variable-sweep concepts have been developed around the world, notably in the Soviet Union.

The Flight Research Airplanes

The X-series airplanes.- Concurrent with the analytical and experimental model studies of high-speed flight, there was also some thought in the early 1940's of a manned airplane flight research program as a way of obtaining accurate full-scale data in the trasonic and supersonic speed regimes. Such an airplane was conceived at NACA-Langley in 1943 at about the same time that others in industry and service laboratories were harboring similar thoughts. The NACA proposed that a jet airplane be built specifically for the purpose of transonic flight research and, with a government decision to undertake such a program, the X-series of research airplanes was born. On the basis of wartime NACA research, together with captured German research data, four major approaches to the problem of high-speed flight were chosen: thin wings, swept wings, low-aspect-ratio wings, and high-speed wing profiles. Both rocket and turbojet propulsion were to be considered.

The Bell X-1 airplane.- The Bell XS-1 with a low-aspect-ratio straight wing was the first of the new experimental airplanes to be completed. On October 14, 1947, the Bell XS-1, piloted by Air Force Captain Charles E. Yeager, broke the sound barrier for the first time by reaching $M = 1.06$ on its ninth powered flight. It was the first of many supersonic flights for a family of X-1 airplanes and the age of supersonic flight was begun. Among other events in the X-1 series were:

- o X-1, M = 1.5 on March 26, 1948
- o X-1A, M = 2.4 and 90,000 feet on December 12, 1955
- o X-1E, 1400 mph and 73,000 feet with 4-percent wing, 1955
- o X-1B, 1600 mph and 90,000 feet with reaction controls; used for thermal studies, 1954-1956
- o X-1D, destroyed during test August 23, 1951

The Douglas D-558-I airplane.- The Navy-sponsored D-558-I Skystreak, the second of the flight research airplanes to fly, had a low aspect ratio, straight wing, and was turbojet powered. The Skystreak began flying in early 1947 and established, temporarily, a world speed record of 650.8 mph.

The Douglas 558-II airplane.- The third research airplane to fly (1949), the D-558-II Skyrocket had a 35-degree swept wing and was originally powered both with a rocket and a turbojet for added takeoff and climb power. Three of these airplanes were built and one of them, with the turbojet removed, was air-launched. With rocket power, it became the first airplane to exceed M = 2. Skyrocket events included:

- o M = 1.86 on August 7, 1951, piloted by Bill Bridgeman
- o M = 2.01 on November 20, 1953, piloted by Scott Crossfield

The Skyrocket also revealed the reality of the cross-coupling, pitch-up, wing-drop, and control effectiveness loss in flight at supersonic speeds.

The Northrop X-4 airplane.- The X-4 was the next research airplane, beginning to fly in the 1948-1949 era. The Northrop X-4 was a special Air Force project utilizing a swept wing, tailless design, to examine the stability and control characteristics at transonic speeds on the premise that elimination of the horizontal tail would relieve some of the transonic problems associated with more conventional wing-tail combinations. The airplane became a reliable test bed for the study of pitch-up but never exceeded a Mach number of about 0.94.

The Consolidated Vultee XF-92A airplane.- This airplane, a 60-degree delta tailless concept with a nose inlet supplying air to a turbojet, was conceived as a prototype for an advanced Air Force fighter-interceptor. It was added to the flight research program in 1951 to study the delta-wing concept for easing the problems of high-speed flight. The airplane was barely supersonic in a dive but was used extensively in obtaining information valuable in the future development of the F-102, F-106, and the B-58.

The Bell X-2 airplane.- Conceived as a part of the original research airplane program, the Bell X-2 was designed for speeds up to M = 3 at 100,000 feet. Because of the expected heating problems, the airplane was made of K-monel and stainless steel. The airplane had a 42-degree swept wing and was powered by a throttleable rocket motor. Because of production difficulties, the supersonic flight program was delayed until 1955. In the summer of 1956, with Air Force Lt. Col. Frank Everest, Jr. at the controls, the airplane did achieve a speed of M = 2.8. A few weeks later, Captain Ivan Kincheloe took the airplane to an altitude of 126,000 feet. On September 27, 1956, Captain Milburn Apt took the X-2 on its final flight and achieved a speed of M = 3.2, marking another major step forward in supersonic flight. The airplane crashed after executing a rolling pull-up near

M = 1.6. An increase in sideslip angle, apparently resulting from loss of directional stability, lead to a structural failure of the vertical tail and destruction of the airplane. The possibility of such an occurrence was indicated in wind-tunnel tests made in 1948-1949.

The Douglas X-3 airplane.- The X-3 Stiletto, originally designed to explore the problems of sustained supersonic flight, had an extremely long needle-nosed body and small tapered wings. The airplane proved to be overloaded and underpowered, however, and was barely capable of supersonic flight, achieving M = 1.1. The inertia characteristics of the airplane were quite different from most all of its predecessors. The mass distribution of the airplane was essentially strung out lengthwise and was about zero in the spanwise direction. This made the airplane a prime candidate for the cross-coupling phenomena wherein pitch oscillations begin to feed into yaw oscillations and vice versa so that motions difficult to control might occur. Data derived from this design were used in many programs later. The problem of inertial coupling had been studied in theory and reported by NACA Langley in 1948 but little attention was paid to the report until the flight problems occurred.

The Bell X-5 airplane.- A subsequent addition to the flight research program was the Bell X-5 variable wing-sweep airplane. For preliminary studies of sweep, Bell Aircraft first modified a P-63 airplane to incorporate a fixed-sweep wing. Designated the L-39, the airplane was flight tested at NACA Langley late in 1947. Some stability problems were indicated, particularly at high lift, and as a result, the airplane was modified by the addition of 4 feet in tail length, a large ventral fin, and various wing leading-edge devices. The X-5 variable-sweep research airplane first flew on June 20, 1951. The wing sweep was variable in flight from about 20 degrees to about 59 degrees. As the wing was swept rearward, it was also translated forward in order to achieve a more consistent stability level. The airplane was barely capable of sonic speed (about M = 1.1) but was used extensively in the study of gust response at low altitude with a wing fully swept. Such information was to become useful later in the decade when variable-sweep tactical fighters were conceived.

The North American X-15 airplane.- The X-15 hypersonic airplane had its origin in a document from Bell Aircraft, January 8, 1952. The document included a proposal for a manned hypersonic research airplane to explore the basic problems of hypersonic and space flight. In June 1952, the NACA Committee on Aerodynamics recommended an extension of the flight research program to the speed range from M = 4 to 10 at altitudes to 50 miles. In June 1956, a contract was awarded to North American for three X-15 airplanes to be powered with a throttleable, liquid rocket engine. The first powered flight was made September 17, 1959, and NASA (by then renamed from NACA) began to fly the X-15 in March 1960. The X-15 program explored many areas of technology in materials, structures, piloting techniques including use of reaction controls and effects of gravity ranging from zero-g to high-g reentry, propulsion, and stability and control. A maximum speed of M = 6.7 (October 1966) and an altitude of 354,200 feet were achieved during the course of the flight program which extended from 1959 to 1968 with a total of 199 flights. There were plans to extend the program with a modified airplane to explore hypersonic cruise but development delays, high costs, and the loss of the number-three airplane in a reentry accident, led to the cancellation of the X-15 program in November 1968 and the temporary end of an era of manned flight research airplanes. Other vehicles in the X-designated series were:

- X-6 - Convair nuclear-powered bomber
- X-7 - Lockheed reusable supersonic ramjet test vehicle
- X-8 - Aerojet reusable upper atmosphere research rocket
- X-9 - Bell rocket testbed for standoff air-to-surface missile
- X-10 - North American testbed for Navajo intercontinental supersonic ramjet cruise missile
- X-11 - Convair ICBM research model testbed for Atlas
- X-12 - Jet-powered version of X-11
- X-13 - Ryan VTOL tail-sitter
- X-14 - Ryan diverted-thrust VTOL
- X-16 - Bell high-altitude long-range reconnaissance aircraft. Apparently gave way to Lockheed U-2
- X-17 - Lockheed ballistic research rocket
- X-18 - Hiller tilt-wing VTOL
- X-19 - Curtiss-Wright tilt-prop VSTOL transport
- X-20 - Boeing orbital glide vehicle (Dyna-Soar)
- X-21 - Northrop laminar-flow-control aircraft
- X-22 - Bell tilting ducted-prop VSTOL
- X-23 - Martin lifting-body reentry vehicle
- X-24 - Martin manned lifting-body vehicle
- X-25 - Bensen rotary-wing flight crew escape vehicle
- X-26 - Lockheed quiet observation aircraft
- X-27 - Lockheed fighter engine test bed
- X-28 - Osprey police patrol seaplane
- X-29 - Grumman forward swept-wing demonstrator projected to fly in 1984

The Century Series Era

In the latter 1940's, various airplane designs intended for supersonic flight were underway. The translation of research data, both wind tunnel and flight, into operational military airplanes began to emerge in the 1950's and led to a rash of designs that reflected almost all types of configurations. It was the era of the "Century Series" airplanes in which some problems were exposed and, in most cases, corrective measures were applied by the experimentally developed "fix" rather than by an innovative technological development. Most of these airplanes experienced stability problems that should have been predictable based on knowledge gained from general research wind-tunnel testing and from the X-series of flight testing. Some of these problems and solutions will be described.

The North American F-100.- Following a company line of fighters that included the P-51 Mustang and F-86 Sabre, the F-100 Super Sabre became the first operational USAF airplane capable of sustained, level, supersonic flight (about M = 1.3). The early models of the F-100 experienced some problems of inertia coupling and insufficient directional stability and several airplanes and pilots were lost. Wind-tunnel tests at NACA Langley revealed a large directional instability for the wing-body that placed a high demand on the stabilizing contribution of the vertical tail. In addition, the stabilizing contribution of the vertical tail decreased markedly at moderate angles of sideslip. These revelations confirmed the need for increased directional stability and a new vertical tail with a 27-percent area increase was put on the airplane.

The Convair F-102.- The F-102 Delta Dagger was an outgrowth of the XF-92A fighter-interceptor research airplane. The first airplane showed no hope of reaching its supersonic design speed and was barely able to penetrate the transonic range. Accordingly, production was halted while extensive studies were undertaken to improve the interceptor performance. Among the subsequent modifications, based on NACA Langley research, were the application of the transonic area rule that resulted in a "coke bottle" fuselage to reduce the transonic drag rise penalties; a new wing design with a conically cambered leading edge and reflexed wing tips to improve the drag due-to-lift characteristics; a new vertical tail location and, subsequently, an increase in tail size to improve the supersonic directional stability; and a total extension in fuselage length of 11 feet. A modified airplane, nicknamed the Hot Rod, reached a Mach number of 1.22 at an altitude of 53,000 feet and production was resumed.

The McDonnell F-101.- The F-101 Voodoo was the first USAF twin engine, supersonic fighter-interceptor airplane having a speed capability of about M = 1.6. The design was characterized by nozzles located forward of the tail portion of the airplane rather than at the base of the airplane. Part of the rationale for such an arrangement is to keep the engine-associated weight (and airplane center of gravity) more forward, and to reduce the duct-flow losses by shortening the duct length. A consequence of the arrangement, however, is that the afterbody and tail regions are subjected to the jet exit flow. Accordingly, heat protection of the afterbody must be considered as well as the location of the horizontal tail. The high tail location used on the F-101 was a contributor to a serious problem of pitch-up stability. The F-101 design was the subject of wind-tunnel and rocket-model tests by NACA Langley in 1955 in order to determine the stability and control boundaries. The pitch-up problem was alleviated by an active inhibitor built into the control system. Two views of a wind-tunnel model are shown in figure 4. The F-101 tunnel tests included studies of the launch characteristics for the internally carried weapons and the model with the Genie missile in the extended launch position is shown in figure 4.

The Lockheed F-104.- The F-104 Starfighter, designed for low minimum drag, set a speed record of M = 2.1, an altitude record of 103,395 feet, and, for a time, simultaneously held the world records for speed, altitude, and time-to-climb. Along with the remarkable performance, the F-104 had problems in the form of cross-coupling (due to the inertia distribution), pitch-up (due to the high-tail location), and low-directional stability at high M and high angle of attack (due to the inherent instability of the long body and other geometric constraints). A photograph of the NACA wind-tunnel model of the F-104 (fig. 5) emphasizes the long body, the small wing, and the high tail. A modification made as a result of NACA wind-tunnel tests was the addition of a fairly effective ventral fin to improve the directional stability.

The Republic F-105.- Following the company lineage of the P-47 Thunderbolt, the F-84 Thunderjet and the F-84F Thunderstreak, the F-105 Thunderchief design for a supersonic fighter-bomber came into being. The original design of the F-105 did not incorporate the transonic area rule. However, early wind-tunnel tests made in the Langley 8-foot transonic tunnel indicated that substantial drag improvements could be realized through the application of some body contouring and the modification was made to the third airframe. In addition, the original transonic inlet was changed to a supersonic inverted scoop inlet as a result of NACA tests. Other modifications made as a result of NACA-Langley wind-tunnel tests were an enlarged vertical tail and the addition of a ventral fin to enhance the supersonic directional stability. Photographs of the modified model are shown in figure 6.

The Convair F-106.- An outgrowth of the F-102 Delta Dagger configuration was an advanced interceptor originally designated F-102B that was subsequently redesignated the F-106 Delta Dart. The F-106 is similar in appearance to the F-102 with perhaps the most noticeable external difference being a change in vertical tail planform from a near-delta shape to a larger area trapezoidal shape that was made to improve the directional stability. The F-106 had a more powerful engine, increased payload, increased range, and speed (slightly in excess of M = 2). The F-106 was designed for internal carriage of the Falcon and Genie missile. Tunnel tests included the missile launch characteristics. A photograph of the tunnel model with extended missiles is shown in figure 7.

The Grumman F11F-1.- The Tiger, first airplane designed using the transonic area rule, demonstrated relative ease in negotiating the transonic range in July 1954, using about 25 percent less thrust than required by the F-100. The design was verified through extensive NACA test. The tunnel model (fig. 8) included various tail planforms, a drooped horizontal tail, and large folding ventrals.

The Chance Vought F8U-1.- The Crusader featured an underslung chin inlet and had a variable-incidence wing. The airplane was extensively tested by NACA and some suggested modifications included large folding ventral fins that were incorporated on some versions.

The Convair B-58.- The Hustler was the first U.S. supersonic (M = 2) operational bomber. Following the Convair fighter tradition, the B-58 was area ruled and had a delta wing with conical camber and elevon control. Four podded engines were used and the payload (and some fuel) was carried externally in a large droppable pod beneath the body. Some B-58 problems surfaced when vertical tail structural failure occurred in sideslip during asymmetric engine-out flight at supersonic speeds. A region of low directional stability aggravated by control-induced adverse yaw was revealed in NACA wind-tunnel tests and corrective control system changes were made.

The McDonnell F4H.- The Phantom II was originally developed as a Navy shipboard fighter in 1958. Wind-tunnel tests at NACA-Langley in the late 1950's revealed that the original F4H design had some of the characteristics of its ancestors including a severe pitch-up, low-directional stability, and low-effective dihedral. Several subsequent modifications made to the production design were the sharply drooped tail panels (originally almost horizontal) to alleviate pitch-up, outboard wing leading-edge extensions to improve the high-lift stability, and turned-up wing-tip panels to improve the roll/yaw ratio. Photographs of the original and revised tunnel model configurations are shown in figures 9 and 10. Tests of the revised model also included the effects of semi-submerged Sparrow missiles for supersonic carriage. In 1963, the airplane was procured by the USAF as a tactical fighter (originally designated by USAF as F-110) and, through many modifications, the airplane remained in production as the F-4 for over two decades.

The General Dynamics F-111.- On November 24, 1962, the U.S. ushered in a new era of tactical fighters with the initial development contract to General Dynamics/ Grumman for the TFX (F-111), two-place, twin-engine, variable-sweep, tactical fighter multi-mission airplane. The missions were to include M = 2.5 capability at altitude, M = 1.2 penetration at sea level, ferry range of 3600 miles, with operation from rough fields on 3000-foot strips as well as operation from Navy carriers. Initial NACA work leading up to the TFX began as early as 1945 with wind-tunnel tests of swept and yawed wings, variable-sweep tunnel tests in 1947, and the Bell X-5 variable-sweep airplane flight tests in 1948. NACA studies in the later 1950's showed the potential of variable sweep for combining supersonic capability at altitude with good subsonic range, good low-speed landing and takeoff, alleviating gust loads to provide high-speed penetration at low altitude, and increasing loiter time. Various ensuing research models lead to a wing-pivot location that minimized stability variations with sweep without the necessity of wing translation as had been used on the X-5.

Following the contract award for the F-111 to General Dynamics/Grumman, a period of technical and political difficulties began that were to last for years. The political hearings began in 1963 in response to Senate suspicions that the award to General Dynamics was politically motivated. As for the development of the airplane, some problem areas surfaced in inlet/engine performance, stability and control, weight increase, and so on. The first airplane flew on December 21, 1964, and the delivery of operational airplanes began in October 1967 to the Air Force. However, the Navy never procured any F-111's and cancelled its program in 1968. Subsequently, the Navy developed its own tactical fighter, the F-14, and the Air Force developed its own tactical fighter, the F-15.

The North American B-70.- In late 1954, a military requirement, WS-110, was proposed for a sustained supersonic cruise strategic bomber to replace the B-52. It was to operate from existing runways, cruise unrefueled for at least 6000 nautical miles, and have a $M = 3$ capability at altitude. The North American XB-70 Valkyrie was chosen, first flew on September 21, 1964, and achieved $M = 3$ on October 14, 1965. The XB-70 was designed to make use of the "compression lift" generated beneath the wing by the wedge-shaped sides of the engine ducts. Unfortunately, additional drag was also generated and efficient lift-to-drag ratios for cruise were problematical. The XB-70 was designed so that the wing tips could be drooped to 65 degrees which, at supersonic speeds, would improve the directional stability. The B-70 became embroiled in technical and political problems and presumably lost out to the concept of mixed ICBM's and B-52's as strategic deterrents and was cancelled.

The Lockheed SR-71.- One of the best secrets in the U.S. was the Lockheed A-11, developed by Kelly Johnson and the "skunk works" team as a high-altitude, $M = 3$ cruise, reconnaissance airplane follow-on to the subsonic U-2. Wind-tunnel tests were underway (some at NASA Langley) in the latter 1950's. The airplane was not publicly revealed until the spring of 1964. A fighter version, the YF-12, flew early in 1964, and the prototype SR-71 Blackbird strategic reconnaissance airplane flew December 22, 1964. The airplane, at various times, has held several world records for speed and altitude. In September 1974, an SR-71 flew from New York to London in one hour and fifty-five minutes at an average speed of about 1807 mph ($M = 2.7$). In July 1976, the SR-71 set records of 2193 mph ($M = 3.3$) over a straight course, 2092 mph ($M = 3.1$) over a 100 km closed course, and a sustained level-flight altitude of 85,069 feet. Many new technical lessons related to high-speed flight were applied in the SR-71 design.

The Rockwell B-1.- The Rockwell B-1 variable-sweep, four-engine airplane was developed as a strategic bomber both for high-altitude cruise and supersonic flight as well as low-altitude high-speed penetration. Four airplanes were built with the first flight on December 23, 1974. The airplane exceeded $M = 2$ in April 1976 and demonstrated high-altitude cruise and low-altitude terrain-following penetration. The airplane, which like the B-70, was the intended replacement for the B-52, also became entangled in technical and political problems. The B-1 was cancelled by President Carter in June 1977 and reinstated by President Reagan in 1981.

Some lessons, perhaps not yet well learned, that might be surmised from programs such as the B-70, the F-111, and the B-1 are that the development of new aircraft may depend as much, if not more, on political problems as on technical problems.

Other Military Airplane Programs.- A few other development programs from which much was learned, although operational status was not reached, should be noted.

The Northrop XP-79A was begun in 1942 as a unique rocket-propelled flying-wing fighter design following the pattern of the German Me 163 Komet. Although the rocket version was eventually cancelled, a rocket-propelled flight was made on July 5, 1944. Further development was done with a jet-powered XP-79B that was destroyed in a crash September 12, 1945. The unusual magnesium airframe was totally consumed by fire. The airplane was only 14-feet long and incorporated a prone position cockpit which would have permitted the pilot to withstand 21 g's. Wing-tip bellows were used to provide yaw control and a four-point gear was installed.

The Republic XF-91 Thunderceptor design was begun in 1946 as a supersonic daytime interceptor. The airplane was fitted with a jet engine and four rocket motors to provide rapid acceleration and climb capability. The airframe had a unique 35-degree swept wing with adjustable incidence to provide the most effective angle of attack for takeoff, cruise, and landing. In addition, the wing had inverse taper which, in conjunction with leading-edge slats, was intended to reduce the tendency of wing-tip stall at low speeds. The jet version flew in May 1949. In December 1952, the airplane with combined jet and rockets reached 50,000 feet in 5.5 minutes at $M = 1.7$. While this performance could not be matched by contemporary jet interceptors, further development was halted and the interceptor role was subsequently filled by the Convair F-102A.

The Republic XF-103 design was one of the winning entries of the advanced interceptor program initiated in 1949 to provide a new interceptor capable of exceeding $M = 1$ at greater than 50,000 feet and to be operational in 1954. The XF-103 design had a dual-cycle turbo-ramjet engine which was intended to achieve about $M = 4$ at 80,000 feet with a combat radius of about 430 miles. The engine, to be developed by Wright, was to be a conventional turbojet with an afterburner designed to serve the dual purpose of a ramjet engine. Other advances in state of the art included titanium construction, high-temperature hydraulics, downward-ejection escape capsule, retractable ventral fin, and periscope forward vision (no canopy). A metal mock-up was constructed, but after a 9-year development program, and some problems with titanium procurement and fabrication, engine development, and funding, the project was cancelled in September 1957. It is interesting to note, however, that many of the features of the XF-103 design were used later on the Lockheed SR-71, including the concept of the dual purpose afterburner/ramjet system.

The North American F-107A was a ground attack figher-bomber design of 1953 that was in competition with the Republic F-105. Although the F-107 lost the competition, three airplanes were built and extensive flight tests were conducted. The F-107 had no difficulty in achieving $M = 2$ flight in 1956 and demonstrated several features such as the top-mounted inlet, all-moving vertical tail, and spoiler-roll controls.

Another USAF program began in 1955 to develop a long-range interceptor. North American received a contract in 1957 for the XF-108 Rapier design which was to be an all-weather, two-man, twin-engine, long-range interceptor with a combat speed of at least $M = 3$ at 70,000 feet with a 1000 nautical-mile range and 5 minutes of $M = 3$ combat. In addition, the airplane was to cruise at $M = 3$ for 350 miles with 10 minutes of $M = 3$ combat. Finally, there was a requirement for $M = 3$ cruise for 280 miles with a one-hour loiter time followed by a high-speed target intercept 750 miles away. The XF-108 was similar to the B-70 delta-wing canard design but had twin horizontal-ramp side inlets, a centerline vertical tail, and two wing-mounted vertical surfaces for added directional stability. The Air Force believed that the F-108 would be a good mobile missile launcher to intercept enemy aircraft far from their intended targets. A mockup was built but the program was cancelled September 23, 1959, due to funding problems. (Note that almost a quarter of a century later, we are still studying aircraft designs with similar, or less, capability.)

Some Missile Developments

Foreign technology.- German scientists had begun making strides into supersonic aerodynamics with missiles such as the A-4 (V-2), one of which, on a ballistic flight, achieved a speed of $M = 4.7$, an altitude of 275,000 feet, and a range of 116 miles on October 3, 1942. The maneuverable Wasserfall-winged surface-to-air missile, designed for $M = 3$, made 44 successful flights in the 1944 time period. A winged version of the A-4, the A-9 successfully flew to $M = 4$ during the winter of 1944-45. Further plans for the A-9, curtailed by the end of the war, included a manned-version with a pressurized cockpit and tricycle landing gear, that was to fly at $M = 2$ for 400 miles. A rocket-boosted manned A-9 was also envisioned that would have transatlantic range.

There were other German developments worth noting--the Luftwaffe developed a winged, subsonic cruise missile powered by an airbreathing pulse-jet engine. This missile, to become known as vengeance weapon one, V-1, was catapult-launched, controlled in flight by inertial guidance, and employed a predetermined engine shut-off time when the weapon would than dive on its target. The first was launched against London on June 12, 1944. Much of the German (and axis-partner, Italian) work in high-speed missile aerodynamics fell into the hands of the Allied nations at the end of World War II and was useful in stimulating research in other countries.

U.S. Adaptions

Werhner von Braun and 120 other top German scientists were hand-picked through interviews and brought to the U.S. between late 1945 and the summer of 1946 and stationed at Fort Bliss, Texas. There they were to resume flight tests at the White Sands Proving Grounds in New Mexico, using V-2 rockets. Thus it was that the U.S. began to gain experience with missiles. During a 5-year program, 68 German V-2's were fired at White Sands only about half of which were successful. (The Germans achieved about a 75-percent reliability during combat with the V-2.) On Feburary 24, 1949, a two-stage Bumper-Wac (a U.S. Corporal second-stage rocket on a first-stage German V-2) was launched to an unprecedented altitude of about 250 miles. The development of U.S. ballistic missiles was beginning to take shape.

Other U.S. missile programs with some German background included:

- o Corporal, Army Ordnance surface-to-surface missile, based on the German V-2 technology, built by Firestone Tire and Rubber Company.
- o Redstone, Army Ordnance surface-to-surface missile developed by the German group at the Redstone Arsenal, produced by Chrysler.
- o Hermes, Army Ordnance project with General Electric Company, research missile based on the German Wasserfall with prospective outcome to be a medium-range guided surface-to-surface missile. Sometimes referred to as the first

"American made" guided missile--the basic design having been done a decade before then by the Germans.

- Loki, Army Ordnance anti-air defense, barrage-type unguided fin-body rocket based on the German flak rocket Taifun, produced by Bendix.

Although the U.S. did test fire some German V-1 cruise missiles, no development program of this type was pursued. Some large, long-range U.S. cruise missiles of the late 1940's and early 1950's included the Regulus I, Regulus II, Snark, Navaho, Matador, Mace, Hound Dog--all of which were relatively short-lived developments.

U.S.S.R Adaptions

While no attempt will be made to expound on lessons learned by the U.S.S.R. following World War II, the following observations are noted:

- The U.S.S.R. did acquire German technology as well as western (notably U.S. and British) technology.
- The U.S.S.R. exploited jet propulsion.
- The U.S.S.R exploited high-speed aircraft with swept wings, delta wings, and subsequently, variable-sweep wings.
- The U.S.S.R. exploited the German V-2 and quickly developed ballistic missiles of many types.
- The U.S.S.R. exploited the German V-1 and quickly developed cruise missiles of many types--notably antishipping missiles.

EPILOGUE

The World War II time period ushered in a new era in aeronautical research and development. Just prior to the outbreak of the war, testing, modification, and production of aircraft were accelerated in the U.S. The air conflict during the war highlighted the need of aircraft with agility, high speed, long range, large payload capability, and in addition, introduced a new concept in air warfare through the use of guided missiles. Following the war, the influx of foreign technology, primarily German, led to rapid advances in jet propulsion and speed, and a host of new problem areas associated with high-speed flight designs were revealed. The resolution of these problems led to a rash of new design concepts and many of the lessons learned, in principle, are still effective today. In addition to the technical lessons learned related to aircraft development programs, it might also be noted that some lessons involving the political and philosophical nature of aircraft development programs are worth attention.

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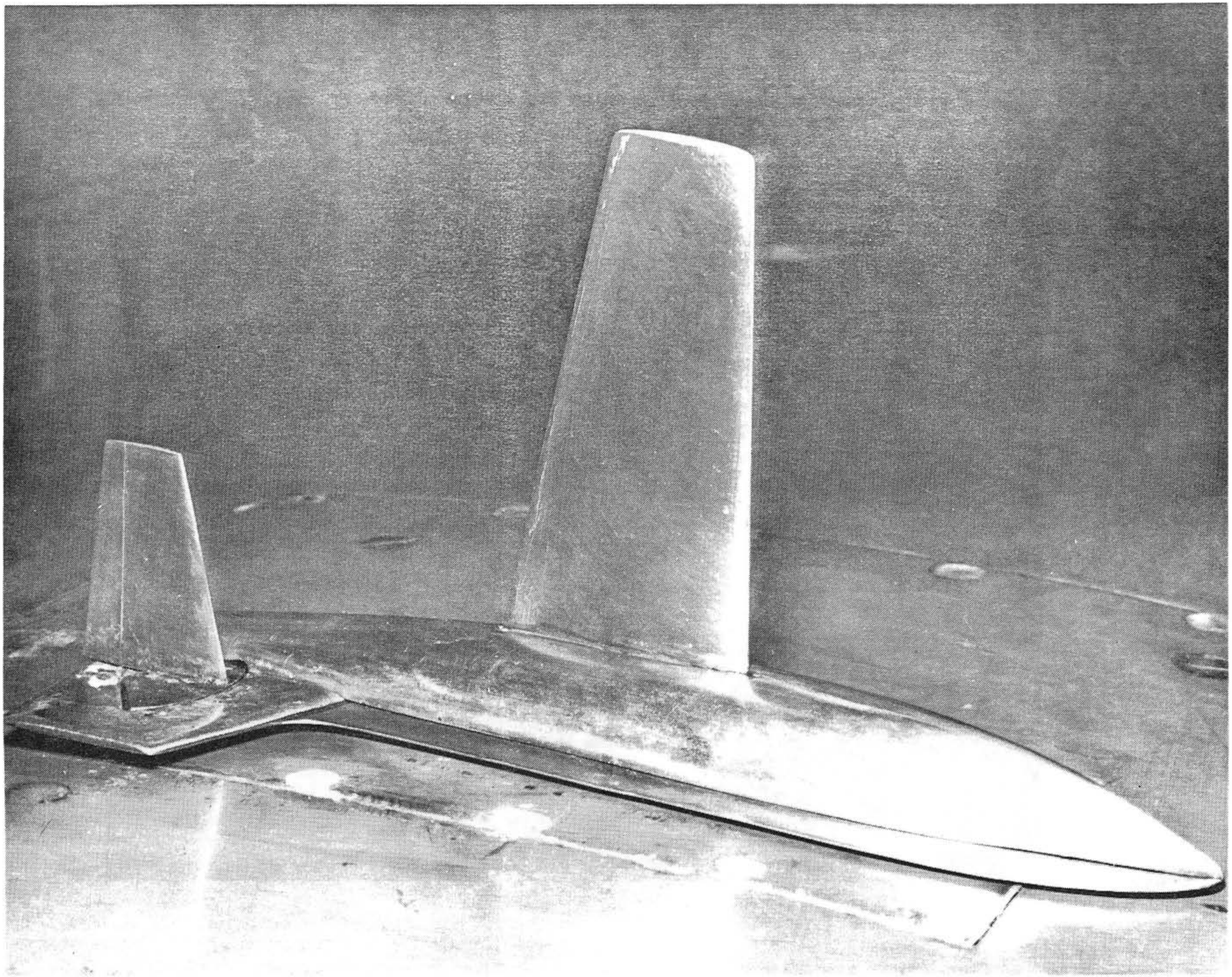


Figure 1.- Semispan model mounted on transonic bump.

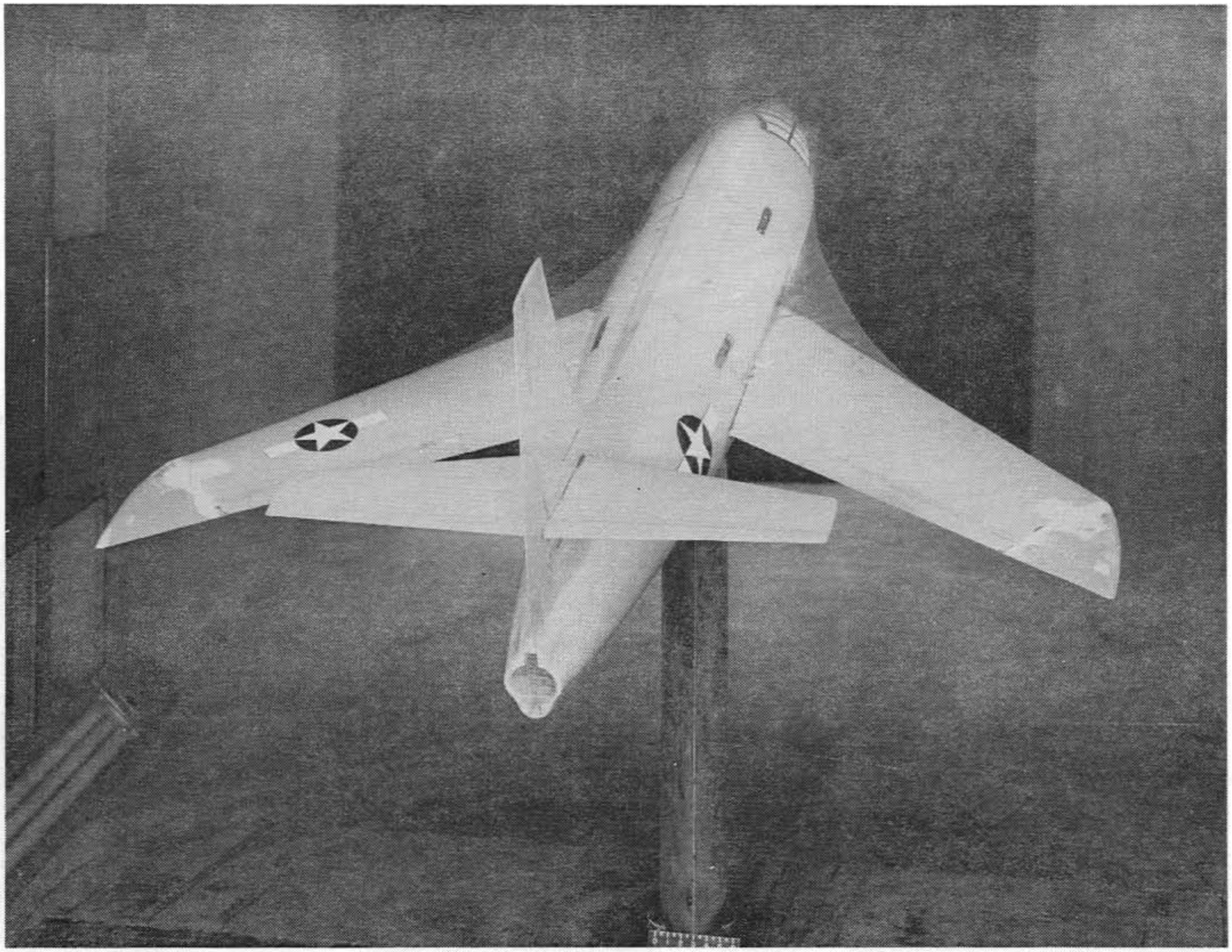


Figure 2.- Swept-wing research model with wing-root strakes.

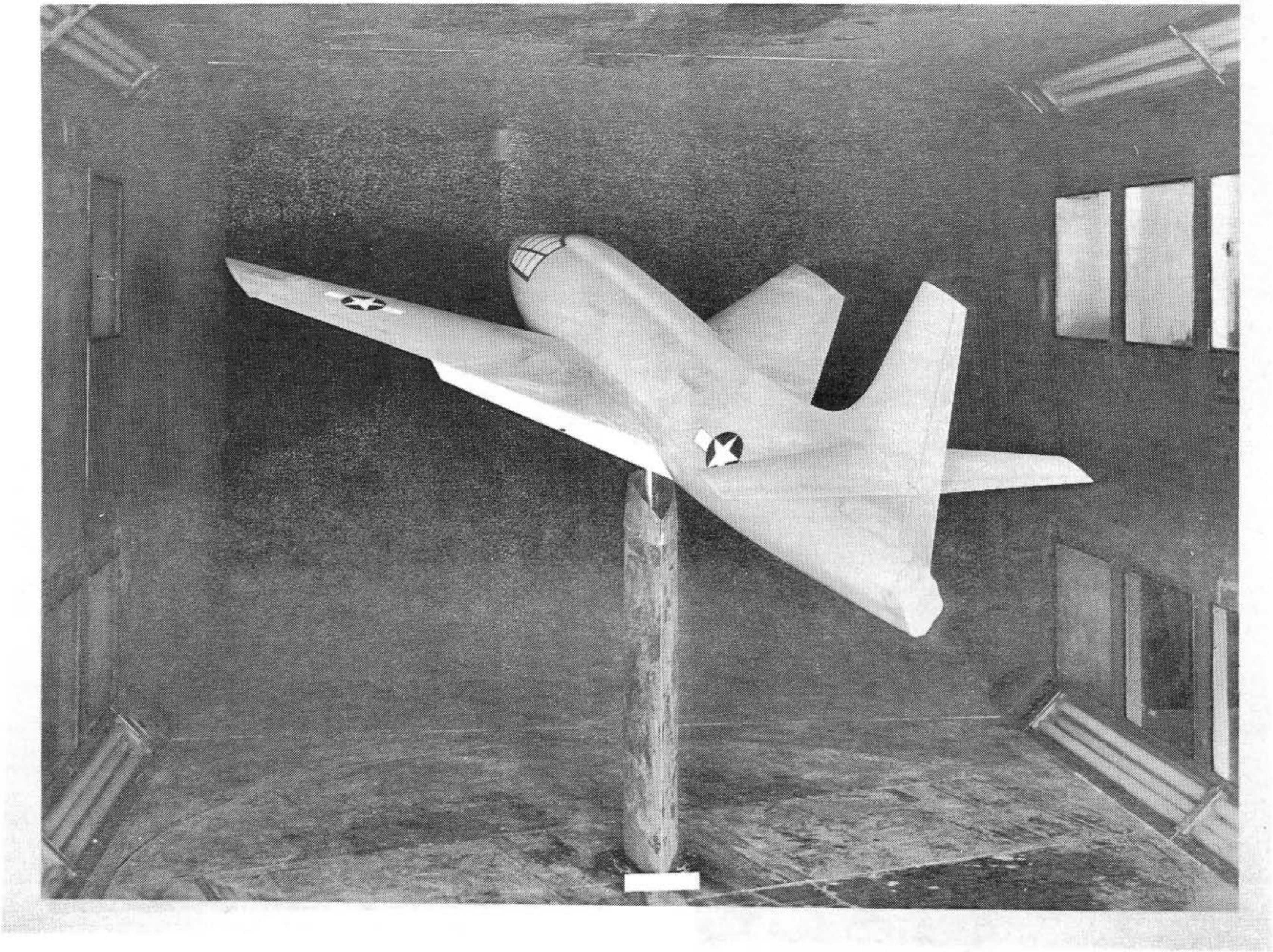
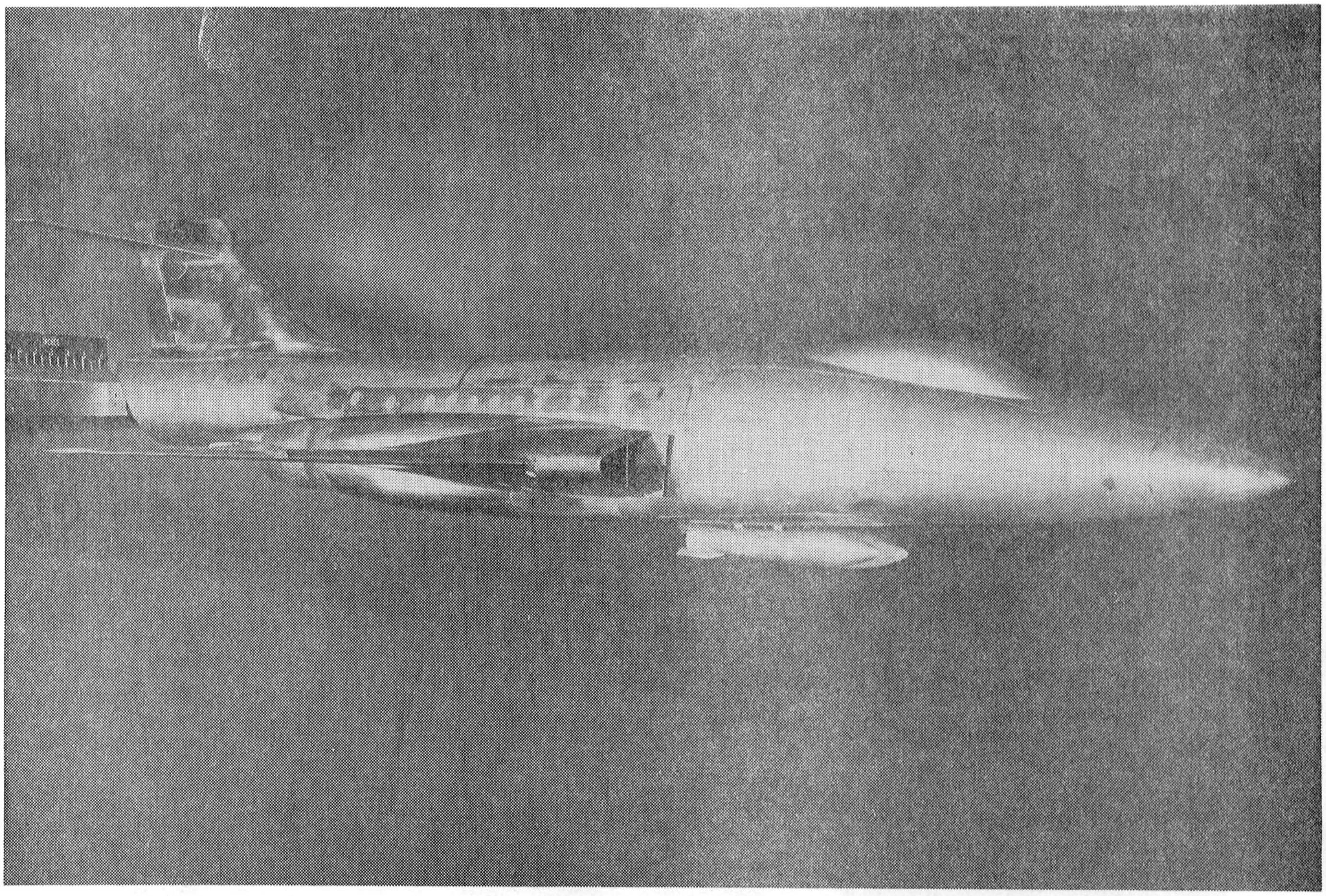
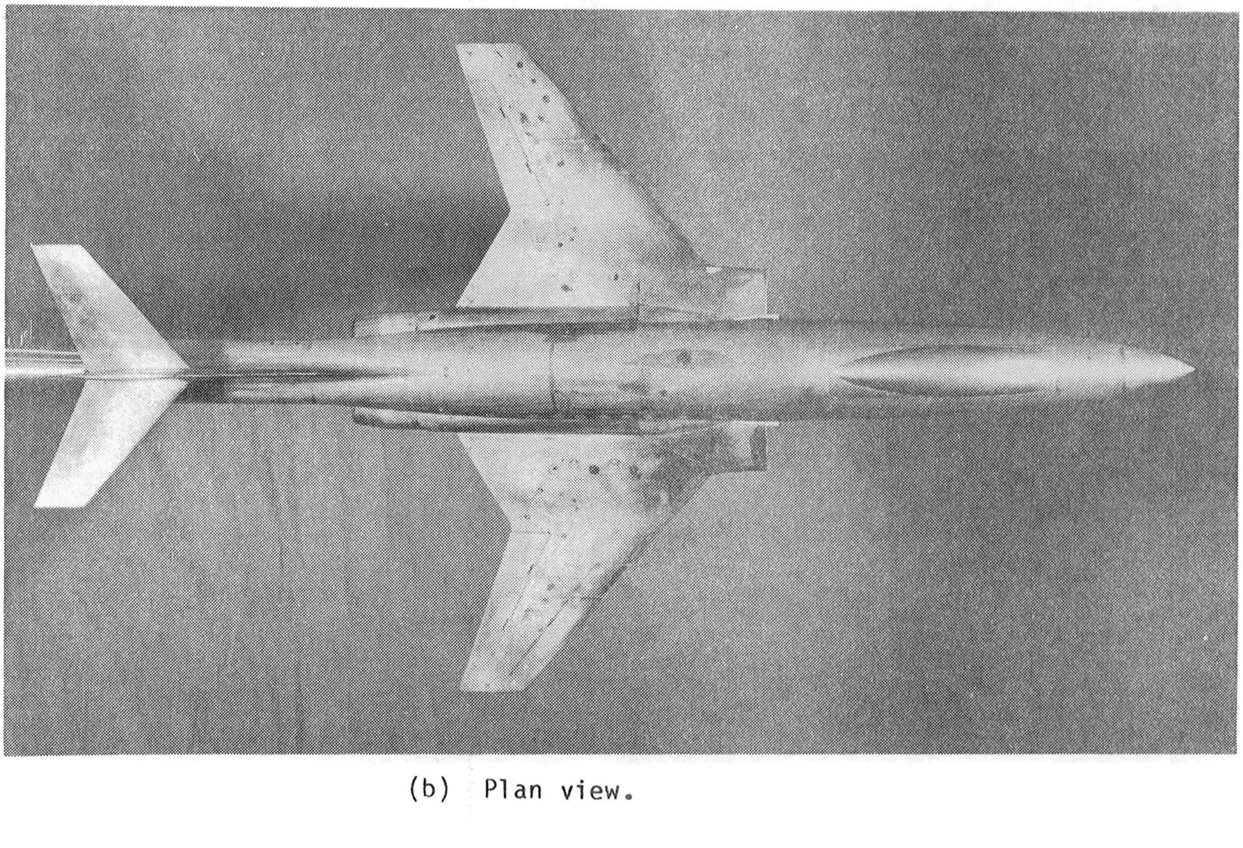


Figure 3.- Research model with forward-sweep wing.



(a) Side view showing store.



(b) Plan view.

Figure 4.- McDonnell F-101 wind-tunnel model.

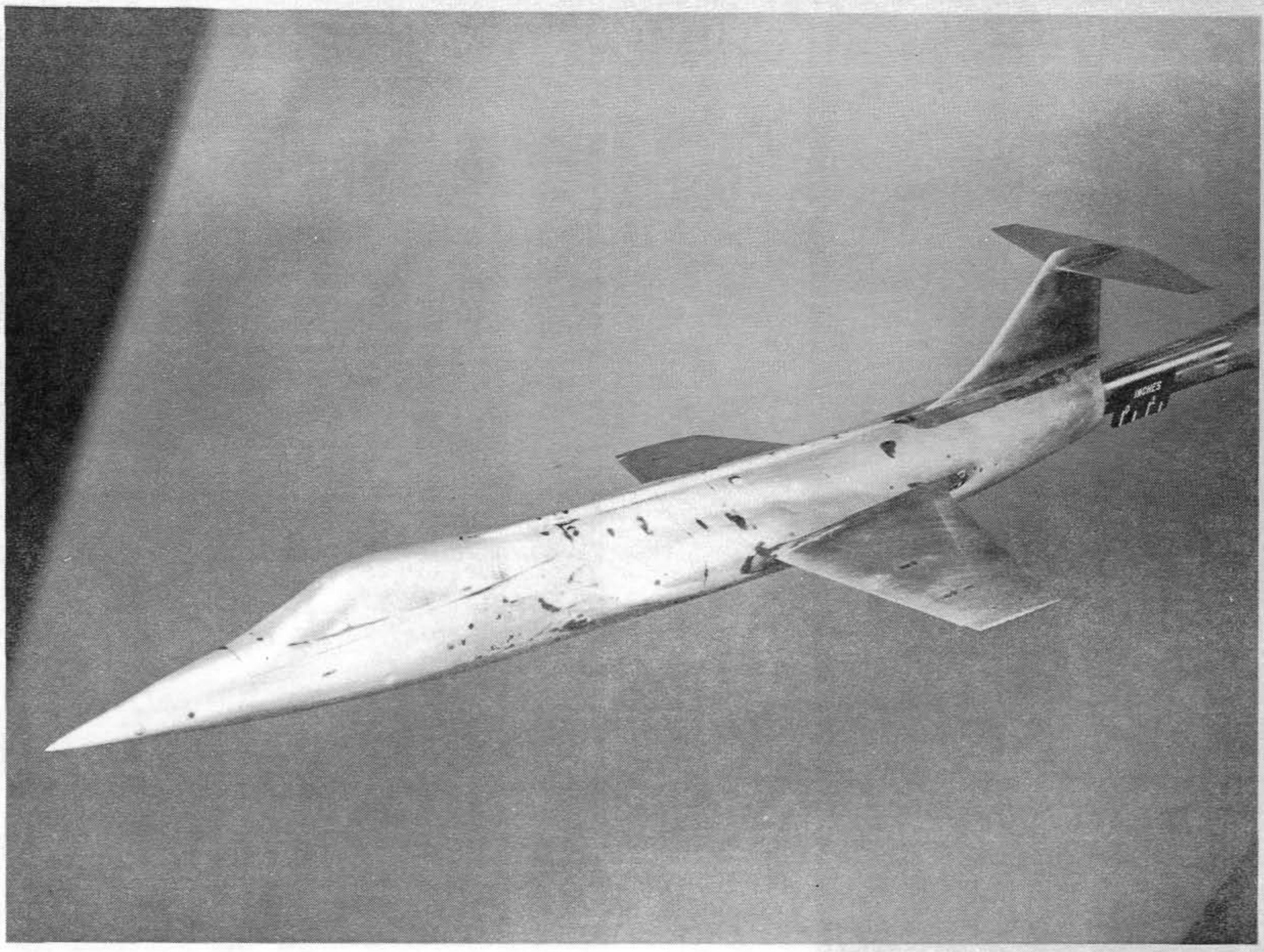
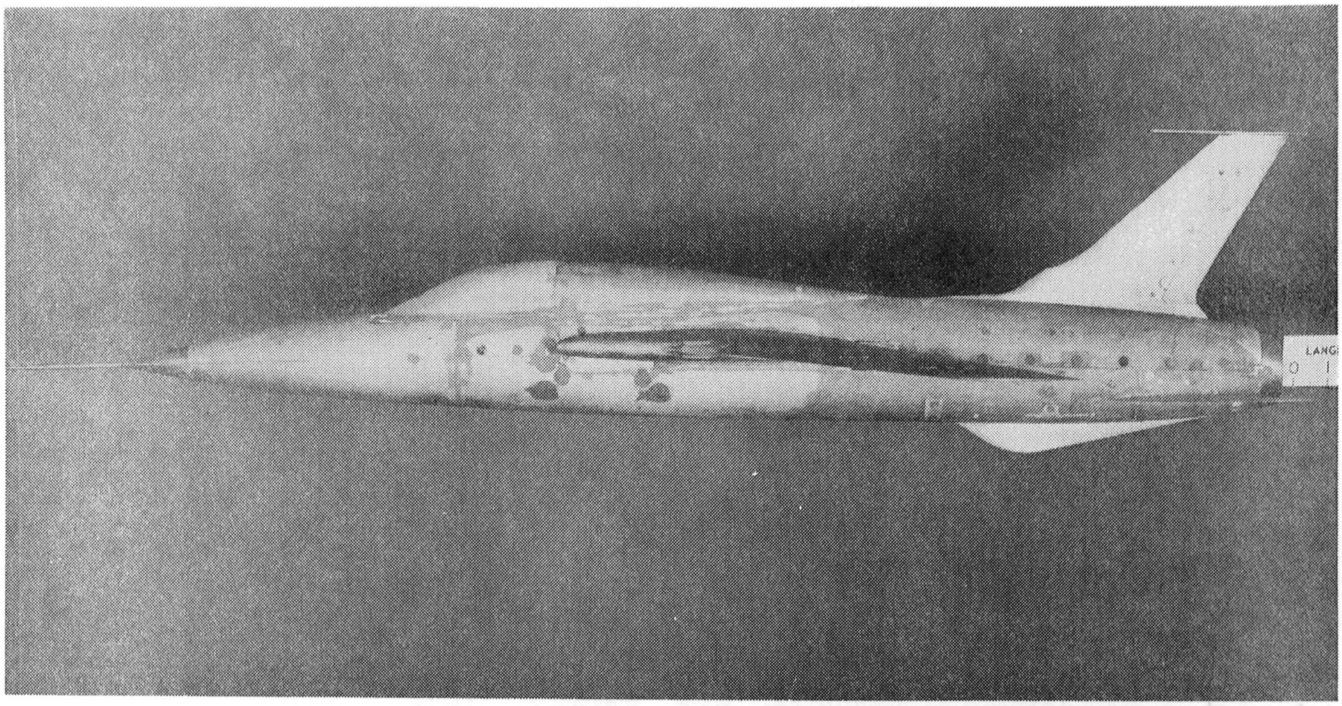
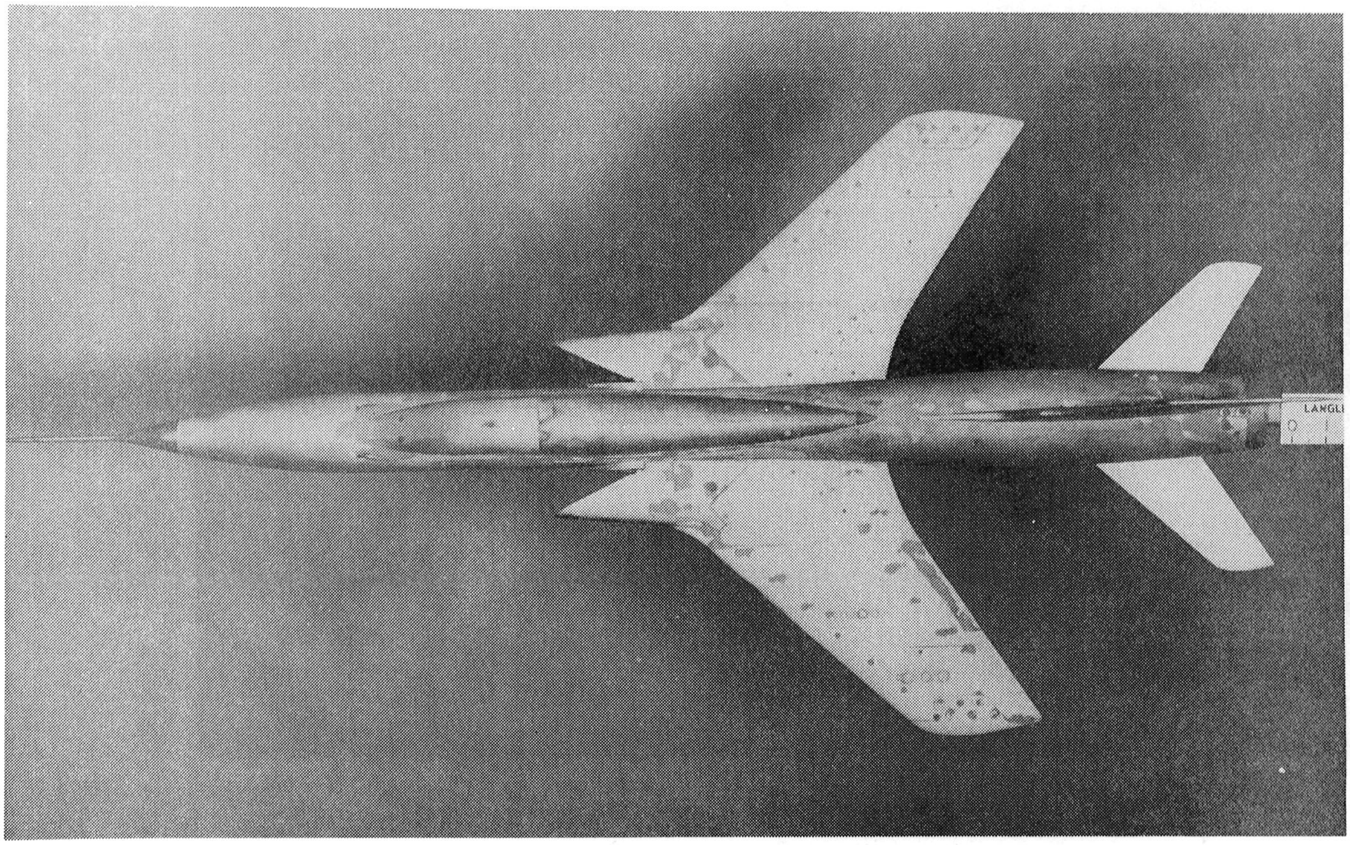


Figure 5.- Lockheed F-104 wind-tunnel model.



(a) Side view.



(b) Plan view.

Figure 6.- Republic F-105 wind tunnel model.

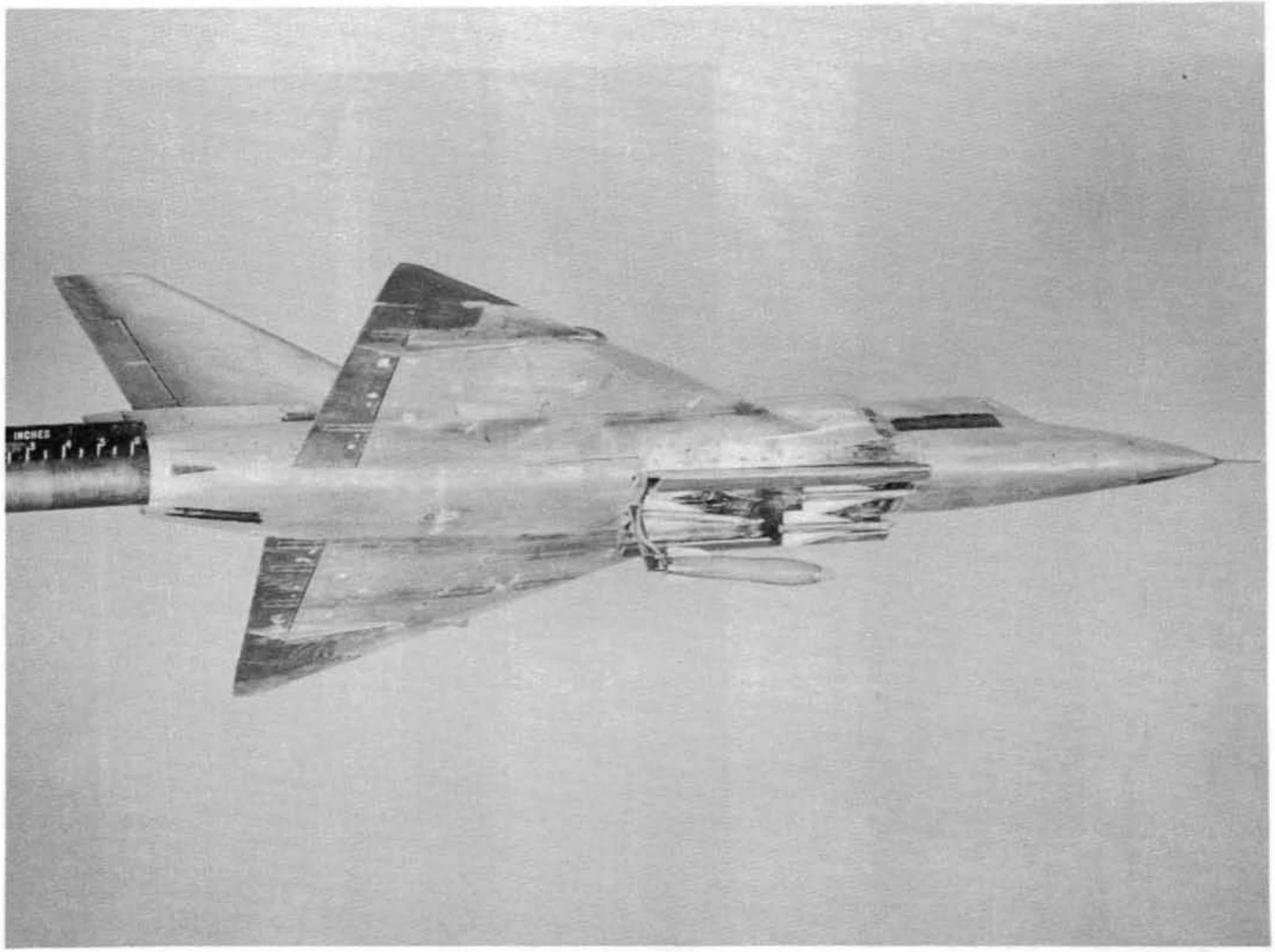
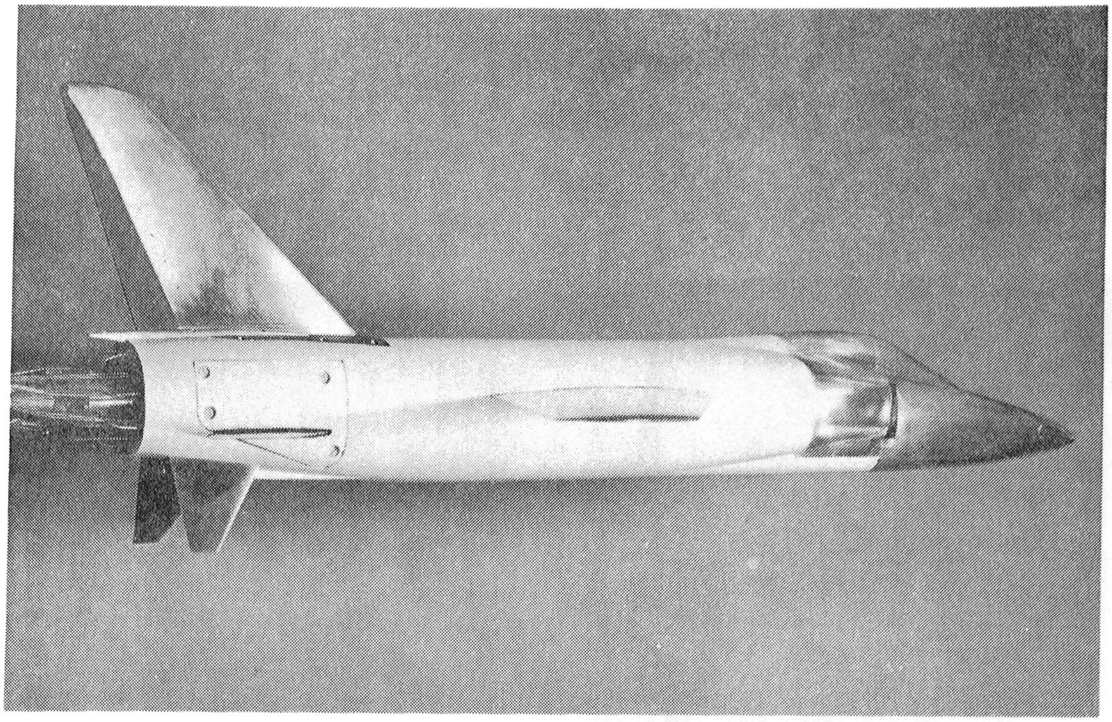
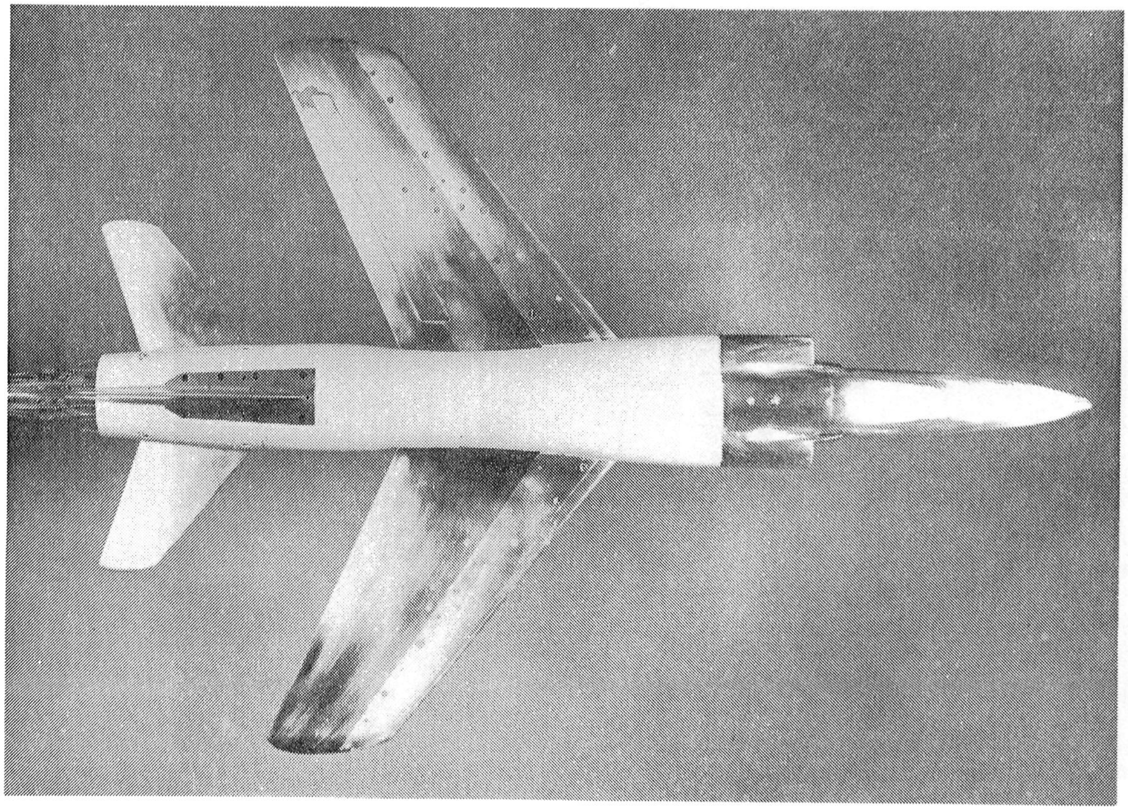


Figure 7.- Convair F-106 wind tunnel model showing stores.

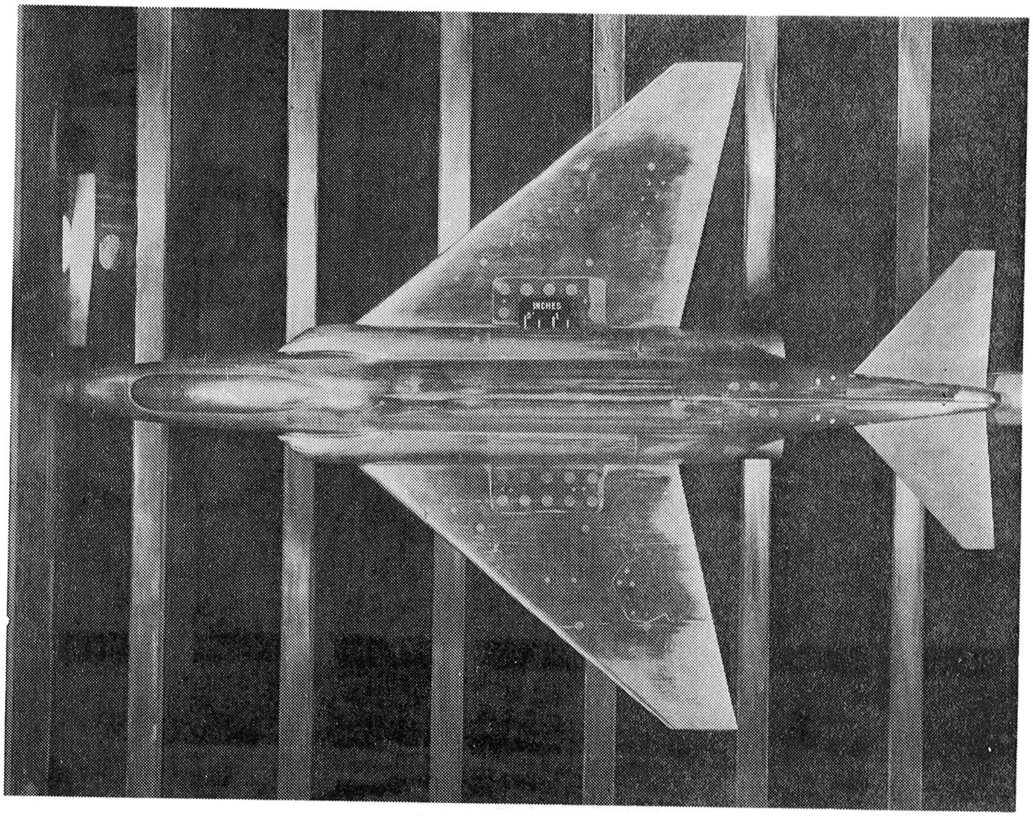


(a)Side view with folding ventrals.

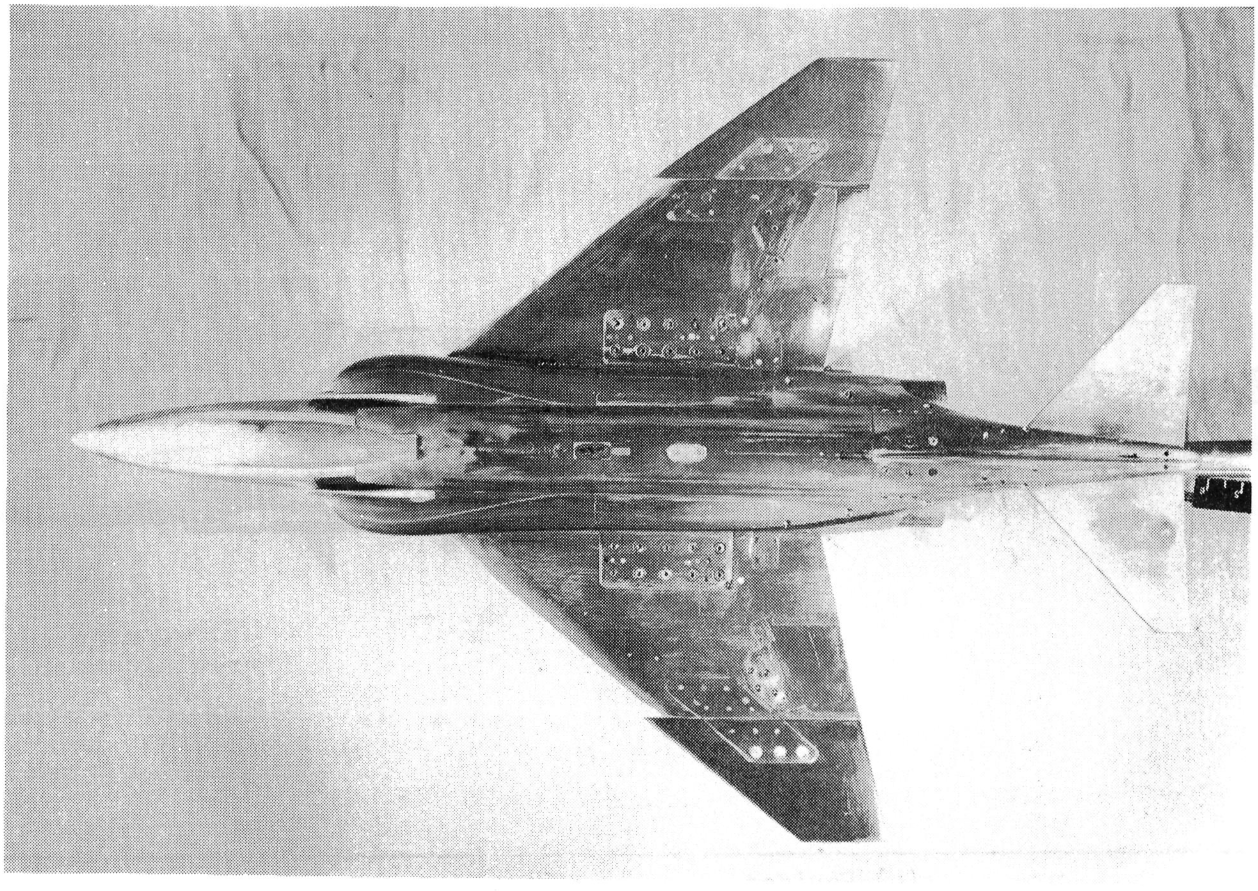


(b) Plan view.

Figure 8.- Grumman F11F-1 wind tunnel model.

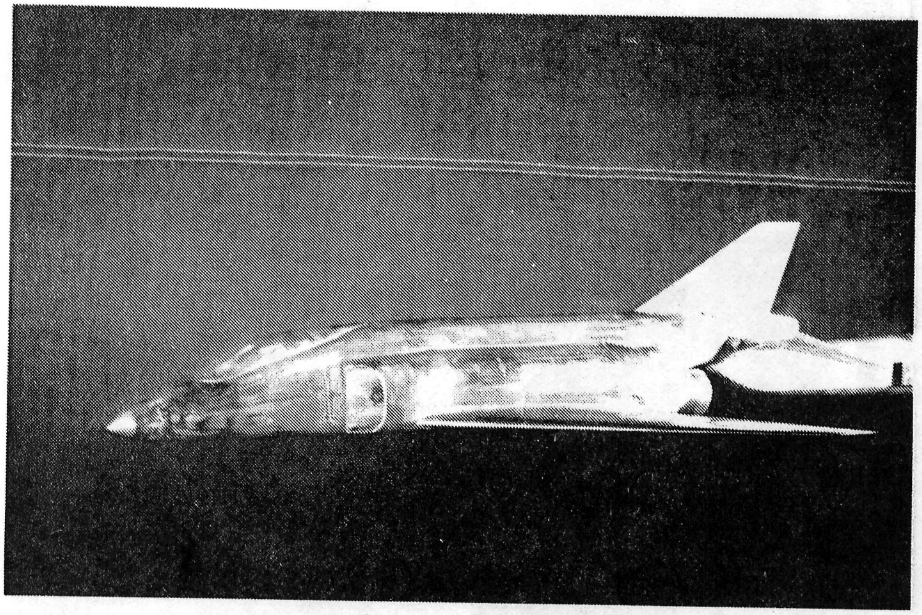


(a) Original.

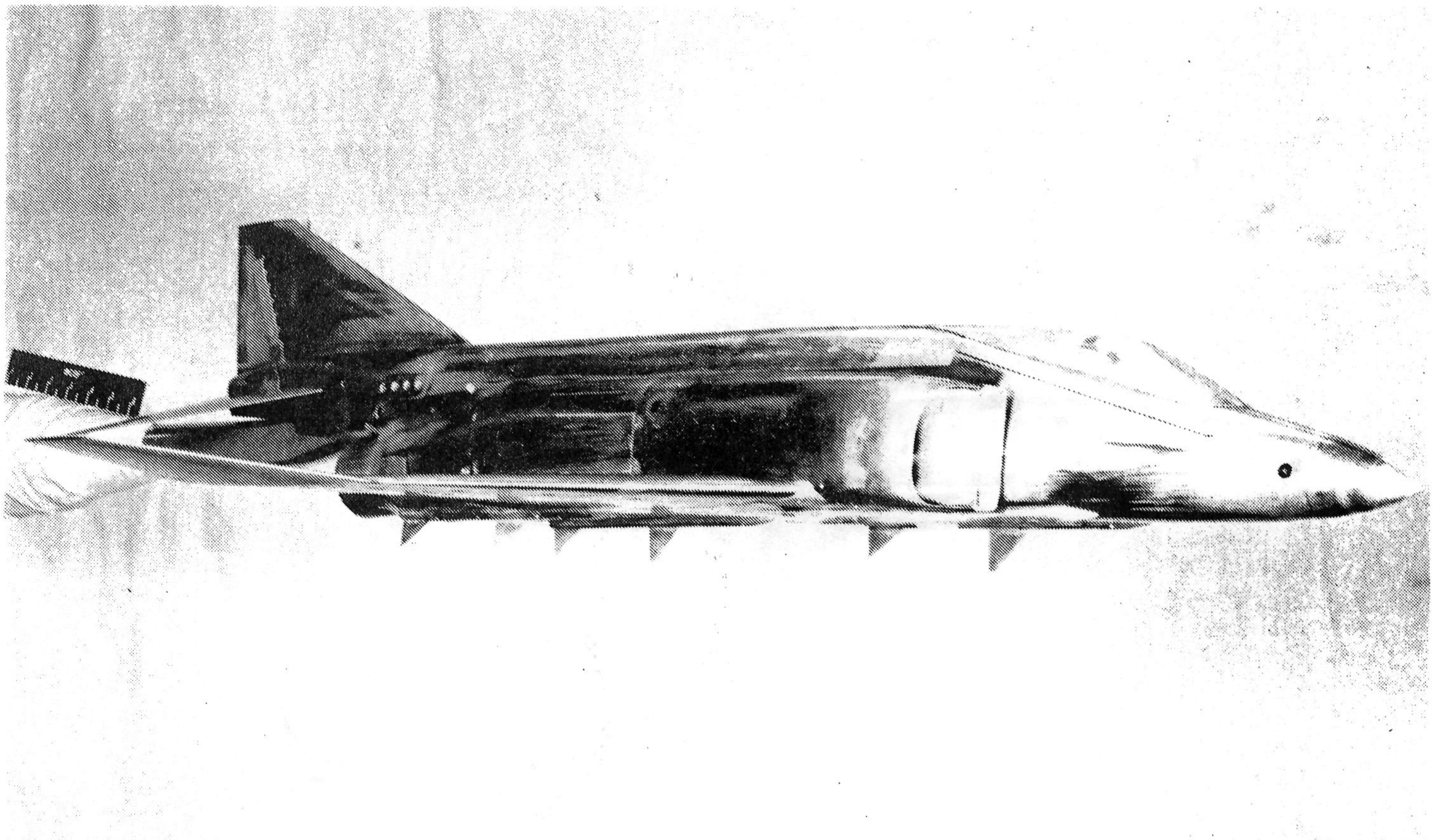


(b) Revised.

Figure 9.- McDonnell F4H wind tunnel model, plan view.



(a) Original.



(b) Revised, showing stores.

Figure 10.- McDonnell F4H wind tunnel model, side view.

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15. Supplementary Notes

16. Abstract

The World War II time period ushered in a new era in aeronautical research and development. The air conflict during the war highlighted the need of aircraft with agility, high speed, long range, large payload capability, and in addition, introduced a new concept in air warfare through the use of guided missiles. Following the war, the influx of foreign technology, primarily German, led to rapid advances in jet propulsion and speed, and a host of new problem areas associated with high-speed flight designs were revealed. The resolution of these problems led to a rash of new design concepts and many of the lessons learned, in principle, are still effective today. In addition to the technical lessons learned related to aircraft development programs, it might also be noted that some lessons involving the political and philosophical nature of aircraft development programs are worth attention.

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