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AERODYNAMIC PERFORMANCE STUDIES FOR SUPERSONIC CRUISE AIRCRAFT

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16. Abstract

In the past three years, significant technical progress has been made in each of the disciplinary research areas affecting the design of supersonic cruise aircraft. The NASA Supersonic Cruise Aircraft Research (SCAR) program has supported an expanded research program in aerodynamics including an ever growing experimental data base, methodology development across the Mach number range, and sonic boom. Progress in the aerodynamics area could facilitate the choice of the highly swept subsonic leading edge, arrow wing, known for superior supersonic cruise efficiency.

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AERODYNAMIC PERFORMANCE STUDIES FOR SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

In the past three years, significant technical progress has been made in each of the disciplinary research areas affecting the design of supersonic cruise aircraft. The NASA Supersonic Cruise Aircraft Research (SCAR) program has supported an expanded research program in aerodynamics including an ever growing experimental data base, methodology development across the Mach number range, and sonic boom. Progress in the aerodynamics area could facilitate the choice of the highly swept subsonic leading edge, arrow wing, known for superior supersonic cruise efficiency.

INTRODUCTION

The National Supersonic Transport Program was canceled in 1971 after a considerable investment of the nation's resources. One of the major factors which contributed to the program's demise was the configuration's economic deficiencies due to marginal range-payload characteristics. In the same period, economically attractive subsonic wide-body aircraft were being introduced into the long-haul aircraft market. The anticipated performance of the former SST was a direct result of the demonstrated technologies which existed at that time. At the close of the program, it was clear to both government and industry that significant improvement in supersonic technology was required to make a second generation aircraft economically viable.

With the prospect of the introduction of foreign supersonic transports in the mid-1970's, the United States is in danger of losing its leadership in the long-haul aircraft market if these aircraft prove to be economically successful. Consequently, in 1972, NASA initiated an Advanced Supersonic Technology (later SCAR) Program. The intent of the program is to give the industry of the country the technology option to proceed with a second generation development of a supersonic transport, if and when that decision is made.

Initially, study contracts were issued with The Boeing Company, the Lockheed-California Company, and the Douglas Aircraft Company to identify and assess the impact of new technology on the concepts and characteristics of supersonic aircraft. Shortly thereafter, NASA accelerated technology programs in the principal disciplines including aerodynamics.

During the first year contractural report, certain aerodynamic technology needs were identified. An expanded low-speed aerodynamic data base for highly swept, low aspect-ratio wings was needed to improve takeoff and landing performance. Typically, takeoff and landing constraints required oversizing the low aspect ratio wing resulting in significant performance, noise, and weight penalties.

Improved ability to predict high angle-of-attack aerodynamic loads was required for designing the aircraft structure. New theoretical methods in the subsonic and transonic speed range were required which included the effect of leading edge separation and vortex roll up. Extended supersonic design and analysis methods were needed to provide more efficient aerodynamic configurations.

Work in the area of sonic boom prediction, minimization, and determination of levels of boom acceptable to the public was recommended, since the overland market for supersonic travel is potentially as large as the international market.

The purpose of this summary report is to present the results to date of the work funded under the AST/SCAR aerodynamic performance technology subprograms: concepts, theory, and sonic boom.

Aerodynamics Program Scope

The AST/SCAR program in aerodynamics can be grouped into three categories: concepts (experimental program), theory, and sonic boom. A summary of the contractural effort in the aerodynamics area is shown in Table 1. The reader should understand that important work funded by the SCAR program in the areas of transonic loads prediction and steady/unsteady aerodynamic methods are included in the SCAR structures and materials program. (Reference 1)

Experimental Program

A status of the SCAR experimental aerodynamics program is shown in Figure 1. High priority has been given to addressing the low speed lift area as well as generating an experimental data base at a design Mach number of 2.2.

When sized for maximum range, the low aspect ratio, highly swept wings required for good supersonic aerodynamic efficiency do not provide adequate, efficient low speed lift. This low speed lift deficiency is usually made up by (1) increasing wing area which adversely affects weight and cruise match, (2) by decreased wing sweep, which adversely affects high speed drag, or (3) by increased takeoff and landing speeds or attitudes, which adversely affect passenger comfort and safety. The SCAR program has supported a series of tests at NASA/Langley Research Center to investigate powered lift as a possible means of improving low speed lift characteristics and permitting a more optimum wing size from range payload considerations (Reference 2). The large model shown in

Figure 2 was used to determine the application of powered lift for conventional engine placements, flap hinge-line blowing, and for unconventional over-wing engine placement. The tunnel tests results (Figure 3) indicate the substantial effects of blown flaps on lift improvement at a given attitude and an almost doubling of the lift with upper surface engine placement. Powered lift techniques offer substantial promise for permitting the design of a more optimum system. This promise includes the potential for reducing wing area, reduction of takeoff and approach attitude, reduced landing gear length and weight, and simplifies the airplane's visor nose. In total, these improvements are about 10 percent of the airplane empty weight.

At this writing, five important experimental programs are in progress. A NASA/Douglas cooperative wind tunnel test is being conducted in the NASA/Ames unitary tunnels. The test program is aimed at validating the aerodynamic characteristics of three Douglas design wings through the transonic and supersonic speed range. A test program in the Langley 16-foot transonic tunnel is being conducted to determine the effect of above-the-wing engine placement on transonic loads and propulsion system interference. A test program has been initiated in the Langley Full-Scale Tunnel to determine the low speed aerodynamic characteristics of the Douglas baseline SCAR configuration. The NASA near-term and advanced arrow-wing powered lift models will be tested in the full-scale tunnel with integrated inboard engine and flap systems. Lockheed is conducting in their facility a low-speed experimental investigation of roll-control effectiveness.

Theory

The ability to predict aerodynamic loads on highly swept wings in subsonic and transonic flow is extremely important in designing the aircraft structure. The flow at the leading and tip edges of a swept wing with sharp edges separates at moderate to high angles of attack, producing vortex sheets that roll up into strong vortices above the upper surface of the wing. The formation of these vortices is responsible for the well known nonlinear aerodynamic characteristics exhibited over the angle-of-attack range.

The leading edge suction analogy described in Reference 3 provides a method suitable for calculating the magnitude of the nonlinear vortex lift on a rather broad class of wing planforms. The total wing lift computed by this method agrees well with experimental data, but the leading edge suction analogy does not give flow field details or detailed surface pressure distributions.

Several attempts have been made in the past to theoretically predict detailed pressure distributions and flow fields about swept wings with leading edge vortex separation. Most of these past methods were limited to slender configurations in which considerable simplification occurred because the problem could be reduced to a solution of Laplace's equation in crossflow plane, for which conformal mapping became a powerful tool. None of these theories can even approximately predict aerodynamic load distributions of wings with leading edge vortex separation, and demonstrates the need for an accurate prediction method for this type of flow phenomenon.

A method developed by Boeing under contract to NASA/Langley (Reference 4) models the flow over wings with leading edge vortex separation as an inviscid and irrotational problem. The method is completely three-dimensional and capable of predicting detailed pressure distributions as well as overall wing-load coefficients. The wing, wake, and primary vortex sheet are modeled as thin surfaces. No attempt is made to model secondary flow separation or multiple primary vortex sheets. Special attention is paid to the modeling of the viscous core of the rolled up vortex spiral within the framework of inviscid flow theory.

Numerous example cases have been executed to validate the method and its generality. Cases selected are compared with available theoretical and experimental data for a range of different geometric configurations including delta, gothic, and arrow wings.

Figure 4 shows detailed surface pressure distributions for a delta wing of aspect ratio 1.4559 at $\alpha = 19.1^\circ$. Upper and lower surface pressures are well predicted for the higher angles of attack, as the comparison with experimental data illustrates. The experimental results clearly show the effect of the secondary vortex separation, which takes place on the upper surface slightly outboard of the main vortex. The present method does not model secondary vortex separation and consequently, produces a slightly different shape for the pressure peaks.

Douglas has conducted a study (Reference 5) to examine the effect of various wing body design constraints on supersonic lift-to-drag ratio, with a view towards reducing the cabin floor angle. Although it was found that substantial reductions in floor angle were not possible without degrading L/D, new insights with respect to supersonic wing body design methods were uncovered.

Study results are summarized in Figure 5. The optimum configuration was a $M = 2.2$ arrow wing design using accepted design procedures pioneered by NASA, (Reference 6), whereby the wing alone is twisted and cambered for minimum drag at the cruise $C_L = .1$. The fuselage, providing minimum zero-lift wave drag, was centered with equal cross section area centroids along the wing-root camber line. The floor angle at L/D_{max} was 6.75°. Floor angles of 2-3° on present day subsonic aircraft result in passenger complaints and difficulties in cabin operations.

In order to reduce the cabin floor angle to 5°, the optimum wing camber surface was constrained at the wing body juncture. The baseline configuration was adopted with a decrement in L/D of .2.

A special feature of the Douglas version of the Woodward paneling method was used to study the effect of design C_L with the wing twisted and cambered in the presence of the fuselage flow field. For a design C_L of 0.85, this procedure resulted in an increase of .25 in L/D over the optimum and a 1/2° reduction in floor angle relative to the baseline.

The baseline wing body resulted in a center of pressure 66 percent of the wing centerline root chord, giving a negative pitching moment with resultant trim drag. A pitching moment constraint study was conducted which resulted in an L/D increase of .4 relative to the optimum and an increase 1.5° in floor angle relative to the baseline. (Center of pressure constrained to 53 percent of wing centerline root chord.)

Results of this study underscore the need for continual refinement and extension of aerodynamic tools. Design methods accounting for fuselage flow field interference and horizontal tail alignment may lead to higher levels of aerodynamic performance than what has been achievable to date. A significant step in this direction has been taken at Langley supported by a contractual effort with Boeing.

Over a period of years, NASA/Langley has developed a basic computerized series of supersonic design and analysis methods for aerodynamic configuration studies (Reference 7). The methods are characterized by their reliability and input simplicity.

The Boeing Company has extended this basic series of methods and combined them into an integrated system of computer programs (Reference 8). The extensions to the methods provide several new features:

- Addition of a near-field (thickness pressure) wave drag program, to complement the existing supersonic area rule program.

- Improved modeling of fuselage in lifting surface design and analysis programs.

- Addition of configuration-dependent loadings in wing design program, so that the wing design is performed in the presence of fuselage and nacelle effects.

- Addition of pressure limiting terms in the lifting pressure programs, to constrain the linear theory solution.

- Optional CRT displays of selected program input and output data and provisions for limited user editing and intervention (Figure 6).

A plot module is included in the system to produce configuration drawings, and a common geometry module is used to permit a single geometry input for all programs.

The basis of the system is supersonic linearized theory, modified in two respects:

- The "Whitham" correction to disturbance positioning is used in the propagation of body pressure fields, which includes the first order correction for the actual characteristic angles.

- The wing lifting pressure modules contain an optional limiting pressure feature to limit the predicted upper surface pressures to be greater than vacuum.

Superposition is used to build up the theoretical force coefficients of a selected configuration.

The goals of the integrated system have been to develop an easily used supersonic design and analysis capability, with recognition of the need for constraints on linear theory methods to provide physical realism, and with inclusion of interactive display for increased design control over optimization cycles.

Low Sonic Boom Aircraft

The primary inpetus for sonic boom research has been the recognized major impact of sonic boom on the economic viability and environmental acceptability of supersonic cruise aircraft. Restricted by sonic boom considerations to strictly overwater cruise legs, supersonic cruise aircraft would generate a minimal environmental problem, but would lack versatility and could have a marginal market potential. Furthermore, design compromises required to provide versatility could lead to a degradation of the already limited economic potential. On the other hand, if permitted to cruise overland with no consideration of the sonic boom disturbance, these future aircraft would perhaps be economically attractive but are currently thought to be unacceptable environmentally.

Recent market studies have indicated that the market potential for supersonic transport aircraft would be 350 to 750 aircraft, depending on the level of technology assumed. This market potential would be more than doubled if routine overland supersonic cruise flight could be made possible through solution or amelioration of the sonic boom problem. It is, therefore, important to develop the technology which will permit the desirable time saving features of supersonic flight to be achieved economically and within acceptable environment constraints on sonic boom.

A concentrated research program in sonic boom was conducted during the 1960's at the Langley Research Center. Field measurements (Reference 9) of sonic boom provided knowledge on the effects of atmospheric and operating conditions on the variability of the sonic boom disturbances. Wind tunnel test procedures (Reference 10) were developed to isolate and prove the effects of volume, lift, and inteference on the pressure disturbance of both simple and complicated shapes, including correlation with flight measurements.

The original assessment of the sonic boom problem was based upon a far-field asymptotic theory which indicated that sonic boom intensity is controlled almost entirely by the aircraft weight and volume, and hence essentially unavoidable. The major contribution to ameliorating sonic booms on which all present work is based, was the observation (Reference 11) that far-field theory does not necessarily apply to large supersonic aircraft, i.e., that it is possible to affect the strength of the boom through shaping of the aircraft. The theory was strengthened by the discovery that the pressure signature would "freeze" when propagating through a real, density-stratified atmosphere (Reference 12).

The last two discoveries are the basis for modern sonic boom minimization techniques as applied to supersonic aircraft design. Minimum sonic boom aerodynamic designs were established in Reference 13, which led to concepts with sonic boom overpressures below 50 n/m^2 (1 lb/ft^2). The stage was set for a industry study of a low sonic boom concept with in-depth consideration of performance, weights and balance, and low-speed operating characteristics.

A study was funded under the auspices of the AST/SCAR program with The Boeing Company (Reference 14). Two configurations were studied with characteristics applicable for overland operation carrying 150 passengers, and incorporating a blended arrow wing. A Mach number 2.7 design with a range of 7,000 km (3780 nmi) and Mach number 1.5 design with a range of 5,960 km (3220 nmi) were studied. Sonic boom intensity goals for the high and low speed designs were 50 n/m^2 (1 lb/ft^2) and 36 n/m^2 (0.75 lb/ft^2), respectively.

Configuration characteristics of the high speed design and near-field sonic boom signature is shown in Figure 7. To achieve a low sonic boom configuration, the lift of the wing must be distributed gradually in the axial direction. This leads to highly swept configurations which are consistent with good supersonic performance. However, for takeoff conditions, the configuration had serious design deficiencies. FAR field takeoff distances in excess of 6,100 m (20,000 ft) were calculated. Second segment climb capability was marginal and could not accommodate an engine failure during takeoff. The low climb-out altitudes resulted in noise levels well in excess of FAR 36 noise rules.

Suggested follow-on work to address the low speed problems of sonic boom configured vehicles has not been funded due to the low level of program funds to date.

The theoretical basis for the work previously described has been based upon linearized theory with second order corrections to the outgoing characteristics and the shock. Some recent investigations have indicated that lower sonic booms may be achievable by operation at hypersonic Mach numbers and higher altitudes. Since the existing theory was invalid at these conditions, development of a new method was initiated.

Work was sponsored by the AST/SCAR program (Reference 15) with New York University to develop a sonic boom theory which included the effects of nonlinear wave propagation in the near field, variations of temperature and entropy in the atmospheric layers, and all the nonlinear terms in the governing equations. Although the method applies to general nonaxisymmetric bodies, results have been obtained to date for only the axisymmetric case. Numerical results indicate that the highly nonlinear effects are important in the prediction of rear shock wave strength. The methods generally predicts shorter signature lengths than the lower Mach number theories.

Sonic boom research grants with Cornell University (Reference 16) during the past nine years have had the following goals: to determine the minimum possible sonic boom of SST generation aircraft; to predict the distortion of sonic boom signatures by atmospheric turbulence; to predict the amplification of a sonic boom that occurs at a caustic known as a superboom; and to determine the magnitude of the sonic boom generated by drag dominated hypersonic vehicles.

As a result of this grant and others, it is now a routine matter to determine the aircraft area distribution required to minimize various sonic boom signature parameters for given aircraft weight, length, flight altitude, Mach number, and volume.

Future Directions

To date, certain recent studies funded under this program have not been completed such that referenceable reports exist. These are:

- o Results of NASA/Douglas cooperative wind tunnel tests
- o NASA/Ames leading-edge radius wind tunnel tests
- o Calculations of aerodynamic characteristics based on a local Mach number distribution

Preliminary results from the first item indicate that Douglas has experimentally validated their predicted L/D at cruise conditions.

In the coming year, an expanded high speed experimental program is envisioned with a view toward aerodynamic validation of industry baseline configurations. A low speed experimental program is being planned centered around the Douglas baseline configuration with modifications for a supersonic executive jet configuration. Low speed tests will continue at Langley to determine the effects of powered lift on both near and far-term arrow wing concepts.

Supersonic theory development will focus on demonstrating the validity of a new finite difference code for supersonic transport configurations. An exact inviscid solution developed by Grumman (Reference 17) for the space shuttle will be applied to transport configurations. Extension have been initiated to apply the solution to complete configurations including arrow wing geometry.

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TABLE 1

AERODYNAMIC PERFORMANCE CONTRACTS

CONCEPTS (EXPERIMENTAL)

NUMBER	TITLE	CONTRACTOR	COST
NAS1-11085	Pressure Distribution and Propulsion Integration Model	Microcraft Inc.	$186K
NAS1-11847	Wind Tunnel Models	Dynamic Engineering and Model Company	$628K
NAS1-13633	Cooperative NASA/Douglas Wind Tunnel Tests	Douglas Aircraft Company	$283K
	THEORY		
NAS1-12052	Development of Extended Supersonic Aerodynamic Analysis System	Boeing Commercial Airplane Company	$ 94K
NAS1-13732	Extension of Above	Boeing Commercial Airplane Company	$ 67K
NAS1-12185	Analytic Study of Predicting Aerodynamic Loads of Supersonic Aircraft	Boeing Commercial Airplane Company	$ 70K
NAS1-13833	Extension of Above	Boeing Commercial Airplane Company	$ 80K
NAS1-12900	Calculation of Aerodynamic Characteristics of Configurations in Subsonic, Transonic and Supersonic Flow Based on Local Mach Number Distribution	Analytical Methods Incorporated	$ 72K
NAS1-13145	Effects on Nominal Cabin Floor Angle on the L/D of a Typical SST Configuration	Douglas Aircraft Company	$ 35K
NAS2-7732	Advanced LH_2 Supersonic Technology Study	Lockheed California Company	$107K
NAS2-7571	Potential Flow Program	Acurex Corporation	$ 58K

TABLE 1

SONIC BOOM

NUMBER	TITLE	CONTRACTOR	COST
NAS1-11877	Low Sonic Boom SST Feasibility Study	Boeing Commercial Airplane Company	$ 65K
NGL-31-001-119	Theoretical Problems Connected With Sonic Boom	Princeton University	$ 15K
NGL-33-016-119	Sonic Boom Research	New York University	$ 226K
L-75054	Bren Tower Testing Support	Atomic Energy Commission	$ 18K
NAS1-10992	Analysis of the Jackass Flats Sonic Boom Flight Test Data	Boeing Commercial Airplane Company	$ 37K
NGR-22-009-618	Laboratory Study of Sonic Booms and Their Scaling Law	Massachusetts Institute of Technology	$ 47K
NGR-33-010-203	Sonic Boom Research	Cornell University	$ 75K
		TOTAL	$2163K

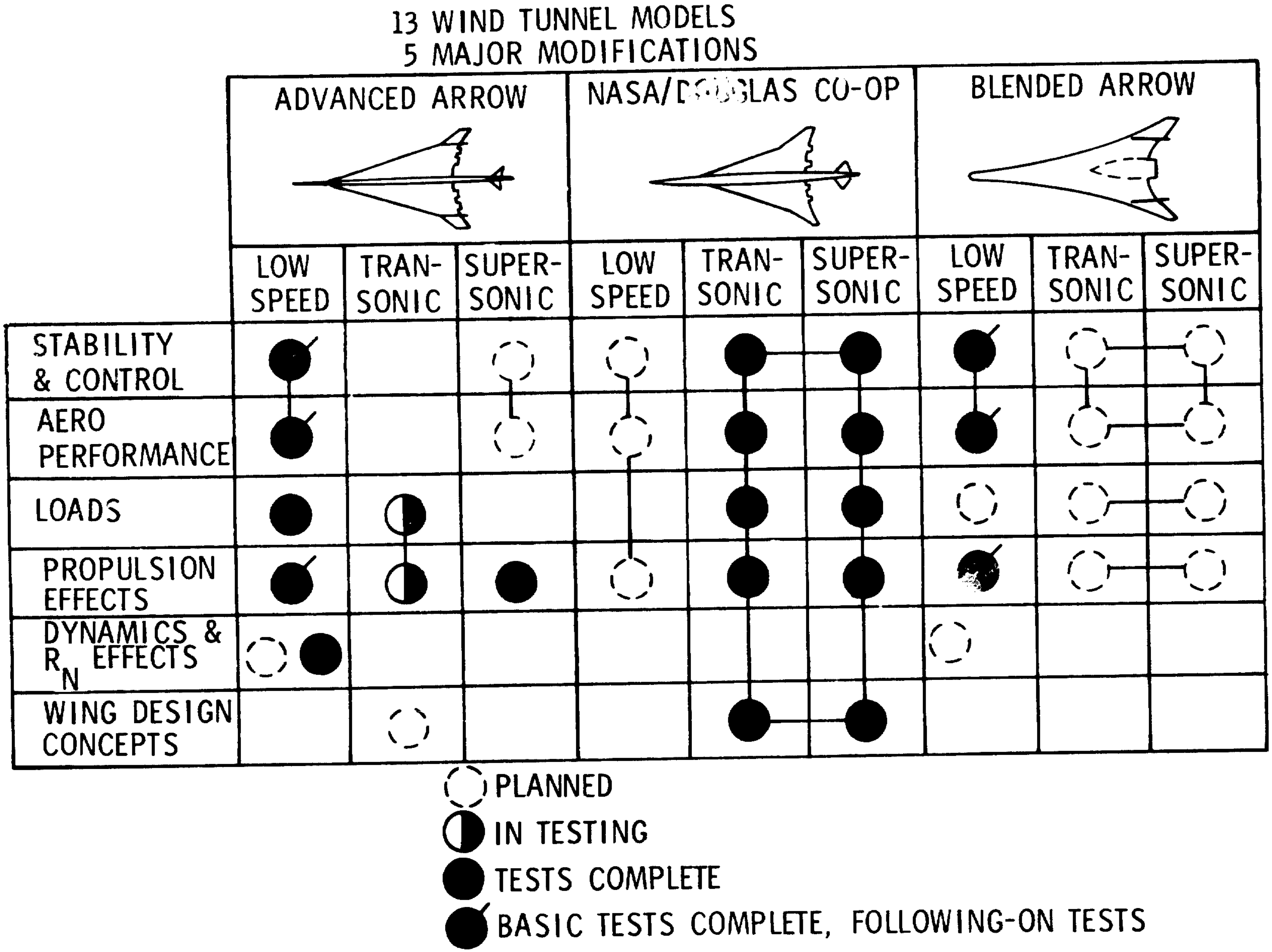

FIGURE 1. - STATUS OF SCAR EXPERIMENTAL AERODYNAMICS PROGRAM

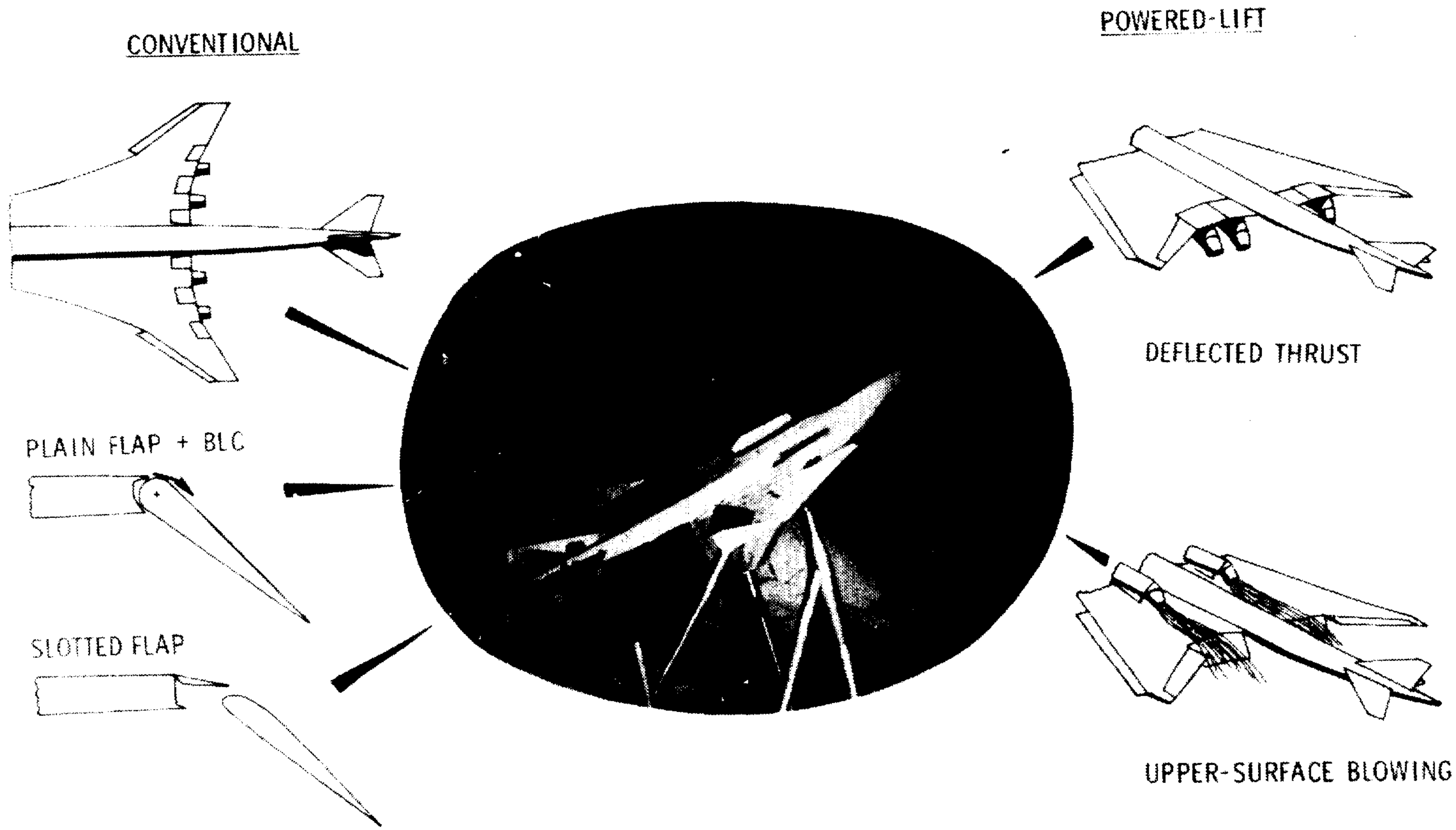

Figure 2. - NASA/Langley powered-lift program

NASA/LANGLEY POWERED LIFT DATA

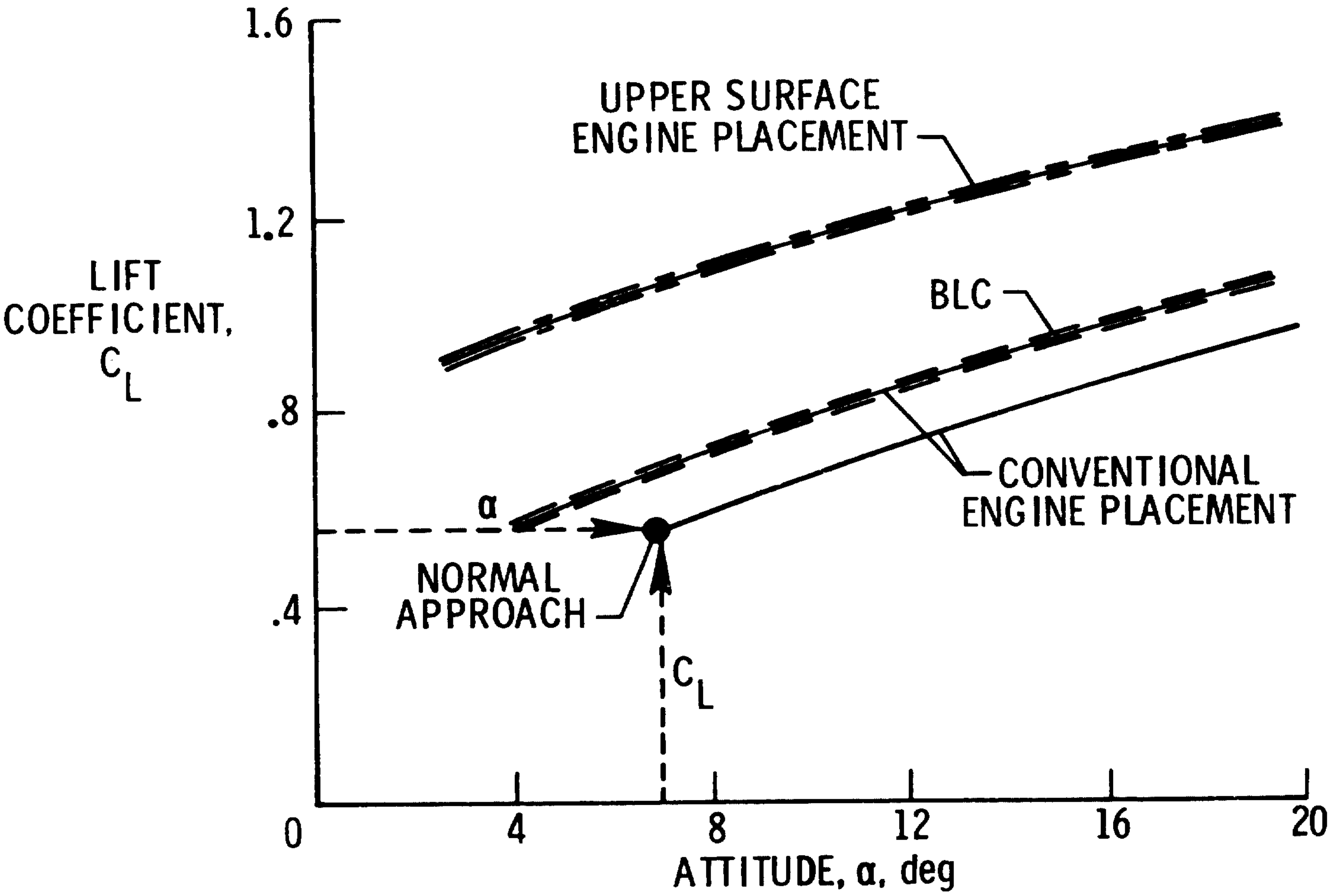

FIGURE 3. - POWERED-LIFT EFFECTS ON SCAR MODELS

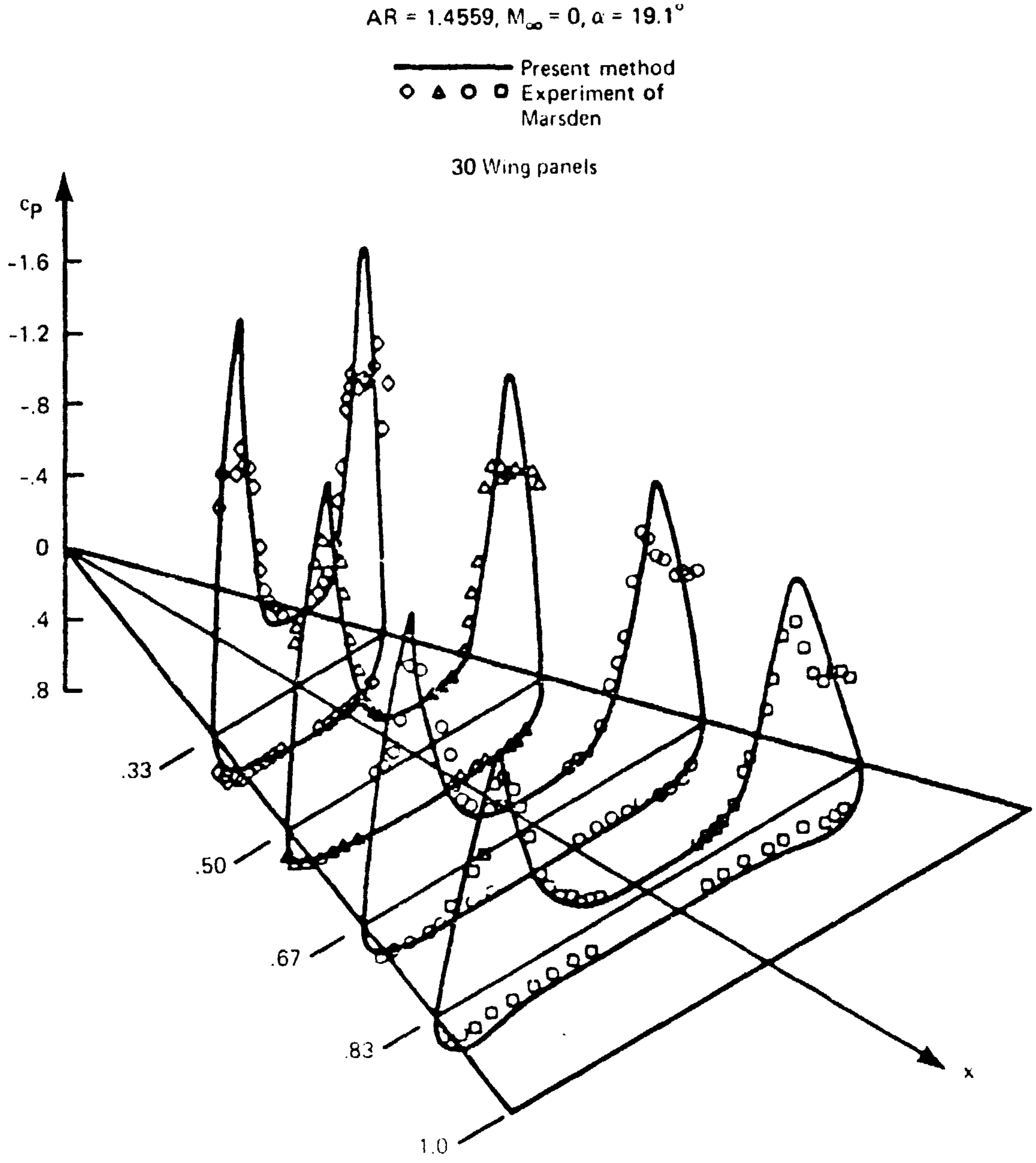

Figure 4. - Surface pressure distribution of delta wing, α = 19.1°

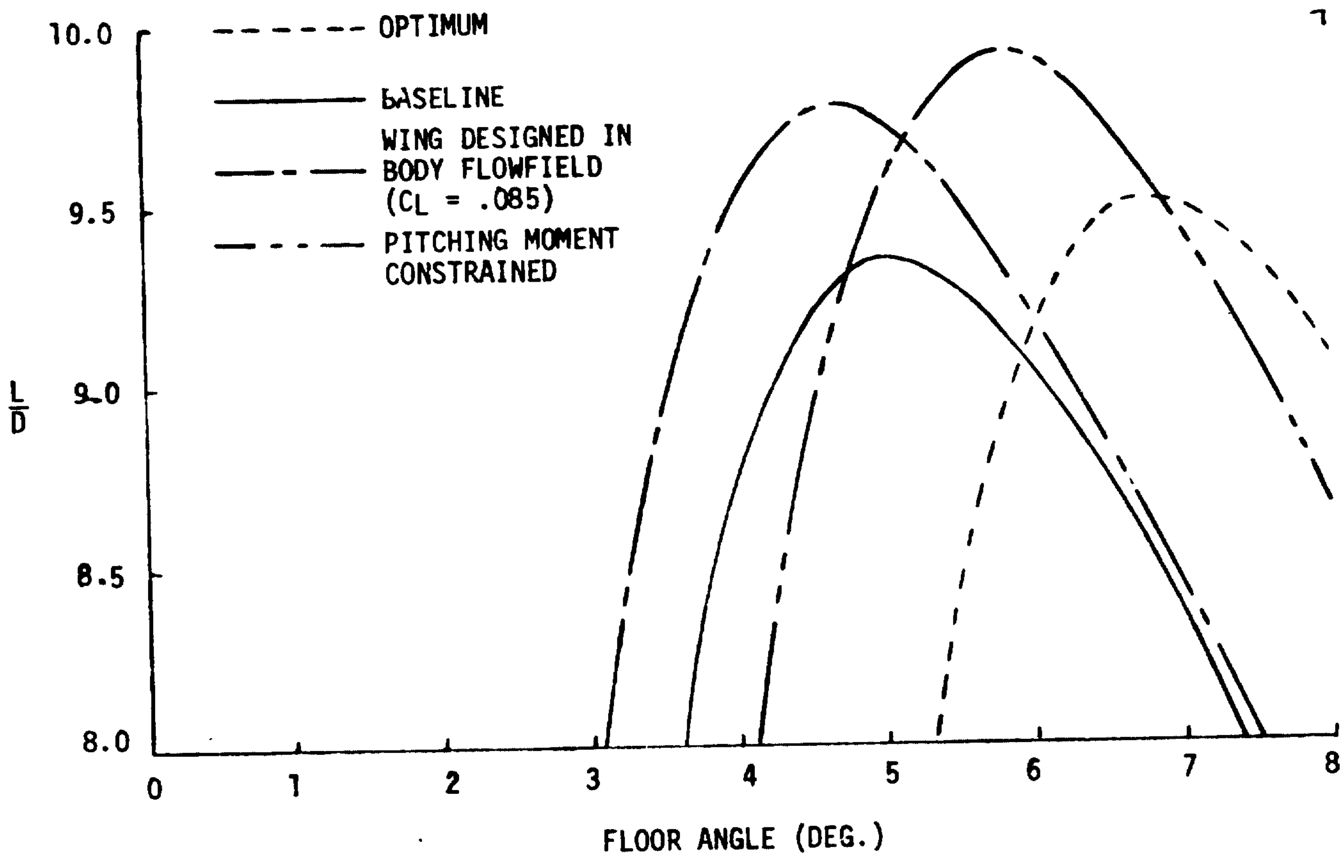

Figure 5. - Results of Douglas floor angle study

INTERACTIVE GRAPHICS

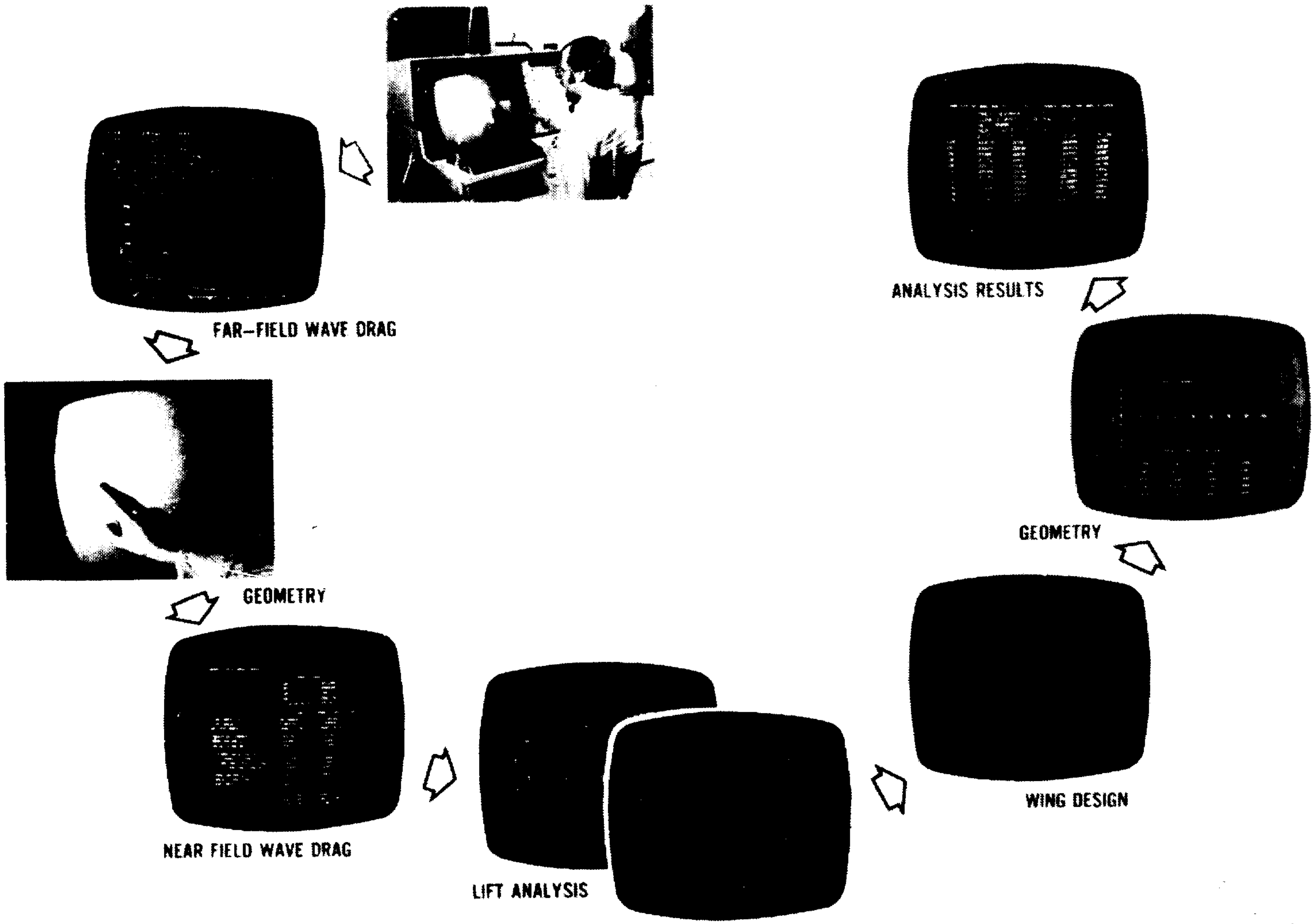

FIGURE 6. - INTEGRATED SYSTEM OF AERODYNAMIC DESIGN AND ANALYSIS METHODS

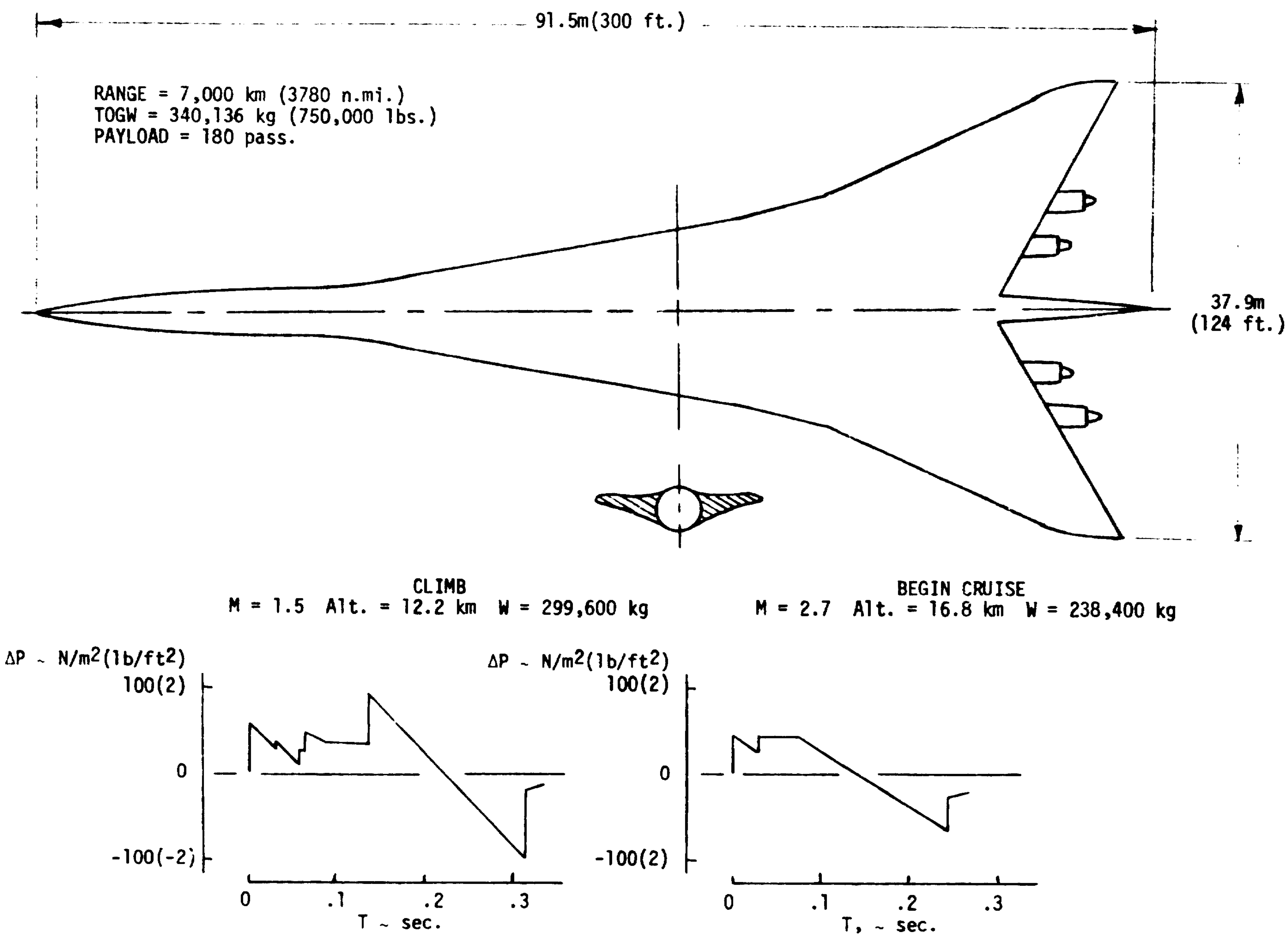

Figure 7.- Boeing Mach 2.7 low sonic boom configuration