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INTRODUCTION

Even before the first successful airplane flights, the idea of swept and sometimes variable-sweep wings, often appeared in early airplane designs. These early applications of sweep usually were linked to stability and control considerations and are not a part of the evolution of variable sweep for high-speed airplanes with which we are presently concerned. A chronology of research related to the development of high-speed variable-sweep aircraft covering the period of this paper is shown as figure 1. The concepts of both fixed-sweep and variable-sweep high-speed aircraft trace their beginnings to aerodynamic research carried out in Germany during the latter half of the 1930's and early 1940's. This research established the important benefits of wing sweep in delaying the onset of the so-called "compressibility drag" associated with the formation of shock waves which were predicted by both theory and wind tunnel tests to occur on the wing at speeds above about 500 mph.

While the Germans, during World War II, were the first to apply swept wings to high-speed aircraft and had periodically considered variable sweep, other pressures during the war and the dismantling of their aeronautical industry after the war precluded any serious research relative to variable-sweep aircraft. However, aerodynamic researchers in the United States discovered and verified the advantages of sweep independently of the German research, although some 5 years later, and in 1945 as our research effort was expanding and the German swept-wing results became available, the aerodynamic technology required for successful variable-sweep high-speed aircraft began to evolve.

This evolution spanned some 20 years and included early Langley wind-tunnel studies, U.S. flight experience with two variable-sweep aircraft based on an early concept, and a joint program with the United Kingdom followed by an extensive Langley research program which provided much of the technology for the world's first production variable-sweep aircraft. This aircraft, the F 111, was soon to be followed by others, both in the U.S. and Europe. The purpose of this paper is to review the research carried out primarily at the NACA/NASA Langley Center which contributed to the development of these new aircraft. Summary papers that have addressed different aspects of variable-sweep history have been published previously.[1]

WORLD WAR II AND AFTERMATH

The developing war clouds in Europe during the late 1930's did indeed alter the pace and nature of aeronautical research in the United States--particularly that carried out by the National Advisory Committee for Aeronautics (NACA), which embodied the largest assembly of research facilities and technical personnel in the United States. NACA had one laboratory, located at Langley Field, Virginia, with a complement in late 1939 of 523 personnel, of whom 278 were technical. Although NACA had been created during World War I to provide a base for making United States aircraft competitive with European aircraft of the period, there was little sustained interest in military aircraft improvement following World War I. Aircraft were considered as secondary arms of the Army and Navy, and in spite of the efforts of such individuals as General Billy Mitchell and Major Alexander de Seversky[2] to demonstrate a much higher potential value, the supporters of traditional land and sea weapons prevailed.

Soon after the onset of World War II in Europe, it became obvious that aircraft were much more effective than had been assumed by those responsible for U.S. military policy. It was also apparent that German and British fighters were far superior to any that existed in the U.S. inventory--primarily because of a speed advantage of about 100 mph. Consequently, an intense effort was started in order to expedite the development of improved aircraft. NACA was authorized to build new laboratories at Moffett Field, California and at Cleveland, Ohio. Many additional personnel were hired; however, the meagre complement of experienced people had to be distributed among the three laboratories, and their talents almost totally committed to direction of studies in support of the many new military designs that were being developed. Emphasis was placed on making the most of existing technology in accelerated development of improved aircraft. The policy was effective to the extent that it enabled the United States during the critical years of 1943 to 1945 to bring new aircraft into service that were equal to most German aircraft in speed and were clearly superior in range and combat effectiveness. The penalty for this approach, however, was that the ability of NACA to conduct basic and innovative research for future applications was severely limited. It may have been fortunate that Germany was unable to produce decisive numbers of the advanced aircraft they introduced near the end of the war, since the allies had nothing competitive to offer.

Experiences in combat during the early war years, such as the stability and control problems encountered during high-speed dives, emphasized the importance of compressibility effects on the wing and the empennage as the aircraft approached the speed of sound. No longer were the problems associated with compressibility confined to the tips of the propellers. Although NACA had wind tunnels capable of operating up to a Mach number of 0.9 and at Mach numbers of 1.4 and above, it became obvious that further increases in aircraft speed would require a research capability in the region of the speed of sound, the so-called transonic range. Unfortunately, the wind tunnel designs of that day were incapable of providing valid data in the transonic range. Some interim techniques were soon developed, however, so that during the latter part of the war, the United States had quite an effective capability for solving high-speed problems and for supporting innovative research.[3]

Several significant events occurred late in the war that led to a clear appreciation of the transonic test techniques. During the summer of 1944, two German swept-wing fighters (shown in fig. 2), the rocket-powered Me 163 and the turbojet powered Me 262A, were observed in combat; and later the JU-287 bomber with its forward-swept wing was observed on the ground. At that time, U.S. research and design people had no basis for understanding the significance of wing sweep at high speeds. However, just a few months later--in January 1945--R. T. Jones, of the NACA Langley Aeronautical Laboratory, completed a theoretical study[4] showing that the compressibility drag rise could be delayed and reduced by use of wing sweep, as illustrated in fig. 3. Jones pointed out that when an infinite-span airfoil is at an oblique angle to the airstream, the aerodynamic pressures at both subsonic and supersonic speeds are determined solely by the velocity component perpendicular to the airfoil leading-edge. He reasoned that since this velocity decreases as the sweep angle increases, compressibility effects would be delayed progressively with increasing sweep. For practical airplanes of finite span, it would appear that the advantage suggested by Jones could be realized by a finite wing skewed relative to the direction of flight, or by symmetrical wings having either swept-back or swept-forward wing panels.

In a little more than 2 months, the United States began to receive information acquired by the Allied forces in Europe indicating that the supersonic advantage of sweep had been discovered in Germany by Adolf Busemann and that he had presented his results in a paper at the Fifth Volta Conference[5] in Rome in 1935. It is ironic that invited papers were presented at the Conference by representatives of many countries, including the United States[6]; however, apparently little attention was given to Busemann's findings other than by a few individuals in Germany. It also became evident that the Germans had conducted wind-tunnel studies by mid-1940 that showed an advantage of sweep at high subsonic speeds as well as confirming the advantage of supersonic speeds.[7] Within a very short time after obtaining the German information, Langley made use of its new test techniques and demonstrated that the advantage of sweep also existed at transonic speeds. By combining information from the various sources--the theoretical findings of Busemann and Jones, the German experimental data at subsonic and supersonic speeds, and the NACA transonic data--a perspective of the benefit of wing sweep was developed. This is shown qualitatively in figure 4 in terms of the ratio of lift to drag, or aerodynamic efficiency, over the speed range. It is indicated that the efficiency of a straight wing with its longer span--though very favorable through most of the subsonic-range--becomes unattractive as Mach 1 is approached. In contrast, the three potential applications of the oblique-wing concept, represented by the broad shaded band, appear attractive in the transonic and supersonic ranges. The conclusion drawn by many in the United States during 1945 and 1946 was that the best of all worlds would involve having straight-wing characteristics at low speeds and swept-wing characteristics beyond the point where compressibility effects began to appear.

The course taken by NACA at this time was to enlarge the data base on swept wings in all technical areas to enable designers to evaluate both fixed sweep and variable sweep in relation to their mission objectives. One example was an interim study of the low-speed stability, control, and performance of wings of many different planforms (illustrated in fig. 5). This study[8] began in July of 1945 and provided a base for considerable work in such areas as aerodynamics, structures, and flight dynamics. There seemed to be little urgency for testing a specific design of symmetrical variable sweep, since the data resulting from the more general investigation of various planforms provided the base needed for any preliminary studies.

The oblique-wing (or skewed-wing) concept was a somewhat different matter, since there were widespread reservations about the flying qualities of highly unsymmetrical aircraft, and a free-flight investigation of an oblique-wing model was undertaken during March of 1946.[9] The tests were made in the Langley Free-Flight Tunnel, which used an inclined airstream to allow continuous gliding flight with no model thrust required. A photograph of the model in flight is shown in figure 6. The controls were actuated by electrical pulses through a flexible trailing cable. Surprisingly, the flying qualities of the model were quite good. There were some changes in longitudinal and lateral trim as skew angle increased, but these were easily handled by the controls up to a skew angle of about 40°. At higher skew angles, the lateral control became weak, until at 60° the ailerons were no longer adequate for both handling the lateral trim change and providing desired roll control. It is interesting that the characteristics of this small and rather primitive model are consistent with results from a flight investigation of a manned oblique-wing aircraft (fig. 7) recently made at the NASA Dryden Flight Center.[10]

Quite understandably, the free-flight oblique-wing tests in 1946 did not bring about an immediate rush to develop oblique-wing aircraft. The idea of symmetrical variable sweep was receiving increasing attention, though more from the standpoint of obtaining full-scale flight experience with different sweep angles than of deriving a mission advantage from the ability to vary the sweep angle in flight. However, there were several people who had thoughts of developing a variable-sweep research airplane to evaluate the mission advantages. One, C. J. Donlan of the Langley Research Center, who directed during the latter part of 1946 what is believed to be the first wind tunnel study of the symmetrical variable-sweep concept.[11] In these tests, the X-1 research airplane model was modified to accomodate a wing at various sweep angles. Figure 8 shows sketches of the basic X-1 and of the model with a modified wing positioned at 0°, 15°, 30°, and 45° sweepback. The wing was assumed to sweep about a fixed pivot point on the fuselage centerline, which was believed to be the most practical arrangement for the X-1 airplane without a major redesign. The tests included effects of a cutout at the wing root which opened as the wing sweep was reduced. It was thought that the cutout would vary the downwash at the tail in a way to reduce the travel of the airplane center of lift; however, only a very small improvement was obtained.

Photographs of the X-1 model in the tunnel are shown in figure 9. Test results along with analytical studies yielded the perspective of variable sweep summarized in figure 10. The figure shows travel of the center of lift and center of gravity in percent of the wing mean chord as the wing sweep angle is changed. A stable condition exists when the center of lift is rearward (to the right in the figure) of the center of gravity. Although some positive stability is almost essential, too much stability will result in excessive trim drag in addition to restricting the manueverability of the airplane. The plot on the left side applies to the condition of a fixed pivot, that is, no wing translation as the sweep angle is changed. The data are given for a stability margin of about 5 percent chord with the wing at 15^{0} sweepback. As the sweep angle is increased to 45^{0}, the stability margin becomes in excess of 50 percent at subsonic speeds and 70 percent or more at supersonic speeds. These values clearly are much larger than could be tolerated.

One solution, although undesirable from complexity and weight considerations, is to provide fore and aft translation coordinated with the sweep changes. The plot on the right illustrates stability variations that seem desirable and that can be achieved by a translation of about 50 percent of the mean chord. If a larger translation is available for use at supersonic speeds, then the effect of a shift in the center of lift with Mach number can also be reduced.

The X-1 model tests left little doubt that sweep variation about a fixed pivot located within the fuselage is not acceptable. Donlan briefly considered a more complex variable-sweep approach for the X-2 research airplane, which at that time was in a very early stage of detail design; however, the thinking of both Langley and the Bell Company soon shifted to the possibility of a variable-sweep version of the Messerschmitt P-1101 design. The only prototype P-1101 was discovered by an Allied team near the end of the war in an almost completed and flyable state. One may be tempted to believe that the wings were to be attached to the fuselage through a variable-sweep mechanism, such as had been designed by Lippisch[12] while working at Messerschmitt. The evidence[13] indicates however that flight-adjustable sweep was not intended, but that the wings were to be attached to the fuselage at different sweep angles to permit flight tests at 35°, 40°, and 45° to assist in the selection of sweep angle for the more advanced P-1110 design. The P-1101 prototype was shipped to the United States after the war and delivered to the Bell Company, since they had expressed interest in both ground-adjustable sweep and flight-adjustable sweep over quite a large sweep range. At that time, severe stability problems were being identified for swept-wing aircraft, and the Bell Company believed that a major effort was needed to (1) determine how much sweep could be tolerated in a fixed-sweep airplane and (2) evaluate potential advantages of in-flight variable sweep.

EARLY VARIABLE-SWEEP AIRPLANES

Late in 1948, the Bell Company proposed that the U.S. Air Force fund a limited production of variable-sweep aircraft based on the Messerschmitt P-1101 design. After much study, the Air Force concluded that the configuration and size of the proposed airplane were such that the range and capability of carrying weapons would be very limited and therefore, rejected the proposal. Bell next proposed construction of two variable-sweep research airplanes. This proposal was accepted in February of 1949 and the aircraft became the Air Force/NACA X-5 research airplane. It was the world's first variable-sweep aircraft and had provision for a translating wing with sweep angle varying from 20° to 60°, as shown by a superposition photo in figure 11. In profile, the X-5 differed little from the P-1101, as shown in figure 12. Also, the wing area, fuselage length, and gross weight differed little between the two airplanes. Although the P-1101 was not a variable-sweep aircraft project and never flew, it is clear that the post-war transfer of German data on swept wings and the availability of the P-1101 prototype in the United States contributed significantly to the development of the world's first variable-sweep aircraft.

The first flight of the X-5 was made at the NACA High-Speed Flight Station on the California Mojave Desert on June 20, 1951. The research program proceeded quite smoothly and yielded a wealth of information on stability and control, loads. buffeting, and performance for several sweep angles between the two limits (20° and 60°). As for evaluation of the airplane itself, the findings were not spectacularly impressive. At minimum sweep, the landing and takeoff performance as well as the rate of climb and loiter capability were good compared with fixed-sweep fighters of that period. The sweep mechanism performed well throughout the program and provided the stability margins that were desired. The sweep and translation mechanism ended up somewhat overweight, however, and added to the bulk of the airplane at the wing-fuselage juncture. This airplane had severe stability problems at high angles of attack for both the low and the high sweep angles, although these problems could hardly be related in any way to the variable-sweep feature. Throughout its lifetime, the X-5 was operated with an interim engine, because the engine planned for the airplane did not become available. Consequently, the maximum level-flight Mach number was only about 0.85, although as much as 0.97 was achieved in a shallow dive.[14]

The X-5 flight program was terminated in October 1955--more than 4 years after the first flight. For about the last 2 years of its life, the X-5 was used primarily in a chase role to support other research investigations at the flight station. It performed well in the chase role because of its good loiter and acceleration characteristics and its wide range of operating speeds. At the time, these latter characteristics did not receive much attention in relation to possible military applications; however, they later were to be given more significance. In the mid-1950's, no clear advantage over fixed-sweep aircraft was identified for the X-5.

A second opportunity to exploit the variable-sweep concept was provided by the Navy's development of the XF10F,[15] which was authorized in December 1950. The aircraft is described on figure 13. The variable-sweep arrangement was generally similar to that of the X-5 in that the longitudinal-stability margin was controlled by translating the wing as sweep was varied. Unlike the X-5, however, the XF10F was to be operated only at the two extremes of the sweep range, that is, 12.5° and 42.5°.

Flight testing of the XF10F began in May 1952. As with the X-5, the airplane was plagued with many problems having nothing to do with the variable-sweep feature, which was practically trouble-free. Severe control system problems that were encountered required makeshift substitutions for both the longitudinal and lateral control systems in order for flight testing to continue. As was the case for the X-5, the XF10F never received the engine it was intended to have and its performance was severely limited. The flight program continued until June 1953, when the Navy cancelled plans for production of the F10F. The cancellation was due in part to the disappointing results of the flight tests and in part to the development of the slant-deck carrier and steam catapult, which allowed fixed-sweep airplanes in the mid-1950's to be operated from carriers. This latter situation greatly reduced the attractiveness of variable sweep.

JOINT PROGRAM WITH UNITED KINGDOM

At the conclusion of flight activities of both the X-5 and the XF10F, military interest in variable sweep was at a low ebb. There still was little hope that supersonic flight could be achieved for more than brief dashes and, with aerodynamic "fixes" alleviating some of the swept-wing problems, a fixed-geometry compromise between low-speed and high-speed needs seemed acceptable. Also, it was difficult to disassociate the X-5 and XF10F problems from variable sweep, even though in fact they had little to do with that feature. In any case, whether justified on not, the subject of variable sweep was not popular in military planning during 1954 and 1955.

During the next few years, however some changes that would lead to a reassessment of variable sweep occurred: (1) industry studies related to the WS-110 (which eventually materialized as the B-70) indicated that sustained supersonic flight was feasible but required higher sweep angles and lower aspect ratios, which would further aggravate takeoff and landing problems and (2) interest was growing in the multimission concept as a means of reducing total military development costs and the number of aircraft types. As a result variable sweep began to emerge as a possible solution.

After the conclusion of the X-5 and F10F programs, there had been very little activity related to variable sweep. Interest was sustained by a few individuals--especially C. J. Donlan of NACA Langley, who periodically engaged in discussions with staff members on the merits of variable sweep in light of the new developments in both technology and military requirements. A low-level effort also was continuing in the United Kingdom because of a long-standing interest of Barnes N. Wallis, Head of Research and Development for the Vickers-Armstrong Aircraft Company. His concept of a variable-sweep supersonic transport had gone through many iterations and, by mid-1957, had been developed in such detail that a decision on whether or not to continue support needed to be made. At that time, a very restrictive United Kingdom policy on the development of new aircraft practically ruled out anything but nominal financial support by the Government; however, an alternative was to approach the United States on a possible joint program to study the merits of Wallis' airplane--then called the "Swallow."

United Kingdom contacts with the United States during May of 1958 led to a request that NACA review the "Swallow" design. The request came to the attention of Donlan and John Stack, an assistant director of Langley and a member of a weapons-development steering group of NATO. Drawings of the "Swallow" configuration are shown in figure 14. The design was a very highly swept arrow wing with no aft tail surfaces and with only a very small fuselage. Wing pivots were located some distance outboard of the centerline. With the wing unswept, a wing aspect ratio comparable to that of fixed-sweep jet transports was realized. Jet engines were mounted on pylons above and below the wing on the outer panels. The pylons were required to pivot so that they would remain alined with the flight direction as the wing sweep varied. The engine nacelles also were pivoted relative to the pylons in order to incline the engine thrust symmetrically for pitch control and asymmetrically for roll control. With the engines at near idle thrust, it was believed that sufficient control could be obtained simply by changing the orientation of the nacelles.

The Langley review of the "Swallow" identified several potential problems; however, both Donlan and Stack shared an interest in variable sweep for a military role. Accordingly, arrangements were made for a visit of a U.K. team to Langley to discuss the Swallow and a possible joint U.S./U.K. program. The meeting was held at Langley in November 1958 and the joint program outlined in figure 15 was agreed to. The U.K. was to test Swallow models at subsonic, transonic, and supersonic speeds but with no provision to determine power effects by simulating engine thrust. Langley agreed to evaluate power effects at transonic speeds and in addition to investigate various Langley-derived variable-sweep concepts, all of which would assume the engines to be located in the body of somewhat conventional wing-body configurations. A second part of the joint program--referred to as "supporting research"--involved arrow-wing studies in which U.K. would investigate pressure distributions and control forces, while Langley would study induced drag as affected by camber and the effects of attaching a center fuselage to the wing. The U.K. agreed to carry out an engineering design study to account for findings from the wind-tunnel tests of the Swallow.

Shortly after the meeting with the U.K. visitors, Langley began preparation of the model and apparatus for the power-effects tests of the Swallow in the Langley 16-Foot Transonic Tunnel. Also, construction began on some relatively simple models of the Langley variable-sweep concepts and the Swallow for investigation at low speed in the Langley 7- By 10-Foot Tunnel. The latter tests began no more than 2 weeks after the joint program agreement. The arrow-wing swallow model was designated configuration I and is shown mounted in the tunnel with wings adjusted to both minimum and maximum sweep angles in the photographs of figure 16. Provision was made for inclining the engine nacelles relative to the pylons to measure control power in pitch for the engine-out condition.

The four configurations tested are shown in figure 17. Configuration I represented the Swallow and Configurations II and III were the initial Langley configurations which utilized wings having planforms and pivot locations somewhat similar to the Swallow but mounted on a conventional fuselage having internal engines. Configuration II utilized a canard for longitudinal trim and a small folding aft tail as a possible means of reducing the undesirable travel in center of lift with sweep changes mentioned earlier. Configuration III eliminated the canard and utilized a large folding aft tail. Longitudinal control was provided by the tail when the wing was in the low-sweep position and by wing elevons when the wing was swept and the tail folded. Configuration IV was added several weeks later as the final Langley configuration and is described subsequently.

The tests in the Langley 7- By 10-Foot Tunnel indicated that configurations I through III exhibited much smaller variation in stability margin with sweep angle than that described earlier for the X-1 with the wing pivot on the fuselage centerline but still larger than desired.

Also considered in the wind tunnel study were the pitching-moment linearity with changes in lift, the directional stability, and the longitudinal control power. For the arrow wing (configuration I), the linearity of the variation of pitch with lift was rated poor, whereas directional stability was rated good. The pitch control power obtained by inclining the nacelles in a vertical plane was totally inadequate for the engine-out condition. For the canard model (configuration II) pitch linearity, directional stability, and pitch control were all rated fair. The folding-tail model (configuration III) was rated good for pitch linearity and directional stability. Pitch control with the aft tail used at low wing sweep was good, but at high sweep, the elevon power was poor.

The final model (configuration IV) was added a few weeks after completion of tests of the first three and was the result of a theoretical study carried out by Langley researchers in parallel with the initial wind tunnel tests. This study dealt with the effect of wing pivot location and the geometry of the forward fixed portion of the wing with regard to the manner in which the aerodynamic load distribution shifted as the wing sweep was changed. An analysis of the results suggested that if the pivot was strategically located outboard of the fuselage, the same span increase could be obtained while simultaneously reducing the shift of the center of lift with sweep. This resulted from a combination of reduced geometry shift of the rotating wing panel and a greater shift of load between that panel and the relatively larger fixed portion. This configuration, if successful, would solve the center-of-lift travel problem and, with its conventional arrangement of the horizontal and vertical tails at the rear of the fuselage, would avoid the additional variable-geometry complexities of the Swallow and the first two Langley configurations.

The wind tunnel tests of configuration IV confirmed its advantage in reducing the center-of-lift travel, with the maximum travel being only 9.5 percent chord at 50° sweep and being essentially the same for the low- and high-sweep conditions. The pitch linearity, though not without fault, was considered satisfactory and given a fair-to-good rating. Directional stability and pitch control both were rated good.

It was the opinion of reviewers of the low-speed test data[16] on the four configurations that the engine-in-fuselage design with the outboard-pivot wing showed promise of being a practical approach. The Swallow-type arrow wing may have had the potential for higher aerodynamic efficiency; however, a very considerable effort would have been necessary to resolve its several problems. A firm judgement was not made on the basis of the low-speed tests in the 7- By 10-Foot Tunnel, however, since the transonic study of a more elaborate model with power simulation had not yet been started. When the transonic results did become available, they failed to show that further pursuit of the Swallow configuration would be profitable.

After completion of the 7- By 10-Foot Tunnel tests of the outboard-pivot design, additional tests[17] were made at Mach 2.01 in the Langley 4- By 4-Foot Supersonic Pressure Tunnel and over a transonic speed range to Mach 1.3 in the Langley 8-Foot Transonic Pressure Tunnel. All these tests were completed by April 1959, and the data were transmitted to the United Kingdom on July 14, 1959. A brief summary of some of the data over the test range of Mach numbers, as obtained with the initial outboard-pivot design (configuration IV), is given in figure 18. At a Mach number of 0.25, a lift-drag ratio of 10.8 was indicated at 12.5° sweep. The value of lift-drag ratio was not particularly impressive; however, the aerodynamicists were confident that refinements in the wing design and the effects of increasing Reynolds number to a flight value would bring improvement, and this was verified later. At 75° sweep, lift-drag ratios ranging from 8.3 at Mach 0.7 to 5.4 at Mach 2 were regarded as good for fighter-class airplanes. At Mach 0.25, roll-control power provided by wing ailerons was good at 12.5° sweep but was considered inadequate at 75° sweep. Differential deflection of the horizontal tail was found to be more effective than the aileron deflection at 75° wing sweep. A satisfactory lateral-control system therefore would seem to involve use of the ailerons at low speed and low sweep, and use of the horizontal tail or possibly the horizontal tail and wing ailerons in combination at high speed and high sweep.

During the program (figure 19), tests were made in four wind tunnels for a total of about 500 hours over the period from December 1958 to July 1959, and the results were transmitted to the United Kingdom in several stages from July to December of 1959. A theoretical study of camber and center-body effects for arrow wings was performed, and the results were transmitted in July 1959. It was concluded by the Langley participants that the Swallow-type configuration did not offer much promise for a near-term application.

The outboard pivot arrangement in a configuration with engines in a center fuselage and a conventional tail at the rear of the fuselage appeared to be a simpler approach, did not show any serious problems over the range of test conditions, and seemed to have attractive performance potential. It was therefore judged most promising for near-term application in a military aircraft. Some details of configuration IV are shown in figure 20.

APPLIED RESEARCH PROGRAM

Once the configuration IV data were in hand, Langley carried out the preliminary design of an attack aircraft which indicated attractive multi-mission capabilities, and the research program was rapidly expanded to provide the technology required for successful application of the configuration concept. The technical areas of the program included

- Configuration refinements (aerodynamic performance, stability, and control)
- Aerodynamic performance analysis
- Propulsion aspects
- Sweep mechanisms
- Structural dynamics
- Flying qualities

Close contact was maintained with the Navy, the Air Force, and the airframe and engine manufacturers to assure that research applicable to the various mission requirements was carried out. This program, which continued for approximately 3 years, involved nearly every major wind tunnel facility at the Langley Research Center and played a principal role in the development of the F-111, the F-14 and the B-1. Space will permit only a very brief overview of the program, which can best be described by dividing it into a section related to Navy requirements and one related to Air Force requirements--recognizing, of course, that much was applicable to both--although the program included both general and applied research.

Research related to Navy requirements

The initial configuration studies were related to the Navy's combat air patrol mission and resulted in the construction of the sophisticated high-speed wind tunnel research model shown in figure 21. Prior to construction of this model, however, an existing North American A3J model was modified and provided an early source of additional aerodynamic data. Modification of the A3J was related to the suggestion by John Stack, in July of 1959, that the North American A3J aircraft might be retrofitted with the variable-sweep wing as a possible growth version of the aircraft. The location of the A3J wing on top of a relatively wide fuselage made the retrofitting of a new wing and housing of the required variable-sweep mechanism an attractive possibility.

Following studies by both Langley and North American, a wind tunnel program was initiated, with Langley designing and building an outboard-pivot wing based on the configuration IV concept and North American providing the design and hardware required to investigate their interest in the possibility of utilizing the basic A3J wing modified to provide variable sweep with an inboard pivot and small fixed glove. The Langley studies of possible combat air patrol aircraft designs were factored into the design of the outboard-pivot wing. Sketches of the plan and side views of the resulting configuration are presented on the left-hand side of figure 22. The inboard-pivot configuration, which utilized the basic A3J wing and was provided by North American, is shown in the upper right. In the lower right is shown a fully-folded-wing concept studied later in relation to Air Force requirements.

In November of 1959, the A3J model was tested with both the outboard- and inboard-pivot wings in the Langley 300 mph 7- By 10-Foot Tunnel. The results,[18] which were the first obtained with the outboard-pivot concept on an actual aircraft model, added further substantiation of the advantages previously demonstrated with that configuration.

In December of 1959, the Navy solicited feasibility studies from industry on the application of variable sweep to the combat air patrol mission. The next month, Langley extended its research using the A3J model with the Langley wing to transonic and supersonic speeds in the Langley 8-Foot Transonic Pressure Tunnel and the 4-Foot Supersonic Pressure Tunnel, providing additional design information for the industry combat air patrol studies.

Because of the growing interest in the variable-sweep concept shown by the Navy, Air Force, and industry, Langley broadened its research program[19] to include such areas as wing flutter, the development of high lift and lateral control systems, wing pivot structural design, and various aspects of flying qualities. During this period Langley researchers also stressed the importance of the development of a new turbofan engine to match the new aircraft versatility offered by the variable-sweep wing.

While the A3J and CAP II models continued to be used in the expanded program, additional models were constructed for the various specialized studies. Two of the many studies can be described with the photographs of two of the additional models shown in figure 23. On the left is a photograph of a 1/9-scale model of the A3J, modified by the application of the outboard-pivot variable-sweep wing. This is a dynamically-scaled ratio-controlled model used in drops from a helicopter to study spin entry and recovery characteristics. In addition to the usual remotely operated controls, the sweep angle could also be remotely adjusted. A total of about 30 drops were made with the modified A3J model plus an additional 20 with a general-research model. Spin-recovery techniques, including the use of wing-sweep changes, were developed during this study. On the right of figure 23 is a multiple-exposure photograph of a CAP II model undergoing a wing-sweep transition during free-flight powered-model tests in the Langley Full-Scale Tunnel. For the free-flight tests, thrust was provided by compressed air supplied through a flexible hose to a nozzle at the rear of the fuselage. The aerodynamic controls were operated remotely by two pilots, one for pitch control and the other for roll and yaw. The model was relatively easy to fly during the sweep transitions for the sweep range of 25° to 75° contemplated for the CAP airplane. Some erratic motions resulting from wing stall and a directional divergence occurred at low sweep angles, but they were alleviated by the use of leading-edge flaps.

The results of the extensive research program coupled with industry and Navy studies indicated that the new variable-sweep wing concept was sound and, when combined with the new turbofan engines, offered the Navy the option of a single aircraft with true multimission capability. While the Navy eventually developed and procured the F-14, it was delayed by events described in the next section.

Research relative to Air Force requirements--During the period of the research directed toward the Navy requirements, Langley had kept in contact with the Air Force regarding possible application of variable sweep to their future tactical-aircraft requirements. Following a review of the Langley research in July 1959, the Tactical Air Command began looking at the possibility of variable sweep for an aircraft to meet their requirement for a vertical-takeoff aircraft having high-altitude supersonic and on-the-deck strike capability combined with long-range ferry capability. Then in February 1960, the NASA Langley staff was briefed by TAC on their revised mission requirements. They stated that they were convinced that VTO capability could not develop in the time period specified and had changed their requirements to a STOL operation out of 3000-foot fields. They had prepared a Qualitative Operational Requirement which called for a ferry mission of 3500 nautical miles and an 800-nautical-mile-radius attack mission with the outbound leg consisting of 400 miles subsonic on-the-deck followed by 400 miles on-the-deck at Mach 1.2 and a return at optimum altitude (the so-called low-low-high mission). John Stack offered NASA assistance and the research program was extended to include the Air Force requirements.

Although Langley researchers had been considering long-range on-the-deck operation, this was the first they had heard of the Air Force interest in a long-range supersonic on-the-deck penetration and it raised a new challenge in aircraft design. It quickly became apparent that (1) the weight of the aircraft would be dictated by the high rate of fuel consumption resulting from the extremely high drag associated with the supersonic on-the-deck operation and (2) the high response of the aircraft to low-altitude air turbulence would be a major contribution with regard to pilot and airframe fatigue and weapon delivery accuracy.

Although the variable-sweep concept provided the major step toward the solution of these problems, it was obvious that other design factors would have to be carefully factored in. For practical wing loadings, flight at high speed and low altitude is very inefficient from an aerodynamic standpoint, and the previous studies of low-altitude high-speed missions had been limited to Mach numbers of 0.9 or less to minimize the additional penalties associated with supersonic wave drag. The increase to Mach 1.2, while offering important tactical advantages, was accompanied by extremely large aerodynamic penalties, dictating not only the engine thrust required but the fuel weight and volume to be provided for. Since the lift-dependent, or induced,drag is small at the high dynamic pressures involved, there was little advantage in attempting to improve this portion of the drag, and the effort was placed on minimizing the supersonic wave drag and the skin-friction drag. This requires a long-slender aircraft.

The second factor that strongly impacts the sea-level dash mission is, as mentioned previously, the importance of reducing the aircraft gust response. This requires a reduction in wing lift response to angle-of-attack change, which could be best accomplished by reducing the exposed wing area during dash. For the sea-level dash, the optimum configuration, therefore, becomes essentially a high-fineness-ratio flying fuselage.

With the general characteristics of the high-speed on-the-deck configuration defined, the configuration requirements for the various missions can be illustrated as in the top portion of figure 24, where three "point design" aircraft representative of the Air Force requirements are shown. To meet these diverse requirements with a single aircraft, it appeared that the variable-sweep concept previously studied could be extended by continuing the sweep process beyond 75° until a large portion of the wing was essentially "shielded" by the fuselage, resulting in a reasonable approximation of the flying-fuselage concept. It must be kept in mind that the concept required for low-altitude flight is extremely inefficient in relation to the aerodynamic efficiency developed by conventional-altitude-cruise designs, but that it is a necessary tradeoff for the supersonic on-the-deck penetration mission.

As a first step in assessing the feasibility of such an extreme departure in aircraft design, Langley researchers carried out preliminary design studies of five variable-sweep configurations, covering a variety of engine arrangement, inlet locations, wing planforms, and wing pivot locations. From these studies it was concluded that an aircraft having a length on the order of 82 feet, an equivalent area distribution approaching the theoretical optimum, a cross sectional area of 45 square feet or less, and a takeoff weight in the range of 60000 pounds would be required to meet the low-low-high mission. In addition, a wing span of approximately 68 feet would be required in the low-sweep mode to provide the high aerodynamic efficiency required at subsonic speeds.

To provide an early indication of the overall aerodynamic and design implication of the fully-folded-wing concept, the outboard -pivot variable-sweep wing that was under investigation with the A3J model was modified to provide the fully-folded concept previously described. The design, model construction, and tests in the Langley 8-Foot Transonic Pressure Tunnel were completed within 6 weeks of the Air Force disclosure to Langley of the supersonic on-the-deck mission.

After the results of the design studies for the Air Force Mission and the A3J variable-sweep-wing wind-tunnel studies for the Navy mission were presented to the Air Force, Langley was asked to provide assistance to the STOL task force at Wright-Patterson relative to the TAC requirements (SDR-17). Although SDR-17 did not specify a variable-sweep aircraft, the Wright field team was taking a serious look at a variable-sweep design based on the Langley concept. It soon became apparent to the Langley team that wind-tunnel data were urgently needed in order to fully evaluate the performance of the slender-aircraft fully-folded-wing concept and a high-priority study was initiated on March 29, 1960. By working around the clock for 2 weeks, the team constructed models of three Langley configurations and the Wright Field configuration and tested them in the Langley 8-Foot Transonic Pressure Tunnel.[20] Two of the Langley configurations are illustrated in figure 25. Configuration 7 utilized a pivot located within the fuselage, while configuration 8 utilized the outboard-pivot wing design. Although the inboard-pivot wing exhibited the problems with shift in aerodynamic cneter discussed previously, it was included to provide tradeoff information relative to the new dash mission, since it provided for a more complete wing retraction and was expected to offer some structural-weight advantage.

Photographs of the wind-tunnel models are shown in figure 26. The photograph on the left is of configuration 8 with the wings open to the 25° sweep condition. On the right is a photograph of configuration 7 with its wing in the fully-folded condition and mounted on the sting support system in the Langley 8-Foot Transonic Pressure Tunnel. The results of these and later wind tunnel studies indicated that the resulting high-fineness ratio configurations offered sizable reductions in supersonic wave drag.

Following the initial studies related to the sea-level dash, complete wind tunnel tests were made over a wide range of Mach numbers for various sweep angles to define the optimum wing position for each leg of the various missions. An example of some of the results is presented in figure 27, where the aerodynamic efficiency parameter, L/D, is presented as a function of sweep angle for several Mach number and altitude conditions for configuration 8 at a weight of 60000 pounds. The benefits of variable sweep are readily apparent; for example, with the wing in the 25° sweep position, a lift-drag ratio in excess of 18 is obtained for a Mach number of 0.6 at 30000 feet. This provides outstanding ferry range or loiter time, whereas the 75° wing, which is optimum for the supersonic attack mission at 60000 feet and $M = 2.2$, would provide a subsonic lift-drag ratio of only 10. Also illustrated is the previously discussed fact that, while the efficiency of sea-level supersonic operation is very low, there is a distinct advantage of the fully-folded-wing concept. Important benefits of the high sweep angles in reducing gust response were also substantiated.

The studies of configuration 8 were extended to include wind-tunnel investigations of both static and dynamic stability characteristics, longitudinal and lateral control, and a study of the pull-up response available for terrain-following during the low-altitude supersonic mission. Additional designs were tested during the program and studies related to additional design requirements were also carried out.

The propulsion system was an important element of the multimission aircraft concept. Early in the program Langley stressed the importance of a new turbofan engine to match the versatility of the variable-sweep airframe and worked closely with the engine manufacturers. In addition to the engine design, the integration of the engine and airframe was an important aspect--particularly with regard to the sea-level supersonic dash and in the fall of 1960 Langley initiated an extensive propulsion-integration program. The facility selected for this program was the Langley 16-Foot Transonic Tunnel because of its size, transonic capability, and hydrogen-peroxide turbojet-engine simulator capability together with a staff experienced in propulsion research. Briefly, the results[21] of the program indicated the importance of the afterbody design and nozzle integration, particularly for the sea-level dash mission, and illustrated the favorable interference associated with the long interengine fairings associated with configuration 8.

With the performance capability of the configuration 8 concept now appearing highly favorable, Langley extended its free-flight testing in the full-scale tunnel to cover the handling qualities with the wing transitioning to the fully-folded condition and performed fixed-base simulator studies related to possible roll-coupling and terrain-following problems. This research coupled with the variable-sweep-technology studies carried out by Langley in connection with previously discussed Navy requirements provided information utilized by industry and the Air Force in the Tactical Fighter study.

However, events were soon to take place that were to preclude the application of the slender-aircraft concept to the TFX (tactical fighter-experimental). In February of 1961, the Secretary of Defense ordered that the requirements of the Air Force, Navy, and Army be combined into a Tri-Service tactical fighter. Eventually, it was reduced to a Bi-Service tactical fighter for the Air Force and Navy with proposals being sent to industry. Because of Navy carrier compatibility requirements, the maximum length of the aircraft was specified at 73 feet. Recognizing that the length reduction combined with the increased cross-sectional area required to recover fuel volume would result in a low-fineness-ratio configuration with lighter supersonic wave drag, the Air Force reduced the supersonic part of the on-the-deck leg of their low-low-high mission to 200 miles and increased the subsonic leg to 600 miles.

Evaluation of the proposals for the TFX began on December 6, 1961, and lasted until November 24, 1962, when the General Dynamics/Grumman team was awarded the contract to develop the aircraft. A discussion of the development of the F-111 is beyond the scope of this paper. However, it is felt pertinent to point out that the low fineness ratio of 8 resulting from the length restriction coupled with a large increase in cross-sectional area and a rapid afterbody closure produced very high supersonic wave drag, which was a major factor leading to an increased weight, and a further degradation in the supersonic dash distance. Despite these problems, the F-111 demonstrates commendable multimission capability and the large number of subsequent variable-sweep aircraft developed throughout the world tends to confirm the soundness of the variable-sweep concept for aircraft requiring multimission capability.

The Langley configuration research leading to the F-111 can be briefly summarized with figure 28, where the three major phases of the research are illustrated: (1) the 1958 conceptual research resulting in the basic outboard-pivot aft-tail configuration; (2) the 1959 research directed toward the Navy's combat air patrol requirements, illustrated by the Langley CAP II configuration but also including the broad research utilizing the A3J model with the Langley wing; and (3) the extensive 1960 research on a series of slender configurations with fully-folded-wing capability, as represented by configuration 8, which were designed to include the original long-range sea-level supersonic dash of the Air Force mission. The similarity between these configurations and the resulting F-111 is readily apparent.

During this time period, Langley also provided wind tunnel support for joint Industry/Langley studies dealing with application of the concept to the TFX.

While only a brief overview of the Langley program was given here, some appreciation of the magnitude of the program can be obtained from the fact that at least 10 of Langley's wind tunnel facilities were used and a total of over 8000 occupancy hours were devoted to the research.

INTERNATIONAL DEVELOPMENTS

Since the Langley research and the development of the F-111, a large number of variable-sweep aircraft have been built throughout the world. In the United States, of course, the F-14 fighter was procured for the Navy and the Air Force B-1 bomber was carried to the prototype stage before being cancelled.[22]

With regard to Soviet aircraft, it is interesting to note that the four variable-sweep aircraft along with several variants appear to represent the majority of their military aircraft development since the mid-1960's. The similarity to the U.S. configurations and the fact that the first Soviet version was not observed until 1967 would suggest the possibility that they relied heavily on intelligence reports of the U.S. development.

The two West-European variable-sweep aircraft are the French experimental prototype in the Dassault Mirage research series, which did not go into production, and the Panavia Multi-Role Combat aircraft "Tornado" currently in production.

CONCLUDING REMARKS

The progression of the variable-wing-sweep concept from its earliest suggested use for high-speed airplanes to the degree of acceptance that presently exists has been found to be considerably more complicated than the simple introduction of the new wing and its mechanism in place of a fixed-sweep wing in essentially the same airplane. To obtain maximum benefit from variable sweep, new requirements must be imposed on other items--such as the propulsion system, the high-lift devices, and the controls. Even for a fully-integrated design, it is not reasonable to compare a variable-sweep airplane with a fixed-sweep airplane in the context of the same specification, since each design approach has its own unique advantages.

The rather widespread design, manufacture, and use of variable-sweep airplanes in several countries shows that the development process has become a matter of routine engineering, with little or no more uncertainty of end-product performance than would be expected for a fixed-sweep design. Nevertheless, the opportunity still exists for a more complete understanding of the best way to exploit the unique capability of variable-sweep airplanes. Also, the potential of several design approaches other than those in current use--such as the variable-skew wing and variable forward sweep--is far from established at this time.

NOTES

1. Available summaries of variable-sweep development are: Polhamus, Edward C., and Hammond, Alexander D.- "Research Relative to Variable-Sweep Multimission Aircraft" (Included as a part of "Compilation of Papers on the Future of Manned Military Aircraft," by the Staff of NASA), TM X-420; Toll, Thomas A., Polhamus, Edward C. and Aiken, William S., Jr.- NASA - "Variable-Geometry Research," AGARD Rep. 447, April 1963; Baals, Donald D. and Polhamus, Edward C.- "Variable-Sweep Aircraft-Past, Present, and Future," AIAA Aeronautics and Astronautics Engineering, June 1963; Spearman, M. Leroy and Foster, Gerald V.- "A Summary of Research on Variable-Sweep Fighter Airplanes," NASA TM X-1885, December 1965; Staff of the Langley Research Center - "Summary of NACA/NASA Research and Development Leading to the F-111 (TFX), NASA LRC LWP 285, December 22, 1966; Air International-"The Annals of the Polymarph: A Short History of Variable Geometry, Parts I, II and III," March, April, May 1975; Perry, Robert L., "Innovation and Military Requirements: A Comparative Study." Rand Corp., RM5182 PR, August 1967; Kress, Robert W.- "Variable-Sweep Wing Design: Contribution to 'The Evolution of Aircraft Wing Design," AIAA Dayton-Cincinnati Section Meeting, March 18-19, 1979.
2. DeSeversky, Alexander P.- "Victory Through Air Power," Simon and Shuster, 1942.
3. U.S. Transonic Experiments: Mathews, Charles W. and Thompson, Jim Rogers.- "Comparative Drag Measurements at Transonic Speeds of Straight and Sweptback NACA 65-009 Airfoils Mounted on a Freely-Falling Body," NACA MR L5G-30; Gilruth, R. R. and Wetmore, J. W.- "Preliminary Tests of Several Airfoil Models in the Transonic Speed Range," NACA ACR L5E08, May 1945; Gilruth, R. R.- "Resume and Analysis of NACA Wing-Flow Tests." Proceedings of the Aeronautical Conference. London, 1947; Shortal, Joseph A.- "A New Dimension (Wallops Island Flight Range-The First Fifteen Years," NASA Reference Publication 1028, December 1978.
4. Jones, Robert T.- "Wing Planforms for High Speed Flight." NACA Rep. 863, June 27, 1945.
5. Busemann, A.- "Aerodynamicher Auftrieb bei Uberschallgeschwindigkeit," Luftfahrtforschung, Bd 12, Nr 6, October 3, 1935, pp. 210-220.
6. Von Karman, Theodore.- "The Wind and Beyond," Little, Brown, and Company, 1967. pp. 216-223.
7. Ludwieg, H.- "Sweptback Wings at High Velocities (Preliminary Results)," August 1940. Goodyear Aircraft Corp., Translation Report No. R-30-18, Part 7.
8. Early U.S. Sweepback Studies: Letko, William and Goodman, Alex.- "Preliminary Wind Tunnel Investigation at Low Speed of Stability and Control Characteristics of Sweptback Wings." NACA TN 1046, April 1946; Purser, Paul E. and Spearman, Leroy.- "Wind Tunnel Tests at Low Speed of Swept and Yawed Wings Having Various Planforms." NACA RM No. L7D23, May 22, 1947.
9. Campbell, J. P. and Drake, H. M.- "Investigation of Stability and Control Characteristics of an Airplane Model with Skewed Wing in the Langley Free-Flight Tunnel." NACA TN 1208, May 1947.

10. Andrews, W. H.; Sim, A. G.; Managhan, R. C.; Felt, G. R.; and McMurtry, T. C.- "AD-1 Oblique Wing Aircraft Program." SAE Tech. Paper 801180, October 1980.

11. Studies of Variable Sweep on Bell X-1 model reported in: Spearman, M. Leroy and Comirarow, Paul.- "An Investigation of the Low-Speed Static Stability Characteristics of Complete Models Having Sweptback and Sweptforward Wings." NACA RM L8H31; Donlan, Charles J. and Sleeman, William C., Jr.- "Low-Speed Wind-Tunnel Investigation of the Longitudinal Stability Characteristics of a Model Equipped with a Variable-Sweep Wing," NACA RM L9B18.

12. Miller, Ronald and Sawers, David.- "The Technical Development of Modern Aviation." Praeger Publishers, 1970, pp. 170, 256 (adjacent figure).

13. Information on Development of Me P-1101 obtained from: Air Technical Intelligence Review No. F-IR-6-RE, "Survey of Messerschmitt Factory and Functions, Oberammergau, Germany," August 1946, pp. 172-176; Proposed Aerodynamic Research airplane. Bell Aircraft Corporation Report D-80/1, January 26, 1949; Letters from Josef J. Hubert, formerly of the Messerschmitt Company, to Edward C. Polhamus, January 15, 1981 and February 5, 1981.

14. X-5 Flight Test Reports from the Langley Research Center Files.

15. Information on XF10F given in papers by Perry and Kress of Note 1.

16. Alford, William J. and Henderson, William P.- "An Exploratory Investigation of Low-Speed Characteristics of Variable-Wing-Sweep Airplane Configurations." NASA TM X-142, 1959.

17. Transonic and Supersonic Tests of Configuration IV from: Alford, William J., Luoma, Arvo A., and Henderson, William P.- "Wind-Tunnel Studies at Subsonic and Transonic Speeds of a Multiple-Mission Variable Wing-Sweep Airplane Configuration." NASA TM X-206, November 1959; Spearman, M. Leroy and Foster, Gerald V.- "Stability and Control Characteristics at a Mach Number of 2.01 of a Variable Wing-Sweep Configuration with Outboard Wing Panels Swept Back 75°." NASA TM X-32, August 1959.

18. Spencer, Bernard J., Jr.- "Stability and Control Characteristics at Low Subsonic Speeds of an Airplane Configuration Having Two Types of Variable-Sweep Wings." NASA TM X-303, August 1960.

19. Selected Papers on Expanded Program: Stonesifer, John C. and Goetz, Robert C.- "Transonic and Supersonic Flutter Trend Investigation of a Variable-Sweep Wing." NASA TM X-598, October 1961; Henderson, William P. and Hammond, Alexander D.- "Low-Speed Investigation of High-Lift and Lateral-Control Devices on a Semispan Variable-Sweep-Wing Having an Outboard-Pivot Location." NASA TM X-542, May 1961; Hassell, James L., Jr.- "Low-Speed Flight Characteristics of a Variable-Wing-Sweep Fighter Model." NASA TM X-1036, February 1965.

20. Bielat, Ralph P., Robins, A. Warner, and Alford, William J., Jr.- "The Transonic Aerodynamic Characteristics of Two Variable-Sweep Airplane Configurations Capable of Low-Level Supersonic Attack." NASA TM X-304, August 1960.

21. Runckel, Jack F.; Lee, Edwin E., Jr.; and Simonson, Albert J.: "Sting and Jet Interference Effects on the Afterbody Drag of a Twin-Engine Variable-Sweep Fighter Model at Transonic Speeds." NASA TM X-755, January 1963.

22. There is renewed interest in the B-1 within the Defense Department and a modified version, with wing sweep angle variable between 15° and 60°, is the prime candidate for the Air Force Long Range Combat Aircraft (LRCA).

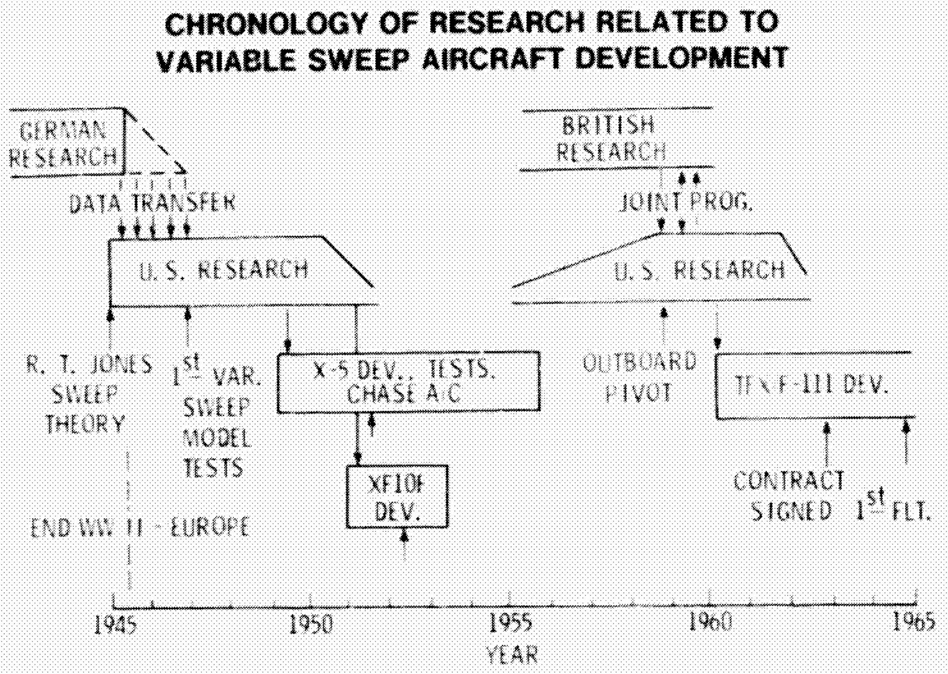


Figure 1.

(Me 163 courtesy National Archives, Me 262A and Ju 287 courtesy Smithsonian Institution)

Figure 2.

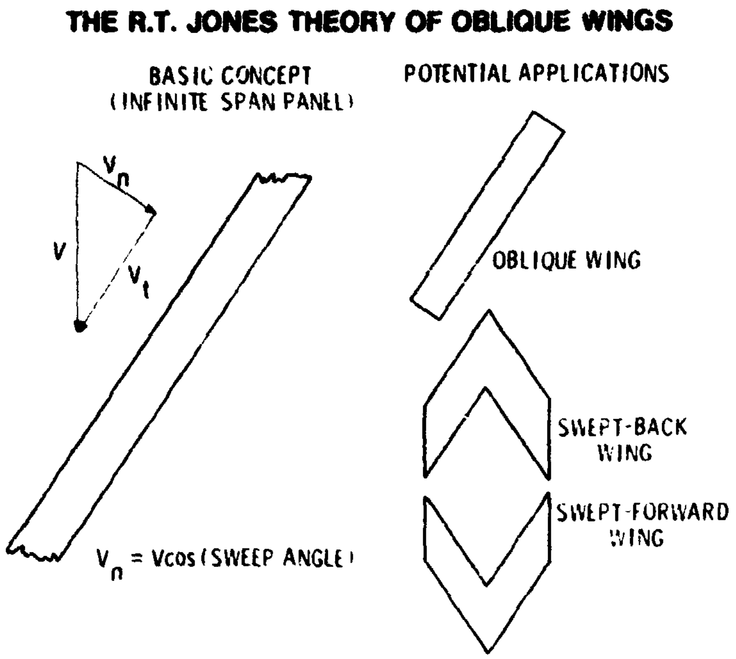


Figure 3.

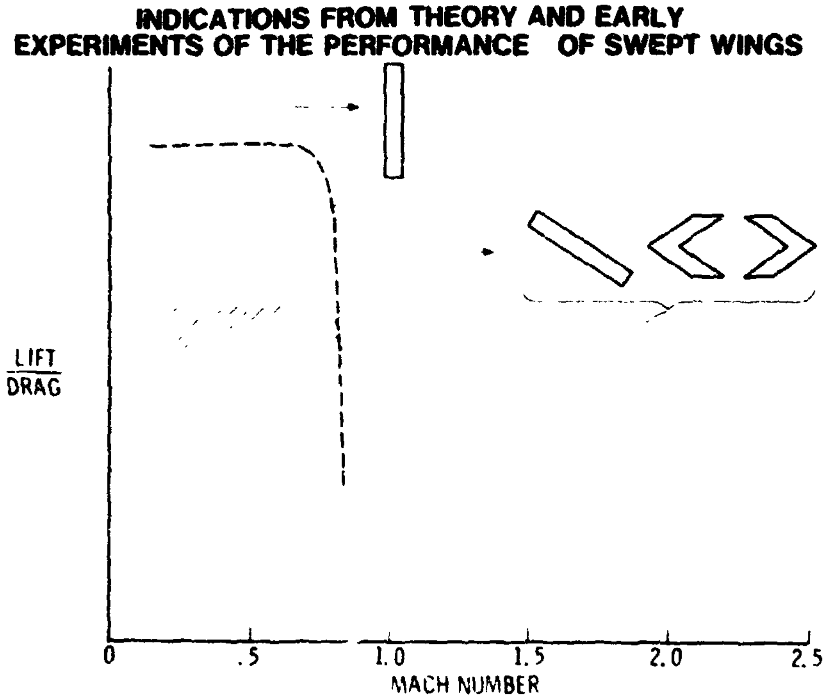
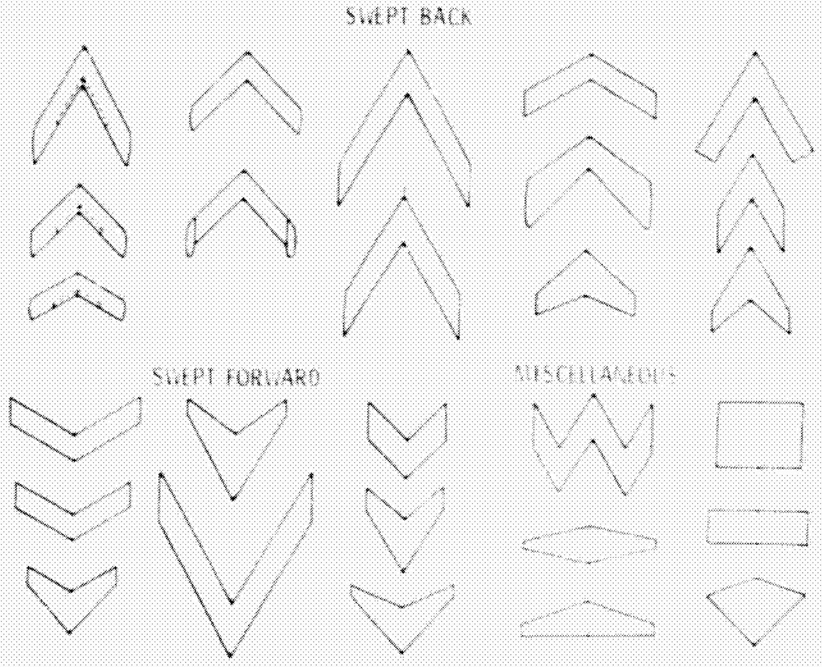
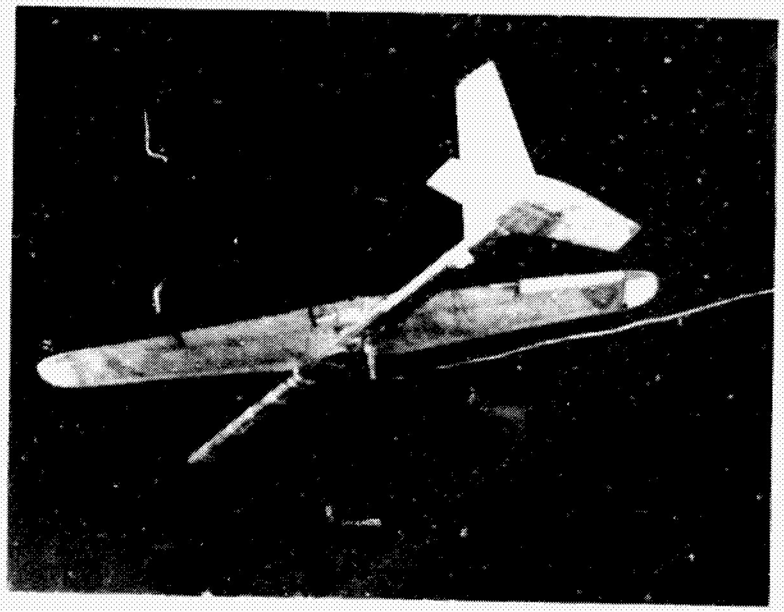


Figure 4.



LOW SPEED PLANFORM INVESTIGATIONS FOLLOWING VERIFICATION OF JONES THEORY

Figure 5.



OBLIQUE-WING MODEL IN FREE-FLIGHT TUNNEL - 1946

Figure 6.

AD-1 OBLIQUE WING RESEARCH AIRCRAFT - 1980

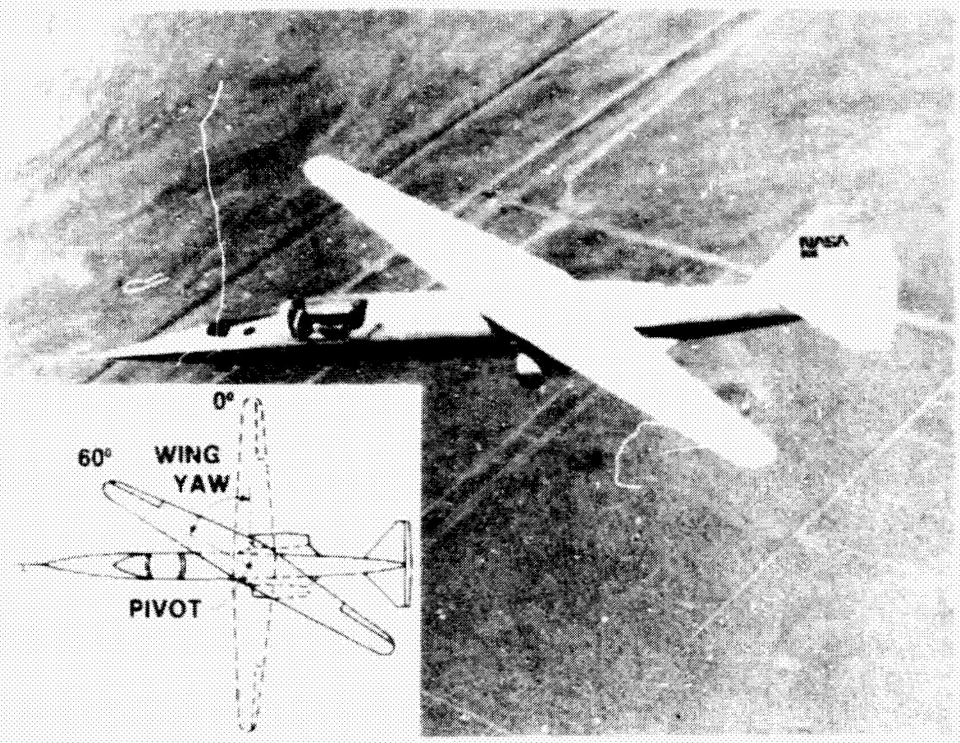


Figure 7.

WIND-TUNNEL STUDY OF X-1 AIRPLANE MODEL WITH A VARIABLE-SWEEP WING

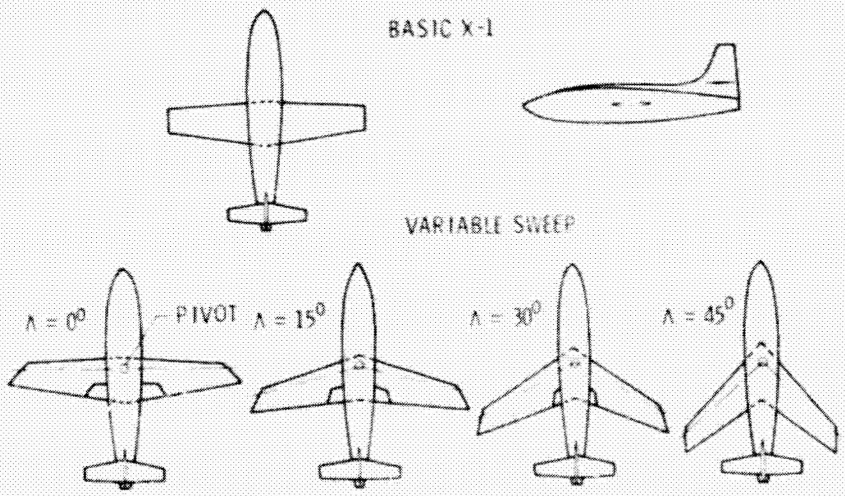


Figure 8.

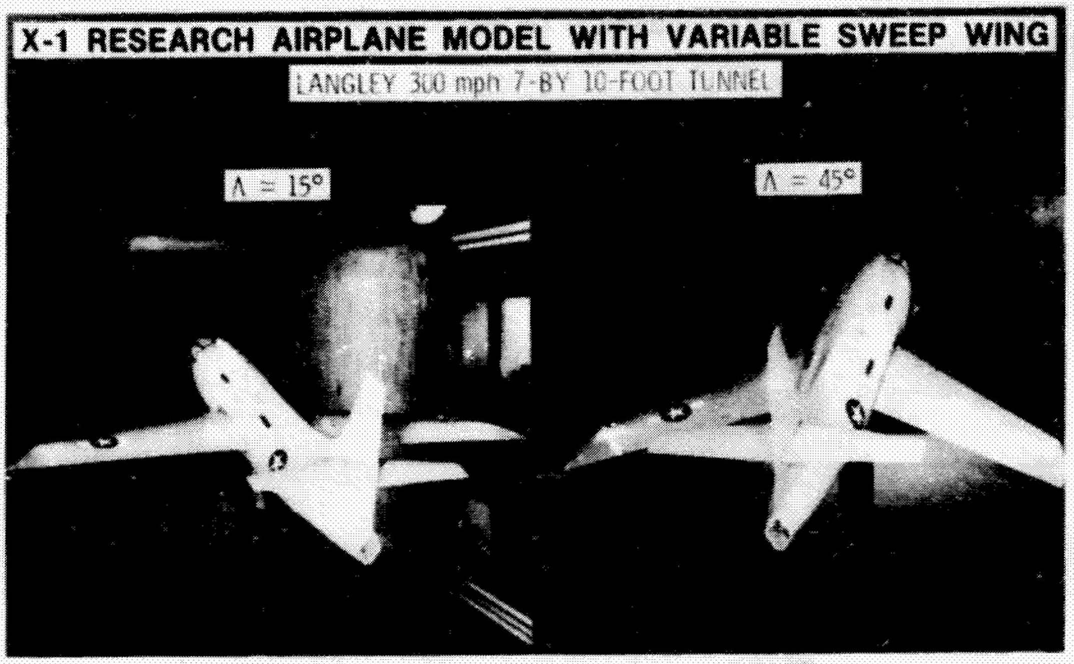


Figure 9.

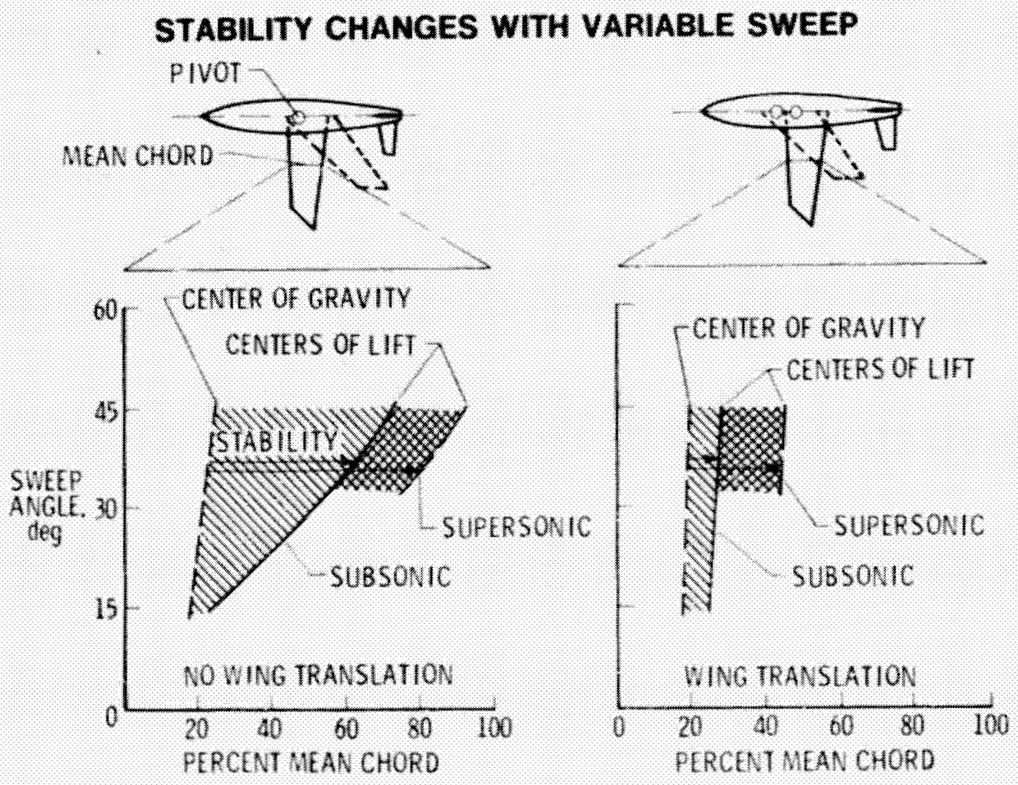


Figure 10.

SWEEP VARIATION OF BELL X-5 AIRPLANE

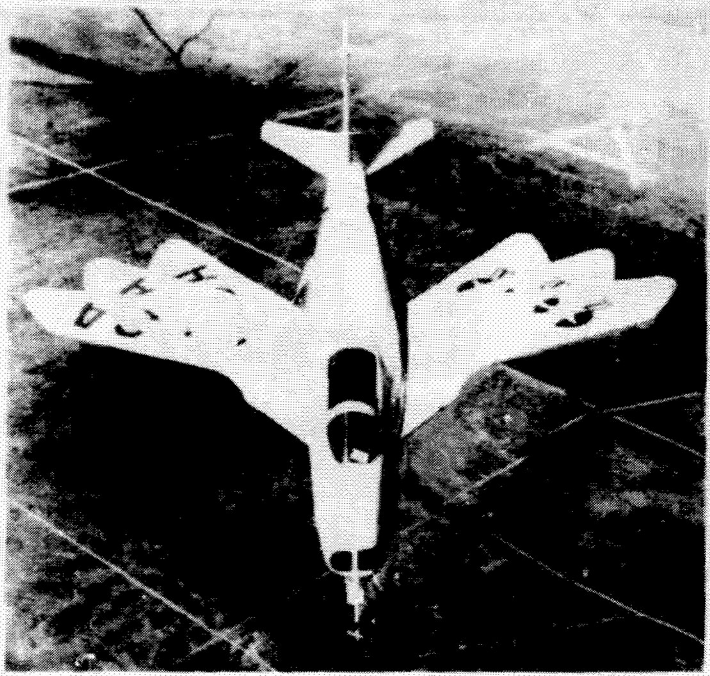
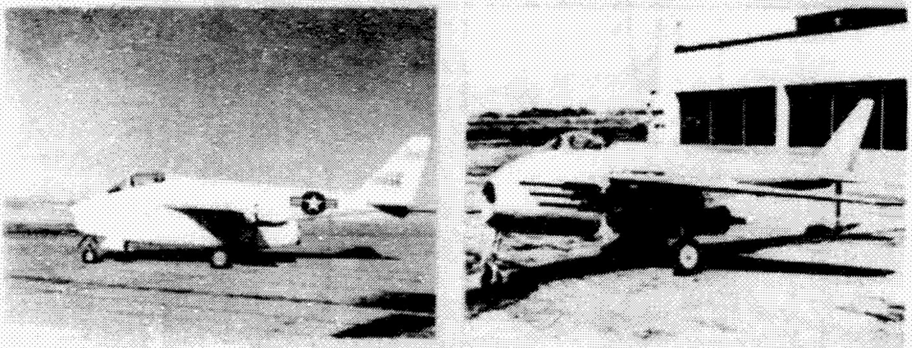


Figure 11.

BELL X-5 AND MESSERSCHMITT P-1101



X-5

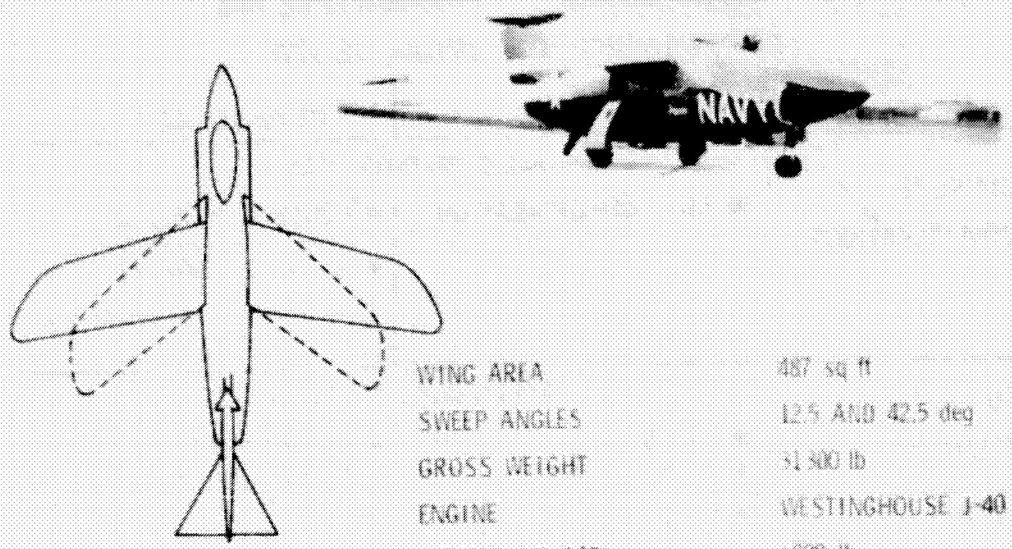
P-1101

	X-5	P-1101
WING AREA	170 sq ft	165 sq ft
FUSELAGE LENGTH	33 ft	30 ft
GROSS WEIGHT	9900 lb	9020 lb

(P-1101 courtesy
Smithsonian Institution)

Figure 12.

GRUMMAN XF10F



WING AREA	487 sq ft
SWEEP ANGLES	12.5 AND 42.5 deg
GROSS WEIGHT	31,500 lb
ENGINE	WESTINGHOUSE J-40
THRUST (NO A/B)	6800 lb
MAX. SPEED (DESCENDING)	0.98 M

Figure 13.

ARROW WING (SWALLOW) CONFIGURATION

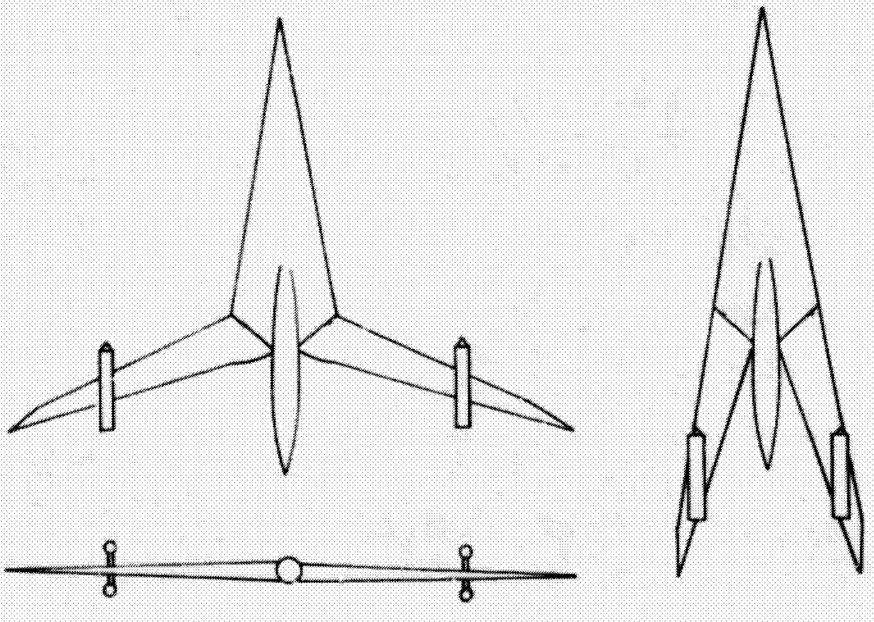
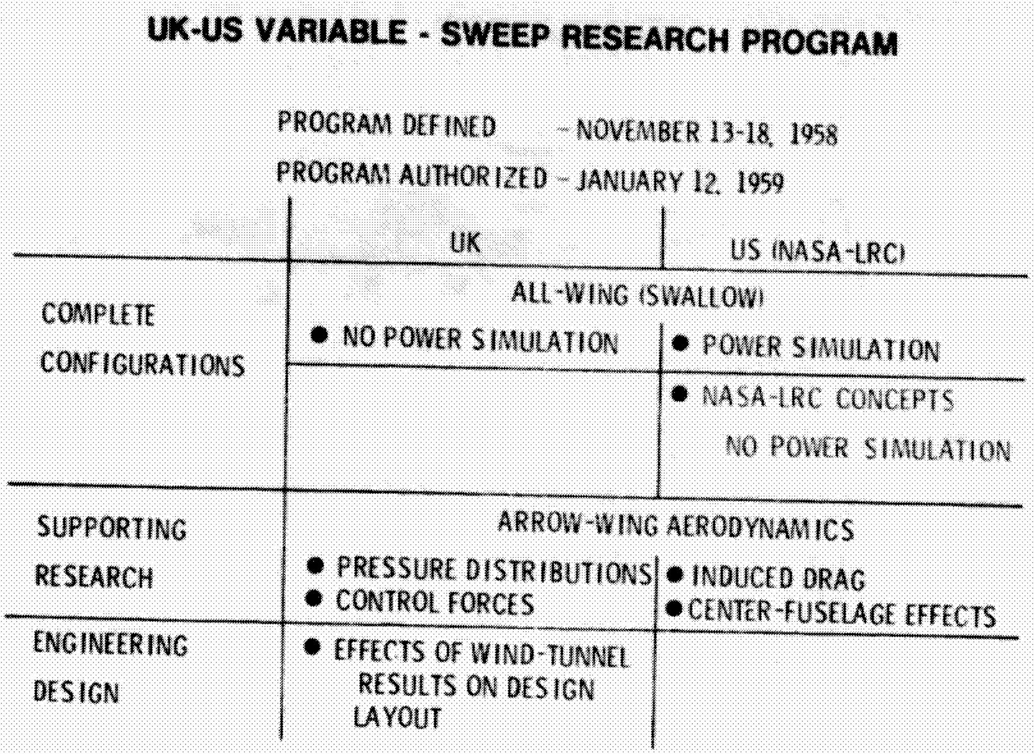


Figure 14.



UK-US VARIABLE - SWEEP RESEARCH PROGRAM

PROGRAM DEFINED – NOVEMBER 13-18, 1958

PROGRAM AUTHORIZED – JANUARY 12, 1959

	UK	US (NASA-LRC)
COMPLETE CONFIGURATIONS	ALL-WING (SWALLOW) ● NO POWER SIMULATION	● POWER SIMULATION
		● NASA-LRC CONCEPTS NO POWER SIMULATION
SUPPORTING RESEARCH	ARROW-WING AERODYNAMICS ● PRESSURE DISTRIBUTIONS ● CONTROL FORCES	● INDUCED DRAG ● CENTER-FUSELAGE EFFECTS
ENGINEERING DESIGN	● EFFECTS OF WIND-TUNNEL RESULTS ON DESIGN LAYOUT	

Figure 15.

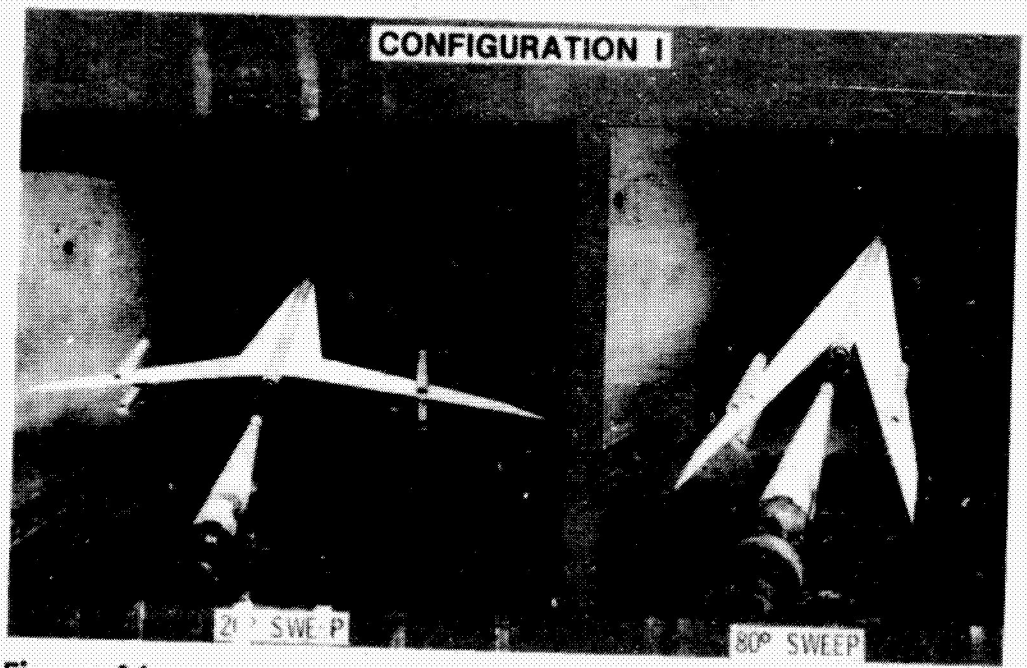


Figure 16.

VARIABLE-SWEEP-CONFIGURATION STUDY

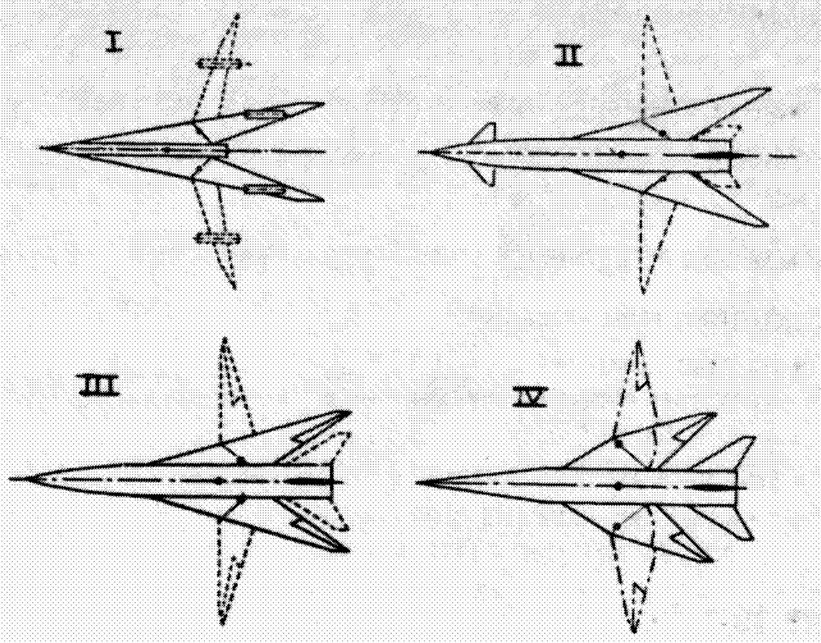


Figure 17.

EFFECTS OF MACH NUMBER - CONFIGURATION IV

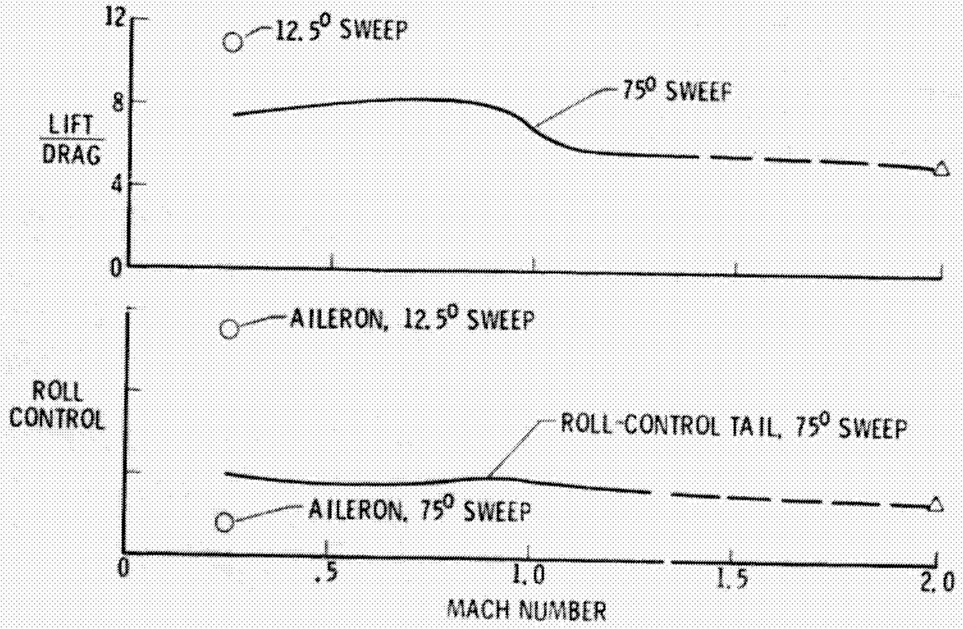


Figure 18.

WORK PERFORMED BY NASA-LRC UNDER U. K. - U. S. PROGRAM

- WIND-TUNNEL STUDIES
  - 7 BY 10-FOOT 300 hr
  - 8-FOOT TRANSONIC 80 hr
  - 4-FOOT SUPERSONIC 40 hr
  - 16-FOOT TRANSONIC 80 hr

  TESTS PERFORMED - JAN. - JULY, 1959
  DATA TRANSMITTED - JULY - DEC., 1959
- ARROW-WING AERODYNAMICS STUDY - RESULTS TRANSMITTED - JULY, 1959
- CONCLUSIONS FROM PROGRAM
  - ALL-WING (SWALLOW)
    - SEVERAL PROBLEMS NOT EASILY OVERCOME FOR NEAR TERM APPLICATION
  - WING-BODY-AFT TAIL (OUTBOARD-PIVOT)
    - NO SERIOUS PROBLEMS FROM LOW-SPEED TO M = 2
    - MOST PROMISING FOR NEAR-TERM APPLICATIONS

Figure 19.

CONFIGURATION IV

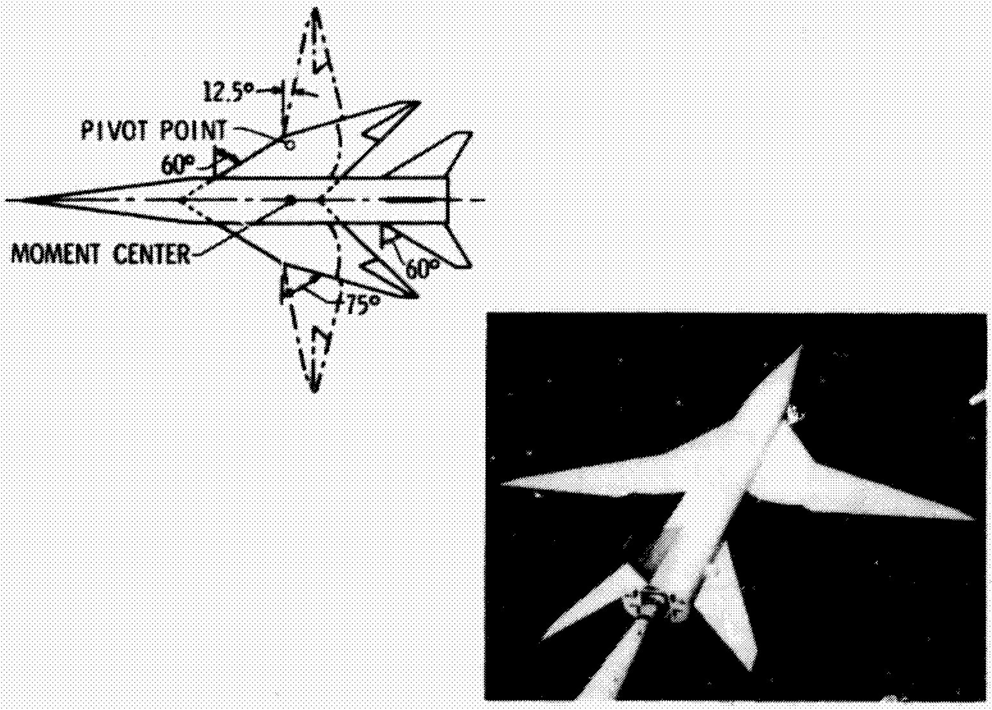


Figure 20.

LANGLEY CAP II RESEARCH CONFIGURATION

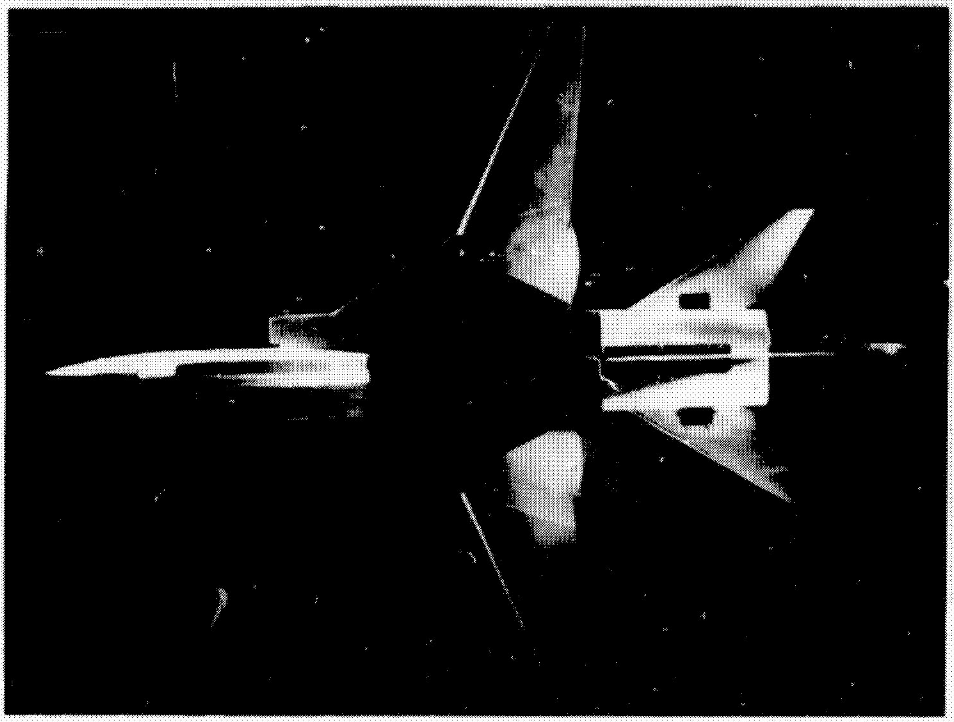


Figure 21.

APPLICATION OF OUTBOARD PIVOT CONCEPT TC A3J MODEL

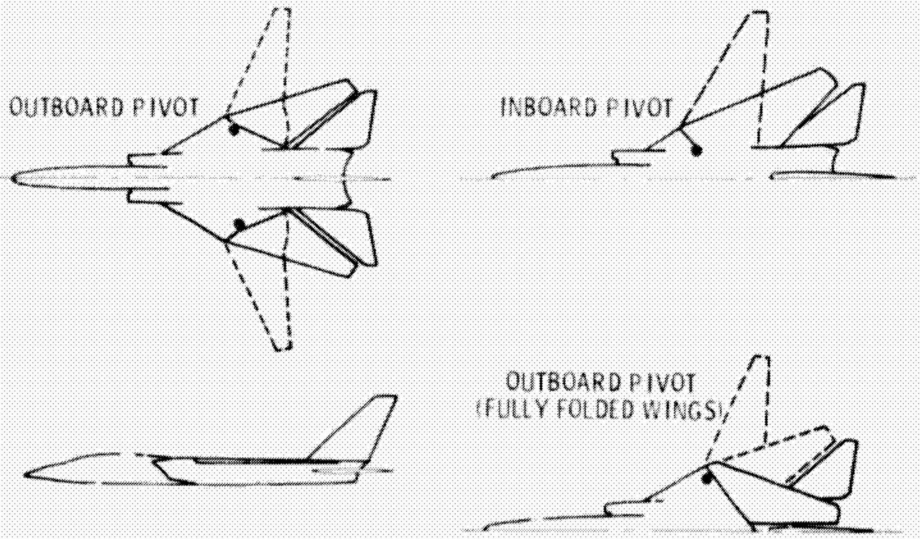
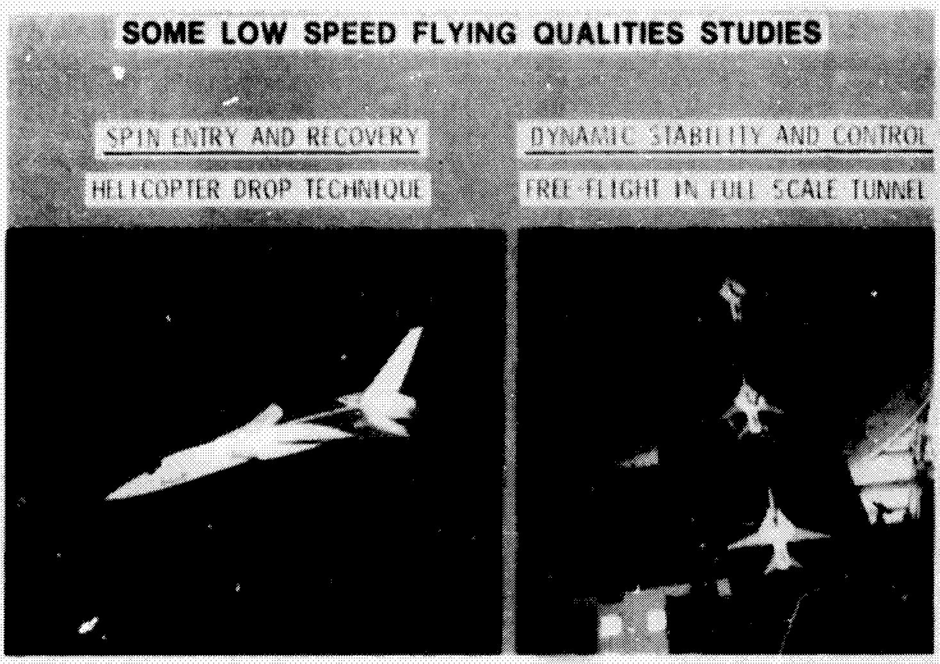


Figure 22.



SOME LOW SPEED FLYING QUALITIES STUDIES

SPIN ENTRY AND RECOVERY

HELICOPTER DROP TECHNIQUE

DYNAMIC STABILITY AND CONTROL

FREE-FLIGHT IN FULL SCALE TUNNEL

Figure 23.

CONFIGURATION REQUIREMENTS FOR VARIOUS MISSIONS

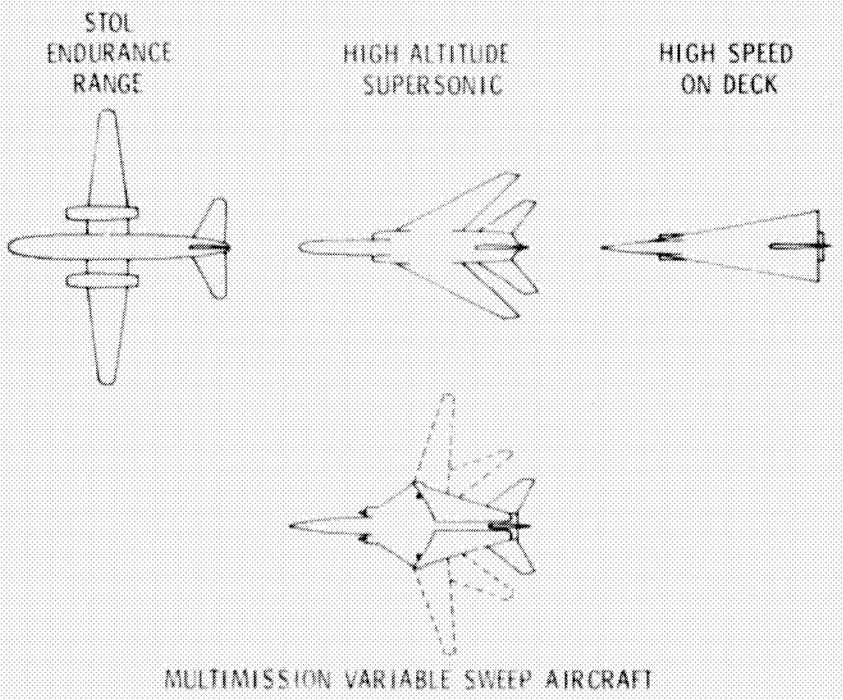


Figure 24.

TYPICAL CONFIGURATIONS USED IN RESEARCH ON MULTI-MISSION TACTICAL AIRCRAFT

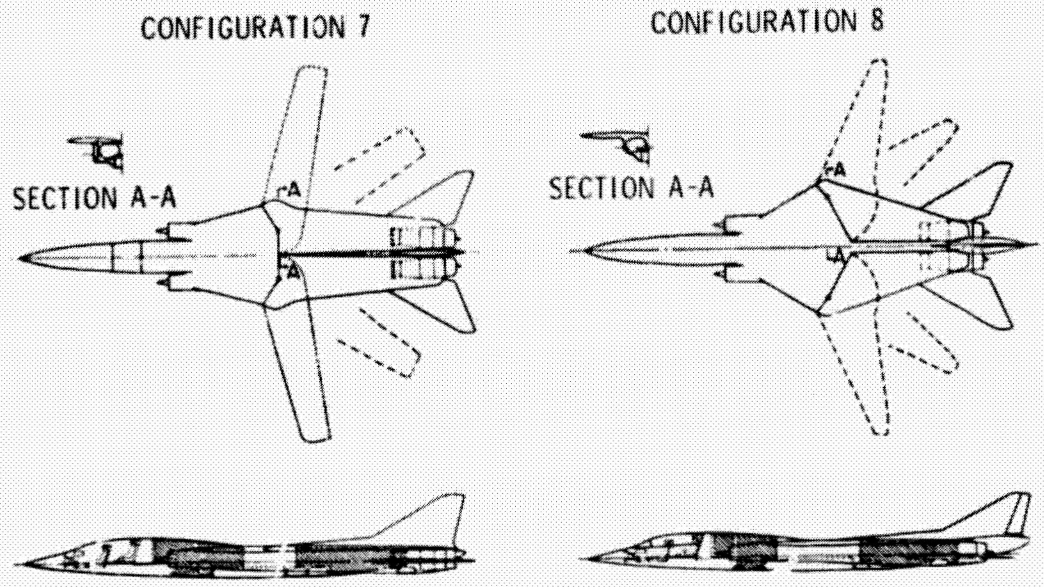


Figure 25.

WIND TUNNEL MODELS OF CONFIGURATIONS 7 AND 8

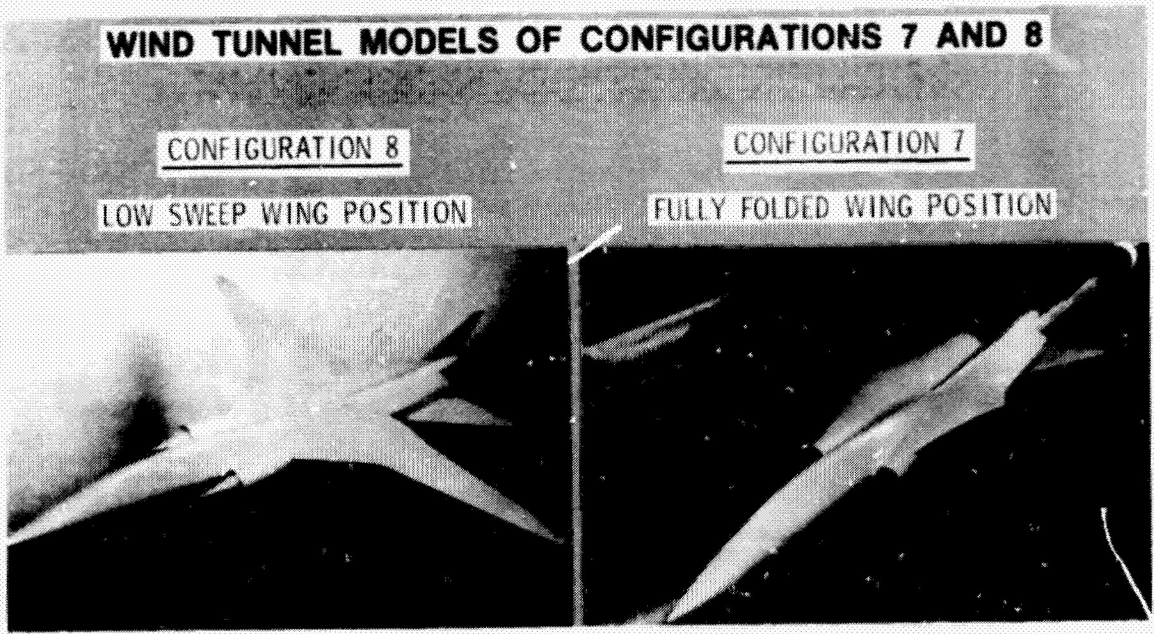


Figure 26.

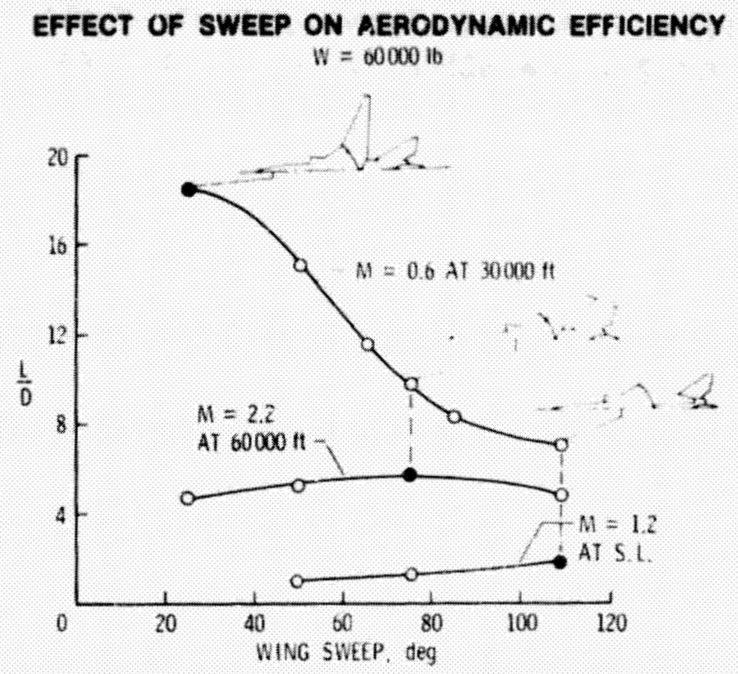


Figure 27.

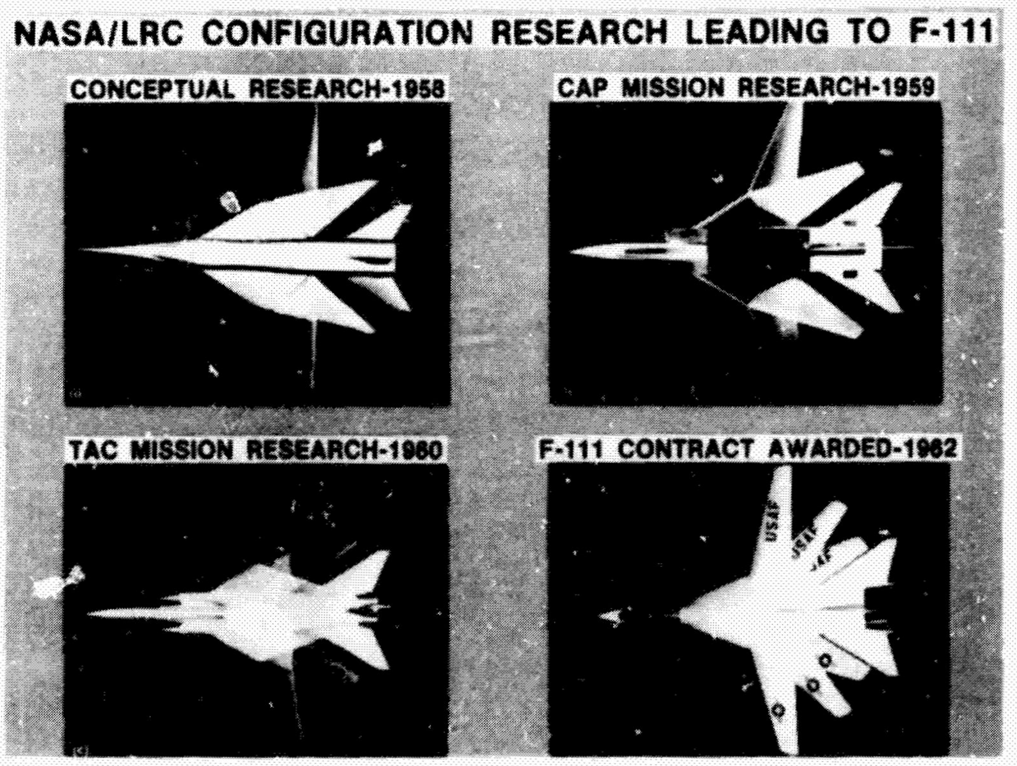


Figure 23.