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RECENT SUPERSONIC TRANSPORT RESEARCH

by

The Staff of The NASA Langley Research Center

Compiled by

William J. Alford, Jr. and Cornelius Driver

Introduction

The prospect of commercial flight at supersonic speeds has served for the last decade as a stimulus to aeronautical research in the United States and abroad. Within the United States the intensive development programs in support of supersonic military aircraft provided a broad background of technical knowledge upon which to base initial concepts, studies, and research programs. This potentiality of commercial supersonic flight was specifically assessed in December 1959, in a technical summary of supersonic transport problems prepared by NASA and presented to the FAA, (ref. 1). Research effort within NASA and elsewhere increased significantly with the inauguration of a national program in 1961 and continued to expand as the program gained momentum.

NASA research has encompassed most of the basic disciplines. In the area of configuration aerodynamics, for example, over 30 basic configuration concepts have been explored. The four most promising concepts emerging in late 1962 from this research are illustrated in figure 1. Two of these configurations are fixed-wing arrangements and the other two incorporate variable-sweep wings. A recent and more complete discussion of the four SCAT (Supersonic Commercial Air Transport) configurations is presented in reference 2. In order to provide a focus for further NASA research, contracts were let to

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the Boeing and Lockheed Companies in February 1963, to study these four configuration concepts in depth from the viewpoint of the aircraft manufacturer and the airline user. The studies were completed in September 1963, and were reported to the industry along with other research results in a supersonic transport conference held at the Langley Research Center on September 19-21, 1963.

The broad conclusions of the SCAT Feasibility Studies and the accompaning research studies were as follows. Derivatives of at least two of the four configurations were judged to be technically feasible in that they could meet the basic mission requirements within the prescribed operating restrictions. These studies demonstrated the desirability of a Titanium airframe and the necessity for advanced engines. However, it was indicated that the resulting airplanes would be larger and heavier than corresponding subsonic jets, and their economic feasibility was questionable. It was obvious that ways would have to be found to obtain further major increases in flight efficiency. It was clear that major attention would have to be paid to the sonic boom, which was shown to have become a dominant factor in aircraft design and operation.

The purpose of the present paper is to review some of the major research activities of the last two years, conducted by NASA, its contractors, and others in support of the supersonic transport with emphasis in the areas of improved flight efficiency, stability and control, structures and materials, and operating problems.

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PERFORMANCE AERODYNAMICS

Most early supersonic research aimed at drag reduction dealt with wave drag. These initial efforts led to the "area rule" concept, and through extensive calculative and experimental research, to the present linear theory methods for treating wave drag and component interference. These analytic methods generally show good agreement with experiment for reasonably slender configurations. Programs have been developed for high-speed computers which have turned linear theory methods into a practicable and powerful design tool.

In the area of supersonic drag due to lift, experiment showed that the theoretical gains were attainable only for conditions where linear theory was applicable - that is, where the configurations were reasonably slender and local slopes not extreme and where cruise lift coefficients were moderately low. The aforementioned progress in the area of wave drag and interference led to the low-drag, slender configurations for the supersonic transport which met the linear theory requirements. Linear theory methods were developed for handling a wide variety of arbitrary planforms, and experiment showed as much as 85 percent of the theoretical improvement in drag-due-to-lift due to twist and camber could be obtained for arrow type planforms.

A set of computer programs was developed to mechanize these complex computations. The resulting programs, within the restraints of linear theory, permit calculations of camber surfaces of arbitrary wing planforms with specified pressure distributions. Inversely, they permit determination of pressure distributions on wing planforms with arbitrary surface warping.

Figure 2 illustrates a typical build-up of a configuration drag polar as accomplished by use of the NASA computer programs. Items shown are wave drag, friction drag, and drag-due-to-lift values for: (1) the selected warped-wing configuration, (2) a flat-wing version of that same configuration, and (3) the theoretical lower bound for the chosen wing planform. Part (3), the lower bound, provides a quick answer as to whether or not the aerodynamic performance objectives can be met with the planform selected. Any properly warped wing must fall between the flat wing and the lower bound, but will not be necessarily tangent to the lower bound because of practical design restraints.

These calculative methods which provide the drag polars of figure 2, involve the determination of camber-plane pressure distributions which then can be used to develop other aerodynamic characteristics, such as lift-curve slope, pitching moment at zero lift, static longitudinal stability and wing loads. This information can be provided not only for the cruise condition but for a range of lift coefficients and supersonic Mach numbers.

A warped-wing, supersonic-transport-type configuration developed through the use of these new calculative methods and designed to cruise at Mach number 2.6 is shown in figure 3. The wing leading-edge is swept behind the Mach cone and the engine nacelles have been located under the wing and to the rear in a position favorable for lift and drag interference. The final configuration was developed from the initial concept by progressive iteration by means of the computer programs. Extensive wind tunnel tests were conducted to check the validity of the computer results and to evaluate the configuration. The experimental points plotted on figure 2 demonstrate the excellent agreement that can be obtained between experiment and theory.

It is stressed that the sample configuration shown is one of a number of fixed-wing and variable-sweep arrangements being studied by NASA to correlate experiment and theory and define the aerodynamic state of the art. The purpose of this work is to demonstrate the capabilities of new aerodynamic tools and techniques rather than define a specific supersonic transport configuration. Many other factors, such as take-off and landing characteristics, general arrangement, structural feasibility, and ease of fabrication must be considered in detail by qualified aircraft designers and airline operators before an optimum configuration can be selected.

Attempts to improve flight efficiency cannot omit considerations of trimming the configuration at some reasonable level of stability consistent with subsonic requirements and the total change in stability from the low-speed to the supersonic cruise Mach number. In contrast to the flat wing case, it is possible to design the warped wing with a pressure distribution which eliminates the necessity for control deflection at the cruise lift coefficient (configuration has a positive pitching moment at zero lift). The data shown in figure 4(a) compare the trimmed lift-drag ratio for the comparable "flat" and "warped" configurations. These data show the somewhat higher peak efficiency of the warped wing compared to the flat wing, and the relative insensitivity of the warped wing to static margin as practical stability levels are reached. This factor is of major significance to the SST in view of the wide range of loadings and variation of stability level with Mach number.

Recent studies have shown that the location of the engine nacelles can provide powerful favorable drag and lift interference effects. As mentioned previously the engine nacelles of the sample configuration were located beneath and well aft on the wing. The compression waves from the nacelles impinge upon the receding slopes of the wing, thereby producing both favorable lift and thrust interference, figure 4(b). In this case these effects are seen to be sufficiently powerful to overcome both the wave and friction drags of the nacelles for lift coefficients at and above the cruise lift coefficient. Additional research on these interference effects is presently underway.

The improvement in flight efficiency $\left(\frac{M\frac{L}{D}}{SFC}\right)$ achieved in the period between the SCAT feasibility studies and the present data is shown in figure 5.

The sample configurations just discussed falls at the top of the "Advanced Aerodynamics" band, and exhibits the highest level of efficiency yet measured in this Mach number range. Note, too, that this efficiency level approaches that of the present subsonic jets. These significant gains are attributable to continuous and parallel experimental and calculative research programs aimed at improving supersonic performance.

Any conclusions as the overall vehicle efficiency must be based on an analysis of the complete mission from take-off to landing. Complete mission studies are an absolute necessity to determine the performance potential of a given airplane, to define problem areas requiring research, and to correctly evaluate the effects of design changes. The effects of design changes cannot be determined on the basis of individual component characteristics because of the complex interactions which exist between the airframe aerodynamics, propulsion system, weight, and operating requirements.

The supersonic transport performance is currently determined by the use of sophisticated machine computer programs. Such programs are more or less standard throughout industry. Using specific airplane and engine characteristics the programs are designed to select flight paths which satisfy preselected acceleration and cruise sonic boom limits, to satisfy engine operational limits, to select the cruise altitude which will result in maximum range, to limit normal acceleration, etc. The programs used by NASA have sufficient flexibility to enable the mission to be studied in detail.

Compared to the subsonic transport the major new factor in the SST design process is the requirement to hold the sonic boom overpressures below specified levels during transonic acceleration and supersonic cruise. The boom levels specified are of critical importance because of the powerful effects on aircraft size. Figure 6 shows the gross weight for several configurations as a function of the design maximum overpressure for transonic acceleration. Each curve represents a family of airplanes, each of which has been carefully matched and optimized for minimum gross weight at its particular overpressure limit. As the maximum allowable overpressure is reduced the aircraft is required to accelerate at progressively higher altitudes, which requires greater fuel consumption, a larger wing, and larger engines - all of which increase the aircraft gross weight to accomplish the mission. In each case below some limiting value of overpressure, the growth factor process takes over and gross weight increases precipitiously. Obviously the desirable design point is near the knee of the curve.

The objective of research in the area of configuration effects is to shift the knee of the curve downward and to the left. This is accomplished practically by increasing the aircraft flight efficiency in all parts of the mission and by improving the sonic boom form factor (as will be discussed later). Curves A and B are configurations studied in the SCAT feasibility studies; whereas the sample configuration has been further optimised from the standpoint of aerodynamic efficiency and sonic boom form factor utilizing the newly available techniques. Thus, sonic boom is critically important and can be seen in this figure to rule out one configuration in favor of another, depending on the setting of the maximum allowable boom overpressure.

Because of its importance, sonic boom research, both theoretical and experimental, has been vigorously pursued over the last few years. At first, for fighter aircraft the calculative as well as the experimental schemes dealt only with "volume" effects of the configuration. Major increases in size and weight for the supersonic transport, however, have necessitated consideration of "lift effects" in the case of the SST. The previously mentioned drag due to lift program have played an important role in the analysis of such lift effects by providing a rapid analytical means for obtaining the required lift distributions. This program has been combined with parts of the wave drag program to obtain a new program which calculates the sonic boom shape factor as a function of lift coefficient. Similar programs are now being utilized throughout industry.

The development of the analytic methods was accompanied by a parallel experimental research program requiring special techniques. In order to achieve in the wind tunnel the required "far-field" conditions (that is, with the measurement of the sonic-boom signature being taken many model lengths from the model itself), the models had to be quite small, and the pressure-sensing apparatus very sensitive. The illustration in the top portion of figure 7 provides an idea of the size of the models used.

A correlation of analytical, flight, and wind-tunnel results also shown in figure 7 indicates that the methods used are reliable and adequate for predicting sonic boom overpressure levels. It should be noted that the experimental flight test results are mean values as discussed in a later section of this paper. The prediction bands for the wind tunnel and theoretical results allow for the variations in aircraft gross weight and Mach number.

PROPULSION

Early mission studies by NASA and others (ref. 3 and 4) indicated critical areas where technological advances in the elements of the propulsion system were required to assure the feasibility of the SST.

In these critical areas NASA joined with FAA and DOD in sponsoring an engine components and cycle study research program with United States engine manufacturers. The results of this program indicated that the required SST engine is technically feasible, but that a very extensive component improvement program would have to be undertaken to attain adequate levels of performance and weight, together with the long engine life and reliability required for commercial operation. NASA and the military services are continuing to sponsor the necessary basic research to achieve these advances.

The selection of the most promising engine types for the SST has required extensive analytical engine cycle and mission performance calculations. Since on a given flight the engines operate over greatly varying conditions, a wide range of design parameters must be considered, and the engine selection must be made on the basis of overall mission performance. A recent analysis of this type is discussed in the article by Mr. Dugan in this issue. His results indicate the importance of various engine parameters, such as turbine inlet temperature and compressor pressure ratio as well as the effects of other important factors such as engine weight, inlet and exit nozzle performance, and mission operating restraints.

The broad conclusions which Mr. Dugan has reached are believed generally applicable to the airplane configurations being currently considered for the SST. The optimum engine, however, is dependent on the airframe configuration and the mission and operating restraints. For example, in figure 8 the variation of weight ratio with range is shown for two typical configurations using the same engine, properly sized, and operating under the same sonic boom restrictions. The decrease in weight depicts the fuel consumption. The primary segments of the flight are noted. During the climb and acceleration phase configuration A uses one-half as much fuel as configuration B because of the significantly lower transonic drag and better sonic boom characteristics possessed by configuration A. Because of reduced fuel consumption during acceleration, configuration A has a much larger portion of its fuel available for cruise. These differences in fuel consumption would necessarily require that the engine chosen for configuration B have its design parameters selected more to favor good off-design (climb and acceleration) performance than that for A.

Supersonic inlet research is being conducted primarily at the NASA Ames Research Center. Extensive analytical and experimental studies have been made of the internal performance characteristics of a two-dimensional and an axisymmetric inlet. Both inlets employ a combination of external and internal compression for supersonic operation, and each has sufficient variable geometry to provide the airflow matching characteristics dictated by a typical SST engine. Test results from low subsonic to supersonic cruise speeds show that considerable advances in internal flow performance are achievable with appropriate use of bleed flow to control adverse boundary-layer and boundary-layer shock interaction effects. In addition to studying the internal flow performance the additive drag values have also been determined. The inlet research is being conducted with the philosophy that the attainment of the maximum internal performance does not necessarily result in the maximum thrust-minus-drag of the overall propulsion syst... or minimum-cruise-fuel-flow-per-mile because of the relatively large drag contributions of the bleed air. Research is also un...rway to devel..p methods for analytically predicting the dynamic characteristics of complete propulsion systems, including inlets and exhaust nozzles. Cons..derable progress has been made to date, and the results will be very valuable in the design of the complex control systems which must be able to cope with inlet unstart and other flow discontinuities associated with supersonic operation as well as the usual engine transients. The Langley Research Center is stu... the internal flow characteristics of an axisymmetric inlet operating either choked or unchoked at static conditions. This research is being conducte.. in conjunction with a study of the noise suppression characteristics of the same inlet operating with choked flow.

A great deal of attention is being given at the Langley Research Center to ...ine nozzle research because of the large change in range which can result from a small change in nozzle performance. At the present time there is sufficient information available to design complex nozzles which have near ideal performance over the SST flight spectrum, but these nozzles are incompatible with SST weight and control requirements. Consequently, research is being conducted to define the nozzle geometry which will be optimum from the standpoint of performance, weight, and complexity. Nozzle types being studied with hot and cold flow include the conventional convergent-divergent, plug, and blow-in-door ejector types plus several unconventional types.

One final problem area remains after the various components of the propulsion syste.. have been developed, that is, the integration of the propulsion system and the airframe. Two factors make the integration problem important on the SST. First the propulsion system is large. Consequently, the lift and drag interference effects between the airframe and nacelle will be significant as discussed in the previous section on Performance Aerodynamics. A typical nacelle may have a maximum diameter which is about 40 percent of the fuselage diameter and a length equal to about 20 percent of the fuselage length. It is interesting to note that the engine proper occupies only about one-third of this length. Second, the inlet performance is quite sensitive to the characteristics of the flow field just ahead of the inlet. Research on the latter problem consists of experimental measurements of the flow field generated by a typical SST swept-wing configuration, and an experimental study of the dynamic interference problems which exist between closely spaced inlets, or wing and inlet, when a shock is disgorged by the inlet.

STABILITY AND CONTROL

As indicated in the section on Performance Aerodynamics the configuration of the SST will of necessity be considerably different from the current jet transports. These geometric differences and the large difference in cruise speed and altitude result in stability and handling qualities problems which must be solved before an acceptable aircraft can be developed. The solution to these problems with a minimum penalty to performance has been the goal of recent studies of supersonic transport stability and control.

One problem area inherent in supersonic cruising flight is that of providing adequate damping of the dynamic stability modes. The combination of high forward speed and low atmospheric density at cruise altitude results in fundamentally low levels of damping in both the longitudinal short period and the lateral-directional Dutch roll modes. The need for artificial augmentation of damping about the pitch and yaw axes and probably the roll axis also is generally accepted. Simulator research such as that reported in reference 5 has served to indicate desirable levels of damping in normal cruise flight and minimum levels required in the event of augmentation failure including consideration of pilot adaptation to an augmentation failure. One goal of present simulator research is to assess the implication of these findings with respect to current configuration concepts.

A recently completed study of the interaction between structural flexibility and the stability augmentation system (ref. 6) has indicated that the flexibility of the extremely slender fuselages characteristic of some potential configurations will lead to reduced passenger comfort in rough air. A flight control system that augments structural damping as well as damping of the stability modes may be considered for increasing fatigue life. It was concluded that structural damping can be augmented through conventional techniques without significant increase in flight control system complexity.

The evolution of transport aircraft configurations from the reciprocating engine types through the subsonic jets to the supersonic transport has been characterized by increasing slenderness both in dimensional relationships and in mass distribution. One measure of this trend which is of basic importance to the lateral-directional flying qualities is the ratio of the moments of inertia about the yaw and roll axes, I_z/I_x. Typical values of this ratio for the familiar subsonic transports are 1-1/2 to 2-1/2 while those for typical proposed supersonic configurations are from 6 to 10. The familiar type of directional stability in which C_{n_β} tends to restore the sideslip angle to zero through a yawing motion is supplemented for high values of I_z/I_x by a different type of directional stability in which the sideslip angle is restored to zero through a rolling motion about the inclined longitudinal axis. In addition, the roll to sideslip ratio in the Dutch roll mode increases approximately in proportion to the inertia ratio. The resulting interaction between yawing and rolling motions leads to a more difficult control task for the pilot. High values of I_z/I_x can therefore lead to a whole family of objectionable lateral-directional handling qualities characterized by sluggish and oscillatory response to roll control and excessive rolling response to rudder motion, lateral gusts and asymmetric engine failure. These characteristics can be minimized by increasing C_{n_β}, decreasing the magnitude of the effective dihedral, C_{l_β}, and augmenting the roll damping. Unfortunately both the typical increase in C_{l_β} associated with the high-sweep angles required for efficient supersonic cruise and the decrease in C_{n_β} due to increases in angle of attack and Mach number tend to aggravate the situation.

The achievement of a larger ratio of C_{n_β} to C_{l_β} has been one goal of wind-tunnel tests at both subsonic and supersonic speeds. The effect of vertical-tail position and fuselage forebody cross section on the variation of C_{n_β} with angle of attack is shown in figure 9. Replacing the center vertical tail with two tails having the same total tail volume and located well outboard on the wing resulted in improvement in C_{n_β} at high angles of attack. Although not shown, C_{l_β} was reduced somewhat as a result of the reduced height of the twin tails. Similar effects at supersonic speeds have been shown previously in reference 7. Regarding fuselage forebody effects, it has been found that slight deviation from circular cross section can result in considerable improvements in C_{n_β} at moderate and high angles of attack. Inasmuch as fuselage cross-flow characteristics are known to be sensitive to Reynolds number, research is currently underway to determine if these differences are maintained to Reynolds numbers beyond the maximum test value of 6×10^6 (based on fuselage depth).

Inasmuch as the general class of lateral-directional handling qualities problems discussed herein are most apparent at high angles of attack, they are of importance to the supersonic transport aircraft in the landing approach phase of the transport mission. Extensive analytical and simulator studies of landing approach handling qualities lead to a tentative conclusion that the variable-wing-sweep configurations which can approach at low angle of attack by virtue of high aspect ratio and low wing sweep angle and utilizing effective high-lift systems, exhibit approach handling qualities nearly comparable to existing subsonic jets. The fixed wing configurations, characterized by their high leading-edge sweep and low aspect ratio and with their less effective high-lift systems, must approach at higher angles of attack and require stability augmentation with relatively high authority to achieve acceptable handling qualities in the landing approach.

Turning now to longitudinal stability the rearward shift of the aerocynamic center with Mach number coupled with the requirement for positive longitudinal stability at subsonic speeds results in levels of trim drag which could seriously limit the performance. As shown earlier (fig. 4(a)) this penalty can be reduced by the use of wing camber and twist. However, for configurations incorporating variable-sweep, variations in aerodynamic center result from changes in wing sweep angle as well as from the characteristic changes associated with Mach number. Extensive experimental and analytical studies by NASA and substantiated by industry studies have indicated that use of an outboard-pivot location will allow a lower minimum sweep angle while retaining an aerodynamic center location compatible with the cruise design point (fig. 10). A rather complete discussion of the lift distributions associated with the various pivot locations and the explanations of their aerodynamic center variations with sweep angle is presented in reference 8.

At supersonic speeds the combination of large sweep angles and high-panel aspect ratios used on variable-sweep configurations can result in aeroelastic effects sufficiently large to provide reductions in stability to the degree that the supersonic condition could become the critical stability case. It must be remembered, however, that a reduction in stability due to aeroelastic effects does not necessarily imply a reduction in cruise trim drag. The cruise teim drag is dependent upon the wing-body center-of-pressure location which is dictated by the wing warp required for optimum cruise performance and the flexible wing must be built so that it assumes the design shape in one g flight at the design speed.

The avoidance of undesirable motions or excursions in angle of attack (pitch-up) requires linearity in the pitching-moment variation with angle of attack. Past experimental studies have shown that the degree of linearity is a function of wing-sweep angle, aspect ratio, and horizontal-tail location, along with other factors such as fuselage size, engine location, etc. The fixed arrow wing (e.g., fig. 3) which is desirable from a performance standpoint, has an undesirable nonlinearity. Research currently underway, however, has indicated that leading-edge devices tailored to a specific configuration can provide a significant reduction in the severity of the instability.

For variable-sweep configurations, in addition to the classic pitch-up associated with the high-sweep condition, a second type of pitch-up occurs when the outer panel is unswept. A leading-edge vortex, shed from the highly swept forewing, causes the forewing to carry a greater proportion of the total lift at high angle of attack and promotes earlier stall of the outer panel with both effects contributing to an unstable tendency at high angle of attack. A considerable improvement in the pitching-moment characteristics can be obtained with fairly moderate reduction in inboard forewing sweep (Λ_{FW}) and area, as shown in figure 11, indicating that there may be some desirable compromise between performance and stability. A further improvement can be realized by deflecting a leading-edge flap (δ_{FW}) on the highly swept fixed portion of the wing. The data just discussed were obtained from a configuration that utilized a low horizontal tail. As shown in figure 11, raising the horizontal tail as may be dictated by engine location considerations results in the tail contributing to high-lift instability. This may be avoided for moderate tail heights by incorporating negative tail dihedral. Additional gains in pitching-moment linearity are shown to be attainable by the proper application of wing leading-edge devices. Further research to obtain more effective solutions is underway.

Operation on the so called "backside" of the thrust required curve means that an increase in thrust is required to maintain the flight path with decreasing speed. Operation at the speed well below that for neutral speed stability is objectionable. A small amount of speed instability may be tolerable, however, the final answer to this question must await the results of further research. For variable-sweep aircraft speed stability is generally assured because of the higher lift coefficients and lift-drag ratios provided by the higher aspect ratios and the ability to effectively utilize high-lift flap systems. The severity of the speed stability problem for low-aspect-ratio fixed wing configurations brought about by the high induced drag, the inefficiency of high-lift systems on this type of wing, and the difficulty in trimming out flap pitching-moment coefficients is illustrated in figure 12. For the wing loadings shown, landing approach speeds below 170 knots can only be attained through the use of larger wing-flap deflections which would require increased trim capability such as may be provided by a large canard or a rear tail. For the tailless delta configuration shown in figure 12, the use of the extremely low wing-loadings required to reduce the speed corresponding to neutral speed stability is generally inconsistent with the requirements of supersonic performance, and the designer may be forced to accept some degree of speed instability.

STRUCTURES AND MATERIALS

The supersonic transport poses many structures and materials problems associated with the long life time and relatively high temperatures to which the structure will be subjected. Nonuniform temperatures that may exist in the wing and fuselage sections will produce thermal stresses that must be considered in the design. Studies that have been made on the influence of thermal stresses on the weight of the aircraft structure indicate that weight penalties of a few percent of the basic structural weight may be attributed to this factor.

Studies of different structural concepts for the supersonic transport in the Mach 2.5 and 3 range by both industry and NASA indicate that the lightest weight structures can be achieved through the use of titanium alloys. The application of titanium favors skin-stringer construction for both wing and fuselage structures, whereas, stainless steel would require more complex local stiffening (e.g., sandwich construction) to develop high compressive and torsional strengths.

Among the titanium alloys the 8Al-1MO-1V alloy is the principal material of interest. This alloy is relatively new and little fabrication experience exists. In order to explore some of the fabrication problems associated with structural applications of this alloy, NASA has initiated a comparative study of several different methods of fabricating skin-stringer panels representative of wing compression cover skins. Some of the preliminary compressive strength results based on an average of three test panels for each of the three methods of construction are shown in figure 13. The highest compressive strength was obtained from the resistance spot-welded panels, followed by the riveted and the fusion welded (tungsten inert gas, TIG) panels. The maximum difference in compressive strength between the spot welded and fusion welded panels was approximately 12 percent. These initial results were obtained with panels from 8Al-1MO-1V titanium alloy in the triplex annealed condition. Additional panels are being fabricated from the titanium alloy in the double-annealed condition using the previously noted fabrication methods in addition to electron beam welding, diffusion bonding, arc spot welding, and machining from thick plate. To date the fabrication problems encountered are typical of those encountered with a relatively new structural material.

Fatigue properties of the materials are of interest because of the long life requirements of 30,000 to 50,000 hours. Both NASA and industry studies are underway on the fatigue behavior of several promising materials. The studies at Langley include determination of fatigue strength, determination of rates of crack propagation, and residual strength of sheet materials containing cracks. This research is discussed in Mr. Raring's article in this issue.

The requirements for long life have triggered many materials research programs to establish effects of long time exposure on material properties. At Langley investigations were started approximately three years ago to study the stability of several titanium alloy and stainless steel sheet materials after prolonged exposures at 550°F for times up to 40,000 hours. Data on the explosure effects up to 22,000 hours have been obtained to date. The effects of exposure are determined from changes in the mechanical properties at room temperature as well as -110°F and from changes in the tensile spot weld strength. Metallurgical changes in the material resulting from the exposure are also being studied. The data thus far indicate that the titanium alloys and stainless steels of current interest exhibit no significant change in mechanical properties. The only clear evidence of deterioration in these materials has been noted in the tensile strength of spot welds of the candidate titanium alloys and some of the stainless steels. The magnitude of this deterioration for the materials is indicated in figure 14 in terms of the relative strengths, that is, the ratio of the strength after exposure to that before exposure, for exposure times up to 22,000 hours. The shaded areas indicated the spread obtained for three titanium alloys; the Ti-8Al-1Mo-1V was least affected by exposure, next was Ti-6Al-4V and then Ti-4Al-3Mo-1V. The spot weld strength for the stainless steels ranges above and below the data shown for the titanium alloys. No general trend for the steels is available from the tests to date.

The most important result to date from the long time exposure studies has been the slow, steady loss of tensile strength of the titanium alloy spot welds. This result was not clearly established until approximately 10,000 hours of exposure had elapsed. The results beyond 10,000 hours substantiate the trend.

For some time it has been recognized that titanium alloys are susceptible to salt stress corrosion at elevated temperatures and are relatively immune to attack at room temperature. The converse situation applies generally to stainless steels. The magnitude of the national effort underway to explore all aspects of the stress-corrosion problem is discussed in Mr. Raring's article. Langley is studying many aspects of the problem with particular emphasis on the Ti-8Al-1Mo-1V alloy. It is recognized that the true importance of the salt stress corrosion problem will not be established from laboratory tests alone. The actual environment of the aircraft structure in terms of salt encountered and retained on the structure will have to be established. Experience to date with aircraft that contain stressed titanium-alloy parts in engine areas has shown no dfeinite evidence of salt stress corrosion.

OPERATING PROBLEMS

The operational boundaries of Mach number and altitude within which the SST must operate are illustrated in figure 15. The limits of this corridor are determined by considerations of maximum lift, buffeting, engine blowout, atmospheric turbulence, maximum temperature, flutter, boom overpressure, and airframe and engine strength. Such restrictions, however, are common to all supersonic aircraft. In addition, because of economics and mission requirements, the SST must adhere to a rather restricted flight plan. These operational limits and requirements result in a number of problem areas.

In order to define and examine these problem areas, two studies were undertaken by the NASA in cooperation with the FAA. The first of these studies conducted by NASA Flight Research Center involved a number of flights of a supersonic military aircraft (North American A5A) into and out of the Los Angeles terminal area under direction of Air Traffic Control to examine the compatibility of mixed supersonic and subsonic traffic. A second and more extensive study (ref. 9) is currently underway and involves an SST simulator at the Langley Research Center (LRC) and the air traffic control (ATC) simulator at the National Aviation Facilities Experimental Center (NAFEC) of the FAA in Atlantic City, New Jersey (see figure 16). The SST simulator at LRC is essentially a Douglas DC-8 cockpit with current jet transport equipment and with instruments modified where needed to conform to scale or range requirements for SST performance. The SST simulator is being flown in the studies by experienced airline crews. Simulated radio communications (voice) and position data are transmitted to NAFEC by land lines. At NAFEC, the ATC simulation consists of a simulated air traffic control center operated by about 30 experienced air traffic controllers and simulated air traffic sample.

The program is designed to study arrival and departure operations of the SST to and from the Kennedy International Airport for both oversea and domestic operations.

Because of the probable handling qualities problem in the approach configuration as introduced in the section on Stability and Control (see ref. 5), NASA has undertaken to study the handling qualities of several typical SST configurations. Feasibility studies performed by The Boeing Company, under contract to NASA, have indicated use of the Boeing 367-80 test airplane, which is equipped with boundary-layer control and thrust modulation, would be suitable for such a simulation program. Flight tests are scheduled to start in 1965 at the Langley Research Center.

Engine noise of the current large turbojet transports is considered to be of an objectionable level not only in climbout but also in the approach and landing when the aircraft are passing over populated areas and following the normal 2.5^{o}-3.0^{o} glide slope. Recent studies of the SST have shown that the engine noise of the SST will be of a comparable level. An operational technique for alleviating the noise in the approach would be to make the approaches at steeper than normal glide slope in order to increase the distance between the noise source and the observer. A flight program was undertaken to determine the various characteristics of aircraft that may limit the steepness of the approach. Tests have thus far been completed on C-47, T-33, and TF-102 aircraft under simulated instrument conditions (pilot under a hood). Tests using a DC-8F are to be made in the near future.

The maximum operational glide slope was found to be about 6° for both the C-47 and T-33. For the TF-102, the maximum glide slope was at least 7°, the limit of the tests. The limiting factors were found to be the inability to increase drag without approaching the propeller windmilling condition on the C-47 and the inability to reduce thrust on the T-33 without encountering engine flame-out or appreciably increasing the engine response time for wave-off. While the pilots could fly the steeper approaches with only a little less precision than the normal 3° slope, the pilot workload was increased.

The introduction of the supersonic transport may be expected to intensify some of the noise problems associated with current jet aircraft in addition to introduction of new problems associated with the sonic boom. Noise in the community due to the supersonic transport is a function of the type of power plant used and the manner in which it is operated, as well as the configuration of the aircraft in which it is installed. The manner in which the airport noise situation is affected by operational procedures is shown in figure 17(a) for a current intercontinental fan-powered, subsonic jet and for some proposed supersonic transports. 110 PNdb noise-level contours are indicated for both aircraft, with the origin representing the start of take-off roll. Because of the greater thrust requirements for the SST, the noise levels to the side of the runway are generally higher than those for the subsonic airplane. The take-off distance is generally shorter, however, and the altitude over a given location in the community will be generally higher for the superonic transport and as a result community noise levels may be comparable to or less than those of the current long-range aircraft. Power cutbacks during initial climbout are used for current aircraft because of noise considerations, and should be an acceptable procedure for the supersonic transport operations.

The noise during landing approach involves the geometry of the engine installation and the aircraft characteristics in landing approach. For current subsonic airplanes it is generally agreed that the compressor-fan noise during landing approach is more objectionable than the exhaust noise. Figure 17(b) shows a comparison of estimated noise levels during landing approach on a 3° glide slope for some proposed supersonic transport designs and a fan-powered subsonic transport. The extent of the shading represents the variations expected for inlet suppression of the compressor noise. It is apparent that some compressor noise suppression will be required to bring the landing noise levels below those of the current subsonic transport. Current research to minimize the compressor noise consists of reduction of the noise at the source involving studies of rotor-stator interaction and variations in inlet geometry, including choking the inlet. Finally, the possibility of using a steeper approach as a means of increasing the distance between the source and the observer has been discussed previously.

The noise-induced structural-response problems of the supersonic transport are important from the standpoint of maintaining acceptable cabin noise levels and minimizing sonic fatigue. The boundary-layer noise loading will exist for nearly the entire duration of the flight. The noise from the engines, in contrast to boundary-layer noise, is believed to be significant for only a short period during each mission. Sonic fatigue will only be a problem on the structure in the vicinity and to the rear of the engines. The estimated engine noise spectra peak at lower frequencies and reach higher sound pressure levels than the flow noise spectra (ref. 10). Although the acoustic loads are more severe than those for current aircraft, the design of structures to withstand these loads is not a new problem since similar environments have been encountered in current operational vehicles. It is believed that engine noise structural response experience to data is directly applicable; however, the boundary-layer noise problem has not been satisfactorily defined, particularly for long-term exposures at elevated temperatures. Both the flow noise inputs and associated structural responses are currently being studied in NASA research programs.

SONIC BOOM

The sonic boom discussed previously in connection with aircraft design requirements, constitutes an operating problem of such importance that it merits special attention. Figure 18 illustrates some of the basic concepts involved. If the shock waves from an aircraft in supersonic flight could be made visible, they would look about like those shown in the figure. These shock waves are moving at the speed of the aircraft and are observed along the ground track and several miles to each side of the track as transient pressure disturbances, illustrated by the N-wave shape in the figure. This pressure signature has associated with it a Δp which is a measure of the intensity, and a λ which is a measure of the wave length, both of which depend upon the airplane geometry and its operating conditions. Of course, the sonic-boom signature does not always have this N-wave shape, since atmospheric effects can cause the peaks to be accentuated in some cases and rounded off in others.

Initial experiments on the sonic boom, measured under carefully controlled conditions, were begun by NASA in 1958 with a flight test program wherein the first sonic-boom pressure measurements at ground level were obtained from aircraft in sustained supersonic flight. The NASA has performed numerous theoretical and windtunnel studies and has worked closely with the U. S. Air Force and the Federal Aviation Agency in carrying out flight test programs (ref. 11). This research effort had the dual objective of determining the magnitude of overpressure produced on the ground and to attempt to establish the tolerable level of sonic boom exposures as determined by community response.

The range of exposures currently experienced during routine military operations is shown in figure 19, where the sonic-boom intensity is indicated as a function of airplane altitude for fighter and bomber aircraft in steady-level flight and in maneuvers. Also shown are the estimated intensities for various proposed supersonic transports. It can be seen that during routine military maneuvers, exposures approaching 6 lbs/sq ft have been experienced in some communities. The proposed supersonic transports are designed on the basis of 2 lbs/sq ft during transonic acceleration and 1.5 lbs/sq ft during cruise. This requirement is based on very limited window breakage experience indicating that the threshold of possible damage is somewhat greater than 2 lbs/sq ft. (See ref. 12) As pointed out in the NASA SCAT feasibility studies, reduction of design overpressure from these values specified will result in severe range-payload penalties unless accomplished by basic configuration improvements as previously discussed in the section on Performance Aerodynamics (figure 6). It would be well to point out that even though the estimated intensities for the proposed supersonic transports are well within the range of current exposures, the SST signatures will have longer wave lengths. The importance of these longer wave lengths will have to be evaluated along with the wave form effects discussed in the succeeding paragraphs.

The community response aspect of the sonic-boom problem is of prime importance and is the most difficult to evaluate because of its complex nature. For instance, people observe not only the acoustic stimulus, but also are aware of sonic-boom induced vibrations in building components and furnishings. Their reactions are a function not only of their own observations, but also the environment in which they live.

Important findings of the recent FAA-Oklahoma City tests relate to atmospheric effects on overpressure values and wave form and to building response. Statistical results indicate that the spread in peak pressure presumably due to turbulence and other atmospheric anomalies can be such that about 15 percent of the time, pressures may exceed mean values by about 30 percent of mean pressure and 1 percent of the time the pressures may exceed the mean values by 80 percent of the mean pressure. One of the characteristic results of these tests is that the median values of peak pressure are generally lower than the calculated nominal values. The significance of the peak pressure is closely interrelated to the pressure signature or wave form.

In figure 20 are presented tracings of the measured wave forms from an accurately-calibrated and oriented array of matched microphones at separation distances of 200 feet. The wave forms are presented in the proper time sequence and are directly comparable in amplitude. These data illustrate the variations of wave forms obtained for given flights for which the aircraft operating conditions are essentially constant. It can be seen that a wide variation in wave shape occurred even over a distance on the ground of a few hundred feet, and that variations were different for the two flights. The peak overpressures value rises and falls as a function of distance in much the same manner as the surface level of the ocean in the presence of waves. Although not shown in the figure, significant differences in wave shape were measured at separation distances as small as 50 feet. Such variations as these, which have also been observed on other occasions (see ref. 11), are believed to result from temperature and velocity anomalies in the atmosphere, particularly the lower layers. Invariably the highest measured pressures are associated with highly-peaked wave forms, and conversely the lowest measured values are associated with rounded-off wave forms. It is significant to note, however, that the impulse function varies over a much narrower range of values than does the corresponding peak pressure, and can exceed the mean value by 30 percent for about 1 percent of the time.

The overpressures of the magnitude encountered in the Oklahoma City tests were not of sufficient magnitude to cause primary structural damage to well constructed and well maintained buildings (see ref. 13). Also, no damage occurred to any furnishings, appliances, or objects in four test houses during the Oklahoma City tests (ref.13).

SUMMARY REMARKS

In summary, this paper has reviewed a number of research areas in support of the National Supersonic Transport Program and has indicated where improvements in the state of art appear attainable. In the area of performance aerodynamics theoretical methods for calculating and minimizing wave drag, drag-due-to-lift and sonic boom effects have been programmed for use on high speed digital computers. These methods and programs provide powerful tools with which it has been possible to devise advanced aerodynamic configurations which exhibit flight efficiencies considerably higher than those previously demonstrated.

In the propulsion area mission and engine cycle studies have demonstrated the importance of careful airframe and propulsion system integration and matching. There are large benefits to be gained by improved component efficiency in such areas as increased turbine inlet temperature, nozzle efficiency, etc.

Stability and control research indicates that flight at supersonic speed at high altitudes presents problems in providing adequate damping of the dynamic stability modes and probably will require three axis damping augmentation. High values of yaw-to-roll inertia ratio characteristic of the slender fuselages and mass distribution of the SST lead to objectionable lateral-directional handling qualities. For fixed highly swept arrow wings, the possibility of undesirable excursions in angle-of-attack (pitch-up) can be minimized by utilization of tailored wing leading-edge devices. Likewise for variable sweep configurations proper location of the horizontal tail in combination with wing leading devices provides a means to minimize the problem.

With regard to structures and materials it has been determined that design to accommodate thermal stresses will incur penalties of a few percent in structural weight. Research on structural concepts indicates that the lightest structures can be obtained with skin-stringer construction utilizing titanium alloys. Long time exposure at temperature of 550°F of titanium alloys and stainless steels exhibit no significant damage in mechanical properties. However, these tests have indicated some deterioration in the tensile strength of spot welds.

Operating problem research is underway to determine the compatibility of the SST with existing Air Traffic Control Systems. These studies have used both traffic control penetrations by a supersonic aircraft and SST ground based simulators flown by experienced airline crews in FAA controlled simulated air traffic samples. Studies of the engine noise during take off indicate that the levels at the 3-mile point will be comparable to or less than the subsonic jets. For landing some compressor noise supression will be required on the SST to bring the noise levels below those of the current subsonic jets.

Sonic boom research has indicated that large penalties in aircraft gross weight will occur unless the SST configurations are specially designed to minimize this effect. Research conducted in the Oklahoma City sonic boom program indicates the overpressures were not of sufficient magnitude to cause primary structural damage to well constructed and well maintained buildings. Also, no damage occured to any furnishings, appliances, or objects in the four test houses.

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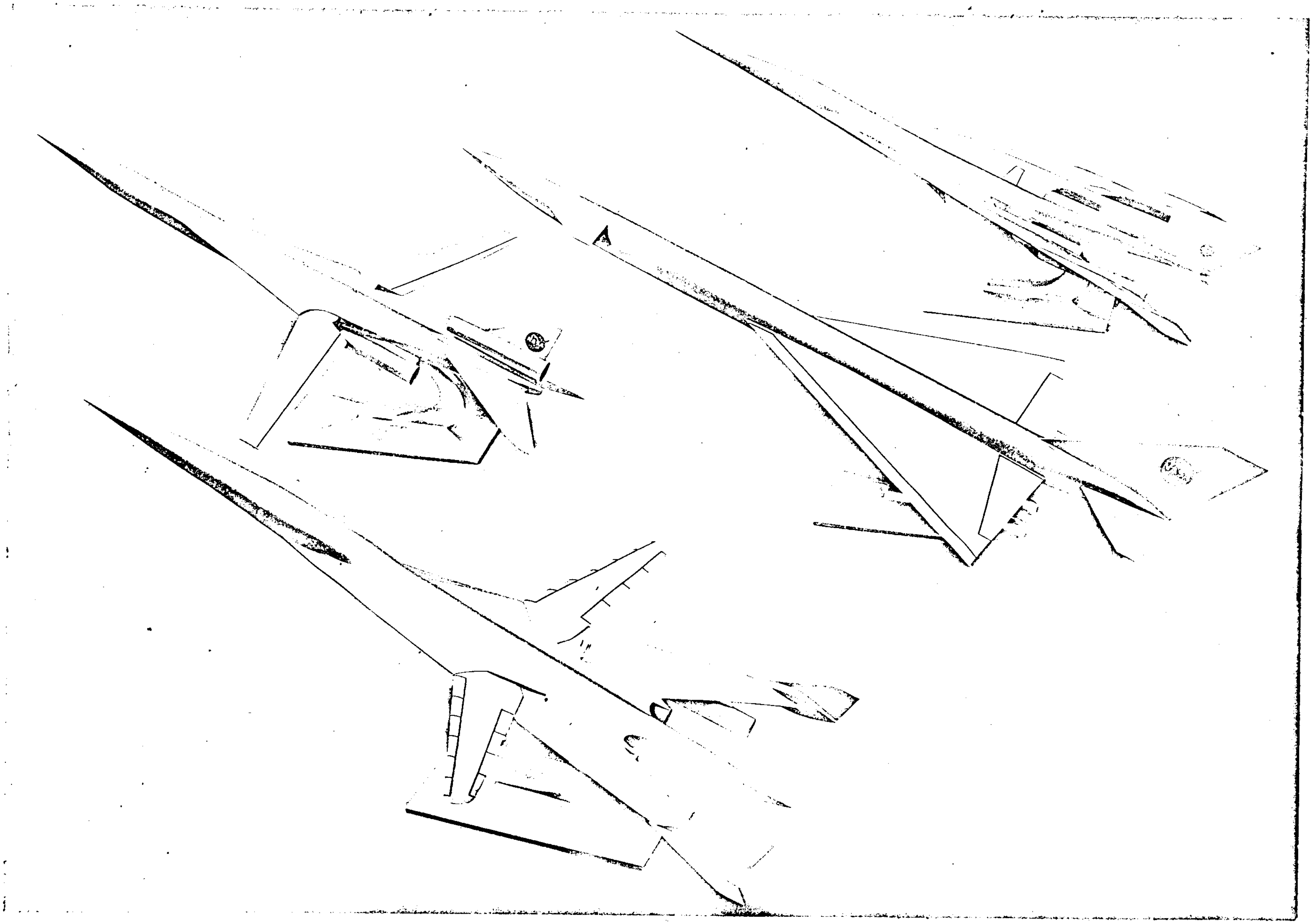


Figure 1. - SCAT feasibility study configurations.

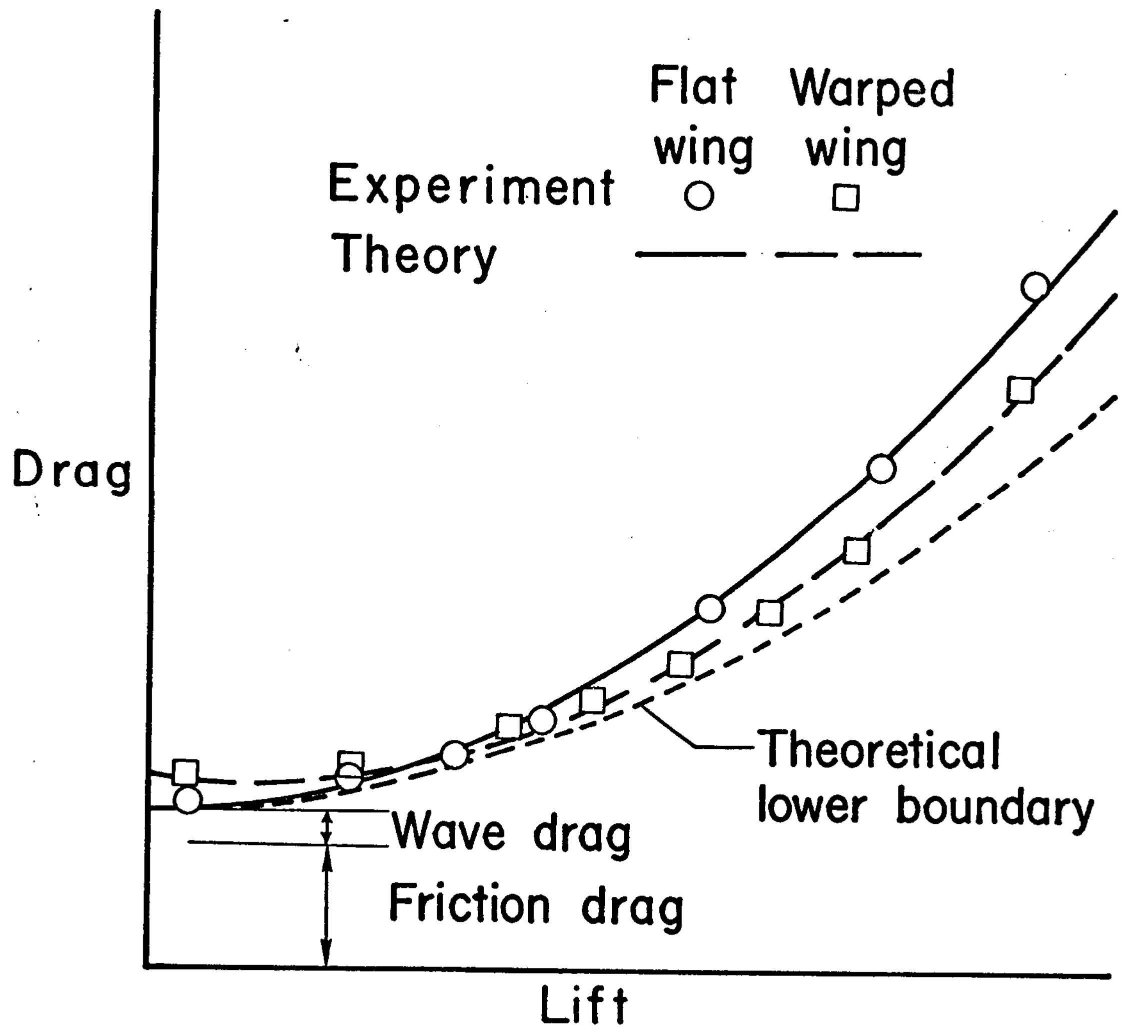


Figure 2. - Configuration drag buildup.

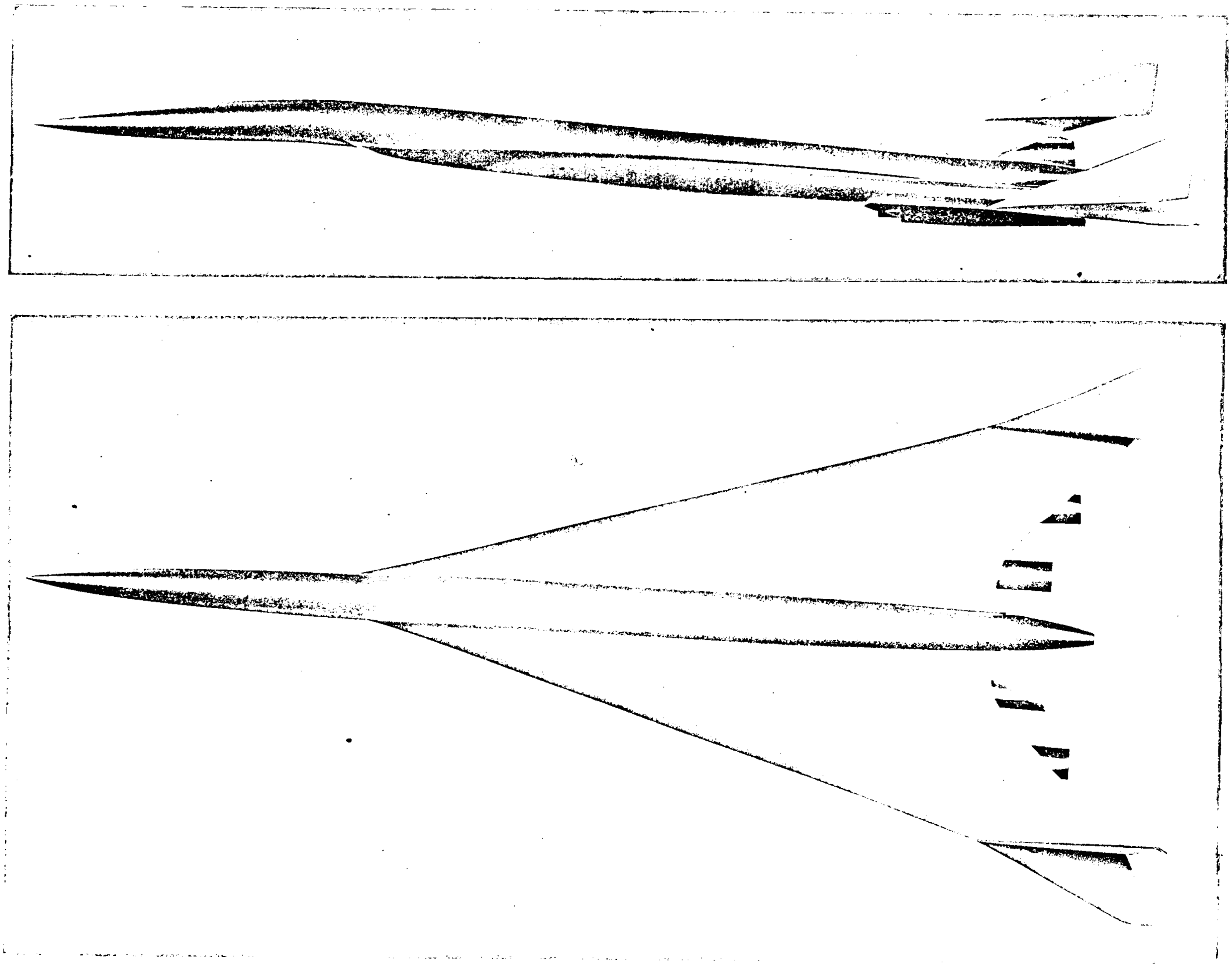
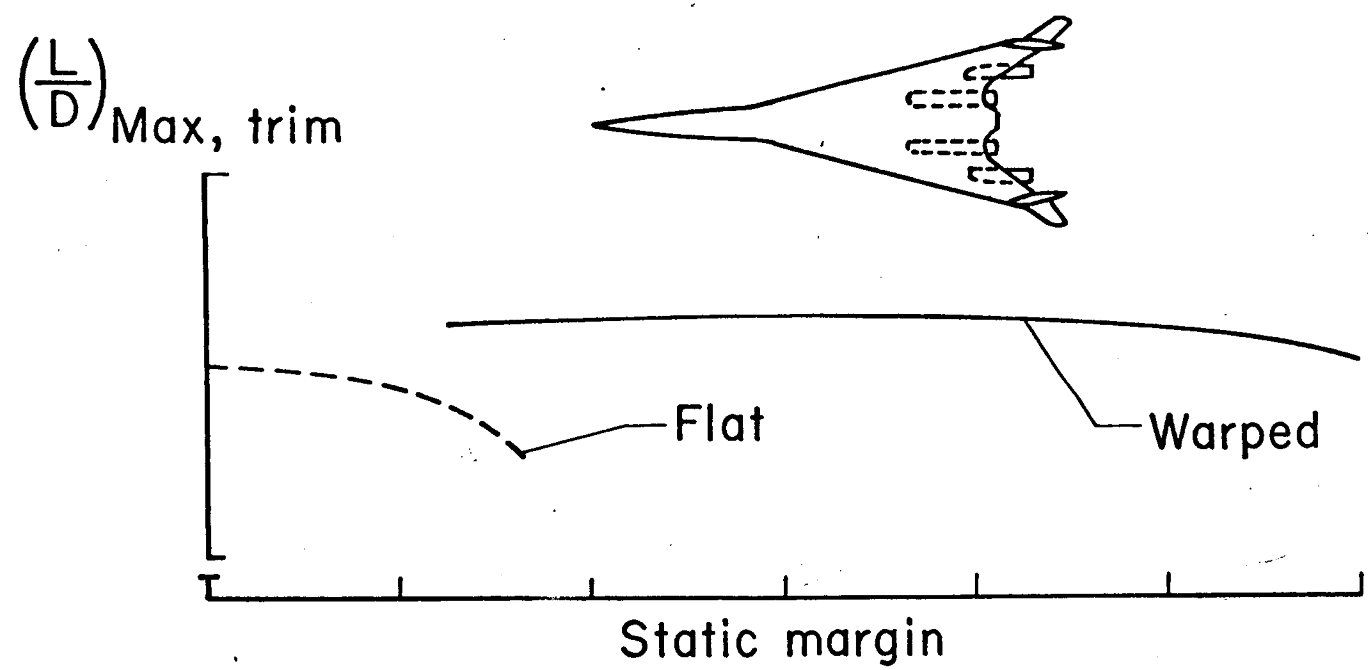
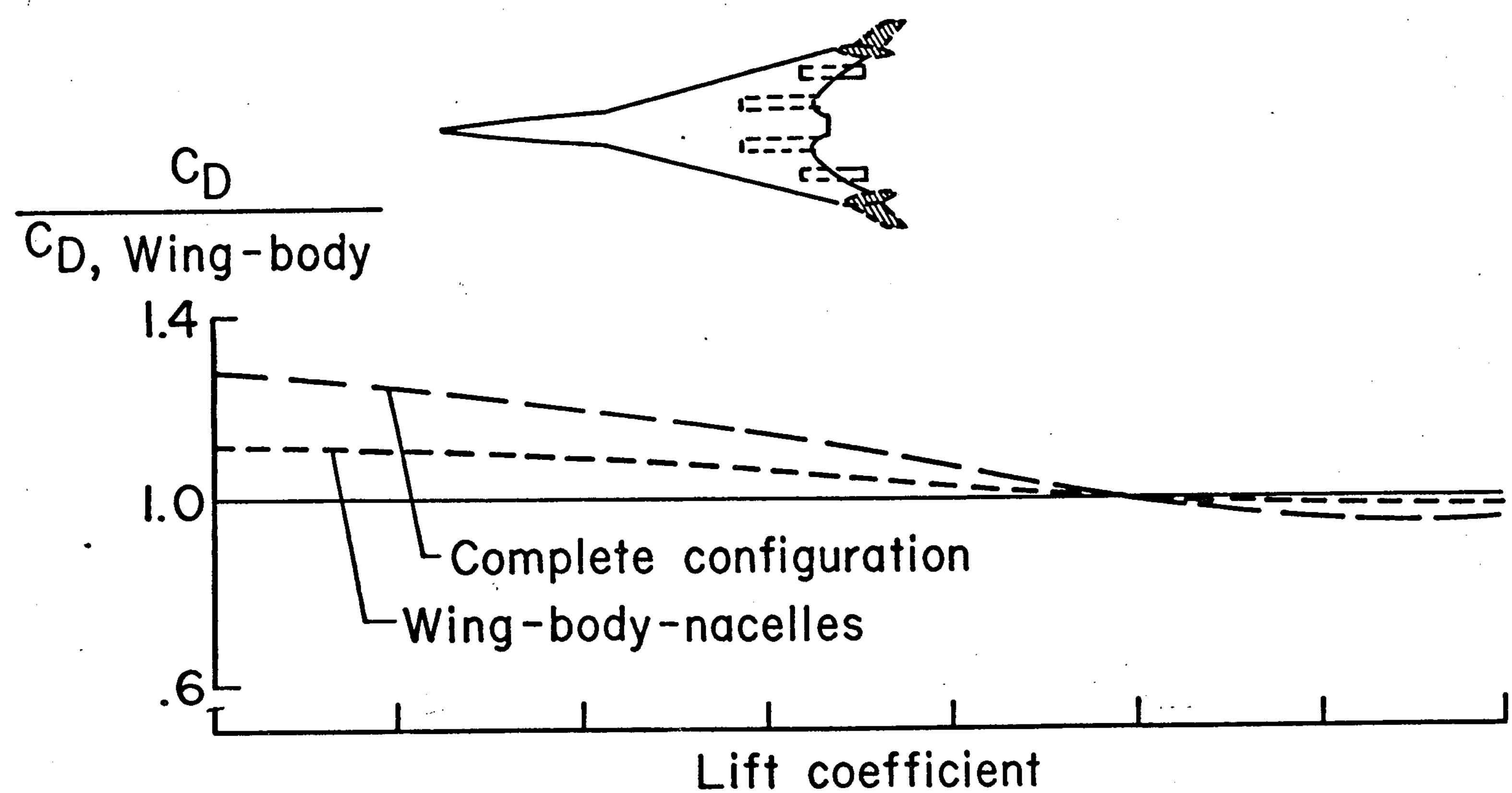


Figure 3. - Sample warped-wing SST configuration.



(a) Trim drag.

Figure 4. - Characteristics of sample warped-wing configuration.



(b) Interference drag.

Figure 4. - Concluded.

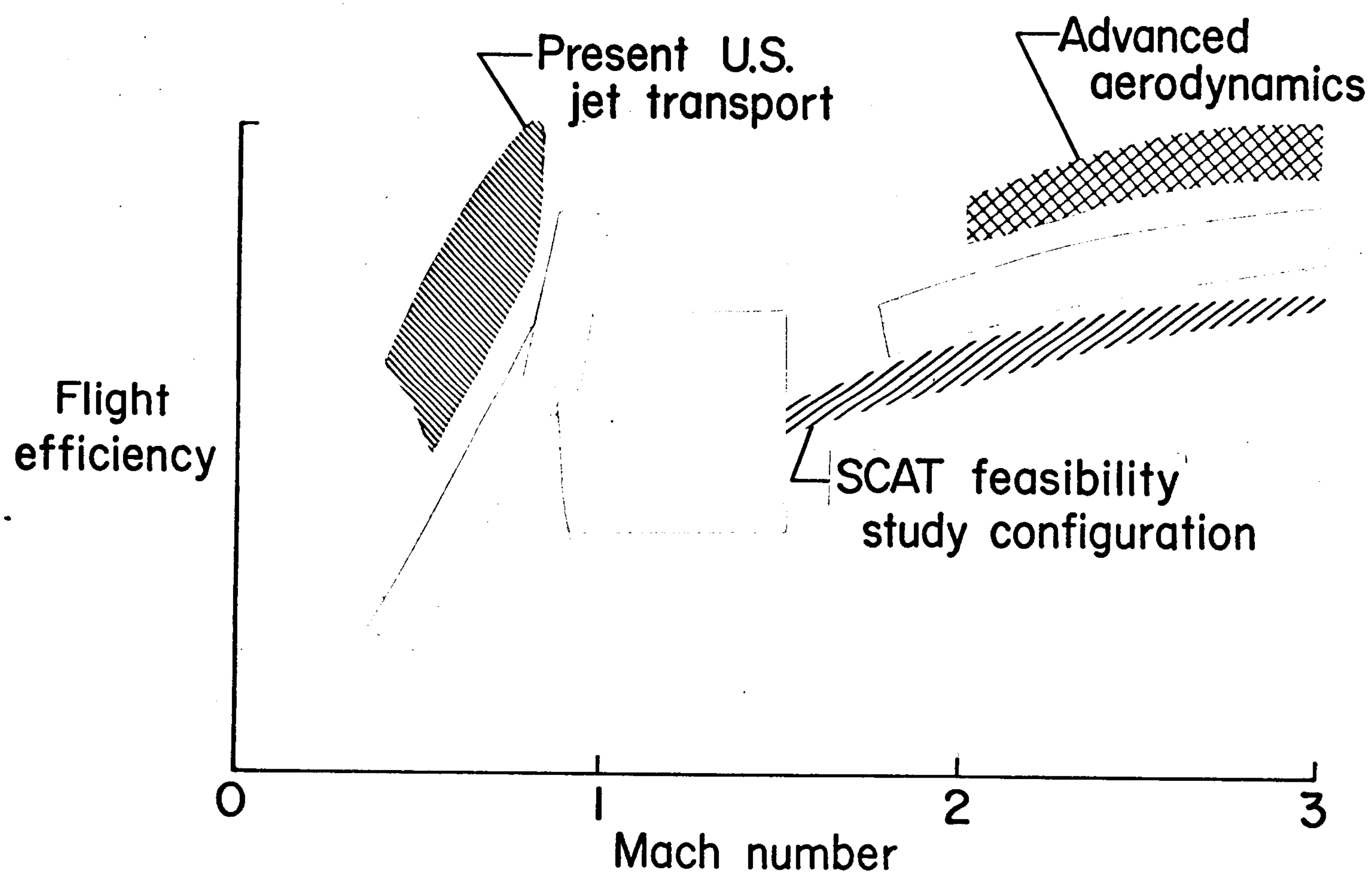


Figure 5. - Flight efficiency.

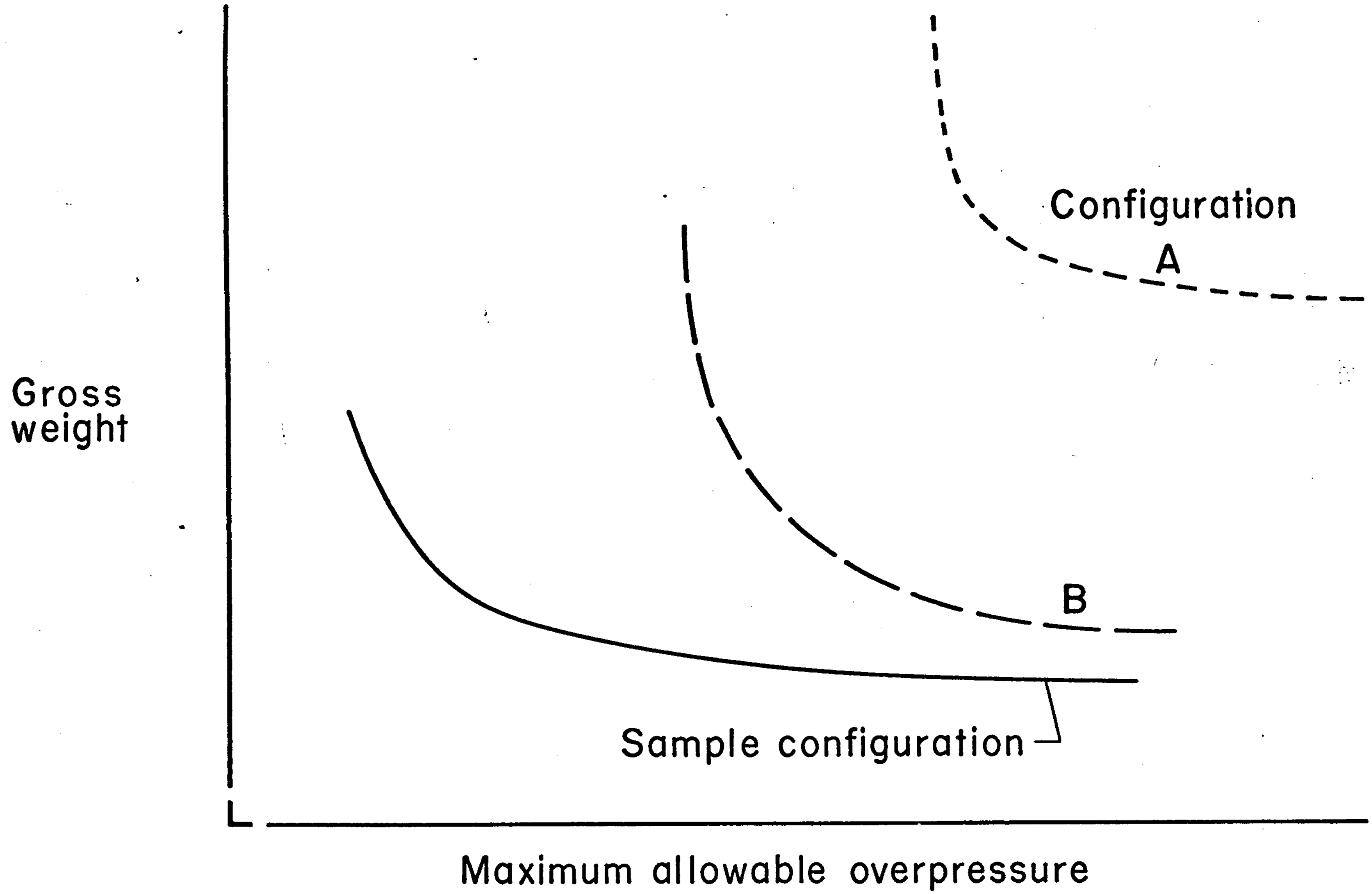


Figure 6. - Configuration variations of gross weight and overpressure.

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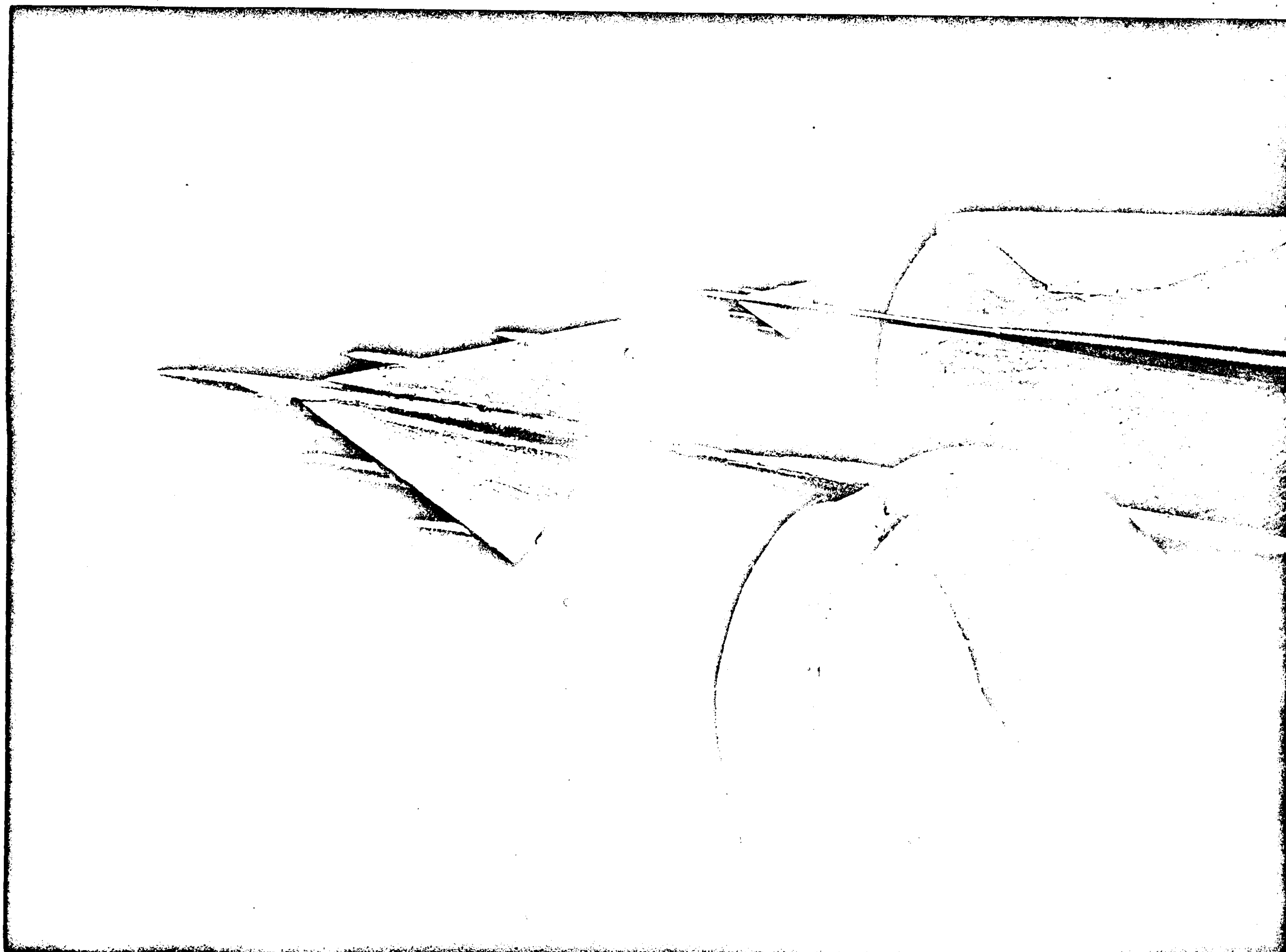


CROP

CROP

CROP

Figure 7 top part.

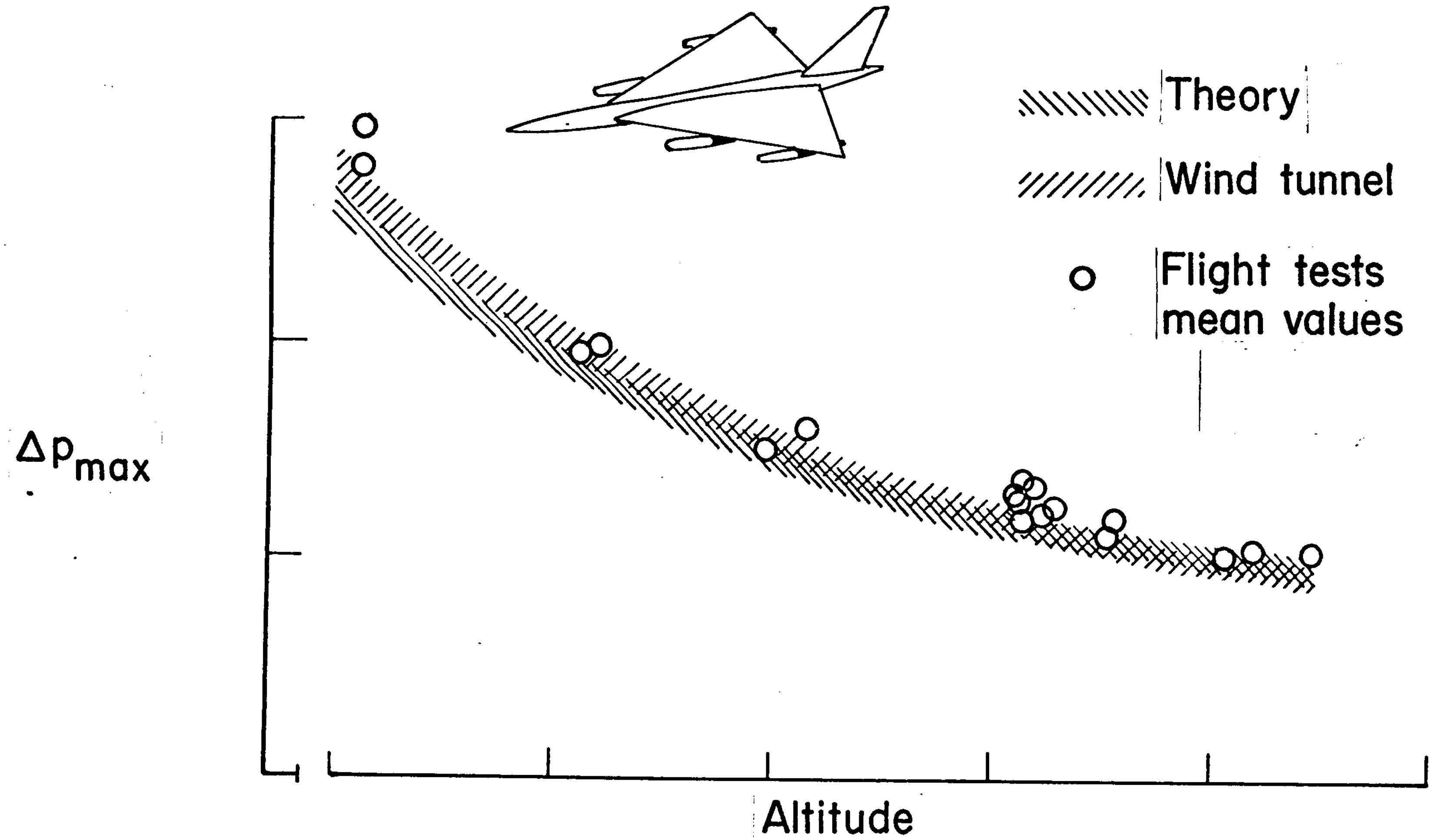


Figure 7. - Sonic boom characteristics.

LOWER/HALF
COMBINE WITH
UPPER/HALF
HALFTONE

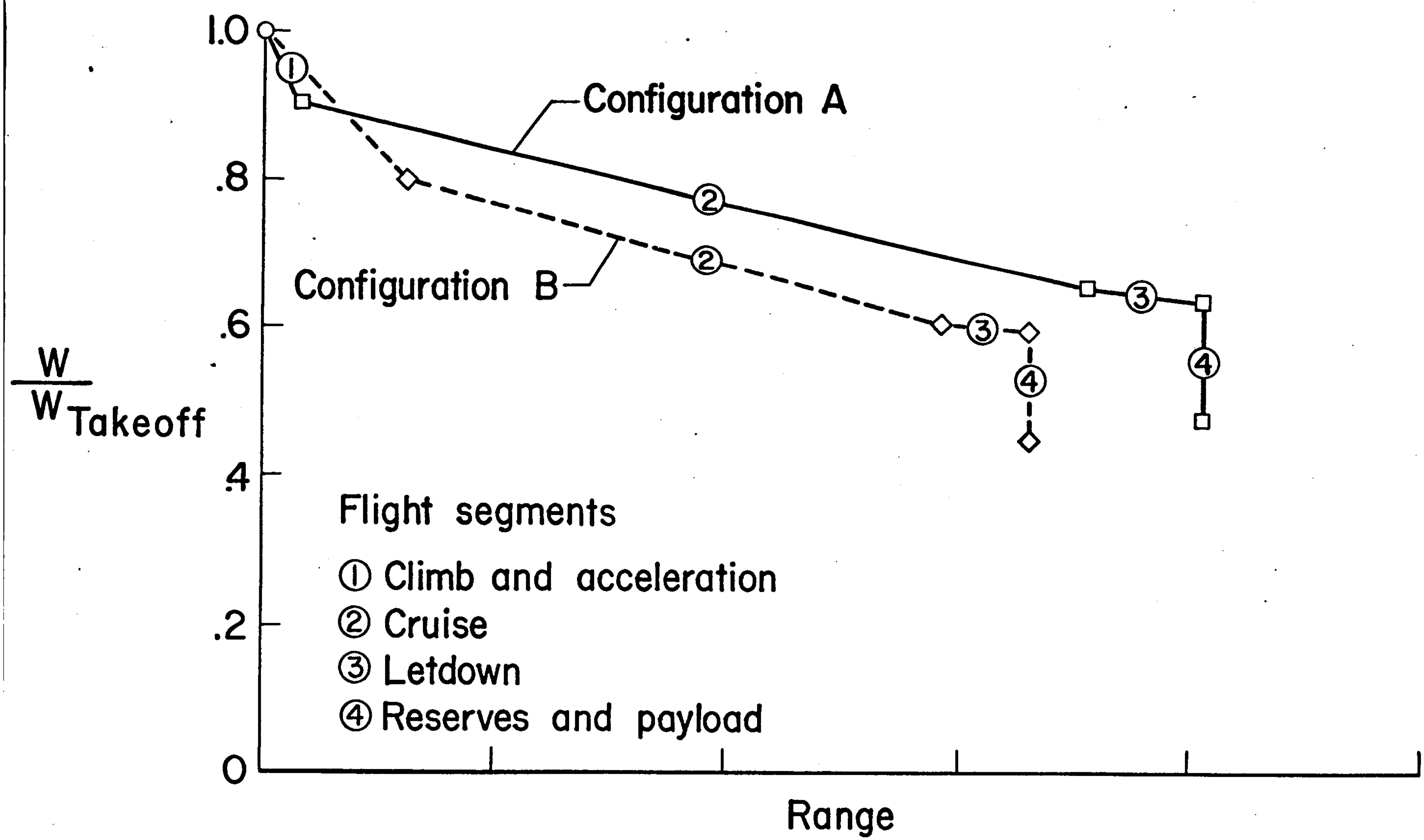


Figure 8. - Fuel usage.

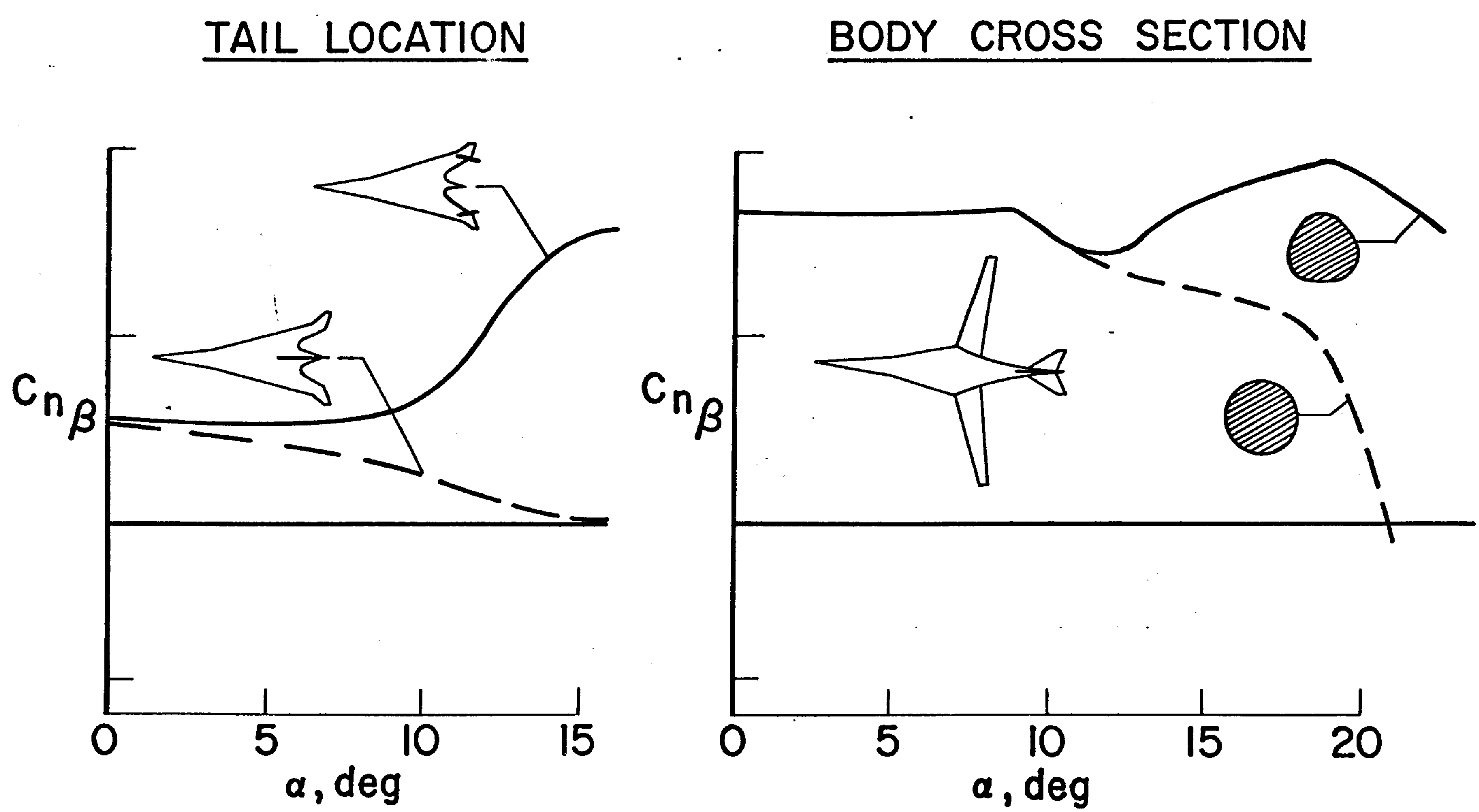


Figure 9. - Low-speed configuration effects on directional stability.

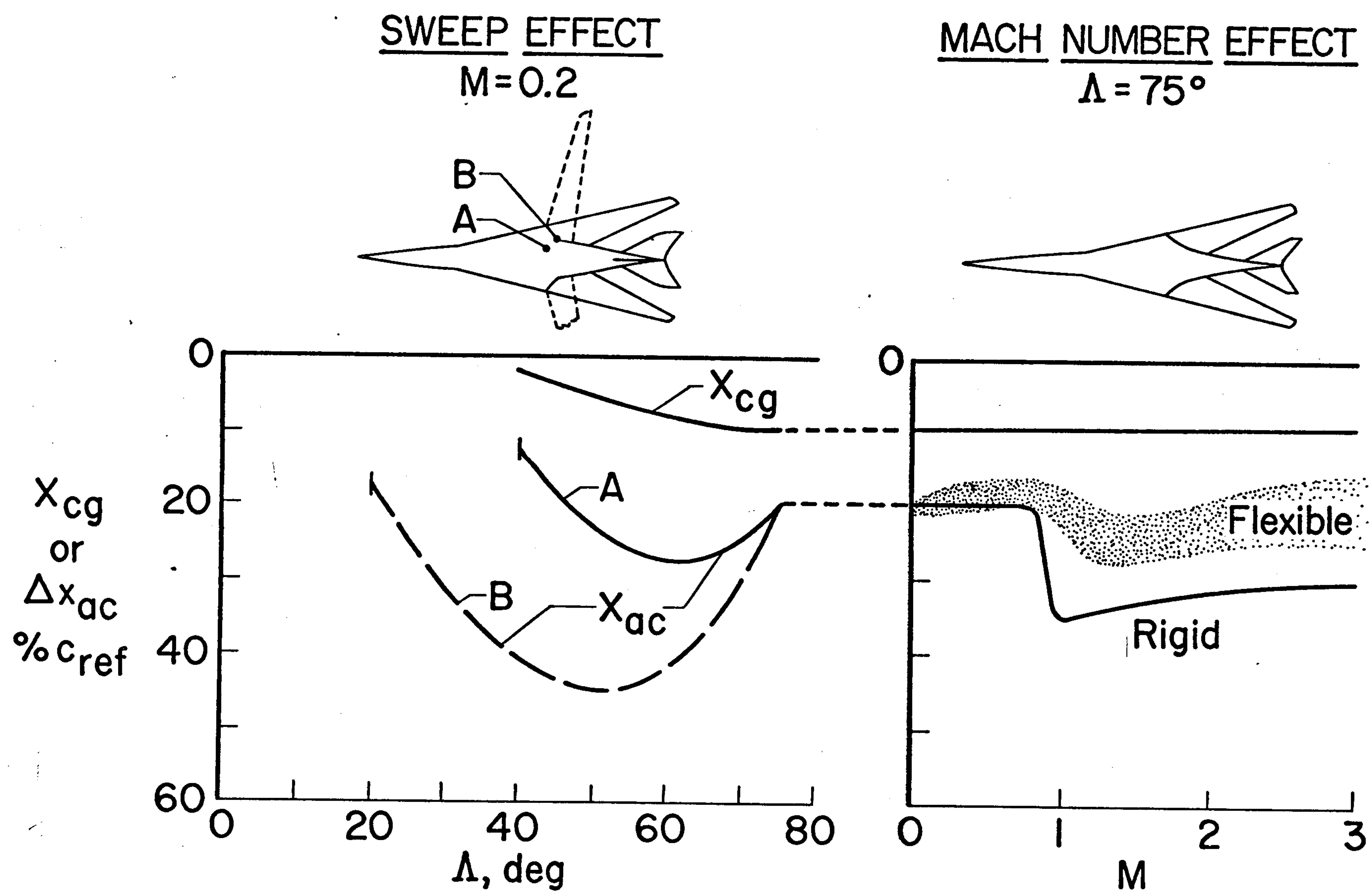


Figure 10. - Longitudinal stability considerations of variable-sweep configurations.

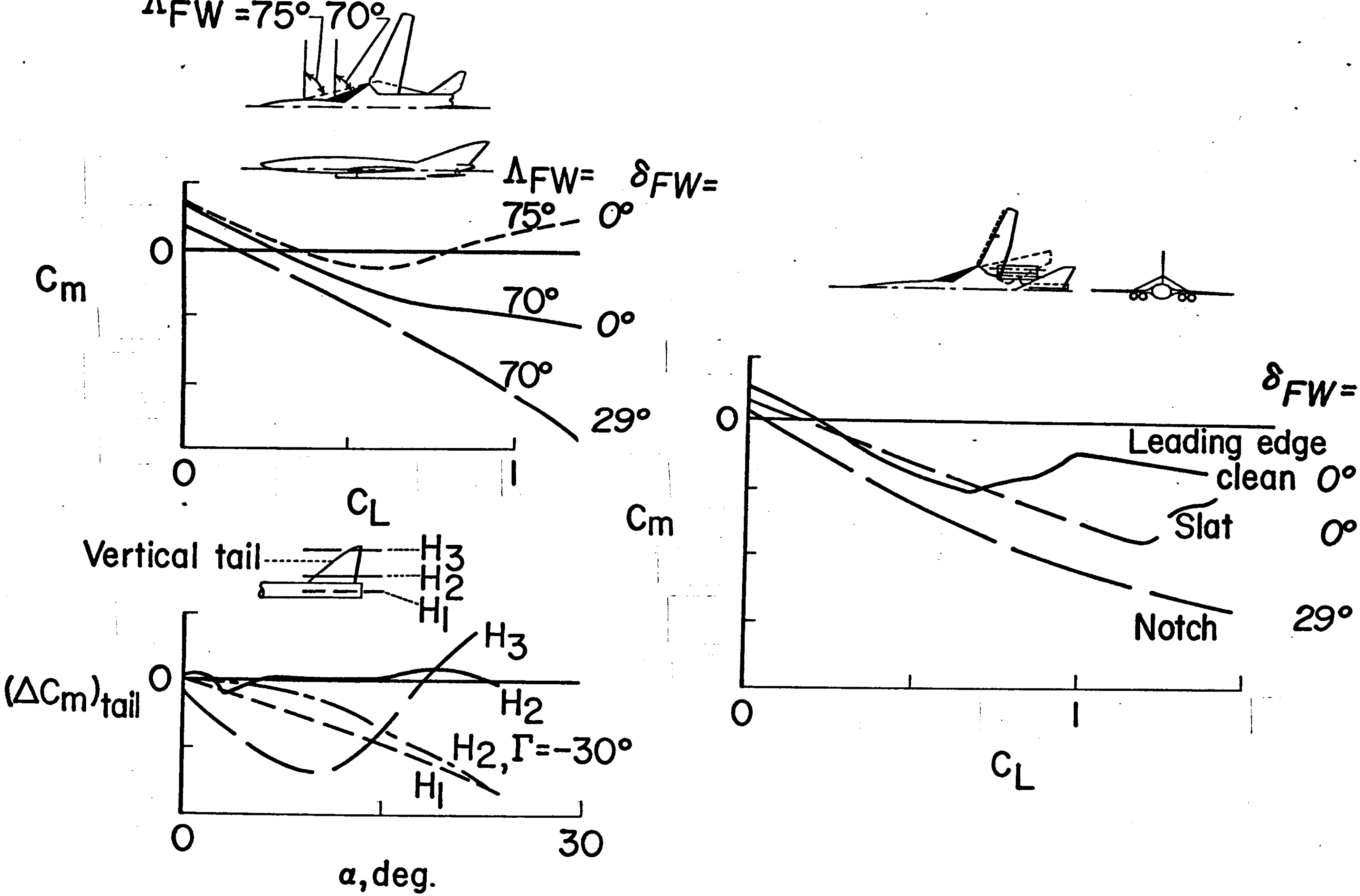


Figure 11. - Low-speed pitching-moment characteristics of variable-sweep configurations

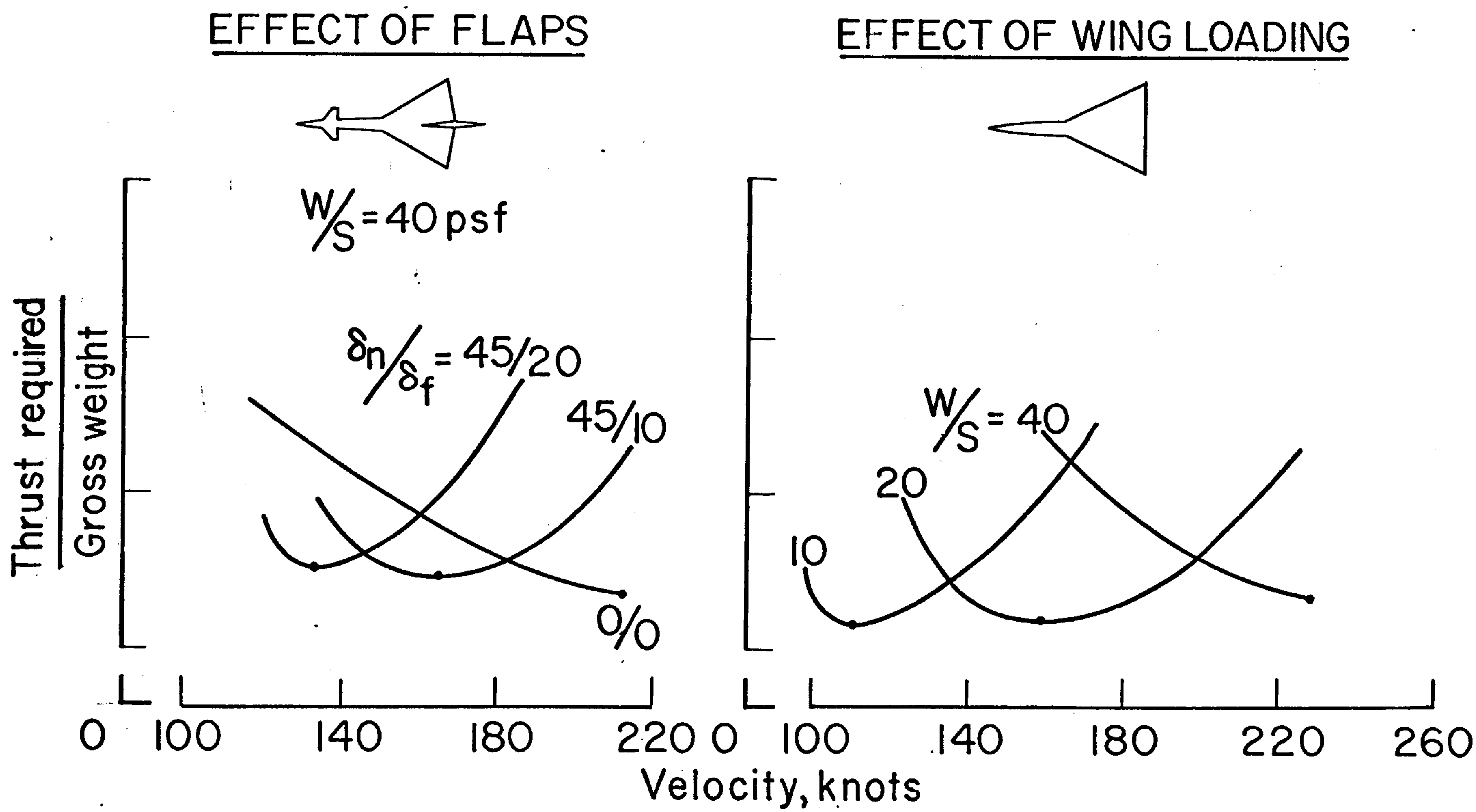


Figure 12. - Landing approach-speed stability.

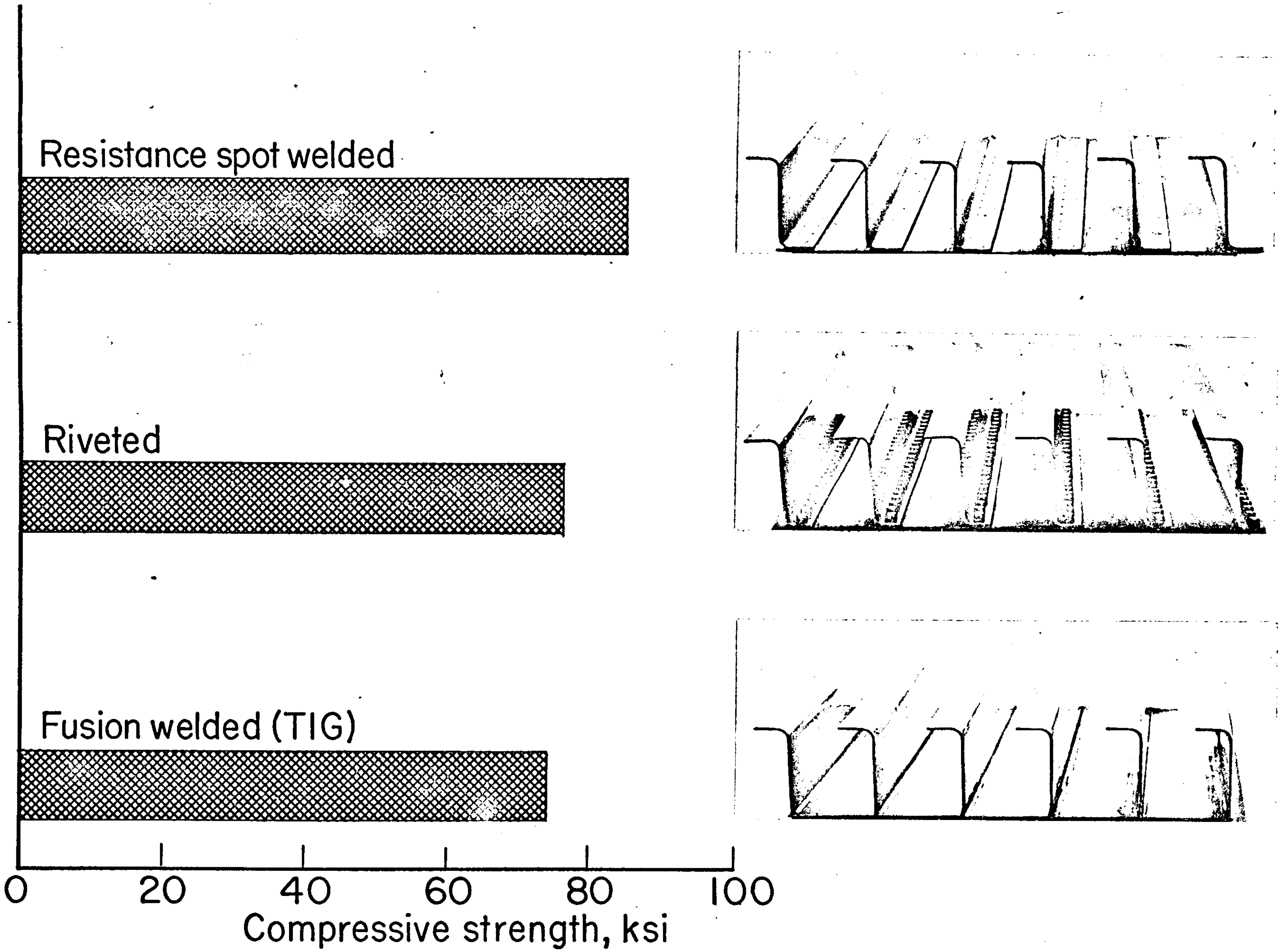


Figure 13. - Compressive strength of skin-stringer panels fabricated from Ti-8AL-1Mo-1V alloy sheet.

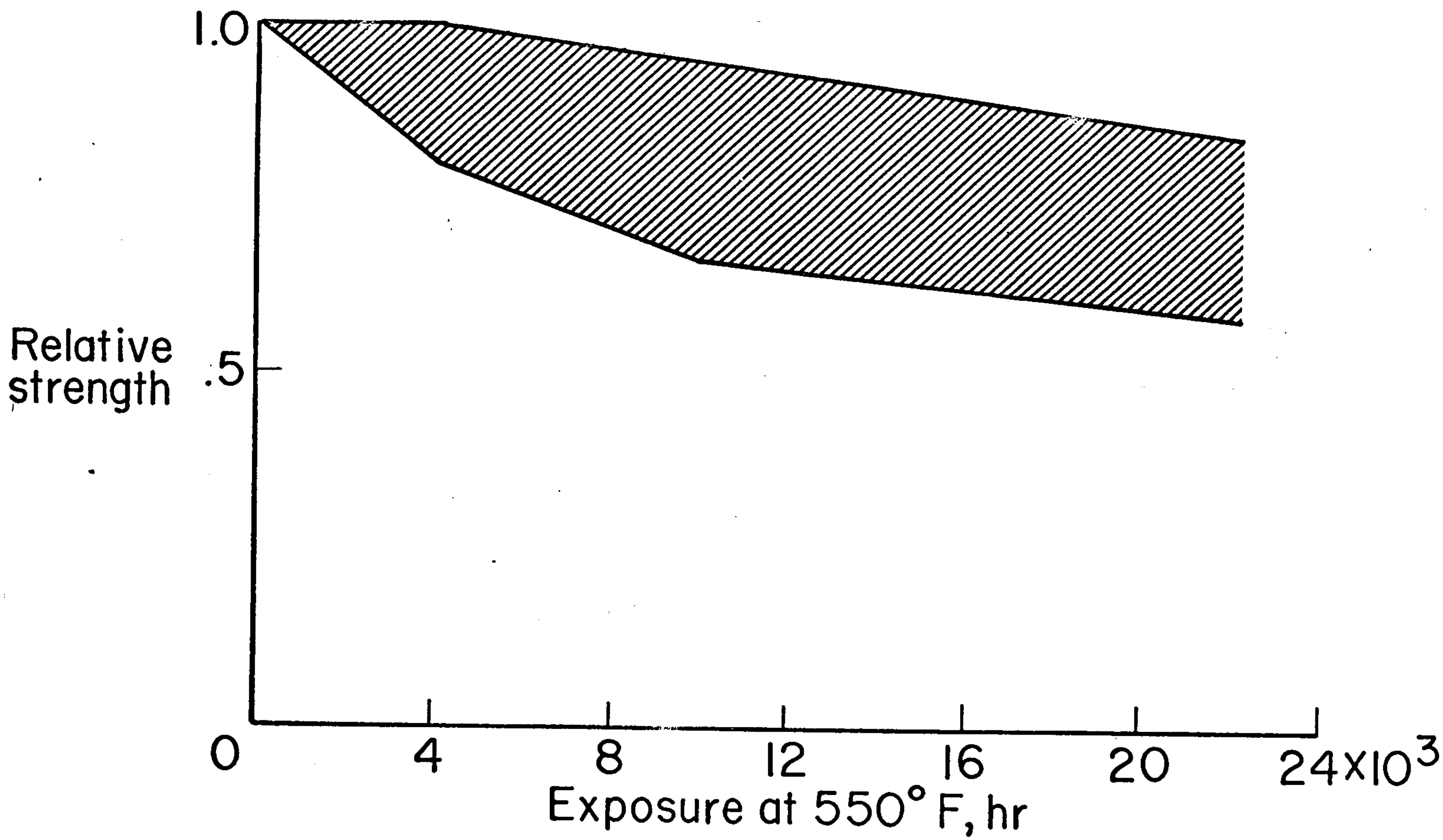


Figure 14. - Tensile strength of titanium alloy spot-welds after exposure at 550° F.

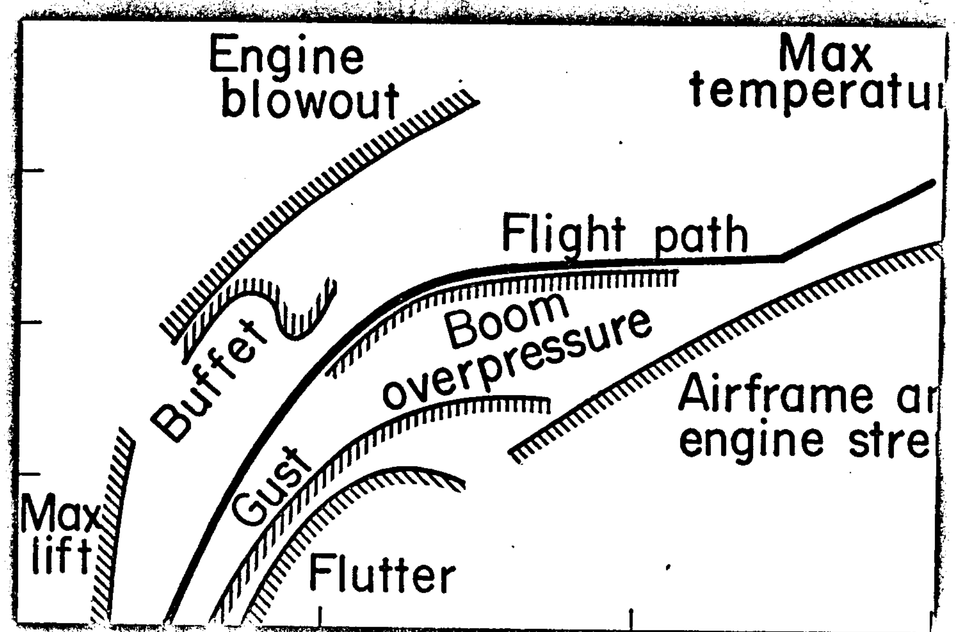
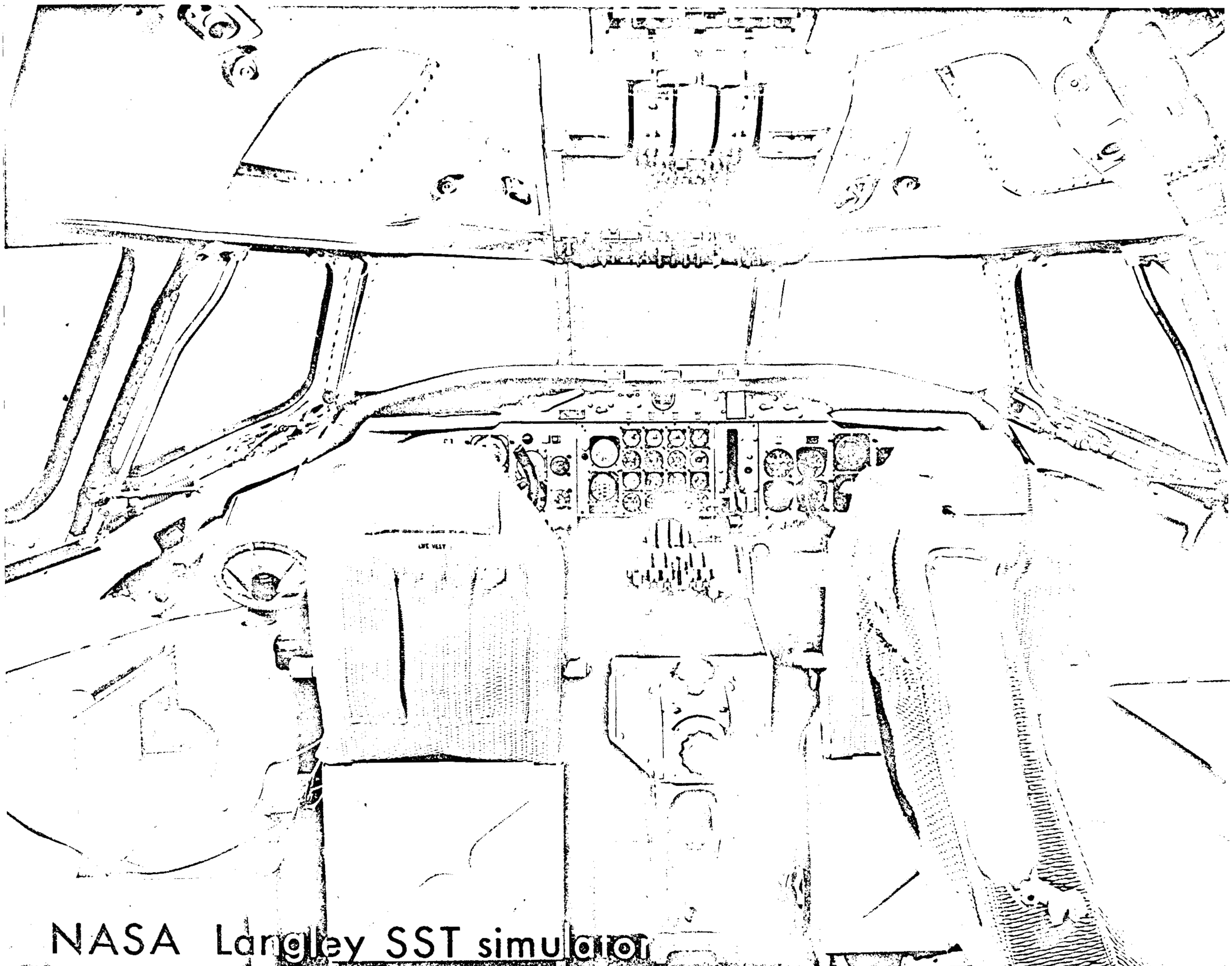
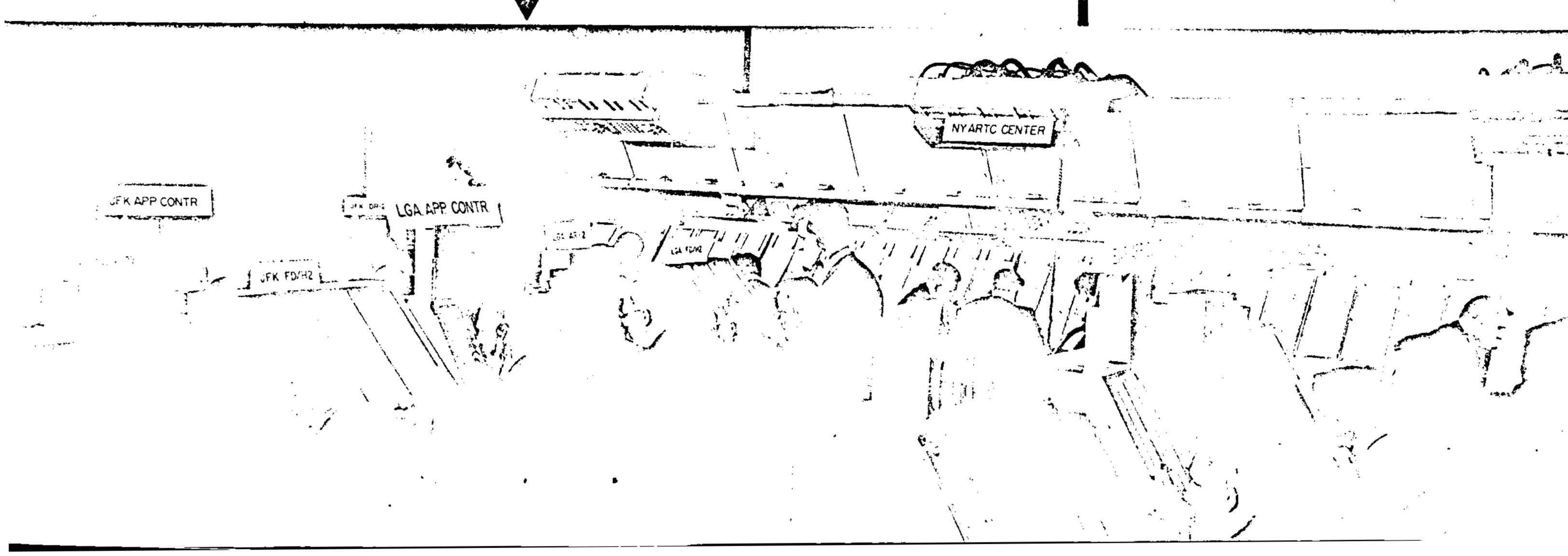


Figure 15. - Operational boundaries.



NASA Langley SST simulator



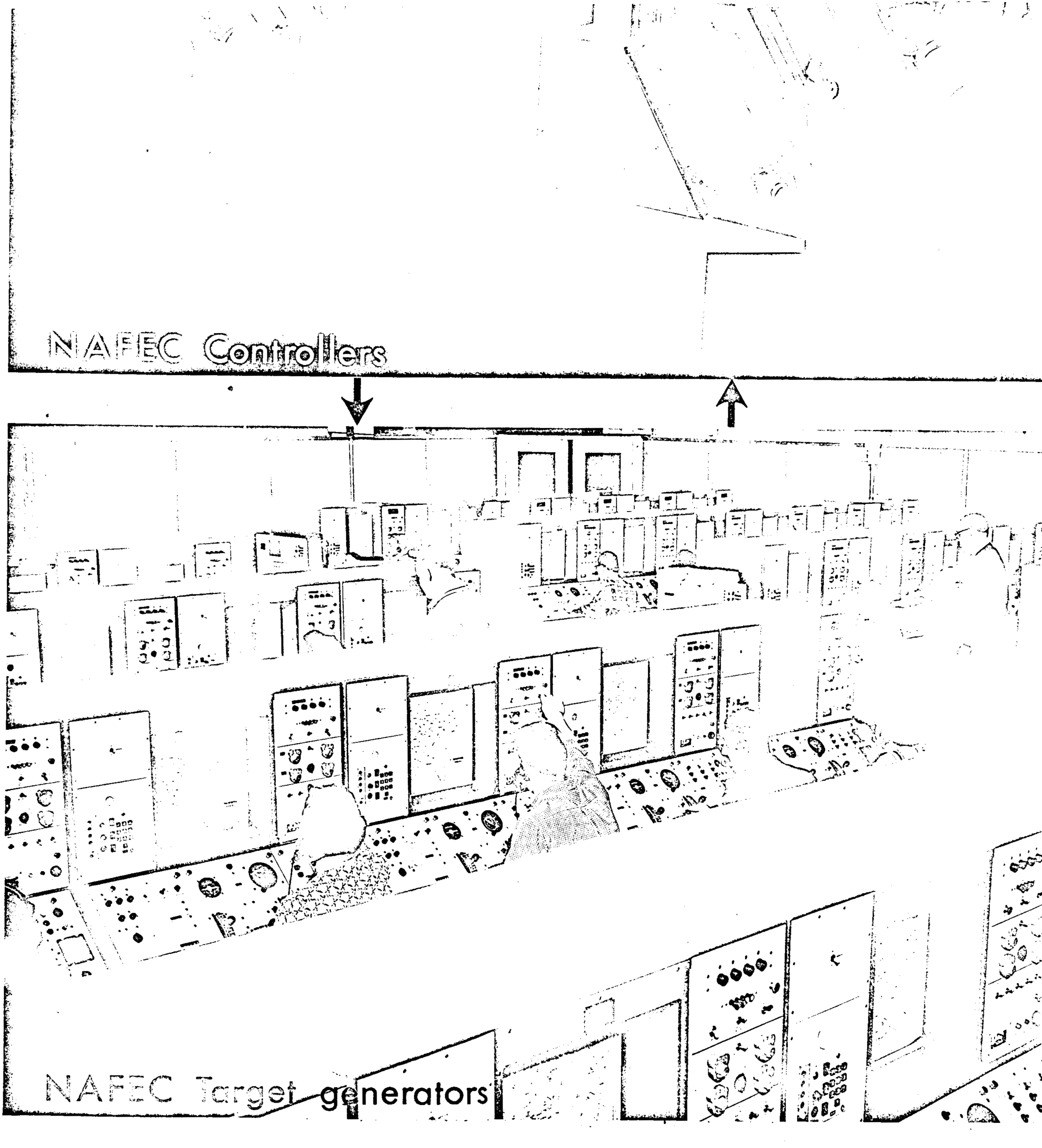
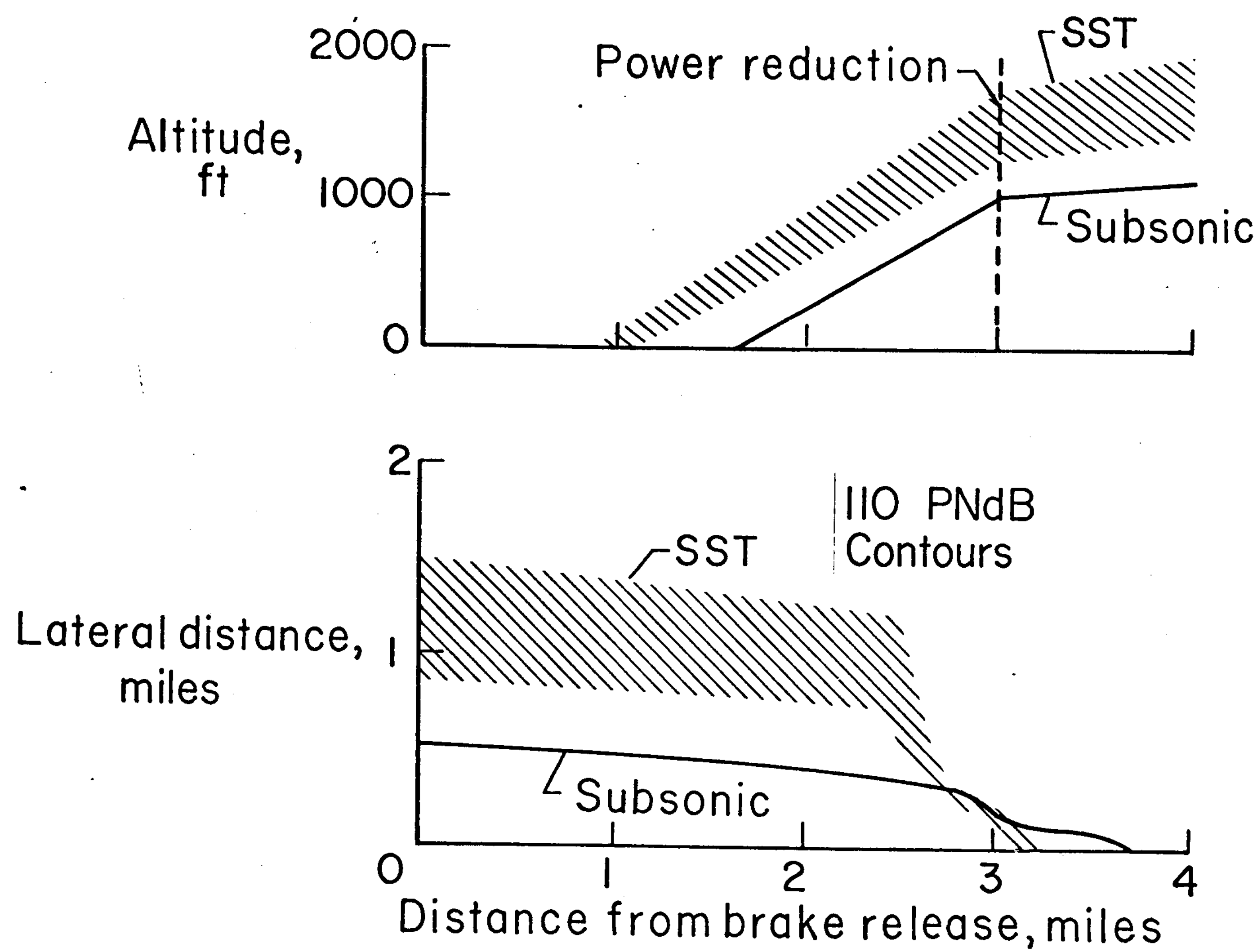
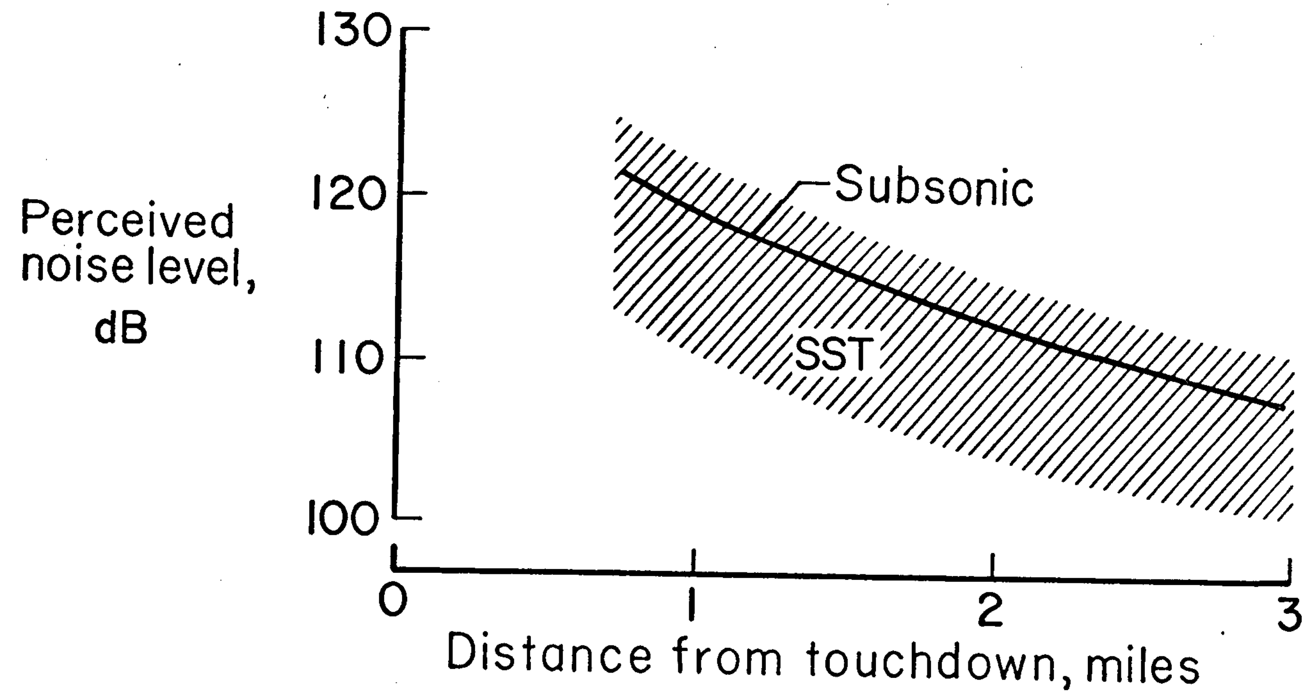


Figure 16. - NASA-Langley FAA-NAFEC land-line hook-up.



(a) Take-off - climbout.

Figure 17. - Airport noise characteristics.



(b) Landing approach.

Figure 17. - Concluded.

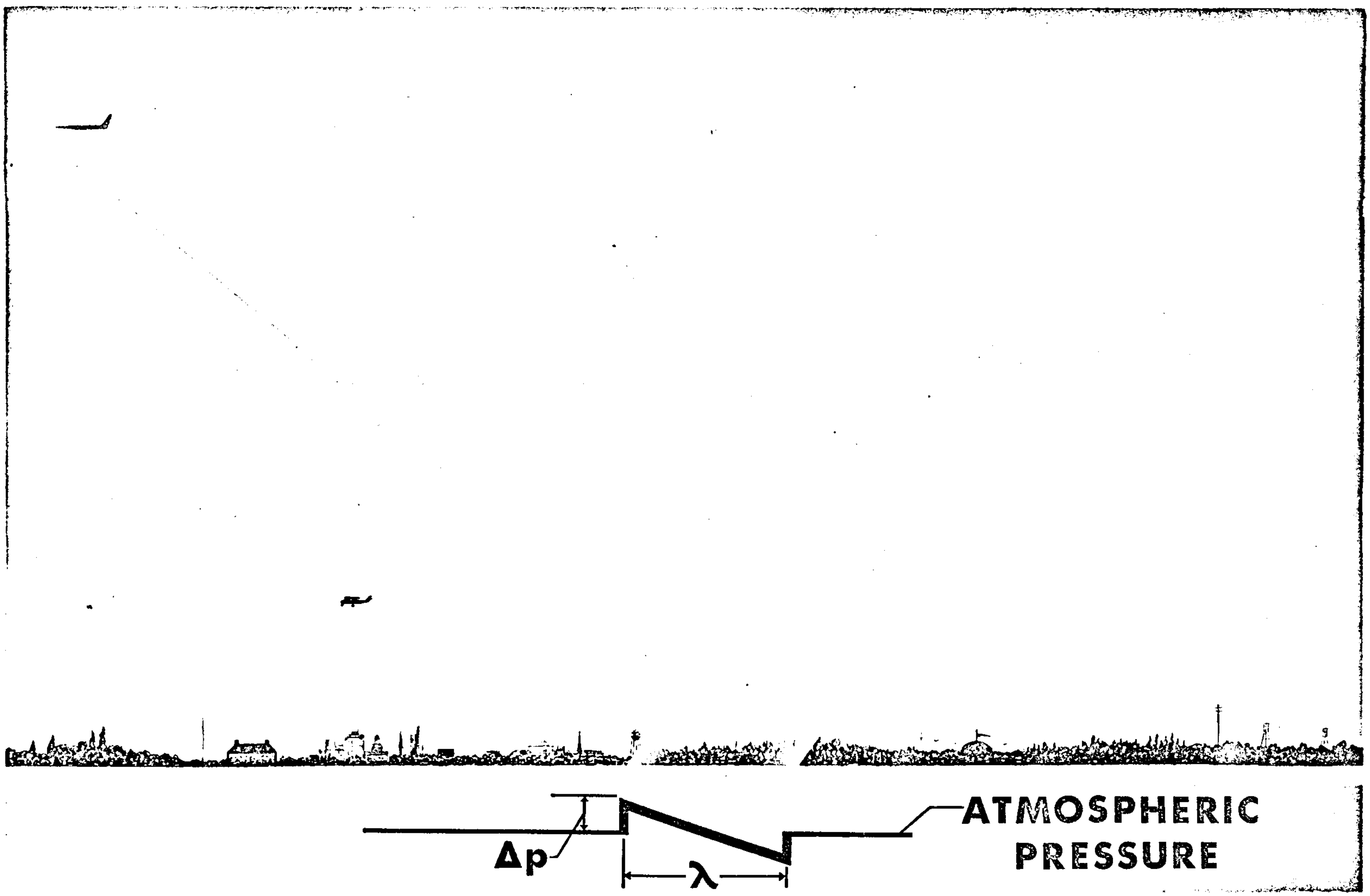


Figure 18. - Airplane shock-wave field.

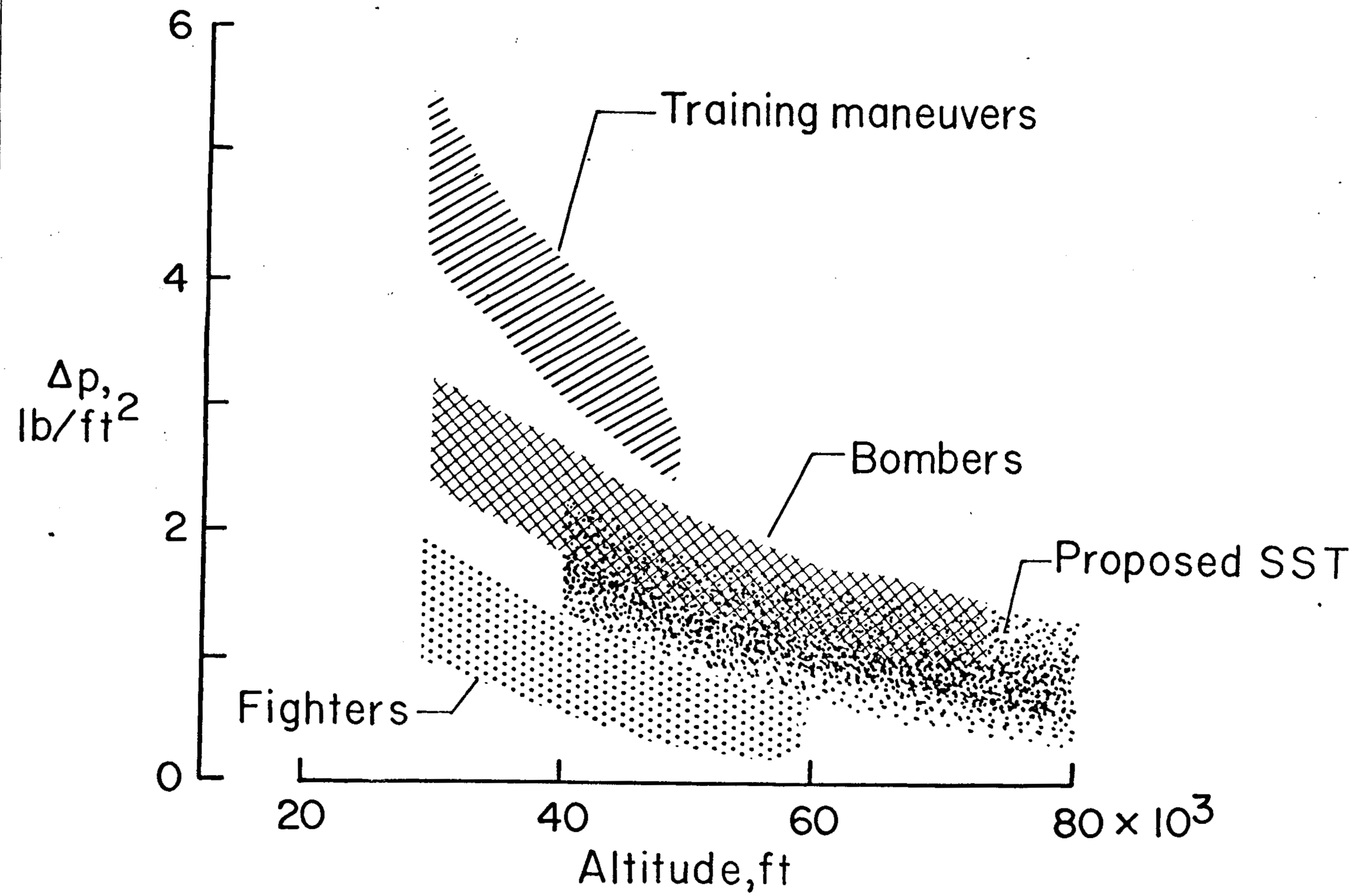
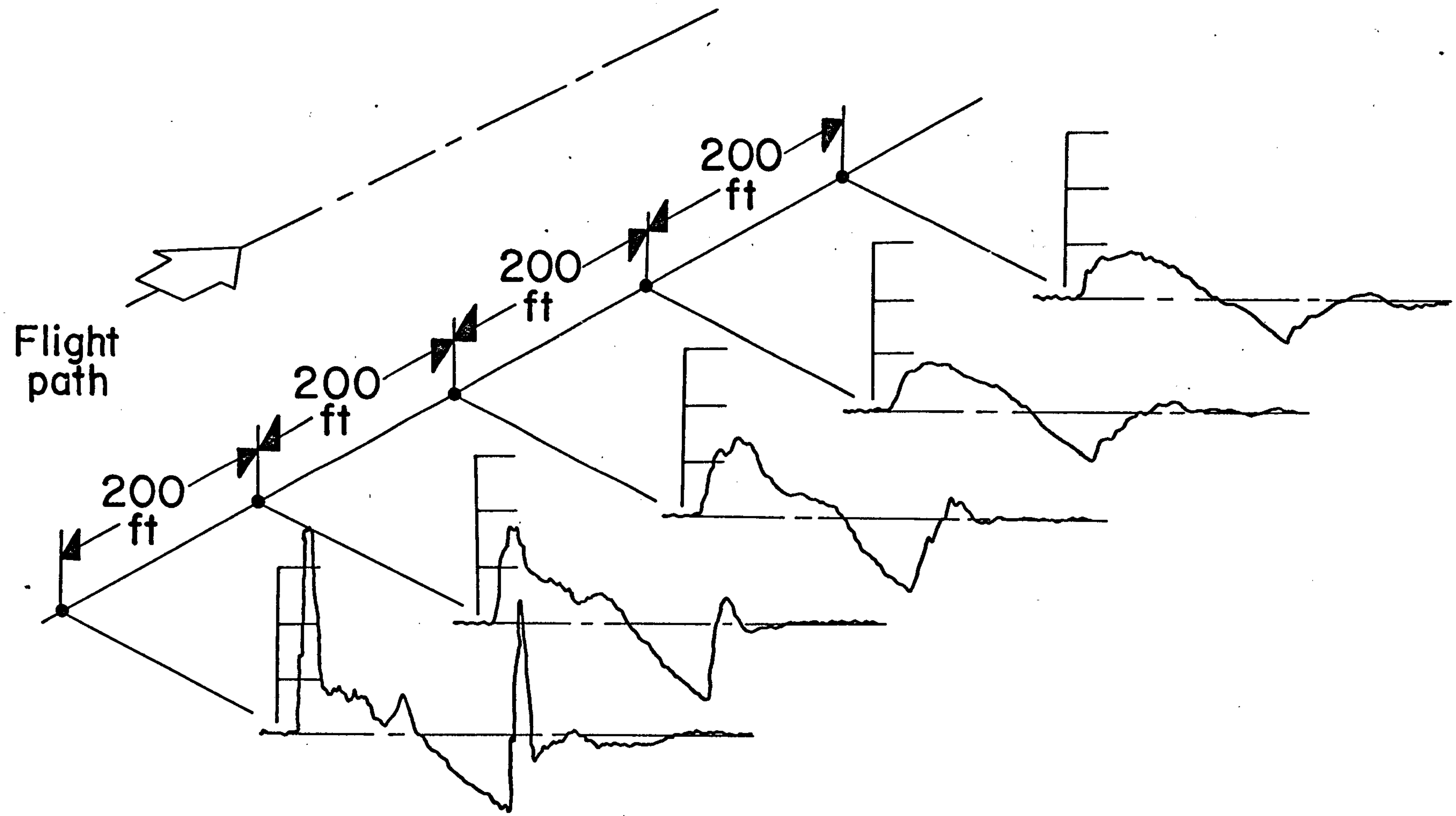
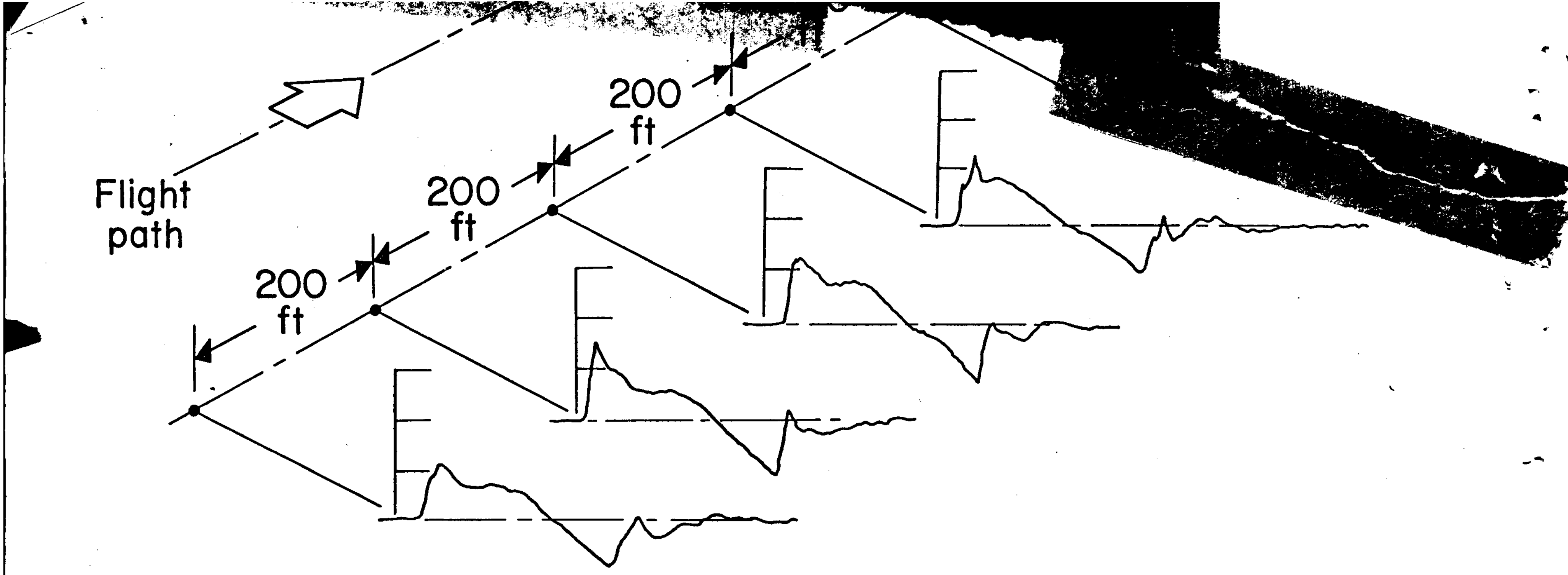


Figure 19. - Sonic boom levels.



(a) Time of flight, 0730 hours.

Figure 20. - Sonic boom wave forms.



(b) Time of flight, 0930 hours.

Figure 20. - Concluded.