NASA Contractor Report 186022

p. 73

Design and Analysis Issues of Integrated Control Systems for High-Speed Civil Transports

Craig A. McCarty, John B. Feather, John R. Dykman, Mark A. Page, and John Hodgkinson

Contract NAS2-12722
May 1992

(NASA-CR-186022) DESIGN AND ANALYSIS ISSUES OF INTEGRATED CONTROL SYSTEMS FOR HIGH-SPEED CIVIL TRANSPORTS Final Report (Douglas Aircraft Co.) 73 p

N92-31656

Unclas

G3/08 0109346

National Aeronautics and
Space Administration

NASA Contractor Report 186022

Design and Analysis Issues of Integrated Control Systems for High-Speed Civil Transports

Craig A. McCarty, John B. Feather, John R. Dykman, Mark A. Page, and John Hodgkinson
Douglas Aircraft Company, New Programs and Technology, Long Beach, California

Prepared for
PRC Inc.
Edwards, California
Under Contract ATD-91-DAC-7103

1992

National Aeronautics and
Space Administration

Dryden Flight Research Facility
Edwards, California 93523-0273

CONTENTS

FIGURES . . . v

ABSTRACT . . . 1

NOMENCLATURE . . . 1

INTRODUCTION . . . 2

IDENTIFICATION OF THE DESIGN AND ANALYSIS ISSUES . . . 3
- Relevant Characteristics of Supersonic Aircraft . . . 3
  - Aerodynamic Stability and Control . . . 3
    - Pitch stability and control . . . 3
    - Directional stability and control . . . 4
    - Lateral stability and control . . . 5
  - Aeroelasticity . . . 5
    - Leading-edge vortex of the advanced supersonic transport . . . 5
    - Flutter of the advanced supersonic transport . . . 6
    - Static aeroelastic corrections . . . 6
    - Structural mode control systems . . . 6
  - Acoustics . . . 6
  - Airframe-Propulsion Interactions . . . 7
    - Interactions with airframe dynamics . . . 8
  - Advanced Supersonic Transport Flight Controls . . . 9
    - System complexity . . . 9
    - Unstable aircraft dynamics . . . 10
    - Ride and handling qualities . . . 11
    - Flexible aircraft dynamics . . . 11
- High-Speed Civil Transport Control Requirements . . . 12
  - Configuration . . . 12
  - Aerodynamic Stability and Control . . . 12
    - Pitch requirements . . . 13
    - Directional requirements . . . 13
    - Lateral requirements . . . 14
  - Aeroelasticity . . . 14
    - Leading-edge vortex effects . . . 14
    - Flutter and its suppression . . . 15
    - Static aeroelastic considerations . . . 15
    - Structural mode control system . . . 15
    - Laminar flow control . . . 15
    - Gust load alleviation system . . . 15
    - Spoilers . . . 15
    - Aerothermoelasticity . . . 15
  - Acoustics . . . 16

PRECEDING PAGE BLANK NOT FILMED

Airframe-Propulsion Interactions 16
Internal inlet–engine–nozzle interactions. 16
Interactions with airframe dynamics. 16
Flightpath Management 17
Flightpath management concepts. 17
Fuel management systems. 17
Control system–composites interaction. 18
Control Design Technology and Methodology Issues 18
Aerodynamic Stability and Control 18
Aeroelasticity 20
State of the art. 20
Shortcomings of the state of the art. 21
Four issues. 21
Plan with tasks and schedule. 21
Acoustics 22
Airframe-Propulsion Interactions 22
Inlet–engine–nozzle integrated control 23
Integrated flight–propulsion control. 24
Control Augmentation and Flightpath Management 24
Controlling unstable, flexible aircraft. 24
Flightpath management. 24
Fuel management. 25

PRIORITIZATION OF THE DESIGN AND ANALYSIS ISSUES 25

TECHNOLOGY DEVELOPMENT PLANS 27

CONCLUSION 27

REFERENCES 27

FIGURES

1 Advanced supersonic transport tail-off pitching moment coefficient for various flap deflections. 31

2 Advanced supersonic transport tail-off pitching moment coefficient with the leading edge deflected. 32

3 Advanced supersonic transport tail-on pitching moment for several tail incidence settings. 33

4 Advanced supersonic transport tail-on pitching moment characteristics used to calculate downwash. 34

5 Estimated yawing moment coefficient as a function of sideslip angle. 35

6 Estimated advanced supersonic transport yawing moment coefficient as a function of sideslip angle.. 36

7 Estimated advanced supersonic transport yawing moment coefficient caused by rudder deflection. 37

8 Advanced supersonic transport lateral control system effectiveness. 38

9 Advanced supersonic transport leading- and trailing-edge flaps, spoiler–deflector, and inverted spoiler–deflector. 39

10 Variable geometry features of NASA low-speed advanced supersonic transport model. 40

11 Mixed compression supersonic inlet performance. 41

12 Advanced supersonic transport general configuration drawing. 42

13 Advanced supersonic transport longitudinal control law for landing approach. 43

14 Advanced supersonic transport lateral control law for landing approach. 44

15 Advanced supersonic transport handling qualities rating. 45

16 Advanced supersonic transport ride qualities evaluation results. 46

17 Advanced supersonic transport flexible mode control law. 47

18 Advanced supersonic transport flexible mode suppression control results. 48

19 Design features and key technologies. 49

20 Technology development plan for defining large transport flying quality criteria. 50

21 Technology development plan for defining the benefits and costs of reduced inlet stability margins. 51

22 Technology development plan for defining control system validation process. 52

23 Technology development plan for generating unsteady aero data for spoiler-slot deflectors. 53

24 Technology development plan for defining the takeoff and landing profile constraints. . 54

25 Technology development plan for defining the reduced inlet stability control system architecture. 55

26 Technology development plan for developing a unified rigid body analytical model. . . 56

27 Technology development plan for developing robust advanced control synthesis and analysis tools. 57

28 Technology development plan for developing the integrated flight-propulsion control system architecture. 58

29 Technology development plan for defining benefits and costs of advanced control modes. 59

30 Technology development plan for demonstrating integrated control of unstable, flexible aircraft. 60

31 Technology development plan for developing aircraft controls for large fuel fraction variation. 61

32 Technology development plan for improving propulsion system performance prediction models. 62

33 Technology development plan for defining advanced high-lift system stability and control characteristics. 63

34 Technology development plan for defining low-boom planform stability and control characteristics. 64

35 Technology development plan for using multidisciplinary optimization. 65

36 Technology development plan for developing constrained optimization synthesis and analysis tools. 66

ABSTRACT

A study was conducted to identify and rank the critical guidance and control design and analysis issues for an economically viable and environmentally acceptable high-speed civil transport, and to define technology development plans addressing the issues. The issues were identified in a multistep process. First, pertinent literature on supersonic cruise aircraft was reviewed, and experts were consulted to establish the fundamental characteristics and problems inherent to supersonic cruise aircraft. Next, the advanced technologies and strategies being pursued for the high-speed civil transport were considered to identify any additional unique control problems the transport may have. Finally, existing technologies and methods were examined to determine their shortcomings for designing and analyzing control systems for high-speed civil transport. Three priority levels – mandatory, highly beneficial, and desirable – were established. Within each of these levels, the issues were further ranked. Technology development plans for each issue were defined. Each plan contains a task breakdown and schedule.

NOMENCLATURE

AST	advanced supersonic transport
ATO	authority to offer
ATP	authority to proceed
CFD	computational fluid dynamics
c.g.	center of gravity
DAC	Douglas Aircraft Company, Long Beach, California
DOF	degree of freedom
EPR	engine pressure ratio
FAA	Federal Aviation Administration
FLADE	fan on blade
HIDEC	highly integrated digital electronic control
HSCT	high-speed civil transport
ISSD	inverted spoiler slot deflector
MAC	mean aerodynamic chord
SCAR	supersonic cruise aircraft research
SSD	spoiler-slot deflector
SST	supersonic transport
TBE	turbine bypass engine
TET	turbine entrance temperature

Symbols

α	angle of attack, deg
β	sideslip angle, deg
C_L	landing coefficient of lift
g	acceleration of gravity
$T2$	time to double amplitude
V_{mca}	minimum air control speed

V_{mcg}	minimum ground control speed
V_{mcl}	minimum landing control speed
V_D	maximum dive speed

INTRODUCTION

Studies of the potential of a high-speed civil transport (HSCT) project that for the 2000 to 2025 period, sufficient passenger traffic will exist to support an HSCT fleet; but such transports must be economically viable and environmentally acceptable (ref. 1). More specifically, the operating costs must be sufficiently low so that airlines will not have to charge premium fares. In addition, the aircraft must operate with extremely low toxic emission levels, meet airport noise regulations, and have an acceptable sonic-boom signature or be efficient enough to operate subsonically for 20 to 25 percent of the flight. Current production level technologies and methodologies are insufficient for designing and producing a supersonic cruise commercial transport that meets these economic and environmental goals.

The NASA High-Speed Research Program is developing the technologies and methodologies required to overcome the obstacles to economic viability and environmental acceptability. The technologies and strategies being pursued include low oxides of nitrogen (NOx) combustors, efficient fuel consumption, careful integration of the inlet with the engine and the nacelle with the airframe, lightweight materials and structures, advanced operating procedures to minimize noise, low-speed high-lift devices, variable geometry propulsion systems, and a highly automated flight deck with synthetic vision. The High-Speed Research Program has two phases. Phase 1 is directed at resolving the environmental issues; it began in 1990, and is scheduled to run through 1995. Phase 2 is directed at developing the enabling technologies; it is scheduled to begin in 1993 and run through 1998. As part of the planning for phase 2, NASA is formulating a supersonic cruise technology program to address the guidance and control systems design and analysis techniques required for a successful next-generation supersonic cruise commercial transport.

The overall objective of this study was to help NASA define the technology program to address the required guidance and control systems design and analysis techniques. The design and analysis of control systems includes defining the requirements, developing the analytical models, synthesizing and implementing the control laws, and testing and verifying the system. Three tasks were defined to meet the overall objective: (1) identify the critical technology needs, (2) rank the critical technology needs, and (3) develop a technical plan to address the key technology shortfalls.

This report is organized as follows. In the next section, a brief description of the process used to carryout task 1 and the results of its application are presented. Next, the critical technology needs are ranked. Then a technical plan for each need is presented. The final section summarizes the conclusions of this study.

IDENTIFICATION OF THE DESIGN AND ANALYSIS ISSUES

This section presents the results of the critical technology identification process. A three-step process was used to identify the critical technology needs. The first step was to identify the control problems that have to be solved. The second step was to determine what technologies and methodologies are required to solve the control problems. The third step was to compare the required technologies and methodologies with the state of the art to identify key shortcomings, i.e., the technology and methodology issues that need to be addressed in phase 2 of the High-Speed Research Program. The organization in the following three sections primarily corresponds to the engineering groups assigned to this study: aerodynamic stability and control, aeroelasticity, acoustics, flight controls, and airframe-propulsion integration.

Relevant Characteristics of Supersonic Aircraft

Since only a minimal database and a preliminary configuration definition exist for the HSCT, the control problems could not be identified directly. Therefore, a technology baseline to compare the HSCT with, was defined by reviewing pertinent reports on relevant supersonic aircraft (e.g., Concorde, SR-71/YF-12, XB-70) and supersonic research programs (e.g., supersonic cruise aircraft research (SCAR) and advanced supersonic transport (AST)), and by consulting McDonnell Douglas experts. The information presented in this section and in the section entitled High-Speed Civil Transport Control Requirements constitutes the results of the first step in the technology identification process.

Aerodynamic Stability and Control

The aerodynamics of the HSCT represent a major part of the problem statement for the control-system designer. Previous supersonic aircraft experience has exposed many problems that we will face in developing a successful HSCT. This section summarizes those aerodynamic issues that are relevant to the HSCT.

Pitch stability and control.—All supersonic aircraft experience an aft shift of the aerodynamic center at Mach 1 and beyond. This shift increases the pitch stability and required trim at supersonic speeds. The tailless Concorde addresses this problem through an aggressive center-of-gravity (c.g.) management system that pumps fuel aft above Mach 1. Similar systems have been used on many supersonic aircraft.

The Douglas Aircraft Company (DAC) and Boeing (Seattle, Washington) supersonic transports (SSTs) took a different approach. A cranked-arrow wing was selected to minimize the aerodynamic center shift. This, with a conventional tail, eliminated the need for a c.g. management system on the AST. The cranked-arrow wing works on the principle that if the inboard sweep is higher than the outboard sweep, spanload moves inboard as Mach is increased. Since the inboard panel is forward of the outboard panel, this offsets the aft shift of the sectional lift.

Despite the advantages of the cranked-arrow wing in reducing the Mach effect on stability, it does not solve high angle-of-attack (α) instability. At high α, strong coherent vortices form along the wing's leading edge and on the forebody. Both sets of vortices produce upward normal forces forward of the

c.g., and are therefore destabilizing. Figures 1 and 2 show that at $\alpha = 5°$ (vortex onset), a 30-percent mean aerodynamic chord (MAC) instability developed for the AST in the tail-off configuration. Wing leading-edge flaps that suppress the wing vortex formation improve stability by roughly 10-percent MAC. However, the airplane is still unstable. These phenomena are also present in the F-16XL, which features a cranked-arrow wing in a tailless layout.

Figures 3 and 4 show that the horizontal tail adds a small amount of stability below $\alpha = 5°$. Above $\alpha = 5°$, the wing and forebody vortices produce a downwash gradient of one, which cancels the tail contribution to stability. Note, however, that the tail was still an effective trimmer–controller. Since the AST was unstable, an aggressive stability augmentation system was required. The conventional tail demonstrated excellent control power and linearity, making it an ideal control effector.

The horizontal tail of the AST features an all flying stabilizer with a geared elevator for control. The dedicated tail-plane with a healthy tail arm was selected to allow for high-lift flaps on the wings. A canard was not selected since it would have penetrated the pressure vessel, interfering with the cabin layout. The tail was sized by the nosewheel lift-off maneuver; which is primarily an elevator power issue. Landing trim was not critical, since the pitch instability offset much of the flap pitching moments at landing coefficient of lift (C_L).

The Concorde has simple-hinged trailing-edge elevons for pitch trim and control. The tailless Concorde lacks high-lift devices, since the trimmer and flaps would have had the same lever-arm yielding no trimmed lift improvement. This required large approach attitudes and a large wing to compensate for the lack of flaps. The XB-70, Saab Viggen & Grippen, and Dassault Rafale feature canards to avoid the inefficiencies of trimming with elevons. Similarly, the Soviet TU-144 and an experimental Dassault Mirage sport retractable canard "moustaches" to improve the trimmed lift in landing without paying additional cruise drag. However, a conventional tail is still a very efficient layout for trimming statically stable configurations, if it has a healthy lever arm.

Directional stability and control.—The directional stability of most supersonic aircraft decreases with increasing Mach number. This is largely the result of the reduction in side wash gradient at the tail for high Mach numbers. Most supersonic aircraft, therefore, feature large vertical tails.

The AST's directional stability was low, but not unstable, at supersonic speeds. However, at low speed and high angle of attack, the forebody and wing vortices produce a negative sidewash at the vertical tail, causing the net stability to drop to nearly zero over $\pm 7°$ of sideslip (see figs. 5 and 6). Fortunately, since there is also a high level of downwash at the empennage, there are no low-energy wakes from the fuselage or wing to engulf the vertical tail. As a result, the rudder effectiveness is almost unaffected by α, and remains a powerful and linear control effector (see fig. 7). The Concorde and SR-71 address the high α instability through use of forebody strakes chines, which produce stabilizing suction loads on the forebody.

The AST features a conventional vertical tail and rudder. Minimum ground control speed (V_{mcg}) with an engine failure was the critical sizing condition for the vertical tail (rudder control power). The crosswind landing de-crab maneuver was not critical since the directional stability is low at landing α. Further, supersonic inlet unstart was not critical, even with a two-engine "zipper" unstart.

Unstart compensation is automatic on the Concorde, which deflects the rudder and ailerons based on compressor entry pressure differences. A totally different approach is taken by the SR-71, which automatically unstarts the good engine to compensate for the initial unstart, then restarts both in unison.

Lateral stability and control.—Swept wings produce high lateral stability at high lift, especially if leading-edge vortices form. However, this stability becomes a liability for intentional sideslip maneuvers like a landing crosswind de-crab, since a large amount of lateral control is required to hold down the windward wing. The AST had well behaved but high lateral stability. This required 75 percent of the available lateral control for de-crab in a 31-kn crosswind, and represented the critical lateral control condition. The low-speed lateral controls that were tested at NASA-Langley on the AST consisted of outboard ailerons and inboard, mid, and outboard spoilers. The ailerons were very effective at all α's, and the same was true for the spoilers as long as the flaps were deflected. At zero flap deflection, the spoilers were anemic or reversed, especially the mid spoiler (fig. 8).

Supersonically, the AST ailerons were locked out because of aeroelastic reversal. Since simple spoilers are ineffective at supersonic and near-stall conditions, spoiler-slot deflectors (SSDs) and inverted spoiler-slot deflectors (ISSDs) were used. Supersonically, camber changes do not change lift, only an α change does. Spoilers cause the flow to separate, but in supersonic flow it can reattach yielding no effective α change. In contrast, SSDs partition the wing section into two panels with new α's. The SSDs and ISSDs double as traditional spoilers for low-speed operation (figs. 9 and 10). The SSD sizing was based on inlet unstart rolling moments (for under-wing engines), which can produce very high roll accelerations (20 deg/sec^2) because of the low roll inertias of these aircraft (ref. 2).

The Concorde and SR-71 use elevons exclusively for lateral control, while most supersonic fighters use the tail-plane for supersonic roll control. Inboard elevon deflection for roll was reduced on the Concorde to limit adverse sidewash on the fin.

Aeroelasticity

The aeroelastic properties of the HSCT also represent a major part of the problem statement for the control system designer. Previous supersonic aircraft experience has exposed many problems that will be faced to develop a successful HSCT. In this section, aeroelastic issues relevant to the HSCT will be summarized.

Leading-edge vortex of the advanced supersonic transport.—The large leading-edge sweep of the AST cranked-arrow wing results in the formation of a vortex. This vortex is present at all α's; its strength is small for low α and increases with α. Wind tunnel tests of a 1/10 scale AST model at low and medium speeds (ref. 3 and 4) indicate $\alpha > 5°$ as the region of increasing importance of the leading-edge vortex. For α up to 5°, lift-and-moment-test results are linear and are identical with analytical predictions that neglected leading-edge vortex effects. Lift does not vary much from predictions for α greater than 5°, but the pitching moment starts deviating rapidly. High-g maneuvers are expected to occur at α below 10° and near 5°. Therefore, it is anticipated that the leading-edge vortex has little effect in the flight envelope, where aeroelastic considerations are important, and probably will only impact takeoff and landing.

Flutter of the advanced supersonic transport.—The low aspect ratio, low wing thickness, and aft-mounted engines of the AST are all detrimental to flutter speed. Previous AST flutter-analysis results (ref. 5) indicate a large weight penalty of 6100 lb to avoid flutter below the analytical certification requirement of 1.2 V_D (V_D is the maximum dive speed). This is equivalent to approximately 10 percent of the payload. Because of unacceptable flutter speeds, the outboard wing could not be used for fuel storage. This corresponds to a reduction of 5 to 10 percent of the total fuel capacity. The analysis neglected transonic effects and is unconservative in predicting the transonic flutter bucket. However, the discrepancy is believed to be small, because the AST wing thickness ratio is low, the wing is highly swept, and the fuselage is very slender.

Static aeroelastic corrections.—Static aeroelastic corrections to the stability and control derivatives are important for long, slender, flexible vehicles where a large fraction of its weight is fuel. A study of this topic for the XB-70 (ref. 6) indicates a large influence on the stability and control derivatives. A dramatic variation in the derivatives exists for changes in vehicle weight from heavy to light.

Structural mode control systems.—Structural mode control systems were implemented on the XB-70 (ref. 7) and the B-1 (ref. 8). The B-1 system was required to control the large vibration levels at the pilot station because of atmospheric turbulence during high-speed terrain following flight. On both aircraft, small canards were placed near the pilot station to supply vertical and lateral aerodynamic forces. They were actively controlled by sensing pilot station acceleration levels and commanding the canards to dampen out the structural modes. This improved the ride quality in the cockpit. A substantial savings in weight was achieved with this approach as compared to direct material stiffening.

Acoustics

In addition to meeting the FAA and ICAO noise certification requirements, commercial airplanes must comply with local airport noise restrictions. The latter could be based on single or multiple monitors or noise footprints, and on single event maximum level or cumulative dosage. Compliance with these requirements can be achieved through low source noise designs of the propulsion and airframe systems and with noise-abatement flight procedures for operations in and out of airports. For example, power cutback after reaching a certain altitude is routinely used to minimize the noise impact on communities near the airport.

Additional noise-reduction benefits may be achievable at selected airports through effective thrust and flightpath management. At present, Concorde minimum-noise routes have been established, particularly at New York (JFK) and London (LHR) airports. At these airports, manual noise-abatement procedures are being performed by the crew based on time from brake release as a function of the following parameters: maximum take-off weight, temperature, and headwind component. During approach operation, particularly at JFK, the Concorde adopts an automatic decelerating technique to minimize community noise.

Airframe-Propulsion Interactions

All powered aircraft exhibit interactions between the airframe and the propulsion system (for example, the coupling of speed, attitude, and altitude through thrust and pitch control). For supersonic aircraft, especially for larger ones, the interactions are more numerous, sensitive, and complex than they are for subsonic aircraft. Moreover, the interactions strengthen as speed is increased and as systems are designed for overall optimum performance. Obviously, the interactions have a large impact on both stability and efficiency. This section discusses some important interactions that the Concorde, XB-70, and SR-71/YF-12 exhibited.

Internal inlet-engine-nozzle interactions.—A supersonic aircraft's propulsion system is comprised of three primary components–an inlet, an engine, and a nozzle. As will be discussed below, all three interact through various mechanisms.

There is a variety of inlet types (e.g., two-dimensional, axisymmetric, external compression, mixed compression, etc.). The primary function of any inlet is to deliver a specific air supply to the engine. When the inlet airflow capacity equals the engine demand, the inlet is said to be matched and, assuming proper nozzle and engine settings, the propulsion system performance is optimal. At all flight conditions, subsonic and supersonic, the consequences of not matching are significant losses of efficiency and increased drag. At supersonic flight conditions, there exists the additional risk of inlet unstart. Therefore, the goal is to always have the inlet matched. To compensate for changes in the properties of the air over the entire flight envelope (i.e., takeoff, climb, cruise, approach, and landing), the inlet is equipped with variable geometry, bleed flows, and bypass flows.

A common measure of inlet performance is pressure recovery. A typical plot of pressure recovery to mass flow ratio for a mixed compression inlet is shown in figure 11. Off-design point operation will occur if the inlet is oversized or undersized. When the inlet is undersized, engine demand exceeds inlet capacity and the normal shock moves downstream. As illustrated on the right-hand side of figure 11, the pressure recovery drops dramatically, while the mass flow ratio remains nearly constant. The downstream movement of the normal shock also causes other problems. When the normal shock moves downstream, it interferes with the boundary layer along the inlet walls. The turbulence caused by the normal shock-boundary layer interference results in distorted pressure gradients at the engine face. A distorted pressure gradient at the engine face increases for noise, reduces engine efficiency, and can lead to compressor stall. When the inlet is oversized, its airflow capacity is greater than the engine demand. The excess airflow must either bypass the engine via valves and ducts or backup and spill out the front of the inlet. Either way, drag is increased and additional aerodynamic control surface trim is required to counter the resulting forces and moments. For example, a fully opened bypass door on the YF-12 causes a 25-percent increase in drag. At smaller openings, a 10-percent increase in bypass flow results in a 2.5-percent increase in drag. Examples of countering control surface requirements are given in the next section.

As discussed in reference 12, the Concorde's wide range of flight conditions necessitates a variable geometry nozzle. The prime reason for a variable nozzle is to simultaneously achieve maximum engine speed and turbine entrance temperature (TET), hence optimize efficiency, over a wide range of intake temperatures. For a turbojet engine operating at constant speed, with a fixed nozzle, the TET will raise as the intake temperature rises. Therefore, for a fixed area nozzle, if the engine were sized

to give maximum TET at takeoff, the engine speed, and thus the mass flow, would have to be reduced at supersonic conditions to keep the TET within limits, thereby reducing efficiency. For the Concorde, the intake temperature varies from −20 °C at high altitude subsonic climb to 153 °C at Mach 2.2 supersonic cruise. Use of a variable nozzle allows a 28-percent increase in massflow at supersonic cruise compared to a fixed nozzle that is sized for takeoff. In addition to allowing efficiency to be optimized, a variable area nozzle enables thrust to be reduced to a virtually constant mass flow. This means that reduced jet velocity, hence reduced noise, can be achieved with little reduction in engine speed. The nozzle setting and the location of the nozzle also affects the aftbody drag and the fatigue of the material on which the jet flow impinges.

So far, interactions between the inlet and the engine and between the engine and the nozzle have been described. It was mentioned earlier that bleeds and bypasses are required in the inlet to compensate for variations in the air properties. On the Concorde, XB-70, and SR-71/YF-12, the bypass flow is exhausted into the nozzle. Varying the nozzle changes the back pressure, which propogates upstream through the bypass to the inlet. Thus, all the elements of the propulsion system are coupled together. As one might gather from this and the previous descriptions of inlet-engine and engine-nozzle interactions, the Concorde, XB-70, and SR-71/YF-12 all required a complex propulsion control system. Many sensors and actuators, and complex logic and algorithms were required to meet the performance specifications.

Interactions with airframe dynamics.—Experiences with the YF-12/SR-71, XB-70, F-104, and F-111 have demonstrated longitudinal and lateral destabilizing interactions, and strong forces and moments caused by unstarts and large bypass flows (refs. 2, 10, 11, 28–36). When a supersonic airplane is flying at $\alpha \neq 0°$ and $\beta \neq 0°$, the air in one side of the inlet slows down. If the throat Mach number gets close to 1, the inlet may unstart. Therefore, the geometry and bleed flows have to be modulated with the α and β. For multiengine aircraft, the bleeds are modulated independently to give the best performance.

The following incident occurred while the YF-12 was flying with a nose-right sideslip and its stability augmentation system off. The leeward, in this case the right-hand side, inlet bleed opened more than the left. The asymmetric bleed flow produced a yawing moment that increased the sideslip angle, which, in turn, caused the bleed to open further–thus creating a destabilizing lateral-directional–propulsion system interaction.

The automatic inlet system also interacts with the phugoid and height modes. The basic airplane phugoid mode had neutral damping, and the height mode was stable. With the automatic inlet system on, the phugoid was slightly divergent, and the height mode was divergent with a time to double amplitude of about 114 sec (ref. 33). The YF-12 bypass doors close with increasing Mach, decreasing drag, and increasing thrust. Similar to the previous example, unless the bypass doors are fully closed, an increase in Mach results an increase in thrust, which in turn causes Mach to increase. Thus, the automatic inlet system interacts with the airframe to reduce phugoid damping.

The propulsion system is also highly sensitive to atmospheric perturbations. A quotation from reference 9 illustrates this: "Trubshaw noted that a temperature change of 1 deg. Centigrade is worth 0.01 in Mach number, and recalled that in a sudden temperature change he found Concorde climbing

at 4,000 ft/min through 50,000 ft in what is now known as an altitude excursion." Similar incidences occurred with the XB-70 and the YF-12/SR-71 (refs. 10 and 11).

Inlet unstarts cause strong and violent lateral and longitudinal aircraft motions. The following two examples illustrate the magnitude of the forces and movements caused by an unstart and the inlet dump doors that are fully opened as part of the restart procedure. The first example happened to the XB-70 during a Mach 3 turn. Due to minor engine perturbations the left inlet unstarted; about 11 seconds later the right inlet unstarted. The change in pressure under the left wing caused by the expulsed shock and the opened bypass doors affected both the lateral and longitudinal control of the aircraft. The loss of thrust, increase in drag, and bypass door flow caused a longitudinal deceleration of about 0.1 g. Although the pilot entered corrective commands, it was estimated that the unstart movements were strong enough to cause a 2.5 g normal acceleration and a 30 deg/sec roll rate.

The second example is of an unstart on the YF-12 at Mach 2.7. The forces and movements for this unstart caused a 0.2-g deceleration, a 0.3-g lateral acceleration and a roll rate exceeding 10 deg/sec. Listed below are the roll and yaw accelerations caused by full bypass, unstart, and maximum aileron and rudder deflections for the YF-12. Note that a fully opened bypass is slightly more effective than the control surfaces, and an unstart is nearly as effective as the rudder.

	Maximum aileron	Full bypass	Unstart
Roll angular accel. (deg/sec^2)	30	35	3
	Maximum rudder	Full bypass	Unstart
Yaw angular accel. (deg/sec^2)	7.3	11	6.4

Advanced Supersonic Transport Flight Controls

From 1971–1980, DAC was under contract to NASA-Langley to perform system studies on the AST. As a part of those contracts, DAC studied control system augmentation, which included control system synthesis, analysis, and simulation efforts. Results of these studies were validated on both fixed and motion base simulators. Since the HSCT is similar to the AST configuration (see fig. 12 taken from ref. 37), most, if not all, of the AST problems and issues will be HSCT issues also. The following sections highlight the past AST efforts, with emphasis on the control system that augmented the basic airframe to provide stability and improve handling and ride qualities.

System complexity.—Modeling of the AST over its Mach and altitude operating region resulted in a high-order, complex system. Simulation of the system included nonlinearities, highly coupled dynamic subsystems, large data tables to accommodate the Mach number range, and complex equations of motion. Wind-tunnel data were used in modeling the AST for simulation purposes. These data were taken from a 1/10 scale low-speed model and from a 1/100 scale high-speed model.

Two basic math models were used in the synthesis and analysis of the AST. A full six degree-of-freedom (6 DOF), nonlinear computer simulation program was used to generate performance data. These data consisted of time histories, responses to winds, and gust disturbances; such data were used

in the validation of candidate control systems. Another computer program modeled a linear version of the AST separately in the pitch and lateral-directional axes. These perturbation models were generated directly from the 6 DOF program. The set of equations so produced represented a linear system operating at a fixed flight condition. These models were used in modern optimal control (time domain) and classical (frequency domain) designs.

Unstable aircraft dynamics.—Probably the most outstanding control issue of the AST was its unstable longitudinal dynamics in the low-speed landing approach and high-speed subsonic climb regimes. The first-order pitch axis divergence at landing had a time to double amplitude ($T2$) of 2 sec. At climb, $T2$ was slightly less than 1 sec. The analytical handling qualities evaluations and pilot opinions in a motion base simulator established level 3 (unaugmented) characteristics with Cooper-Harper ratings of 9 and 10, the worst possible ratings. These situations required a full-time, flight critical control augmentation system in pitch.

One method used to augment the AST stability in pitch and roll was implicit model following. Although the Dutch roll mode was stable, it had low damping (3 to 4 percent at landing and climb, and 12 percent at cruise). Implicit model following employed a model with desirable characteristics in an optimization procedure. This procedure minimized a weighted sum of the square of the difference between the model states and the aircraft states. Weighted also were the control states (aileron, elevator, rudder). The result was a constant-gain feedback system that approximated the responses of the model. There were several desirable features of this method, including crossfeed design (e.g., an aileron-to-rudder crossfeed path), and inclusion of added control surfaces (canards for flexible mode control). One drawback of the technique was the need to linearize the highly nonlinear AST at specific flight conditions. Piecewise synthesis resulted in different designs at specific points, implying a requirement to develop a gain schedule to accommodate all conditions. Robustness should be a consideration in selecting a technique for future HSCT control system studies.

Examples of the control laws generated using implicit model following are shown in figures 13 and 14 (ref. 38). The block diagram in figure 13 represents the longitudinal control law for a landing approach flight condition. Control inputs were to the column and throttle, and constant feedback gains provided the stability compensation for this condition.

The block diagram in figure 14 is the lateral control law for the same landing approach condition. The unaugmented lateral case was stable, but the Dutch roll mode, being lightly damped, required augmentation. Both feedforward and feedback gains were used in this control law, which included crossfeed between the wheel and rudder pedals. The longitudinal and lateral control laws, derived from the low-order linear models, were subsequently verified in the 6 DOF nonlinear simulation program.

Another method of control system synthesis employed in the longitudinal landing approach case was the use of classical techniques to design hard stability augmentation systems. These systems were designed to provide simple, reliable backups in case of primary augmentation system failure. One augmentation system used three gains in the throttle and horizontal tail feedback loops. The second system added proportional plus integral control in the horizontal tail loop, and an input control loop to provide autotrim. The features of classical design methods (gain to phase margins, etc.) were employed to validate the resulting design.

Ride and handling qualities.—The AST, being a long slender aircraft, exhibited undesirable handling and flying qualities and poor ride qualities. The motion at the pilot station was considerable during maneuvering, even in the rigid body cases (flexibility effects only made the situation worse). At normal landing speeds and weights (140 kn and 450,000 lb), the pitch angle was greater than 10°. This angle, coupled with the long distance between the center of rotation and the pilot station (100 ft), caused objectionable accelerations during pitch changes and bank angle changes. Passenger comfort was also affected, especially in the far forward and far aft cabin locations. As a consequence, handling and ride qualities improvement (using active control) were necessary at landing and high-speed climb conditions. The ride qualities were evaluated using a motion base simulator configured to emulate aft seating locations. The static aeroelastic effects (but no flexible mode dynamics) were included in the simulator math model. Subjects were asked to answer questions expressing their opinions on ride acceptability at various locations in the aircraft and at different turbulence levels.

An example of handling qualities improvement that the augmentation systems provided is shown in figure 15 (ref. 38). Several pilots were given landing approach tasks on the motion base simulator for several system configurations. Configurations 1 and 6 were unaugmented (unstable in pitch). The resulting pilot ratings reflect their inability to control the pitch instability. Configurations 2–5 were for various augmentation systems, and were included to rate the different systems. The overall conclusion is that augmentation can provide acceptable to satisfactory ratings, which would otherwise be unacceptable with no augmentation.

In figure 16 (ref. 38) are the results of a ride qualities evaluation using the motion base simulator. All results are with the full augmentation system engaged. Three turbulence levels were simulated (none, light, and moderate). With no turbulence, a comfortable to neutral rating was received, whereas turbulence produced neutral to uncomfortable ratings. The location of the passengers did not seem to be a factor; the ratings were similar at all three locations.

Although no takeoff studies were conducted on the AST, this flight condition most probably would have required handling qualities improvement, especially in a gust environment and programmed lateral and vertical path control for noise abatement. The HSCT will exhibit similar handling and ride qualities deficiencies, and will require control augmentation for improvement.

Flexible aircraft dynamics.—A critical flight condition for the AST in which flexible effects were important was the high-speed subsonic climb condition (Mach 0.6, 5000-ft altitude). Longitudinal aerodynamic and structural mode data were used with a linear perturbation model to synthesize a mode suppression system and to analyze the performance.

A twenty-first-order linear model was used in the analysis. It consisted of 4 rigid body states, 2 actuator states (elevator and canard control), 3 wind gust states (α gust and forward velocity gust), and 12 states representing the first 6 flexible modes (second order each). Implicit model following was used to synthesize the feedback and feedforward gain for this system. Implementation of a full-state feedback system was deemed too complicated, so an order reduction technique was used to yield an eighth order system. The rigid body, actuators, and the first (lowest frequency) flexible mode states were retained. Since direct measurement of the flexible mode states for feedback purposes is not feasible, a state estimator was used to reconstruct these states. Observer theory was used, where the rigid body and actuator states were provided as inputs to the observer, and the first mode flexible

states were the output. Difference equations were then developed for this observer. These equations, used with the differential equations of the continuous aircraft dynamics, provided a hybrid simulation capability for this climb case.

The general block diagram for the flexible mode control law is shown in figure 17 (ref. 38). The elevator and canards were used for control, where the input canard signal was proportional to the column signal. Feedback to these two actuators was derived from the implicit model following technique. There were six direct feedback signals and two indirect ones derived from observer theory.

Performance analysis of the augmented system was accomplished with the full twenty-first-order model. The augmented characteristics of the climb case included a short period mode about 0.7 rad/sec with the first flexible mode frequency at 6 rad/sec with 0.1 damping. After augmentation, the short-period frequency was 1.4 rad/sec with the first mode at 7 rad/sec with 0.5 damping.

An example of the performance improvement with the flexible mode control system is shown in figure 18 (ref. 38). Shown is the spectral density of the normal acceleration (as a function of frequency) at the pilot station for an α gust input. With the mode control system engaged, the short period and first bending modes were suppressed by a large amount, and the fourth bending mode reduced somewhat. The other flexible modes had damping large enough so their effects are not evident on this figure. Flexible characteristics of the HSCT are expected to be similar to the AST, and appropriate synthesis techniques will be needed to provide flexible mode control and handling qualities improvement.

High-Speed Civil Transport Control Requirements

To identify the critical guidance and control system issues, a clear understanding of the control system requirements and the aircraft characteristics is needed. In this section, the HSCT configuration is considered relative to the supersonic aircraft characteristics presented in the previous section.

Configuration

The primary candidate for an economically viable and environmentally acceptable HSCT is a vehicle cruising at Mach 2.4. Advanced technology and key design features are shown in figure 19. The advanced flight control system uses a fly-by-light and power-by-wire technology concept. Early development of the control technologies—for propulsion controls, high-lift systems, and flight controls—will support the NASA High-Speed Research Program and the airplane certification goals of 2005.

Aerodynamic Stability and Control

The HSCT configuration is similar to the AST. Both share a cranked-arrow wing with trailing edge flaps and a conventional empennage. Noteworthy differences are the lack of a droop nose, and the inclusion of c.g. management. The latter is not really required from a stability standpoint, but it offers further fuel-burn improvements. Also, new high-lift concepts are being considered for the HSCT, such as leading-edge blowing, suction, and vortex flaps, with trapped vortex flaps on the wing upper

surface. Further, alternative low-boom configurations feature massive wing strakes that extend all the way to the radome (or canards), and highly swept outer wing panels.

Pitch requirements.—The stabilizer and elevator must have sufficient performance to satisfy the following requirements:

- Nosewheel lift-off,
- stability augmentation,
- landing trim,
- flare and go-around pitch acceleration, and
- stall recovery pitch acceleration.

Of these, the critical item is nosewheel lift-off, since it demands the highest control power. The remaining requirements can be easily met by virtue of the tail's excellent performance in the strong downwash field of the cranked-arrow wing and fuselage. The stability augmentation system will benefit from the excellent elevator linearity. However, elevator linearity at transonic conditions has not been verified in AST wind-tunnel tests.

Very little information is available on exotic flaps or low-boom planforms. The low-boom configuration could have serious deep-stall problems that could require more pitch control power and a robust α limiter.

Directional requirements.—Again, the HSCT is similar to the AST. The nondrooping nose will change the directional stability at high α, but should have no effect on the directional control. The vertical tail and rudder must have sufficient performance to satisfy the following requirements:

- Takeoff engine-out control; minimum ground control speed (V_{mcg}), and minimum air control speed (V_{mca}),
- stability (dutch roll), especially supersonic,
- supersonic inlet unstart compensation,
- landing crosswind de-crab,
- landing engine-out control; minimum landing control speed (V_{mcl}), and
- landing roll-out control in reverse thrust.

Currently, the HSCT tail size is set by V_{mcg}, which requires high rudder power. The other maneuvers are not as critical for the same reasons given in the AST discussion. However, no evaluations were made of controllability in reverse thrust. As with the elevators, the rudder is a linear controller, except possibly at transonic conditions, for which no AST data are available. Note, however, that the Concorde rudder operates successfully despite its unswept hinge line. This is probably because the fin is normally not loaded, unlike the horizontal which must carry a trim load. The low-boom configurations that employ canard surfaces may suffer from high α directional instabilities, depending on whether the canard is a fixed box with a hinged elevator, or is an all-flying surface.

Lateral requirements.—The HSCT will be similar to the AST, unless vortex high-lift devices are incorporated. The lateral controls must have sufficient performance to satisfy the following requirements:

- Takeoff engine-out control V_{mca},
- low-speed roll rate,
- stability (spiral mode, roll subsidence),
- supersonic inlet unstart compensation,
- landing crosswind de-crab, and
- landing engine-out control V_{mcl}.

As with the AST, the critical considerations are crosswind de-crab and supersonic unstart compensation. However, the linearity of the SSDs in supersonic flight and their effectiveness in the presence of an unstart bow wave were not evaluated in testing of the AST. The low-boom layout will change the basic lateral stability, but no unique lateral control problems are expected.

Aeroelasticity

The HSCT integrated flight–propulsion control system is expected to include the following capabilities: (1) stability and control augmentation, (2) structural mode control, (3) flutter suppression, (4) gust load alleviation, and (5) maneuver load alleviation. Control synthesis, analysis, and test and validation of these additional capabilities require a combined rigid body and elastic body aeroelastic plant math model. Each of these capabilities has been demonstrated independently, either in a wind-tunnel test or during flight test for several aircraft configurations. But, they have not been validated or demonstrated collectively, i.e., all at the same time on one aircraft, either for the HSCT or any other configuration.

Leading-edge vortex effects.—The HSCT configuration is similar to the AST configuration. Therefore, the statements made in a previous section concerning the leading-edge vortex are valid for the HSCT. To reiterate, the leading-edge vortex has little effect on 1-g flight conditions except for the lowest flight speeds where α is high. Current theories of unsteady aerodynamics that neglect the leading-edge vortex should be adequate to predict the unsteady air loads on the HSCT at these flight conditions. However, the leading-edge vortex will have an effect on takeoff and landing, initial climb, 2.5 g maneuvers, and possibly atmospheric gust conditions.

Subsonic cruise is expected to occur at α near 5° and supersonic cruise at lower α. Therefore, it is anticipated that the leading-edge vortex will have little effect on 1g flight conditions except for the lowest flight speeds where α is high. However, it will have an effect on takeoff and landing, initial climb, 2.5 g maneuvers, and possibly atmospheric gust conditions.

Flutter and its suppression.—Because of the similarity of the AST and HSCT, the statements made in the previous section concerning the AST flutter speed are valid for the HSCT. A large weight penalty equivalent to 10 percent of the payload may be required to (passively) satisfy the flutter-speed certification requirement by stiffening the wing. Flutter-speed constraints might require the elimination of fuel in the outboard wing, resulting in a 5- to 10-percent loss in total fuel capacity. Previous AST flutter results neglected transonic effects, and are therefore unconservative. There is a high probability that the HSCT will be flutter critical, and an active flutter-suppression system should be developed to avoid the weight penalty and to increase the fuel capacity.

Static aeroelastic considerations.—Making static aeroelastic corrections to the stability and control derivatives is important for the HSCT. Its fuselage is much longer than that of the XB-70 discussed previously, i.e., 318 ft as compared to 186 ft. Their fuselage slenderness ratios are similar. The XB-70 was sized for the high-g maneuvers to meet military requirements, while the HSCT will be sized by the lower g maneuvers to meet commercial transport requirements resulting in a more flexible vehicle. The wide variation in vehicle weight because of the HSCT's large fuel weight fraction will create large variations in the stability and control derivatives during flight.

Structural mode control system.—The reduction of vibration levels and improvement in the ride quality of the HSCT's crew and passengers during atmospheric turbulence will be very important, possibly mission critical. A structural mode control system will most probably be required to achieve acceptable comfort levels. The HSCT's fuselage length is more than double that of the B-1 discussed previously, i.e., 318 ft as compared to 146 ft. Their fuselage slenderness ratios are similar. The HSCT will be more flexible than the B-1, because it will be sized for lower g maneuvers. This flexibility will aggravate the HSCT vibration levels and ride quality, and will increase the need for a structural mode control system. The structural mode control system also will help to extend the vehicle fatigue life.

Laminar flow control.—Laminar flow control is planned for HSCT operation at cruise and possibly upper level climb. Including this effect in the aeroelastic plant math model will reduce the uncertainty of the model. Laminar flow control reduces viscosity effects on the aerodynamics of the system. This will make current inviscid analysis methods of unsteady aerodynamics more acceptable.

Gust load alleviation system.—The FAA is considering a change in the regulations that will require designs to accommodate dynamic gust loads significantly higher than today's design load requirements. Such a change will be very critical to the HSCT, and will probably require a gust load alleviation system. Even if the regulations are not changed, a gust load alleviation system will still be desirable to reduce structural weight, extend vehicle fatigue life, and improve the ride quality of the crew and passengers. This system should work with the structural mode control system.

Spoilers.—The addition of SSDs and ISSDs along with conventional trailing edge control surfaces is being considered for the HSCT. The SSDs and ISSDs will be used for roll control and (possibly) gust and maneuver load alleviation. The unsteady aerodynamic forces caused by spoilers are generally not well known; even less is known about the unsteady effects of the SSDs and ISSDs.

Aerothermoelasticity.—The aerodynamic heating of the HSCT operating supersonically will cause temperature variations throughout the structure because of heat transfer, and will change the elastic characteristics of the structure. Elevated temperatures modify material stiffness properties

resulting in a softer structure; while thermal loads caused by differential expansions result in a stiffer structure. These effects will modify the flexible mode shapes and their natural frequencies.

Acoustics

The HSCT is expected to use thrust and flightpath management to control airport and community noise in a way that is similar to current subsonic aircraft. The propulsion system includes a variable-cycle engine that will achieve improved acoustic performance at takeoff and improved propulsive efficiency at cruise. The engine controls will permit this variation in engine cycle. In addition, the flight guidance control system, e.g., the inertial navigation system, will be an important system for achieving minimum noise routes. Differences in subsonic aircraft performance, and the resultant differences in acoustic performance, may require special routing for HSCT. There also may be a need to optimize the subsonic climb-to-cruise leg (up to Mach 1), so that community noise is reduced compared to the stage 3 fleet, which will be in existence after the turn of the century.

Airframe-Propulsion Interactions

All airframe-propulsion interactions described in a previous section will be experienced by the HSCT. In fact, the advanced technologies, strategies, and operating procedures being pursued for economic viability and environmental acceptability will reinforce them, and introduce additional ones.

Internal inlet–engine–nozzle interactions.—The HSCT will have four under-the-wing mounted nacelles. Each will contain a variable geometry, mixed compression inlet; a variable cycle engine with low NOx combustors; and a convergent-divergent, variable area nozzle with noise suppressors. To improve fuel efficiency and reduce emissions, the propulsion system will operate with reduced stability margins and at elevated temperatures. Consequently, the sensitivity to internal and external disturbances will be increased, requiring a more precise and faster acting control system. In addition, the variable cycle engine concepts being considered, e.g., the fan on blade (FLADE) or turbine bypass engine (TBE), have many more effectors, i.e., actuated variables. An example is a bypass system with its own convergent-divergent nozzle and translating shroud.

Interactions with airframe dynamics.—As discussed in a previous section, the forces and moments generated by the propulsion system will have a large impact on the flight-control system. During normal operations, the variable geometry of the propulsion system will require consideration in the design of the flight-control system. Likewise, the propulsion control system will require knowledge of the flight-control system. The interactions will be even greater for the HSCT; unlike the YF-12/SR-71, the XB-70, and the Concorde, the HSCT is designed to be longitudinally unstable. By purposely making the aircraft unstable, the control system must be faster and stronger, or a reduction in vehicle performance, e.g., ride and handling qualities or trajectory tracking, must be accepted. The key issue here is the interaction and coupling of both systems. An accurate math model including the interactions needs to be incorporated into the control synthesis process during the initial and on-going design phases of the HSCT.

Abnormal operation (e.g., unstart) may cause even more severe problems for aircraft control. Sensing and accounting for these abnormal and emergency situations place added requirements on the control

system. Safe control of flight and preventing the aircraft from entering dangerous flight regimes are some issues in integrated flight–propulsion control system design.

Flightpath Management

All control augmentation issues discussed in a previous section for the AST will apply to the HSCT because of the similarities in configuration of the two aircraft. There are several issues that were not considered for the AST system studies that will be important to HSCT. These issues include flightpath management concepts (control of landing paths and takeoff flight profiles), fuel management (to control the c.g.), and the impact of structural materials (especially composites) on the controllability of the aircraft. The next paragraphs discuss the control issues unique to the HSCT as a result of configuration differences between it and the AST, and the integrated design approach to developing its flight-control systems.

Flightpath management concepts.—Control of the terminal area flightpaths of an HSCT will require special considerations. The HSCT traffic must be mixed with other subsonic aircraft. This mixing includes integrating HSCT's transition from supersonic routes over water to subsonic legs over land with all other traffic. Though the HSCT landing speeds will be comparable to subsonic aircraft (140–150 kn), special consideration of routes is necessary to satisfy noise abatement and for maintaining adequate aircraft spacing. Whatever the guidance concepts employed (ILS, MLS, GPS), the routes stored in the airborne computer may be unique to HSCT. For example, four-dimension guidance may be necessary to integrate the less-frequent HSCTs into the more frequent subsonic traffic. In addition, the HSCT, with its synthetic vision capability, will be capable of landing in very low or no visibility conditions. This landing capability will affect the lateral and vertical flightpaths for HSCT and must be considered in the design of the on-board landing guidance system.

Another unique flightpath management concept for HSCT is the modulation of flaps, slats, and engine control during takeoff. Design considerations may dictate a vertical flight profile that can be achieved only by implementing new techniques during takeoff. Design considerations, safety, and certification are some of the issues of flightpath management for departures.

Fuel management systems.—Fuel management to control the c.g. location will be a full-time system on the HSCT. There are several impacts of fuel management on the flight control system. Control of the c.g. will help in maintaining the desired stability of the aircraft as the fuel is depleted. Moving fuel to other locations will also cause the structural properties to change. The weight and inertia (and therefore damping and frequency) of the structure will change with the amount of fuel. The control system must be designed accordingly. Drastic shifts will require an adaptive scheme with multiple sensors, while minor shifts can be handled with robust control concepts. There are limits on how fast the fuel can be transferred, and this rate will affect the frequency of the system to be controlled. Fuel sloshing also may be an issue, but probably not a major one if there are many (10–20) separate tanks and adequate baffling to reduce fuel movement.

Since a large percent of the total takeoff weight is fuel, there will be a big difference in the characteristics of the aircraft between takeoff and landing. The control system must account for this change, and may require gain scheduling or other techniques to cope with changes in rigid body and

structural dynamic characteristics. Because the weight change is slow, there is no major control issue; however, this condition needs to be considered during the control system design.

Control system–composites interaction.—Composite materials will be used on the HSCT in secondary structures (such as control surfaces) and in the primary structure. Inclusion of a large amount of composites will change the stiffness and natural frequency of the structure. The flight control system must control the aircraft flexible modes, whose frequencies could be significantly different from those of the AST. Adequate math modeling of the structural dynamics for an aircraft system with composites is required, and their impact on the control laws must be considered in the design phase.

Control Design Technology and Methodology Issues

In this section the technologies and methodologies required for designing and analyzing the control systems for the HSCT are discussed. Each required technology and methodology is examined to identify which is sufficient and which needs further research and development for a successful HSCT. The shortcomings are summarized, and the development plans, which are presented in a later section, are briefly discussed. The organization is the same as in previous sections.

Aerodynamic Stability and Control

Since the HSCT's shape is so similar to the AST's, there is a wealth of wind-tunnel test data for all but transonic conditions. Various NASA cranked-arrow configurations have been tested as well, providing more information on canard and twin fin control layouts. The major uncertainties relate to exotic high-lift systems and low-boom planforms.

The state of the art in computational fluid dynamics (CFD) is such that we can predict many aerodynamic stability and control terms in the absence of separation. Panel methods are useful for subsonic conditions, and are not confined to simple configurations. In fact, we can evaluate the complete wing–body–nacelle and empennage with flaps including power effects. The panel methods are accurate up to the onset of significant trailing-edge separation, and they are valid all the way up to stall when the wing is leading-edge stall critical. The effect of leading edge vortices and flaps can be modeled by the Carlson code, which is based on linear theory with empirical vortex modeling. Transonic full potential methods and Euler solvers are valid up to normal Mach numbers of 1.4+ with no separation, but the geometry must often be simplified because of limitations in the computational grid. The AIRPLANE Euler code promises to overcome these grid limitations by using an unstructured tetrahedral grid. Thin-layer Navier-Stokes codes can model separation, but are generally limited to simple geometries.

The aerodynamic stability characteristics of the HSCT are fairly well understood. The airplane will be unstable in pitch at low speed over the operational α range. Yet, the level of low-speed instability falls well within the time-to-double-amplitude experience that the industry has with high-performance fighters; 1 sec for the HSCT in comparison with 0.2 sec for modern fighters. The HSCT will be statically stable in the transonic and supersonic ranges.

Directionally, the HSCT is neutrally stable at very high α, and slightly unstable at high Mach number. Again the level of instability is well within industry experience, if the control effector (i.e., rudder) is linear and has sufficient authority.

The HSCT rudder and elevator control surfaces are surprisingly well behaved control effectors. A typical subsonic transport suffers from a variety of nonlinear control issues related to shock-induced separation or stalled wing wakes engulfing the tail. This is not so for the HSCT, which has a wing that does not truly stall by virtue of its high leading-edge sweep, and tail surfaces that do not have strong normal shocks at trim. The transonic performance of the elevator still needs to be validated. However, this is not a critical technology issue, since any problems can be easily addressed through hinge-line sweep changes.

No test data exist for HSCT-like configurations in reverse thrust. The concern is loss of directional control during landing roll-out or a rejected takeoff while on a wet or icy runway. Fortunately, the cascade-type reversers envisioned for the HSCT allow efflux tailoring to limit tail interference. Consequently, this is not seen as a critical technology issue but a product development issue.

The spoilers and SSDs are not as well behaved as the elevator and rudder. The NASA/DAC-AST wind-tunnel tests revealed some unusual subsonic spoiler characteristics. The spoilers performed poorly at low flap settings, and the SSDs were fully reversed. The latter is not a concern, since they are not intended to operate at these speeds. However, little data exist for the SSDs supersonically, especially in the presence of an unstart bow wave. Wind-tunnel evaluation is needed to determine if the SSDs are adequate for unstart roll compensation, and if not, to develop an option such as asymmetric elevator or relocated SSDs. This is a borderline issue that is probably not critical for technology readiness, since it would not have a significant configuration impact.

Significant questions exist regarding advanced high-lift systems. If some form of vortex trapping is used (beyond the leading-edge vortex flows where we have experience), then we need more low-speed wind-tunnel tests for technology readiness. This information will be needed 2 years prior to engineering ATP if such devices are desired for the HSCT. The key issues will be

- Lateral control effectiveness in the presence of these devices;
- transitional lift, moment, and drag, during deployment;
- vortex stability in the presence of pitch, roll, and yaw rates; and
- vortex trajectories relative to the tail surfaces.

The low-boom planforms are so different from the AST that a major wind-tunnel test program would need to be completed two years prior to engineering ATP. The testing required for stability and control analysis is most critical in the low-speed regime, and should at least cover the following:

- Basic pitch and yaw characteristics, at various flaps,
- pitch and directional trim and control effectiveness, and

- deep-stall characteristics.

In summary, previous SST studies and test data have eliminated most of the critical technology questions for HSCT stability and control. However, if exotic high-lift systems or low-boom planforms are selected, we will need to begin a major wind-tunnel test program.

Aeroelasticity

In this section, the technologies and methods used for aeroelastic analysis are examined. First, a brief description of the state of the art is given. Next, the shortcomings of the technologies and methods are identified. The shortcomings are summarized, and the development plan for each is briefly discussed.

State of the art.—The current state of the technology in aeroelastic analysis includes separate unsteady aerodynamic and structural analyses, and a splining procedure to permit interaction between them to perform the aeroelastic analysis.

The unsteady aerodynamic analysis works like this: traditional lifting surface theories determine the frequency dependent magnitude and phase of the aerodynamic force over a lifting surface element caused by motion of another element. These forces are generally weighted to match wind-tunnel data at the steady-state condition. More modern CFD methods perform numerical integration to solve the governing equations in time; CFD methods are usually more computation intensive compared to lifting surface analysis, and are not widely used for production work.

In a structural aerodynamic analysis, generalized coordinates consisting of a reduced set of flexible, natural mode shapes are derived from simple beam stick models or more complex finite element models. The analytically derived mode shapes, natural frequencies, and damping are validated through full-scale ground vibration testing. Modern finite element methods for structural analysis are also available; these permit application of time varying loads to a deforming structure.

Aerodynamic data are passed to the structural analysis module by a splining procedure. This allows the models for the aerodynamic and structural analyses to be developed based on their individual algorithm requirements.

Structural and unsteady aerodynamic analyses are deemed adequate for analyzing the HSCT for most of the normal operating conditions. For structural analyses, complex finite element models can accurately determine natural frequencies and mode shapes for a given fuel and payload distribution. MSC/NASTRAN can determine the effect of a prescribed temperature distribution by solving the heat transfer problem to obtain internal structural temperatures. It can then solve the normal mode problem while accounting for material stiffness variation with temperature and differential stiffness caused by thermal loads.

For unsteady aerodynamic analyses, lifting surface theory with weighting is expected to be adequate for subsonic flow, using the doublet-lattice method (DLM), and supersonic flow, using the harmonic gradient method (ZONA). For further refinement and to estimate the importance of transonic effects, the computational aeroelasticity program – transonic small disturbance CFD code is well suited for the HSCT configuration.

Shortcomings of the state of the art.—The shortcomings of the state of the art for aeroelastic analysis of the HSCT are confined to three topics. Traditional responsibility for an aircraft's rigid body behavior resides with a stability and control group, while responsibility for flexible body behavior resides with a dynamics group. The rigid body portion of the flexible body model attempts to predict the stability and control specified rigid body behavior. The methodology to blend adequately the rigid body and flexible body models together into one unified aeroelastic plant math model needs improvement.

Many potential aeroelastic systems that might be used on the HSCT have been demonstrated individually in wind-tunnel or flight tests, but not collectively. A free-flying, flexible, wind-tunnel model, flight test drone, or flying prototype of the HSCT configuration combining the stability and control augmentation, flutter suppression, structural mode control, gust load alleviation, and maneuver load alleviation systems must be used to verify the complete system.

Very little steady and unsteady aerodynamic data and analysis capability are available for spoilers, SSDs, and ISSDs. Wind-tunnel tests and enhanced analysis capabilities are needed to obtain this information. In addition, the role of viscous effects must be assessed in transonic flow conditions using more advanced CFD methods.

Another topic of concern, but not necessarily a shortcoming of the state of the art, is the underutilization of emerging methodology. Recent advances in multidisciplinary optimization techniques permit the optimization of aeroelastic systems, including the control system, to further enhance the overall vehicle design.

Four issues.—Four topics make up the critical aeroelastic technology issues associated with aeroelasticity: (1) separate rigid and flexible-body analytical models, (2) undemonstrated integrated control of unstable, flexible aircraft, (3) lack of unsteady aero data for SSDs, and (4) underutilization of multidisciplinary optimization.

Plan with tasks and schedule.—The first critical aeroelasticity issue to resolve for the HSCT (separate rigid and flexible-body analytical models) will require two to three man-years of industry effort to complete the following tasks: (1) identify methods, (2) evaluate methods, (3) implement best method, and (4) validate. This issue must be resolved by the time HSCT hi-fidelity modeling starts, which is assumed to be one year prior to engineering ATP.

To demonstrate integrated control of unstable, flexible aircraft will require a wind-tunnel test or flight test, either a drone or preferably a prototype HSCT. Because of the expense, this task will not be initiated until after engineering ATP, but it should be completed prior to program ATP to evaluate the alternatives if shortcomings are identified.

To resolve the third critical aeroelasticity issue (lack of unsteady aerodata for SSDs) will require 6 man-years of NASA and industry effort to complete the following tasks: (1) add SSD and ISSD capability to CFD, (2) wind-tunnel testing, and (3) correlate CFD with test data. This issue should be resolved by the start of HSCT hi-fidelity modeling, assumed to be one year prior to engineering ATP.

To resolve the fourth critical aeroelasticity issue (underutilization of multidisciplinary optimization) will require three to 4 man-years of industry effort to complete the following tasks: (1) review existing methodology, (2) develop/refine methodology, and (3) demonstrate methodology. This issue should be resolved by engineering ATP to impact the HSCT.

Acoustics

McDonnell Douglas has developed an all-engine flightpath community noise (AEFPNOIS) computer program that estimates the noise levels at the airport and community monitors and takeoff and landing performance for a given initial configuration and operational procedure of the aircraft. This PC-based program has been provided to certain airlines for preflight planning guidance.

It would be desirable to extend AEFPNOIS to a tool that would provide optimal takeoff and landing procedures for the lowest community noise exposure for any given set of airport restrictions and noise monitor locations. Such operational optimization would include the following:

1. Takeoff and landing weight,
2. Takeoff and landing flap settings,
3. Flap retraction during second-segment climb,
4. Takeoff and landing speed,
5. Initial cutback altitude (optimized using inertial navigation system and noise-power-distance database),
6. Cutback power management, and
7. Enroute (far-out monitor) climb.

As part of crew planning, the ambient ground conditions, i.e., maximum takeoff weight, temperature, and headwind component, could be entered in a program containing a database of airport specific requirements and noise monitor locations (limits). The noise model would provide an alternative noise-abatement procedure in addition to expected community noise levels, which could be furnished to an airport noise abatement office for continued good public relations for the particular carrier.

As part of preliminary aircraft design, especially for HSCT applications, the model could be used to optimize a takeoff procedure for proposed acceptance in compliance with current and future noise certification requirements. If such a procedure was judged safe for flight and included in the aircraft flight management system for "routine" takeoff operations, the FAA, JAA, and ICAO might be more willing to accept such noise-related automated operational procedures.

Airframe-Propulsion Interactions

This section discusses the technologies and methods required for designing control systems for the propulsion system and for integrating the flight and propulsion systems. Four levels of control can be considered. The first, or outermost, level specifies the optimum flightpath. The second determines the

optimum aircraft attitude along the trajectory. The third integrates all the aerodynamic and propulsive forces and moments required to trim the aircraft attitude. The fourth level performs stability augmentation, disturbance rejection, and noise attenuation.

Inlet–engine–nozzle integrated control—Because of the high level of interaction, integrating the control of the inlet, engine, and nozzle at the third level, i.e., trim and stability, can significantly improve the overall performance. Throughout the 1970's, much work was performed in the area of improving the shock position stability of mixed compression, axisymmetric inlets by way of active control of bleed and bypass systems (ref. 14–22). This work was directed primarily at the YF-12/SR-71, and dealt with only the inlet and was successful in developing a system that virtually eliminated unstarts and reduced inlet stability margins. Additional work was performed on integrated inlet–engine control, but the concepts were not flight tested (refs. 23 and 24).

For the HSCT, it is necessary to perform research to identify the performance characteristics of the inlets being considered that will identify the inlet stability margins required to achieve the desired performance. This research must also consider the control system hardware, e.g., sensors, actuators, processors, and performance requirements. Sufficient data and inlet math models exist for an analytical study to give results accurate enough for preliminary purposes. The research should be performed as part of the inlet selection process.

Since the mid-1980's, the NASA Dryden Flight Research Facility has sponsored the highly integrated digital electronic control (HIDEC) flight research program (refs. 39–41). Two engine control modes and two systems that integrated the inlet, engine, and nozzle were developed. The first engine control mode is called the adaptive engine control system mode, and trades stall margin for thrust by increasing engine pressure ratio at constant airflow when inlet distortion is low; equivalently, fuel flow can be reduced by keeping thrust constant and reducing the throttle setting as EPR increases.

The second engine control mode is called the extended engine life mode, and increases engine life by reducing turbine temperature at constant thrust by increasing engine pressure ratio while decreasing airflow. The first inlet integration system trims the inlet ramps to improve performance. The second inlet integration system is called performance seeking control, and it contains a Kalman filter that estimates the values of certain engine performance parameters and updates a built-in engine model to match the actual engine (refs. 42 and 43). As this is done the control algorithm optimizes the combined propulsion-airframe system performance.

All the HIDEC modes just described did not improve performance as much as predicted. The consequences of not matching predicted levels for a research program are not severe. However, for a production program the consequences are very costly. Therefore, the accuracy of propulsion system performance prediction models must be improved. This work must be completed in time for the advanced modes to be developed to a point to allow performance guarantees to be given to airlines when authority to offer (ATO) is given. Depending on the airline orders, ATO precedes program authority to proceed (ATP) by about a year.

Before the development of advanced modes, e.g., performance seeking control, the benefits must be identified, and weighed against the costs and risks. This analysis will probably have to be performed with existing performance models since the improvements to the prediction models are not expected

before development begins. The benefits, costs, and risks need to be identified about three years before engineering ATP to allow time for development of the advanced modes.

The robustness of the HIDEC advanced control modes is unknown. The synthesis and analysis did not include a measure of stability margin. It is necessary for safety and risk reduction to have robustness. It is best to be able to design it into the system, while existing systems also need to be analyzed. A significant effort will have to be made to develop robust adaptive control synthesis and analysis tools and methods. The best case scenario is to have the synthesis tools available for the development of the advanced modes. The minimum requirement is to have the analysis tools available toward the end of development.

Integrated flight–propulsion control.—One important issue for HSCT is the implementation of an integrated flight–propulsion design. The architecture for an integrated system definition will require inputs from several engineering technologies. These inputs must be interfaced in such a manner that the control system design can be formulated and implemented successfully. The major issue in this undertaking is the ability of each member of the design team to contribute to the project goal. This goal is to formulate a control system that accounts for as many interactions as possible. This formulation must take place early-on in the design process to be viable. Architecture definition should be developed in a two year period beginning in early 1992. Preliminary data can facilitate the architecture definition, if detailed math models are not available at this time. A preliminary architecture definition should be complete by the end of 1993.

Control Augmentation and Flightpath Management

Controlling unstable, flexible aircraft.—Controlling an unstable aircraft through augmentation will require extending present techniques to satisfy constrained optimization problems. These constraints, often conflicting, present problems to the system designer when an integrated design is to be achieved. After the component systems have been modelled with sufficient accuracy, the tools to synthesize an integrated control system must be chosen and used to complete the design. This selection is the major issue in designing controls for an unstable, flexible aircraft. Because of the critical nature of this system development, a three and one half year effort will be required, beginning as soon as the math models are available, but not later than mid-1992 to meet the engineering ATP milestone.

Flightpath management.—Noise abatement and enhanced operating procedures will be a requirement of the flightpath management system. The constraints for both takeoff and landing profiles must be clearly defined to formulate the controls problem. The requirements issue here is to determine what flightpath will be required for the HSCT. The synthesis–analysis issue is to solve the problem in a manner that satisfies all the constraints imposed on the system. Safety of flight, certification, ATC procedures, and man-machine interfaces are all issues that will drive the flightpath management problem.

The noise abatement task will be addressed by identifying the noise criteria and applying it to the HSCT. The main milestone of this task is the establishment of the requirements. The operating procedures task will encompass establishment of the takeoff and landing constraints, which will then lead to synthesizing the optimal trajectories for the flightpath management system. Both these tasks can be in parallel, and should take about one and a half years. These tasks should start at the

beginning of 1992, but this timing is probably not critical. However, if serious problems in implementing these management concepts are encountered, there must be time to complete the synthesis, analysis, and validation tasks. The final verification phase of the flightpath management system should be complete three years after start of the requirements phase.

Fuel management.—Center of gravity control and control of the aircraft to account for different characteristics between takeoff and landing can be parallel efforts. A one and a half year schedule seems appropriate for these tasks, where the milestone of having the control architecture developed should be at the end of 1994.

PRIORITIZATION OF THE DESIGN AND ANALYSIS ISSUES

Seventeen critical issues were identified in the previous section. Many of them are interrelated, and some of them depend on the results of the research that needs to be performed to address other issues. For example, if studies indicate that using advanced control modes significantly improves performance, then it is necessary to develop the synthesis and analysis tools for robust advanced control modes. All of the issues are listed in the following:

- Define advanced high-lift system stability and control characteristics.
- Define low-boom planform stability and control characteristics.
- Develop a unified rigid and flexible body analytical model.
- Demonstrate integrated control of unstable, flexible aircraft.
- Generate unsteady aero data for SSDs.
- Use multidisciplinary optimization.
- Extend noise prediction program to provide optimal procedures.
- Define the benefits and costs of reduced inlet stability margins.
- Develop robust advanced control synthesis and analysis tools.
- Define benefits and costs of advanced control modes.
- Define the reduced inlet stability control system architecture.
- Improve propulsion system performance prediction models.
- Develop constrained optimization synthesis and analysis tools.
- Define the takeoff and landing profile constraints.
- Develop aircraft controls for large fuel fraction variation.
- Develop the integrated flight–propulsion control system architecture.
- Define large transport flying quality criteria.

A quantifiable prioritization of the issues was not undertaken for this study. There are several reasons for this. First, the HSCT is not defined adequately to perform the studies required to generate the performance data for evaluation. Second, even if the HSCT were adequately defined, the time required to complete such studies is far beyond the period of this study. Finally, it was decided that numerical results from the application of one technology on another aircraft or predicted in a research program could not be considered valid and accurate for the HSCT.

Given that a quantifiable prioritization was not undertaken, the obvious alternative is a qualitative prioritization. Three priority levels were defined: mandatory, highly beneficial, and desirable. A three-stage process was used to rank the issues. First, the study team jointly considered to which category each issue belonged. Once all the issues were assigned to one of the three categories, they were ranked within their category. Finally, the results were reviewed by the HSCT program office.

The highest priority level is mandatory. The issues in this category are those that must be addressed for the HSCT to be viable, i.e., issues related to HSCT control systems that will be required to compensate for vehicle characteristics. An example is stability augmentation and flexible mode control. The following are the mandatory issues in order of importance:

1. Demonstrate integrated control of unstable, flexible aircraft.
2. Develop the integrated flight/propulsion control system architecture.
3. Define large transport flying quality criteria.
4. Generate unsteady aero data for SSDs.
5. Define the takeoff and landing profile constraints.

The second priority level is highly beneficial. Issues assigned to this category are those related to significant performance improvements, i.e., fuel efficiency, drag reduction, weight reduction, etc., and/or risk reduction, i.e., development costs, schedule impacts, etc. The highly beneficial issues are listed in the following:

1. Define the benefits and costs of reduced inlet stability margins.
2. Develop a unified rigid and flexible body analytical model.
3. Define benefits and costs of advanced control modes.
4. Develop robust advanced control synthesis and analysis tools.
5. Define the reduced inlet stability control system architecture.
6. Develop constrained optimization synthesis and analysis tools.
7. Develop aircraft controls for large fuel fraction variation.
8. Improve propulsion system performance prediction models.
9. Define advanced high-lift system stability and control characteristics.

10. Define low-boom planform stability and control characteristics.

The third, and lowest, priority level is desirable. These issues were deemed marginally beneficial or the current technology level is immature and requires a good deal of development. Two issues were categorized as desirable.

1. Use multidisciplinary optimization.
2. Extend noise prediction program to provide optimal procedures.

TECHNOLOGY DEVELOPMENT PLANS

The technology development plans for all the critical issues are presented as figures 20–36. Each figure identifies an issue, briefly explains the issue, states the impact of not addressing the issue, and presents the tasks and schedule for developing the required technology.

CONCLUSION

The critical control system design and analysis issues for the HSCT were identified and ranked. A technology development plan for each issue was presented.

Many issues relate to items that require long lead times in the development of control systems, and therefore need to be considered immediately or the 2005 service date will not be met. Most pressing is the establishment of the fundamental requirements. Trade studies need to be performed to identify the benefits of applying advanced technologies, to determine if automatic controls will be required to meet certification or minimum performance requirements, and to define the costs.

The greatest challenge to HSCT control designers will be to integrate successfully the controls to meet the many, and sometimes conflicting, requirements. Many technologies required have been applied individually, but the HSCT will require all of them to be applied simultaneously.

It does not appear that any revolutionary new technologies or methodologies are required for a viable HSCT. However, significant shortcomings of the existing technologies and methodologies do exist that need to be addressed. Failure to do so will result in a very high risk development program and slip the service date by probably several years. Again, the long lead items must be addressed by the end of 1993 to 1994. This is required to ensure enough time for the development of the necessary technologies and methods to accurately predict HSCT performance to guarantee airline profitability, before committing to full-scale development.

REFERENCES

1. Douglas Aircraft Company, *Study of High-Speed Civil Transports*, NASA CR-4235, 1989.

2. Domack, Christopher S., "Results of a Preliminary Investigation of Inlet Unstart on a High-Speed Civil Transport Concept," presented at the Propulsion/Airframe Integration Meeting, NASA Langley Research Center, December 11, 1990.

3. Radkey, R.L, H.R. Welge, and J.E. Felix, *Aerodynamic Characteristics of a Mach 2.2 Advanced Supersonic Cruise Aircraft Configuration at Mach Numbers from 0.5 to 2.4*, NASA CR-145094, 1977.

4. Douglas Aircraft Company, *Technology Application Study of a Supersonic Cruise Vehicle*, NASA CR-159276, 1980.

5. Douglas Aircraft Company, *Technology Application Studies for Supersonic Cruise Vehicles*, NASA CR-144925, vol. 1, 1975.

6. Wykes, J.H. and R.E. Lawrence, "Aerothermoelasticity: Its Impact on Stability and Control of Winged Aerospace Vehicles," AIAA *J. Aircraft*, vol. 2, no. 6, Nov.–Dec., 1965.

7. Wykes, J.H., C.J. Borland, M.J. Klepl, and C.J. MacMiller, *Design and Development of a Structural Mode Control System*, NASA CR-143846, 1977.

8. Wykes, J.H., T.R. Byar, C.J. MacMiller, and D.C. Greek, *Analysis and Tests of the B-1 Aircraft Structural Mode Control System*, NASA CR-144887, 1980.

9. Coleman, H.J., "Concorde Tour Adds to Operations Data," *Aviation Week & Space Technology*, Aug. 7, 1972, pp. 31–33.

10. Berry, Donald T. and Glenn B. Gilyard, "Airframe/Propulsion System Interactions - An Important Factor in Supersonic Aircraft Flight Control," AIAA 73-831, 1973.

11. Schweikhard, William G. and Donald T. Berry, "Cooperative Airframe/Propulsion Control for Supersonic Cruise Aircraft," SAE-740478, 1974.

12. Young, P., "Propulsion Controls on the Concorde," *J. Roy. Aeronaut. Soc.*, vol. 70, Sept. 1966.

13. Chun, K.S., and R.H. Burr, "A Control System Concept for an Axisymmetric Supersonic Inlet," *J. Aircraft*, vol. 6, no. 4, July–Aug. 1969.

14. Inlet Stability Workshop, NASA Lewis Research Center, Nov. 27, 1990.

15. Fukuda, Michael K., Warren G. Hingst, and Eli Reshotko, *Control of Shock Wave - Boundary Layer Interactions by Bleed in Supersonic Mixed Compression Inlets*, NASA CR-2595, 1975.

16. Sanders, Bobby W. and Glenn A. Mitchell, *Throat-Bypass Bleed System for Increasing the Stable Airflow Range of a Mach 2.50 Axisymmetric Inlet with 40-Percent Internal Contraction*, NASA TM-X-2779, 1973.

17. Mitchell, Glenn A. and Bobby W. Sanders, *Pressure-Activated Stability-Bypass-Control Valves to Increase the Stable Airflow Range of a Mach 2.50 Inlet with 40-Percent Internal Contraction*, NASA TM-X-2972, 1974.

18. Sanders, Bobby W., *Dynamic Response of a Mach 2.5 Axisymmetric Inlet and Turbojet Engine With a Poppet-Valve Controlled Inlet-Stability Bypass System When Subjected to Internal and External Airflow Disturbances*, NASA TP-1531, 1980.

19. Sanders, Bobby W., *Turbojet-Exhaust-Nozzle Secondary-Airflow Pumping as an Exit Control of an Inlet-Stability Bypass System for a Mach 2.5 Axisymmetric Mixed-Compression Inlet*, NASA TP-1532, 1980.

20. Neiner, George H., Gary L. Cole, and Dale J. Arpasi, *Digital-Computer Normal-Shock-Position and Restart Control of a Mach 2.5 Axisymmetric Mixed-Compression Inlet*, NASA TN-D-6880, 1972.

21. Lehtinen, Bruce and John R. Zeller, *Optimal Control of Supersonic Inlets to Minimize Unstarts*, NASA TN-D-6408, 1971.

22. Seidel, Robert C. and Bruce Lehtinen, *Control System Design Using Frequency Domain Models and Parameter Optimization, With Application to Supersonic Inlet Controls*, NASA TM-X-3108, 1974.

23. Cole, Gary L., George H. Neiner, and Robert E. Wallhagen, *Coupled Supersonic Inlet-Engine Control Using Overboard Bypass Doors and Engine Speed to Control Normal Shock Position*, NASA TN-D-6019, 1970.

24. Paulovich, Francis J., George H. Neiner, and Ralph E. Hagedorn, *A Supersonic Inlet-Engine Control Using Engine Speed as a Primary Variable for Controlling Normal Shock Position*, NASA TN-D-6021, 1971.

25. Michael, Gerald J. and Florence A. Farrar, "Development of Optimal Control Modes for Advanced Technology Propulsion Systems," Office of Naval Research Report N911620-2, Mar. 1972.

26. Hiller, Kirby W. and Danial I. Drain, *Control of Propulsion Systems for Supersonic Cruise Aircraft*, NASA CP-001, Proceedings of the SCAR Conference, Langley Research Center, Nov. 9–12, 1976.

27. Albers, James A. and Frank V. Olinger, *YF-12 Propulsion Research Program and Results*, NASA CP-001, Proceedings of the SCAR Conference, Langley Research Center, Nov. 9–12, 1976.

28. Wolowicz, Chester H., Larry W. Strutz, Glenn B. Gilyard, and Neil W. Matheny, *Preliminary Flight Evaluation of the Stability and Control Derivatives and Dynamic Characteristics of the Unaugmented XB-70-1 Airplane Including Comparisons with Predictions*, NASA TN-D-4578, 1966.

29. Wolowicz, Chester H. and Roxanah B. Yancey, *Summary of Stability and Control Characteristics of the XB-70 Airplane*, NASA TM-X-2933, 1973.

30. North American Aviation, Inc., Flight Control Systems-XB-70 Air Vehicles, Contract AF33(600)-42058," NA-60-2, rev. 5, July 1962.

31. Reukauf, Paul J. and Frank W., Burcham, Jr., *Propulsion System/Flight Control Integration for Supersonic Aircraft*, NASA CP-001, Proceedings of the SCAR Conference, Langley Research Center, Nov. 9–12, 1976.

32. Berry, Donald T., Donald L. Mallick, and Glenn B. Gilyard, *Handling Qualities Aspects of NASA YF-12 Flight Experience*, NASA CP-001, Proceedings of the SCAR Conference, Langley Research Center, Nov. 9–12, 1976.

33. Powers, Bruce G., *Phugoid Characteristics of a YF-12 Airplane With Variable-Geometry Inlets Obtained in Flight Tests at a Mach Number of 2.9*, NASA TP-1107, 1977.

34. Gilyard, Glenn B., Donald T. Berry, and Daumants Belte, *Analysis of a Lateral-Directional Airframe Propulsion System Interaction*, NASA TM-X-2829, 1973.

35. Gilyard, Glenn B. and John J. Burken, *Development and Flight Test Results of an Autothrottle Control System at Mach 3 Cruise*, NASA TP-1621, 1980.

36. Burcham, Frank W., Jr. and Peter G. Batterton, *Flight Experience with a Digital Integrated Propulsion Control System on an F-111E Airplane*, AIAA-76-653, 1976.

37. Douglas Aircraft Co., *Technology Application Study of a Supersonic Cruise Vehicle*, NASA CR-159034, 1979.

38. Douglas Aircraft Co., *Technology Study for Advanced Supersonic Cruise Vehicles*, NASA CR-165723, 1981.

39. Yonke, W.A., L.A. Terrell, and L.P. Meyers, "Integrated Flight/Propulsion Control: Adaptive Engine Control System Mode," AIAA-85-1425, 1985.

40. Landy, R.J., W.A. Yonke, and J.F. Stewart, "Development of HIDEC Adaptive Engine Control Systems," *ASME Journal of Engineering for Gas Turbines and Power*, vol. 109, Apr. 1987.

41. Smith, R.H., J.D. Chisholm, and J.F. Stewart, "Optimizing Aircraft Performance with Adaptive, Integrated Flight/Propulsion Control," ASME Paper 90-GT-252, July 1990.

42. Berg, D.F., J.A. Swan, S. Ahdlbatlar, P.D. Shaw, and E.J. Tich, "Performance Seeking Control," AFWAL-TR-88-2067, vol. 1, Oct. 12, 1989.

43. Luppold, R.H., J.R. Roman, G.W. Gallops, and L.J. Ker, "Estimating In-Flight Engine Performance Variations Using Kalman Filter Concepts," AIAA-89-2584, July 1989.

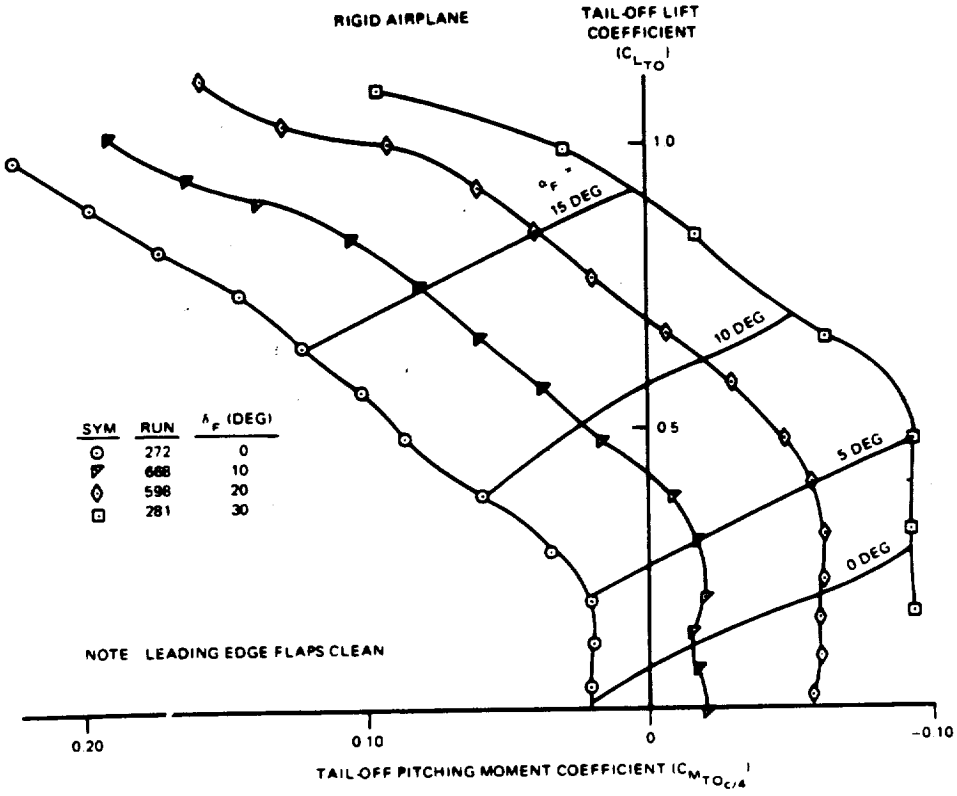


Figure 1. Advanced supersonic transport tail-off pitching moment coefficient for various flap deflections.

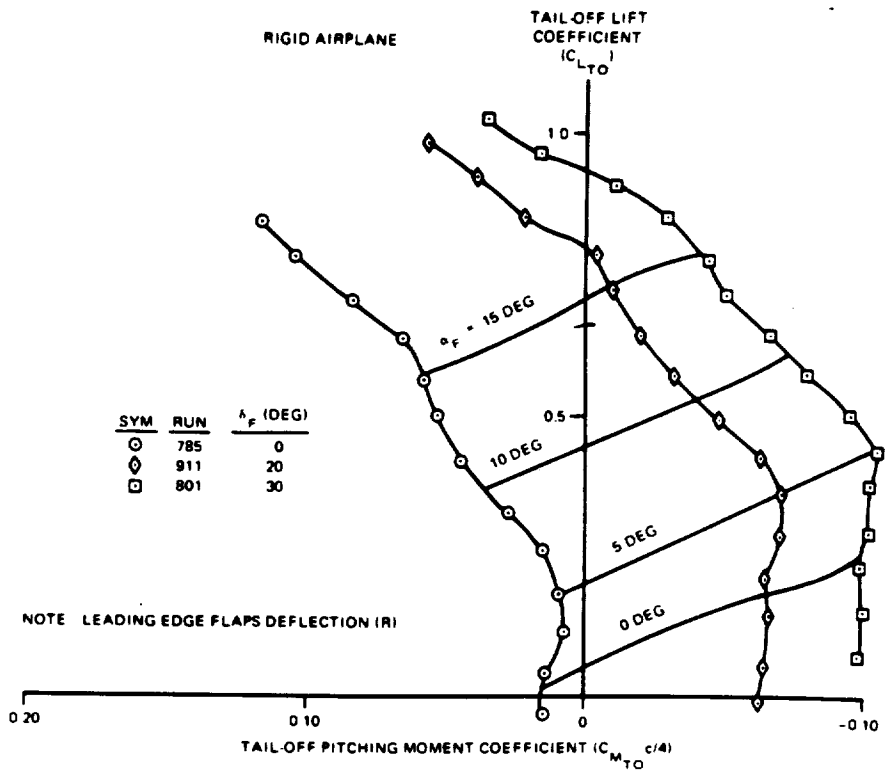


Figure 2. Advanced supersonic transport tail-off pitching moment coefficient with the leading edge deflected.

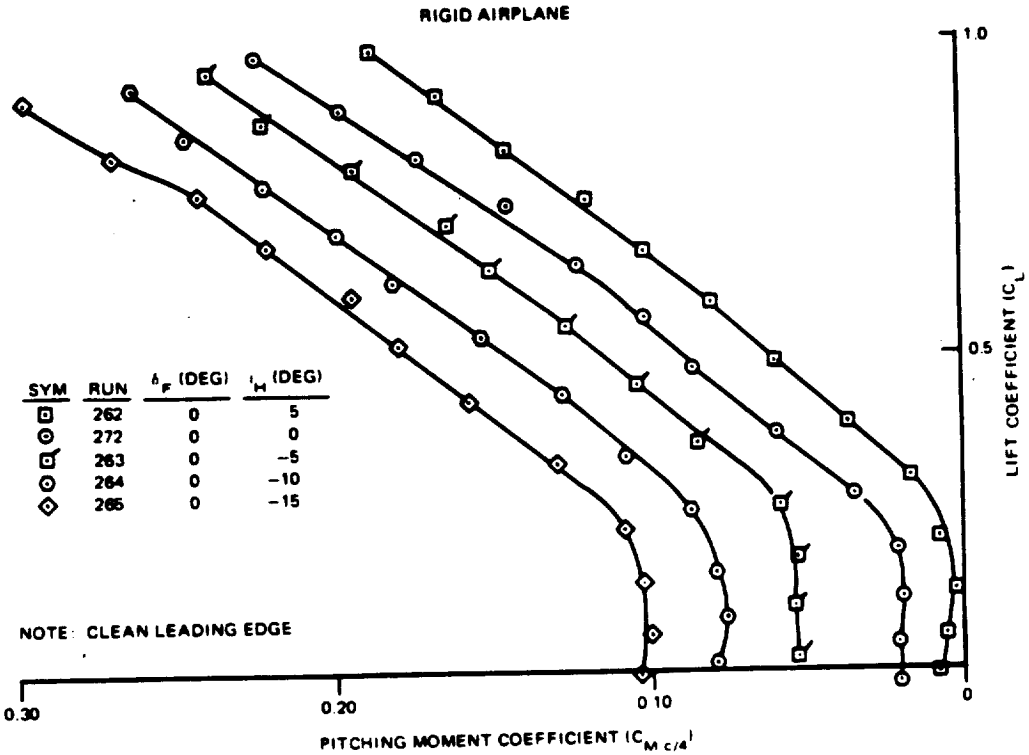


Figure 3. Advanced supersonic transport tail-on pitching moment for several tail incidence settings.

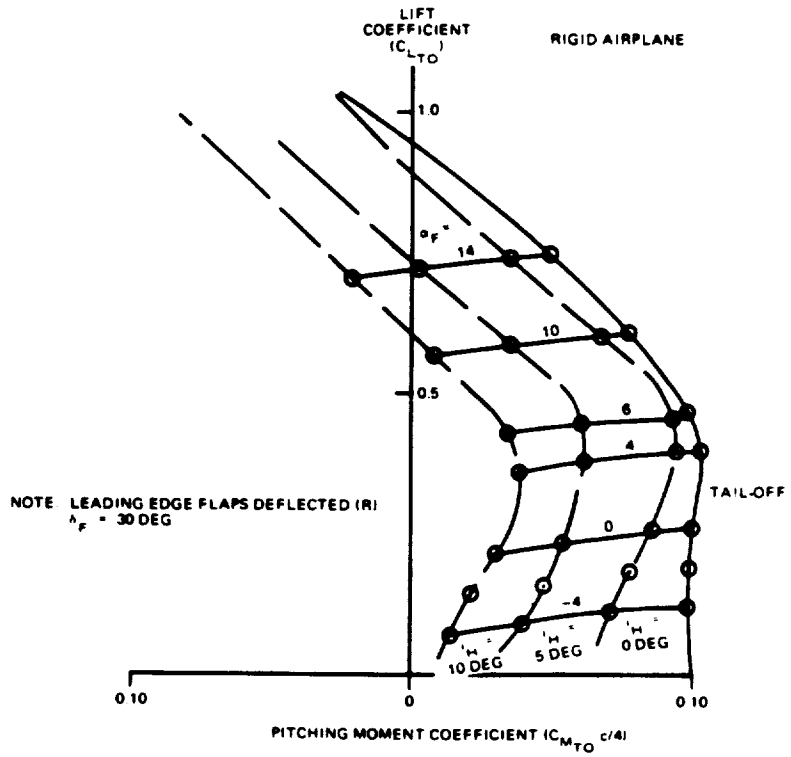


Figure 4. Advanced supersonic transport tail-on pitching moment characteristics used to calculate downwash.

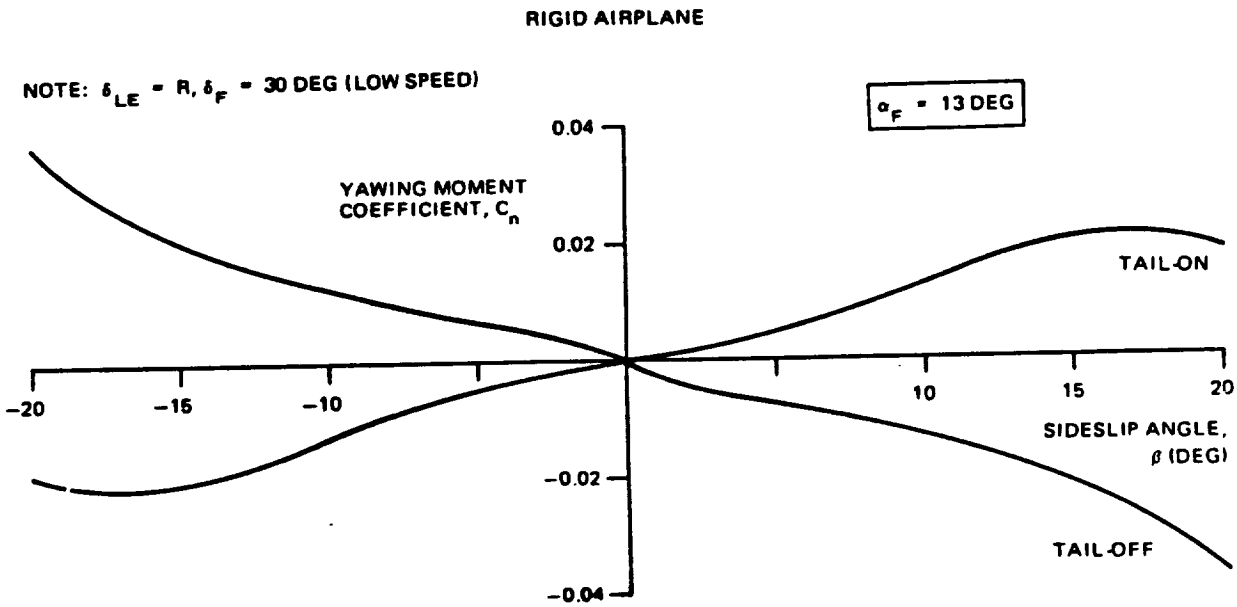


Figure 5. Estimated yawing moment coefficient versus sideslip angle.

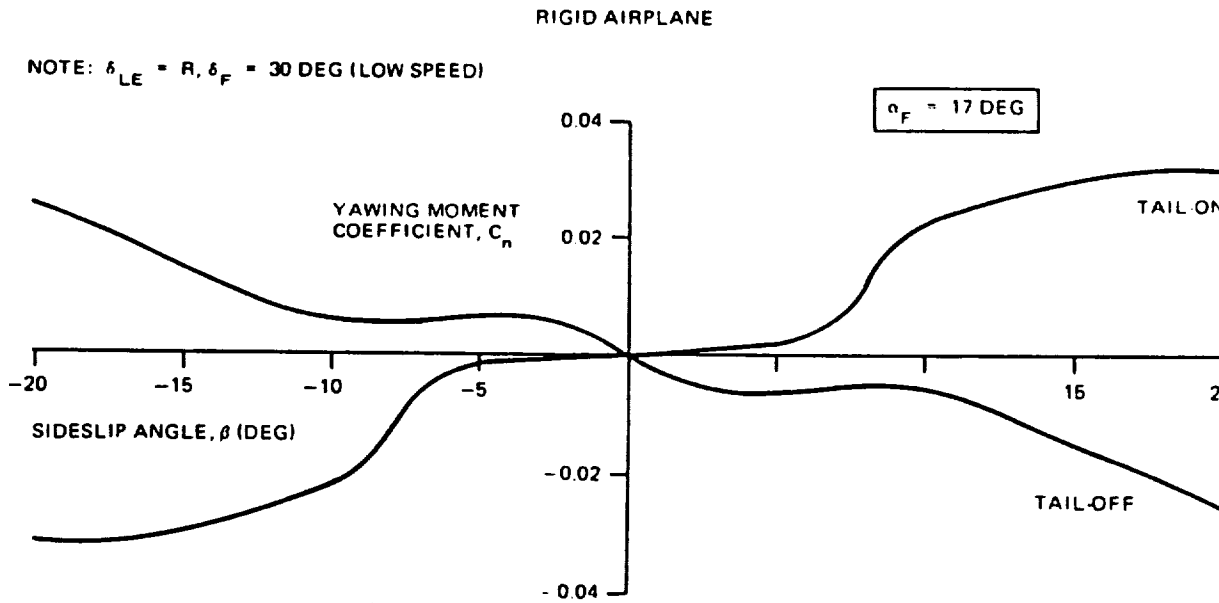


Figure 6. Estimated advanced supersonic transport yawing moment coefficient versus sideslip angle.

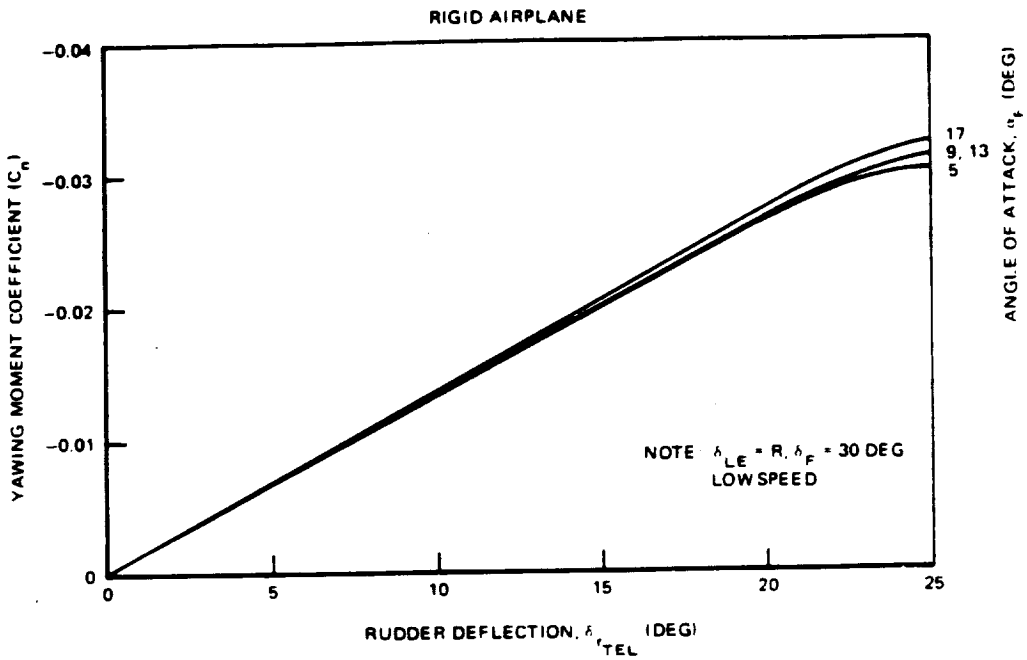


Figure 7. Estimated advanced supersonic transport yawing moment coefficient due to rudder deflection.

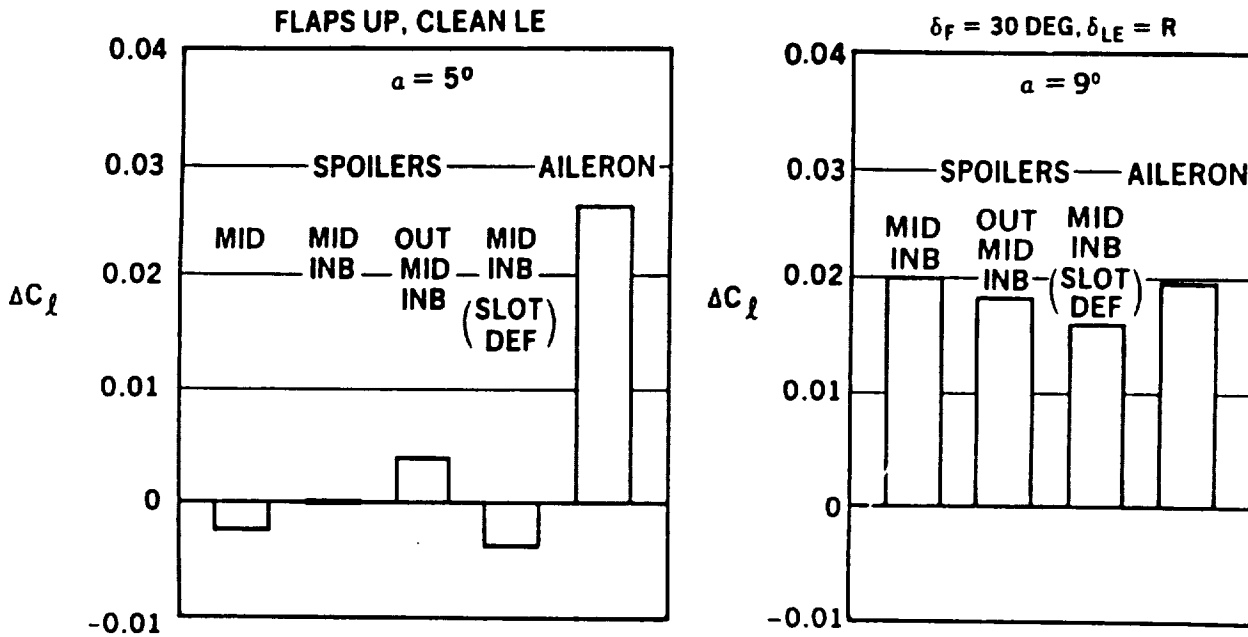


Figure 8. Advanced supersonic transport lateral control system effectiveness.

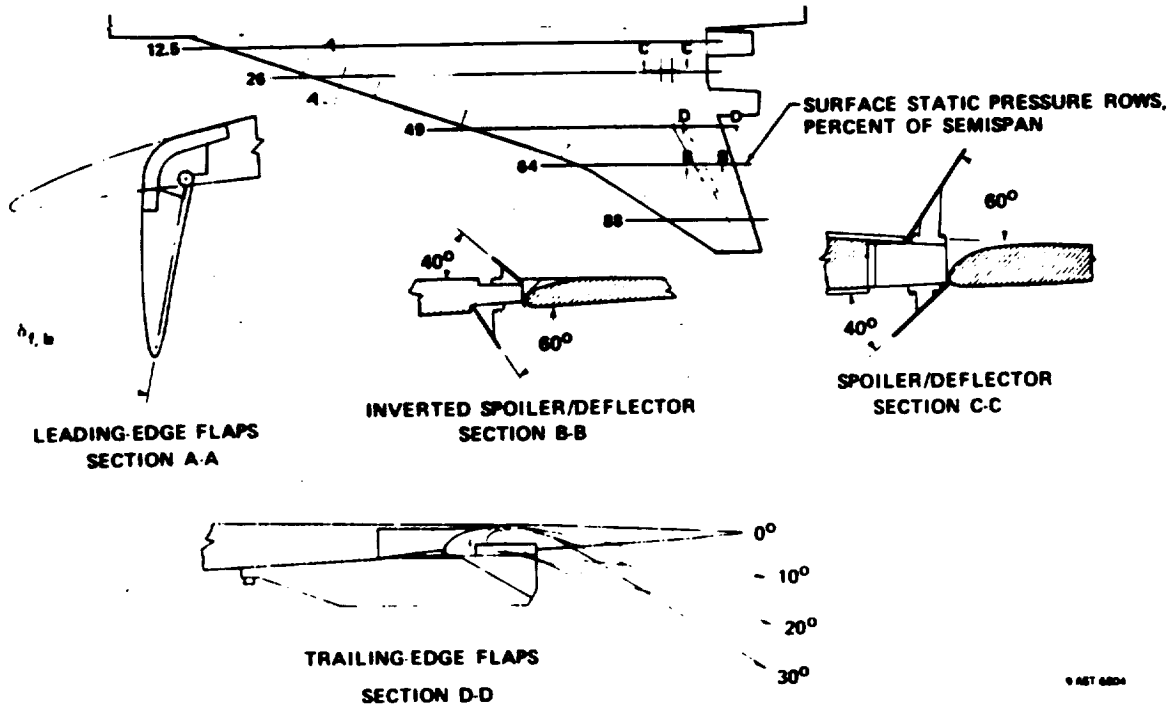


Figure 9. Schematic drawing of advanced supersonic transport leading and trailing edge flaps, spoiler/deflector, and inverted spoiler/deflector.

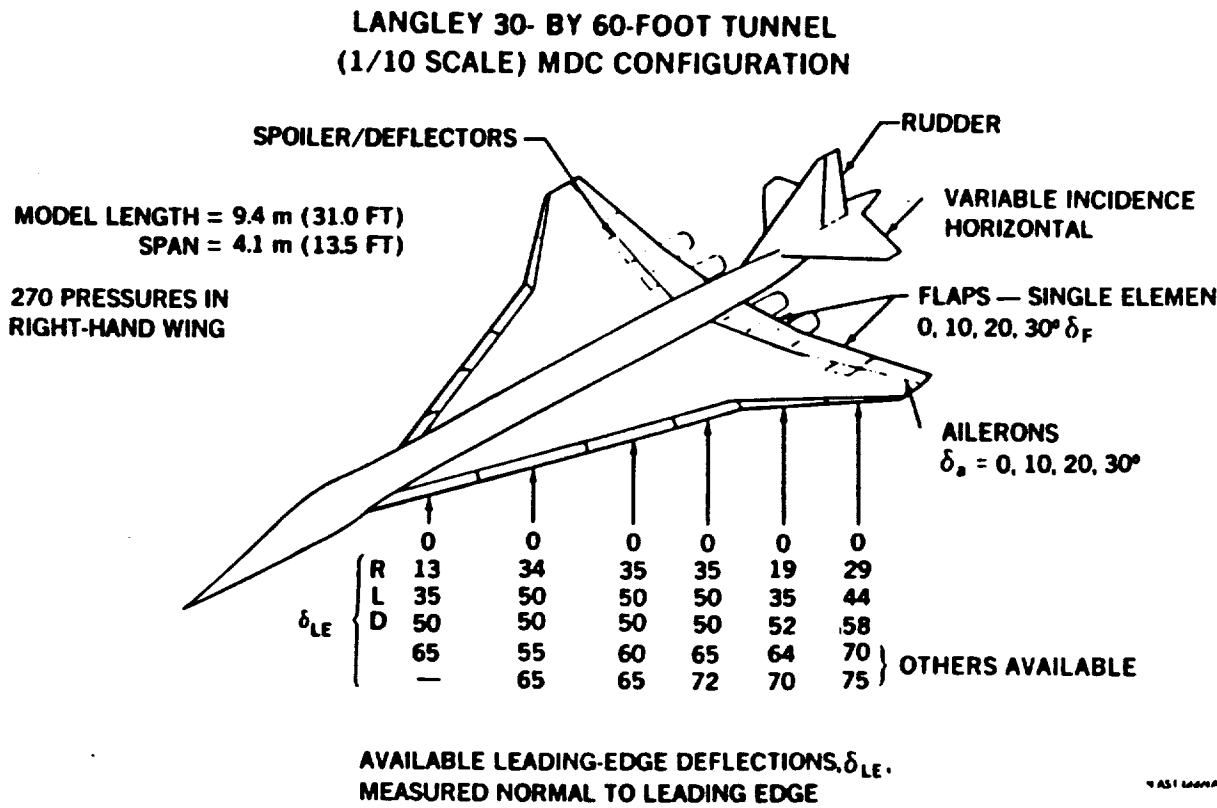


Figure 10. Variable geometry features of NASA low-speed advanced supersonic transport model.

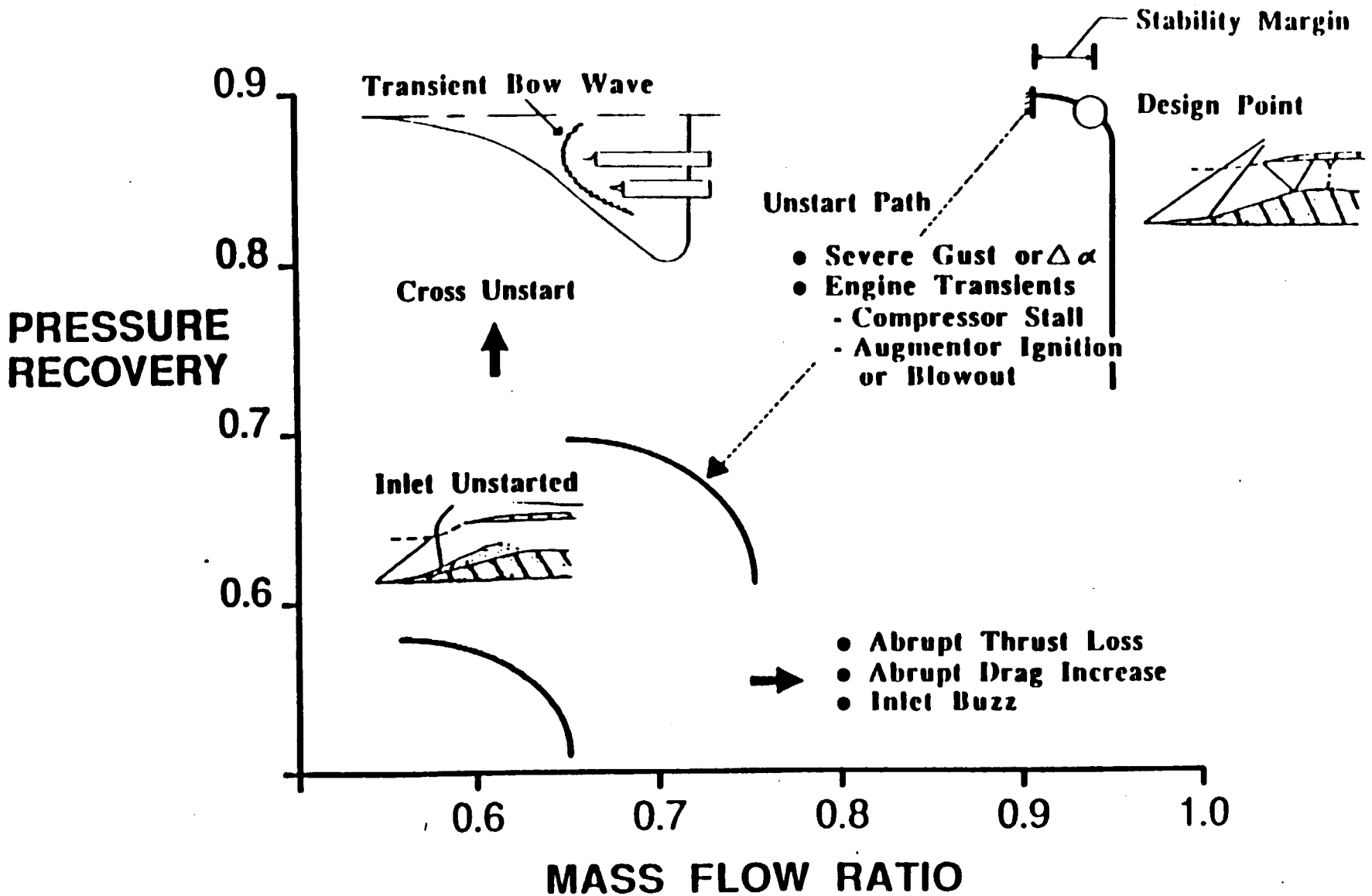


Figure 11. Mixed compression supersonic inlet performance.

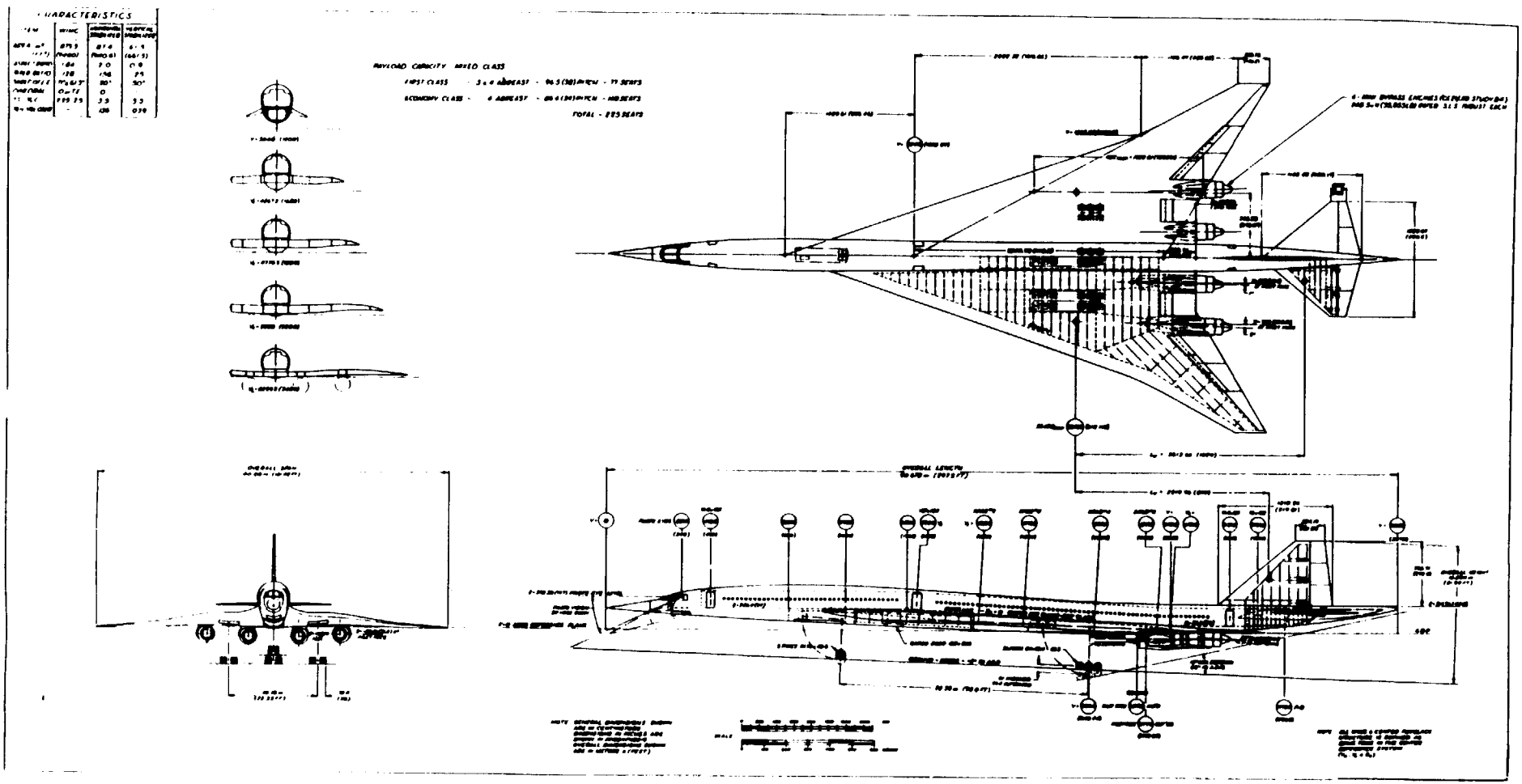


Figure 12. Advanced supersonic transport general configuration drawing.

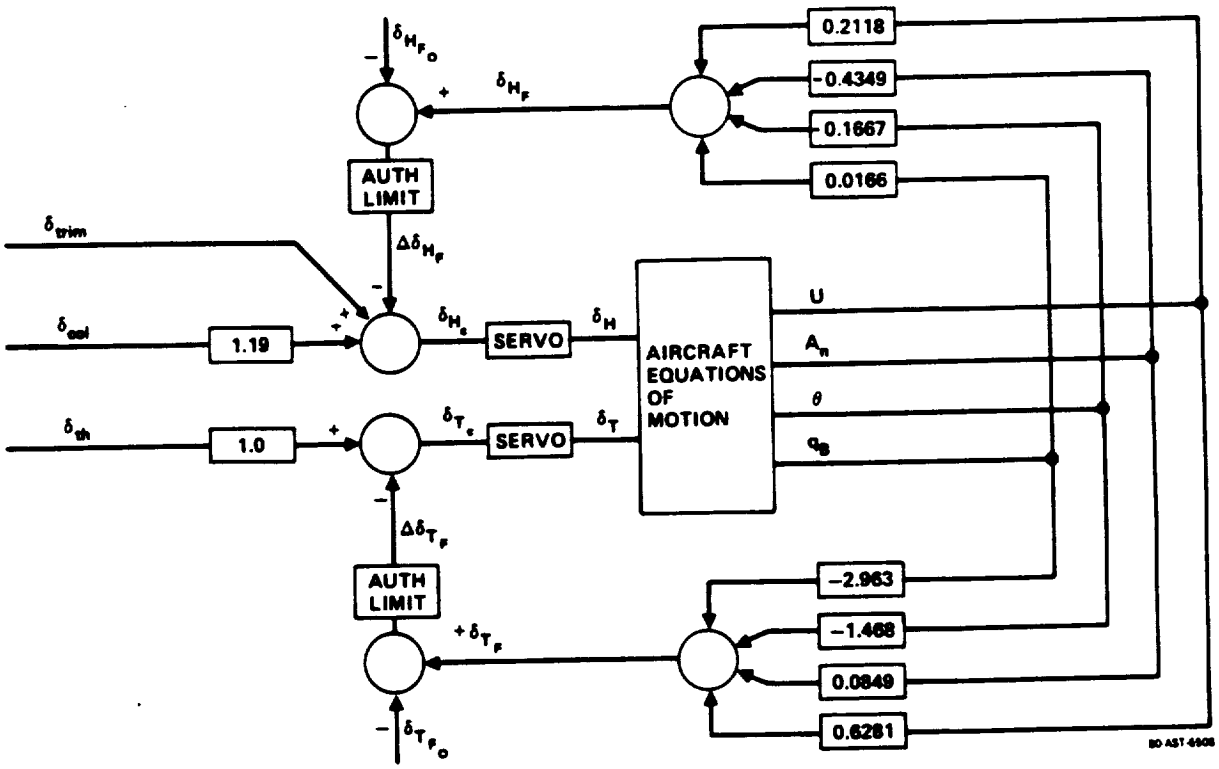


Figure 13. Advanced supersonic transport longitudinal control law for landing approach.

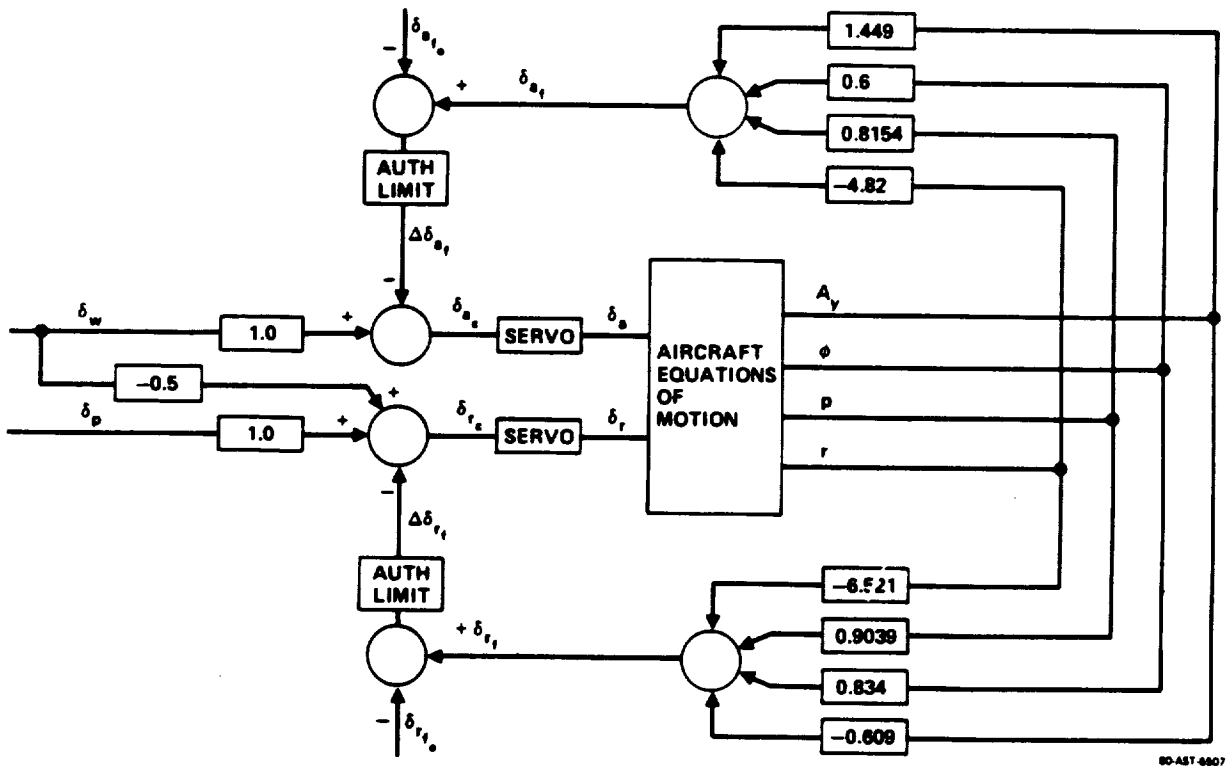


Figure 14. Advanced supersonic transport lateral control law for landing approach.

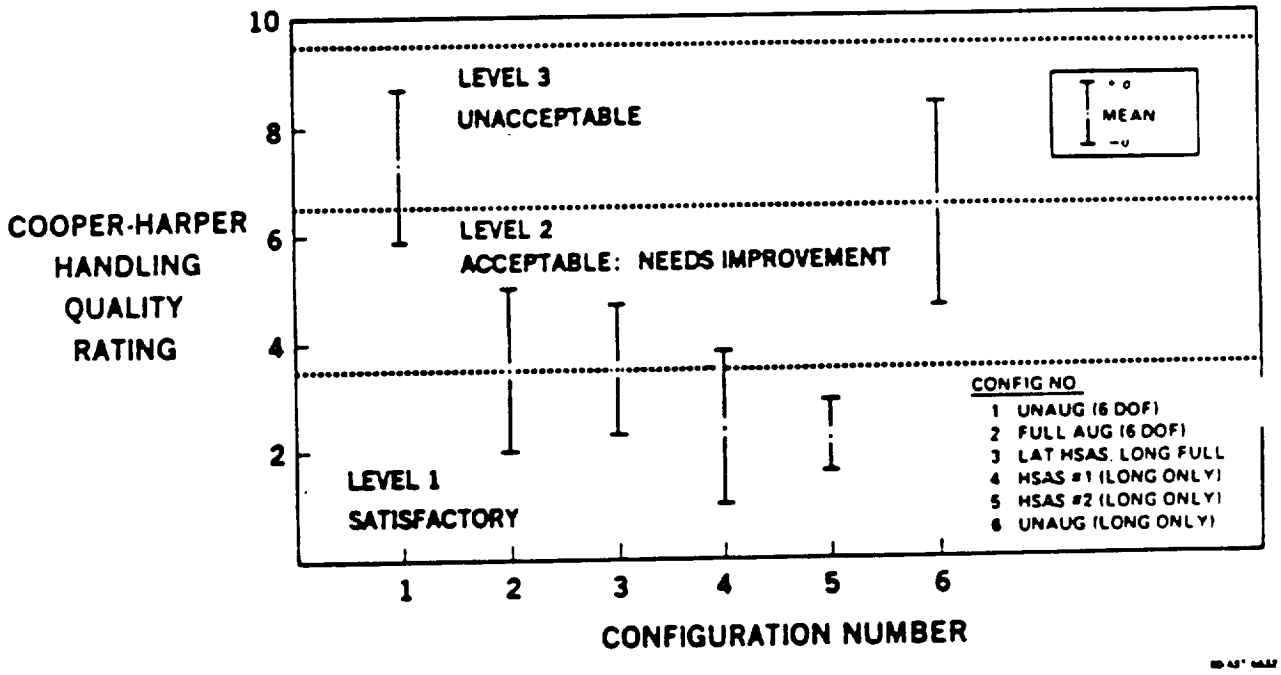


Figure 15. Advanced supersonic transport handling qualities rating.

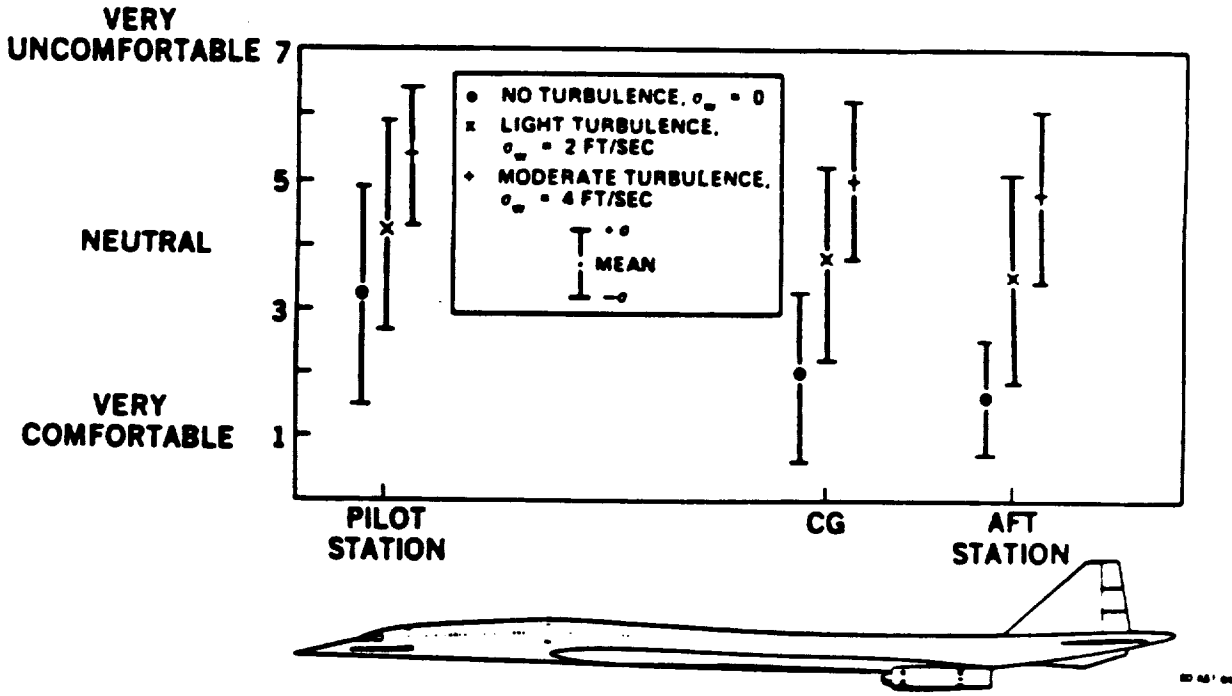


Figure 16. Advanced supersonic transport ride qualities evaluation results.

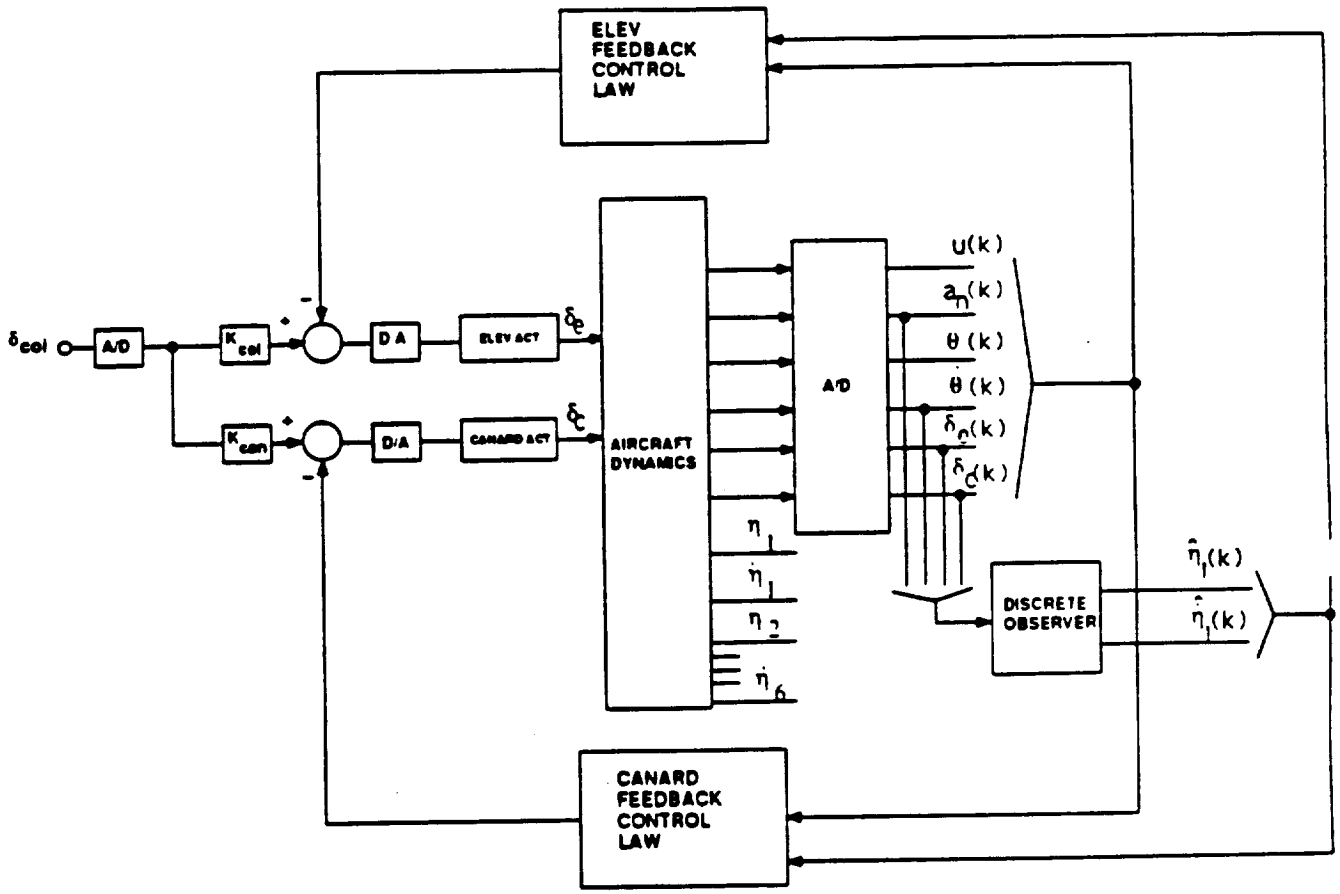


Figure 17. Advanced supersonic transport flexible mode control law.

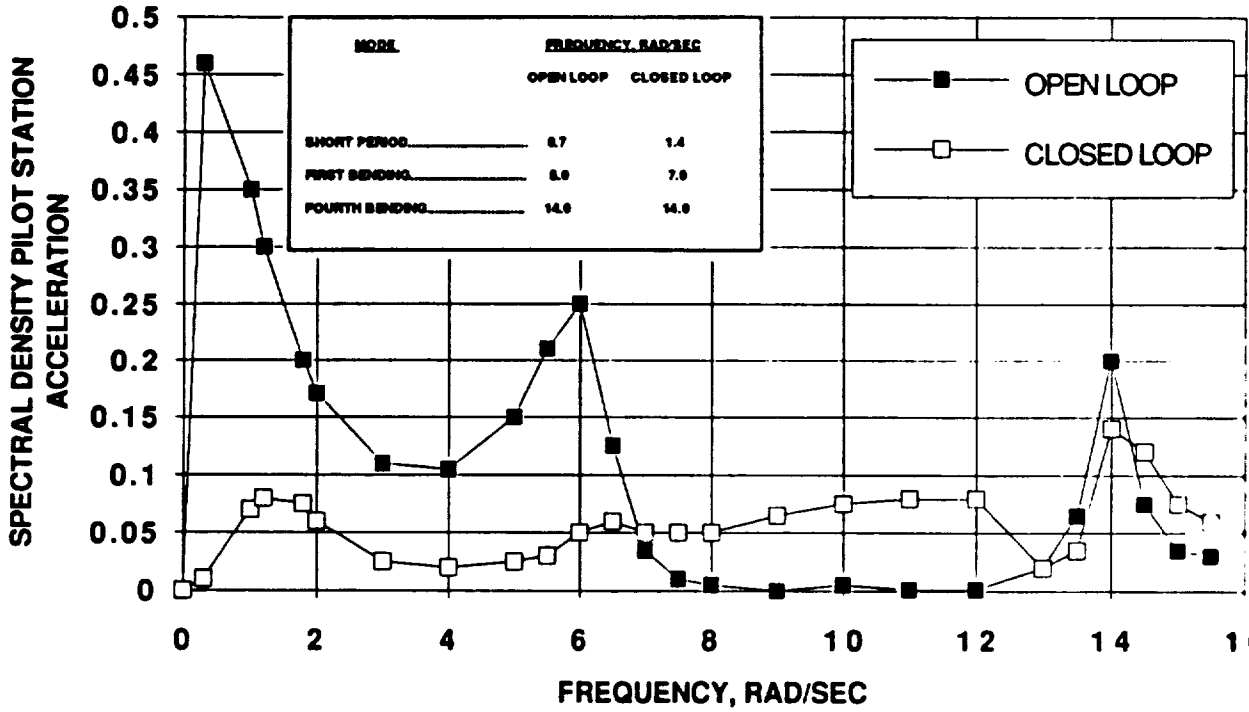


Figure 18. Advanced supersonic transport flexible mode suppression control results.

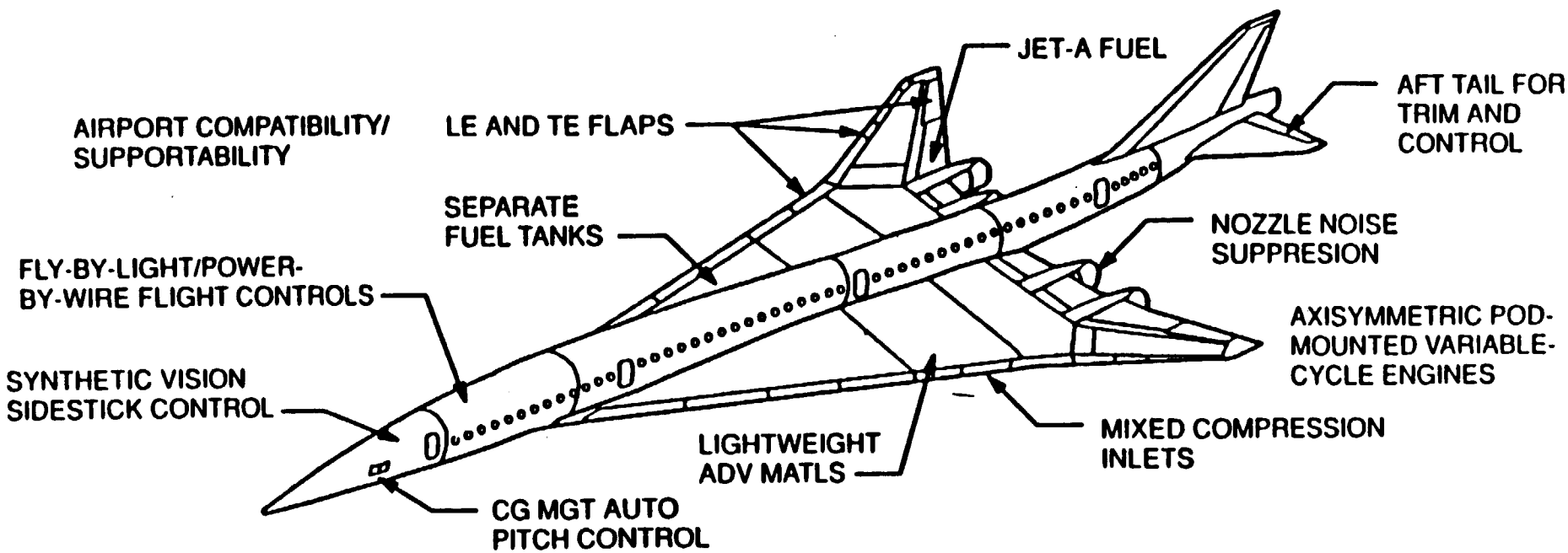
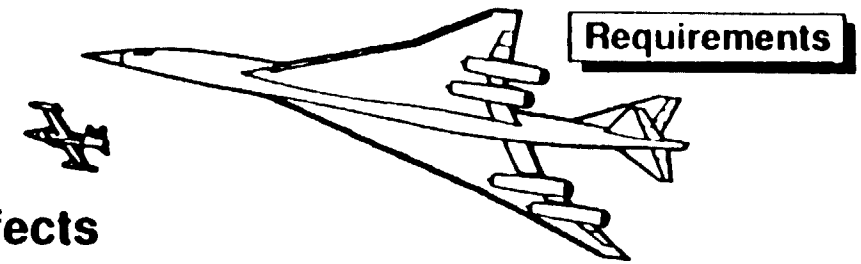


Figure 19. Design features and key technologies.

ISSUE: Control Criteria for
- **Short Period**
- **Time Delay**
- **SAS Response Type**
- **Center of Percussion Effects**



Current Standards are based mostly on NT-33.

IMPACT: Reduced Safety of Flight, Poor to Unacceptable Ride and Handling Qualities

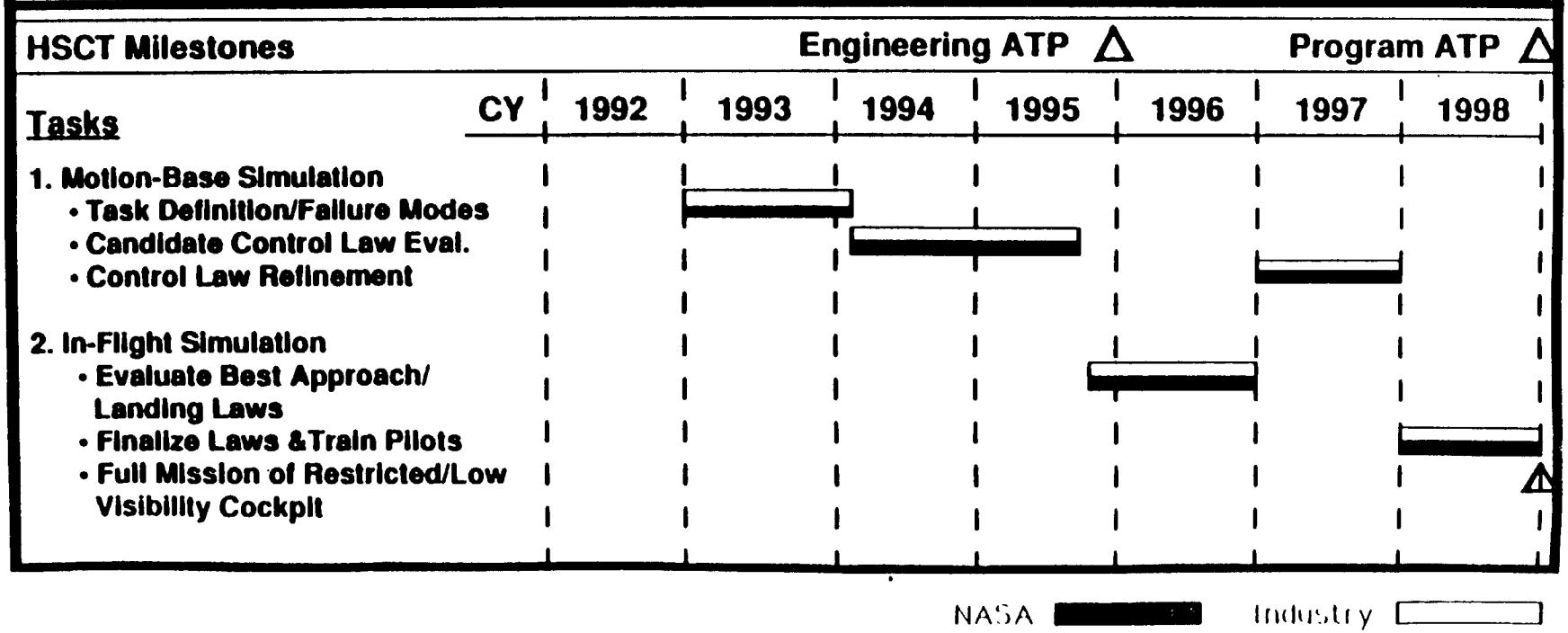


Figure 20. Technology development plan for defining large transport flying quality criteria.

Requirements

ISSUE: Inlet / Normal Shock Position Control System

A trade study to quantify the costs and benefits of an active normal shock position control sytem needs to be performed early in HSCT development.

IMPACT: High Risk Program; Milestones not met

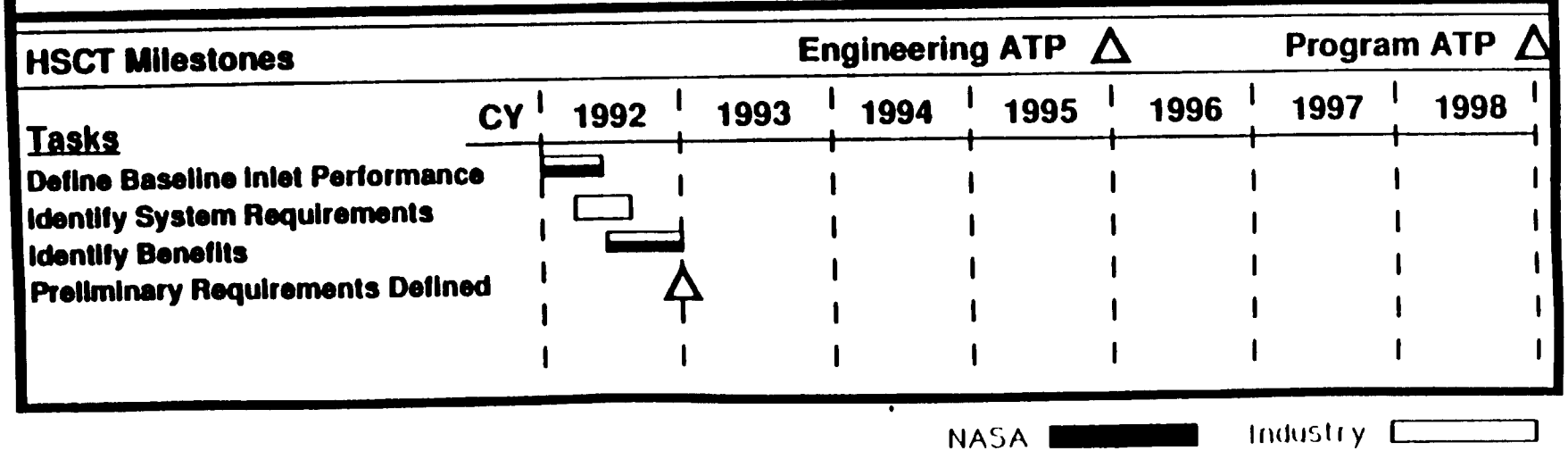


Figure 21. Technology development plan for defining the benefits and costs of reduced inlet stability margins.

Validation

ISSUE: Control System Validation

A joint effort will be required to provide validation of a highly augmentated, integrated control system design that meets specified theoretical criteria with test data substantiation

IMPACT: Certification

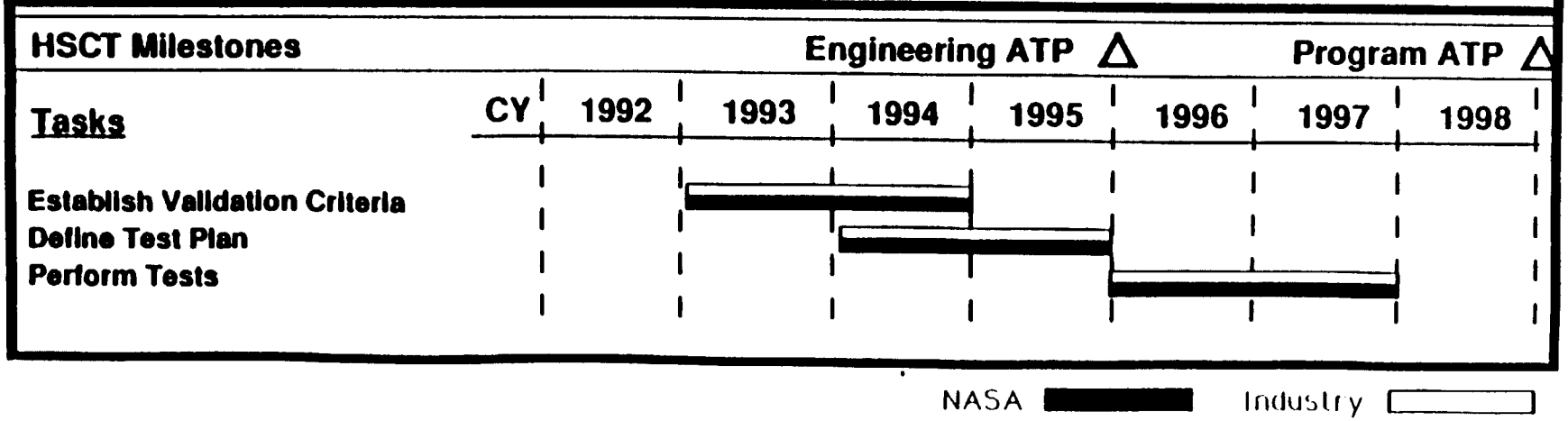


Figure 22. Technology development plan for defining control system validation process.

Modelling

ISSUE: Lack of Unsteady Aero Data for Spoiler-Slot-Deflectors

Limited steady and no unsteady aerodynamic data exist for the Spoiler-Slot-Deflectors (SSD) being considered as an active control effector for the HSCT.

IMPACT: Inadequate Control Synthesis and Analysis Model

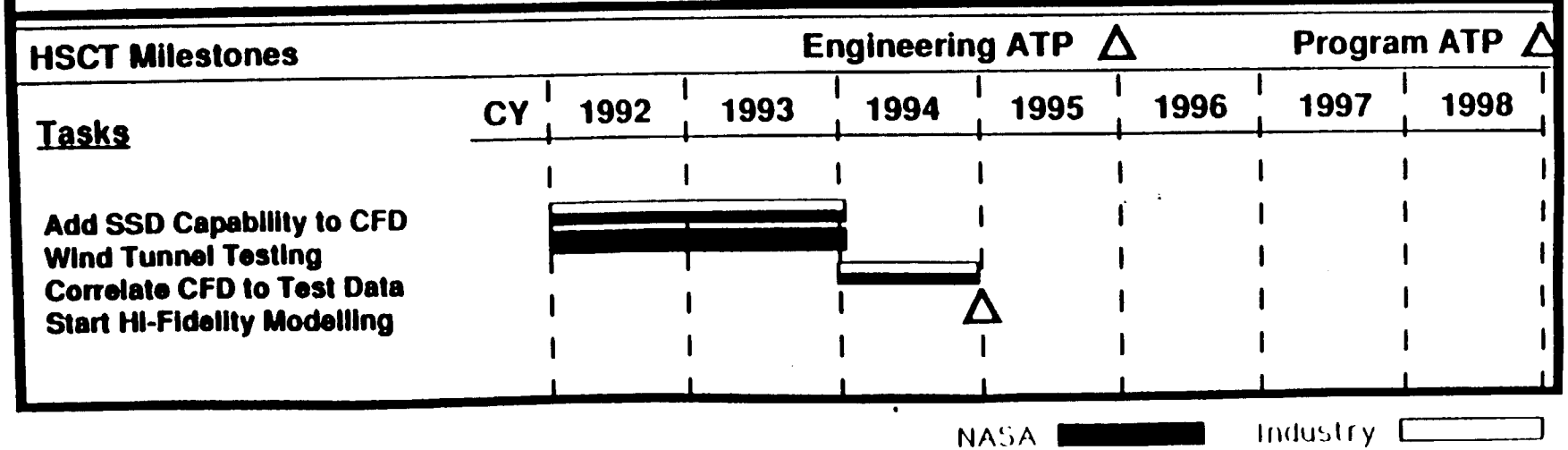


Figure 23. Technology development plan for generating unsteady aero data for spoiler-slot deflectors.

Requirements

ISSUE: Constrained Optimal Flight Path Management

Noise abatement and enhanced operating procedures will be a requirement of the flight management system. The conflicting constraints for both takeoff and landing profiles must be clearly defined to formulate the constrained optimization problem.

IMPACT: High Risk Program; Milestones not met.

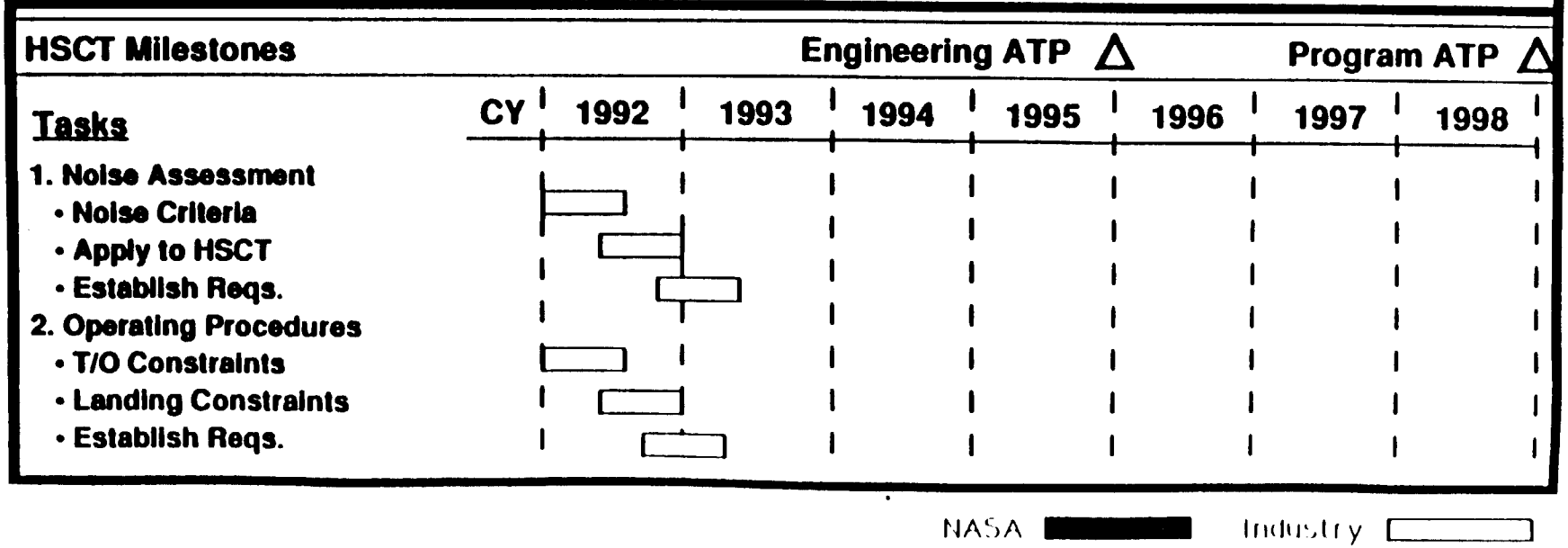


Figure 24. Technology development plan for defining the takeoff and landing profile constraints.

Architecture

ISSUE: Inlet / Normal Shock Position Control System

If cost / performance analysis indicates significant benefits via low stability, high speed (1000 Hz) normal shock position control, the additional interactions and requirements will have to be defined to design the integrated flight / propulsion system.

IMPACT: Reduced Propulsion Efficiency and Safety

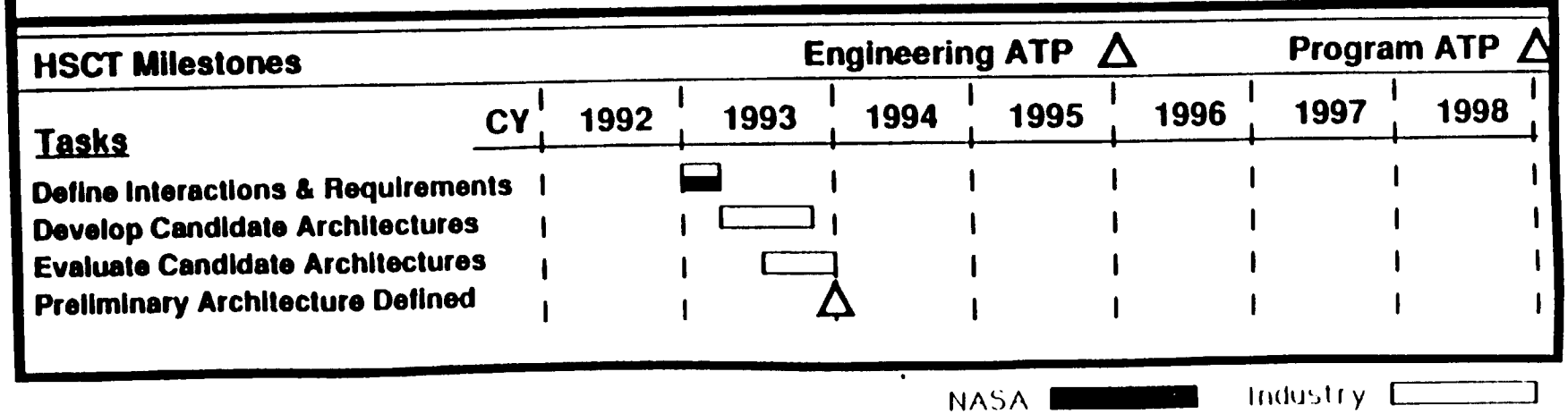


Figure 25. Technology development plan for defining the reduced inlet stability control system architecture.

Modelling

ISSUE: Separate Rigid and Flexible-Body Analytical Models

The methodology to adequately blend the traditionally separate rigid-body and flexible-body models together into a unified aeroelastic aircraft model is immature.

IMPACT: Large Model Uncertainty; Reduced Closed Loop Performance

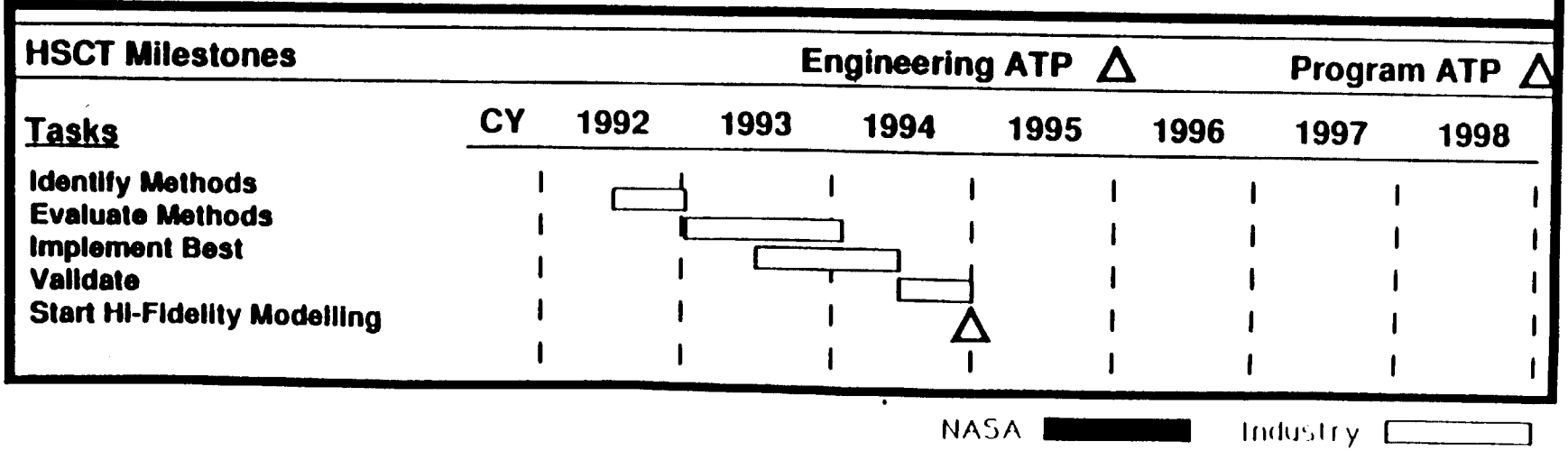


Figure 26. Technology development plan for developing a unified rigid body analytical model.

Synthesis & Analysis

ISSUE: Advanced Control Modes

F-15 HIDEC Performance Seeking Control demonstrated performance improvements through adaptive control. However, stability and / or performance robustness margins were not part of the synthesis or analysis. Robust Adaptive Control techniques need to be evaluated, developed, and demonstrated.

IMPACT: Unstable Control System; Unobtainable Predicted Performance

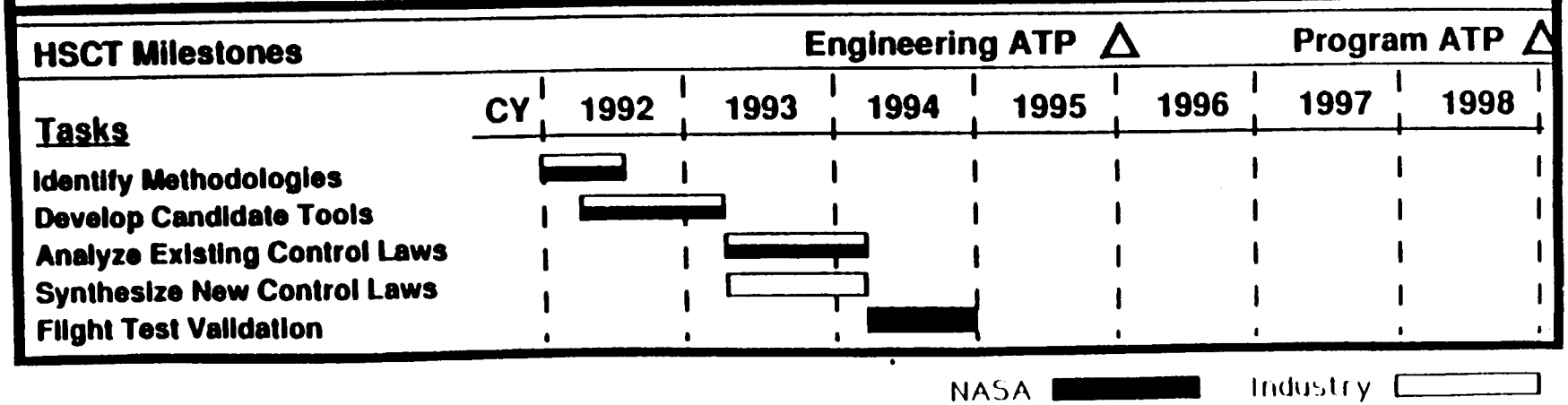


Figure 27. Technology development plan for developing robust advanced control synthesis and analysis tools.

Architecture

ISSUE: Airframe / Propulsion / Controls Interaction

An integrated system definition of the architecture must precede the synthesis effort in order to provide adequate design tools.

IMPACT: Reduced Economics and Safety

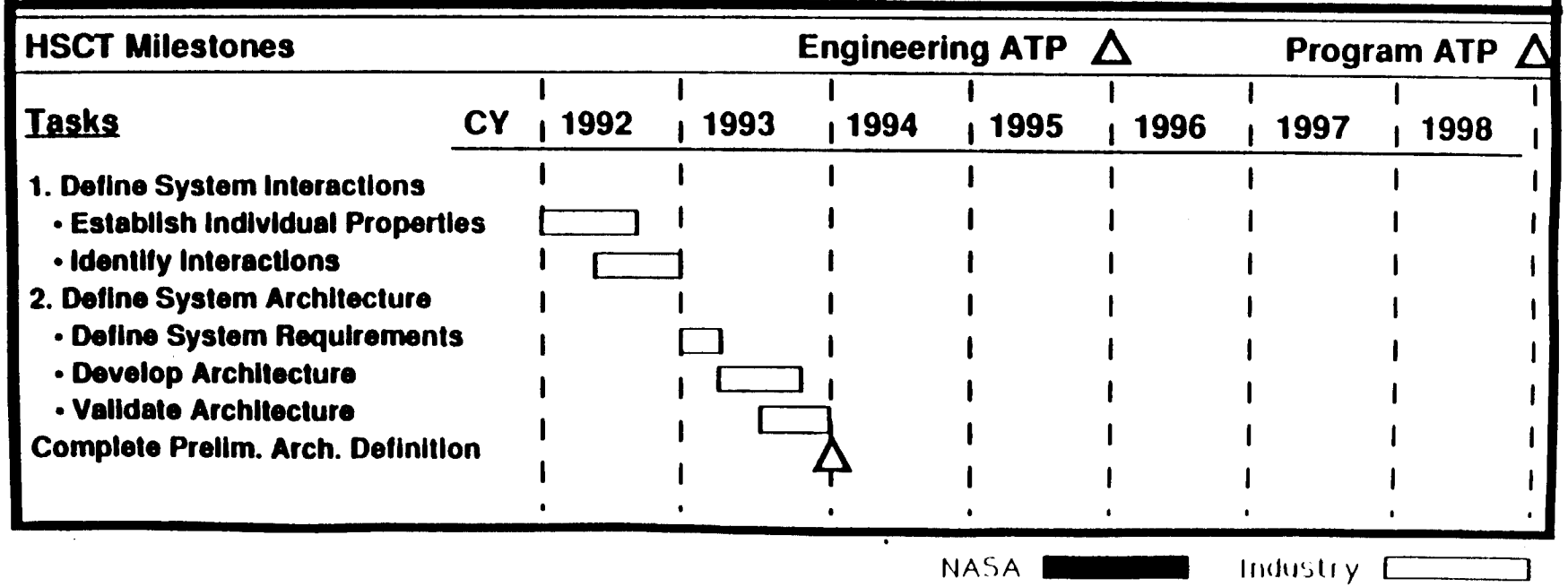


Figure 28. Technology development plan for developing the integrated flight-propulsion control system architecture.

Requirements

ISSUE: Advanced Control Modes

A trade study to quantify the costs and benefits of advanced, e.g., Performance Seeking and Life Extending, control modes needs to be performed early in HSCT development.

IMPACT: Potential Improved Performance Lost

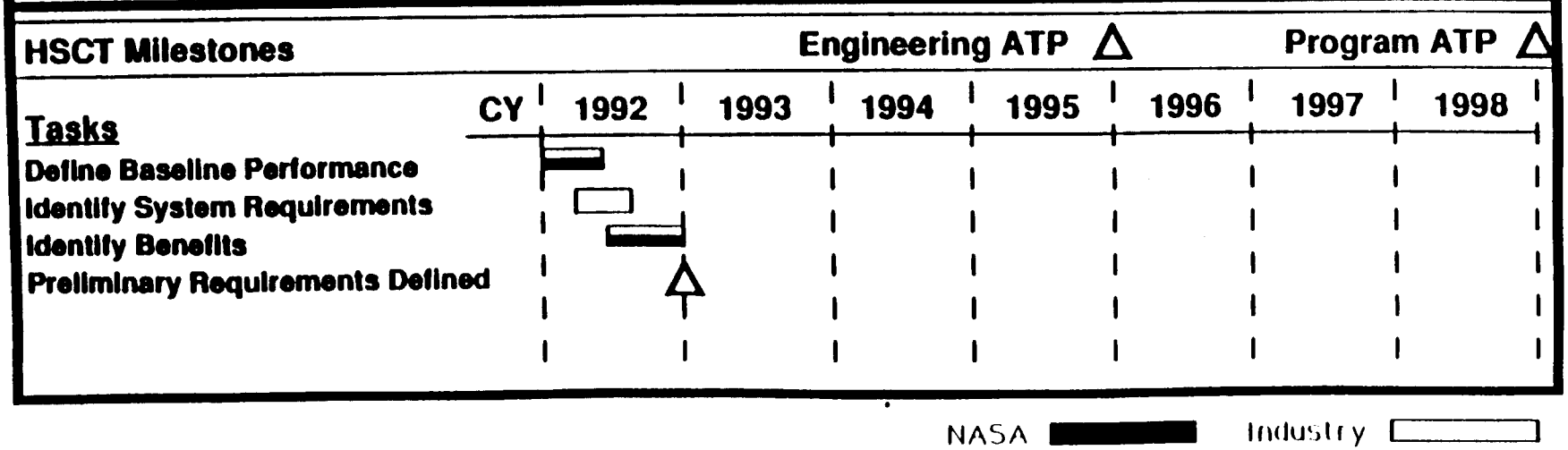


Figure 29. Technology development plan for defining benefits and costs of advanced control modes.

Synthesis & Analysis

ISSUE: Undemonstrated Integrated Control of Unstable, Flexible Aircraft

The HSCT control system will have to simultaneously provide stability augmentation, good ride and handling qualities, flexible mode control, gust and manuever load alleviation, and possibly flutter suppression. Such a control system has not been, and therefore needs to be developed and demonstrated.

IMPACT: High Technology, Safety, and Passenger Acceptance Risk

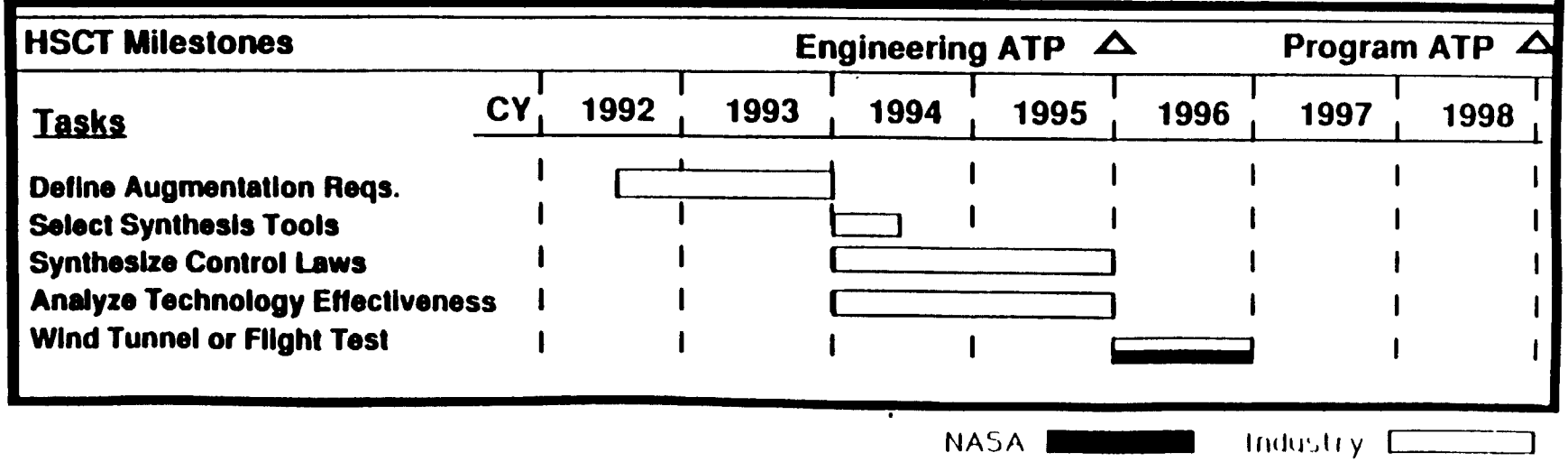


Figure 30. Technology development plan for demonstrating integrated control of unstable, flexible aircraft.

Architecture

ISSUE: Fuel Management Integration

The HSCT control laws will have to account for the large variation in weight and structural dynamic properties from takeoff to landing. Identification of the type and location of sensors and actuators, and evaluation of adaptive and robust control concepts is required.

IMPACT: Reduced Safety and Operating Envelope

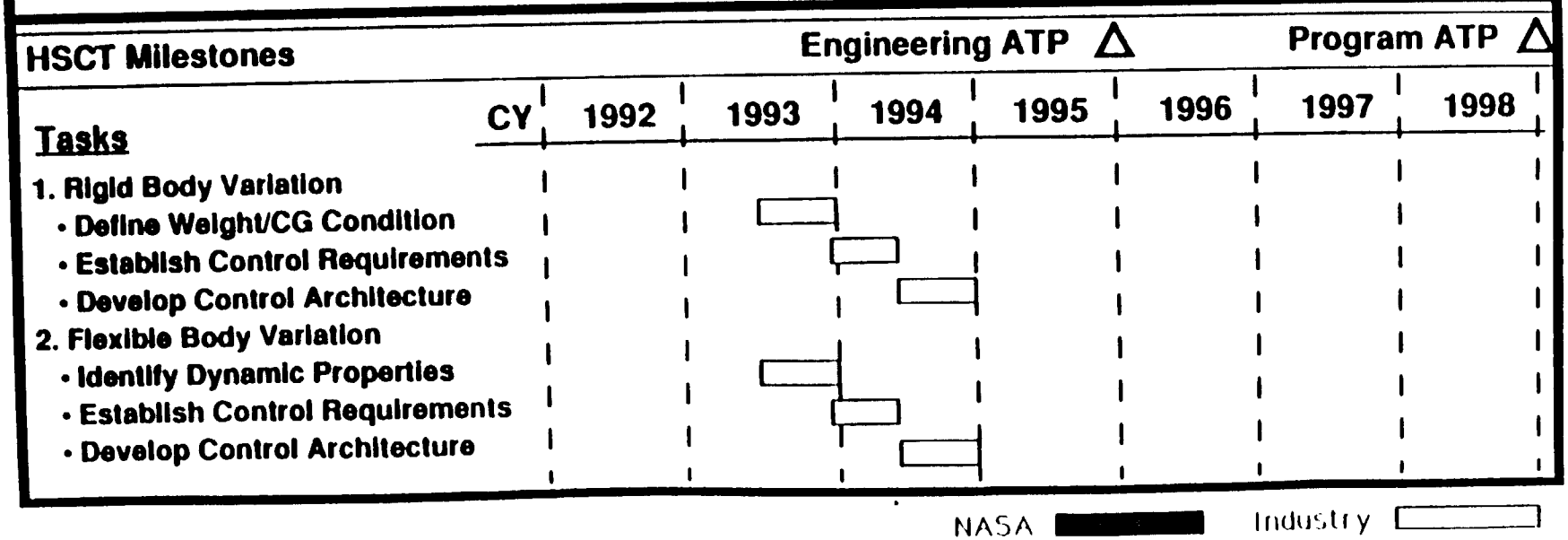


Figure 31. Technology development plan for developing aircraft controls for large fuel fraction variation.

Modelling

ISSUE: Inaccurate Performance Prediction Models

A percent or so in performance is critical to the economic viability of commercial transport aircraft. Current analytical models are unable to reliably predict performance with this required accuracy.

IMPACT: Reduced Certainty of Economic Viability

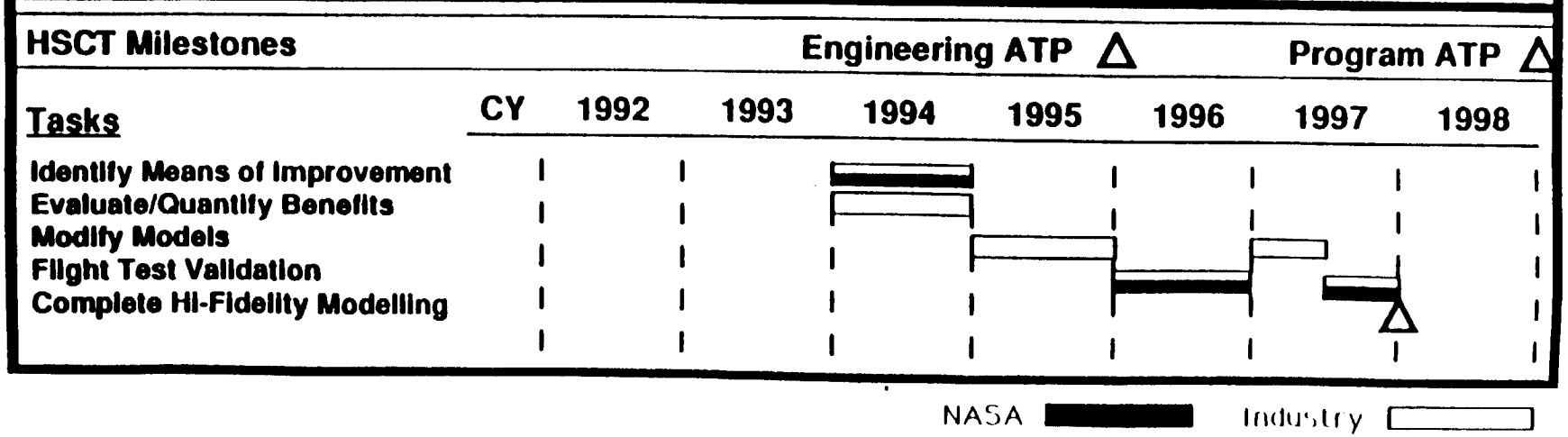


Figure 32. Technology development plan for improving propulsion system performance prediction models.

Modelling

ISSUE: Exotic High-Lift Systems

No data exists for control effectiveness in the presence of these new systems.

IMPACT: May require new types of control devices.

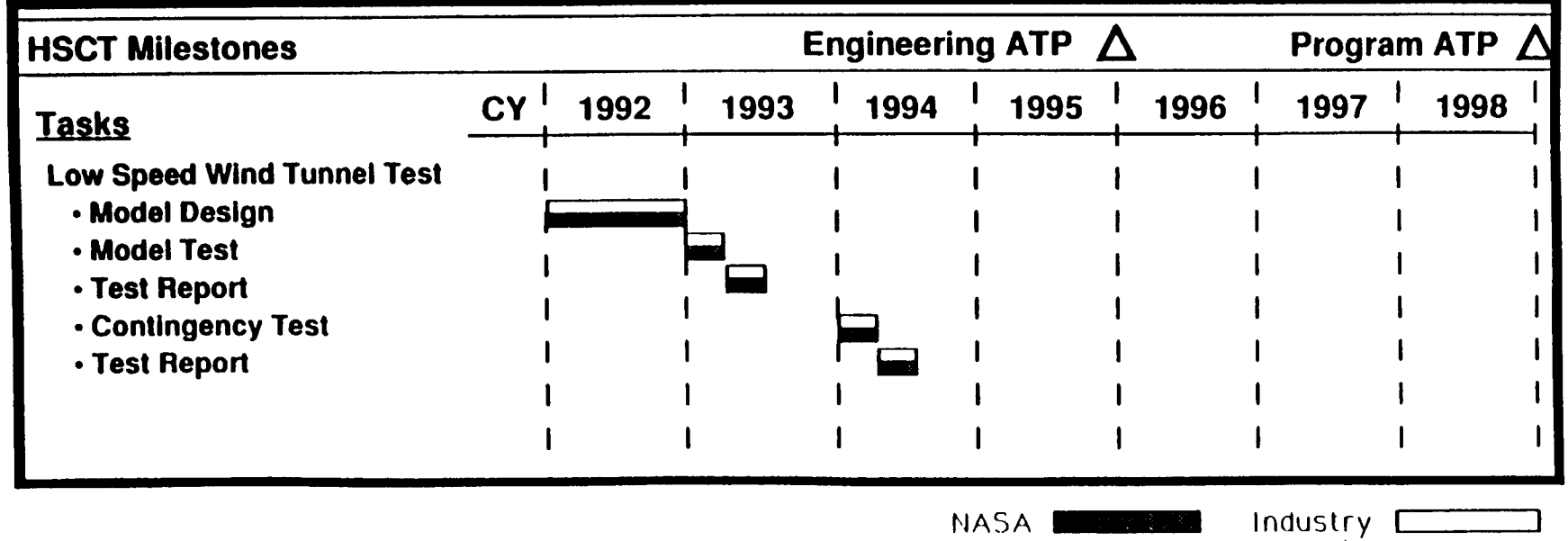


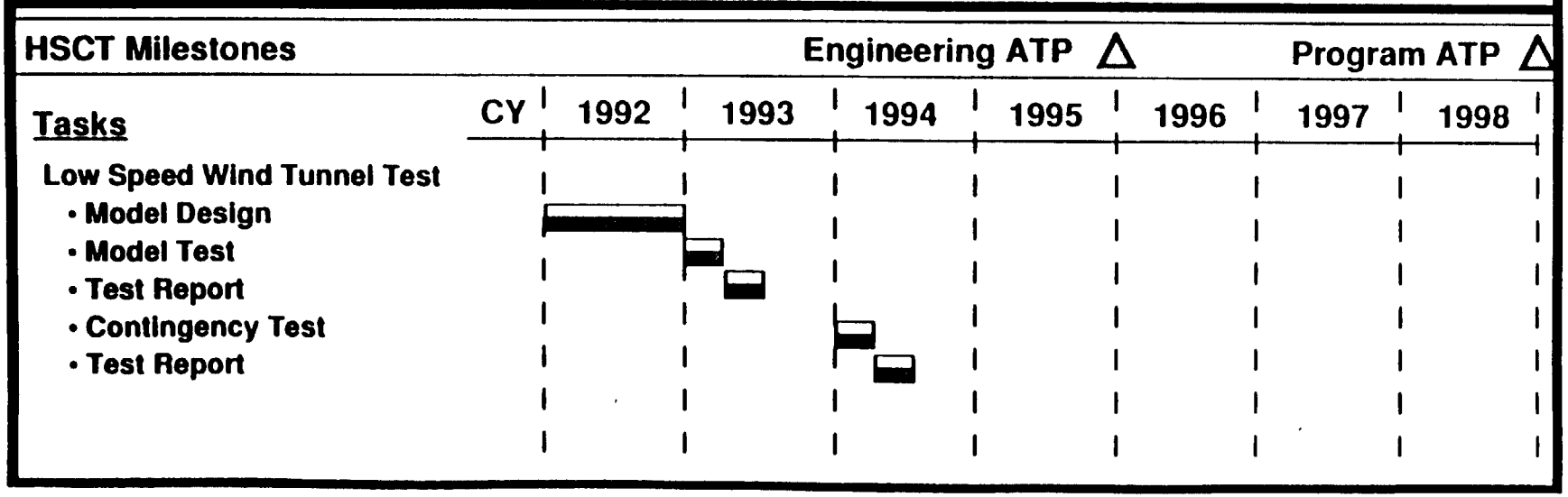
Figure 33. Technology development plan for defining advanced high-lift system stability and control characteristics.

Modelling

ISSUE: Low-Boom Planform Effects

No data exists on low-boom planform effects on Stability and Control.

IMPACT: Control requirements may penalize low-boom planforms with large control surfaces.



NASA Industry

Figure 34. Technology development plan for defining low-boom planform stability and control characteristics.

Synthesis & Analysis

ISSUE: Under Utilization of Multi-Disciplinary Optimization

Recent advances in multi-disciplinary optimization, which permit the optimization of aeroelastic systems, including the control system, to further improve aircraft performance and design, are not being fully utilized.

IMPACT: Unrealized Performance

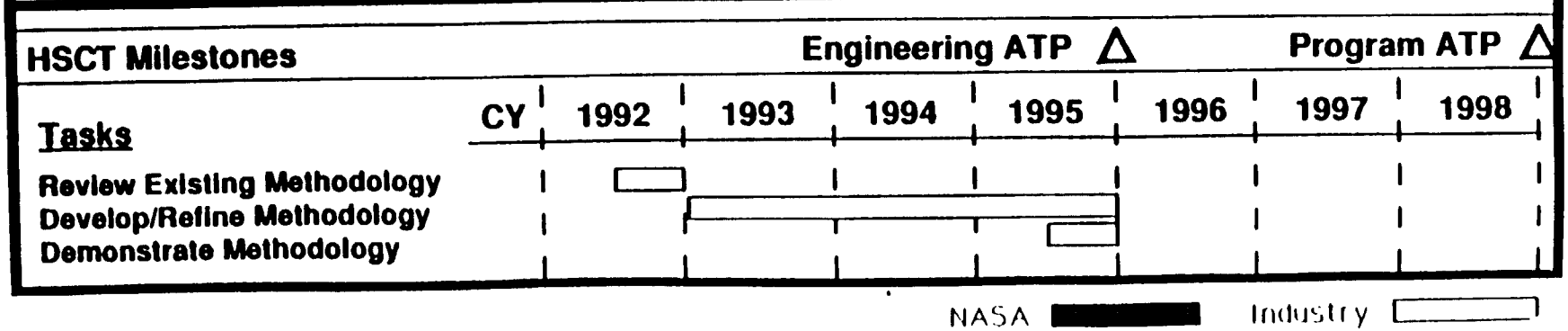


Figure 35. Technology development plan for using multidisciplinary optimization.

Synthesis & Analysis

ISSUE: Flight Path Management

Noise abatement and advanced operating procedures will be required during takeoff and landing for economic viability and certification. Adequate constrained optimization synthesis and analysis tools need to be established, and a solution which satisfies the conflicting constraints provided.

IMPACT: Reduced Economics; Performance Below Certification Reqs.

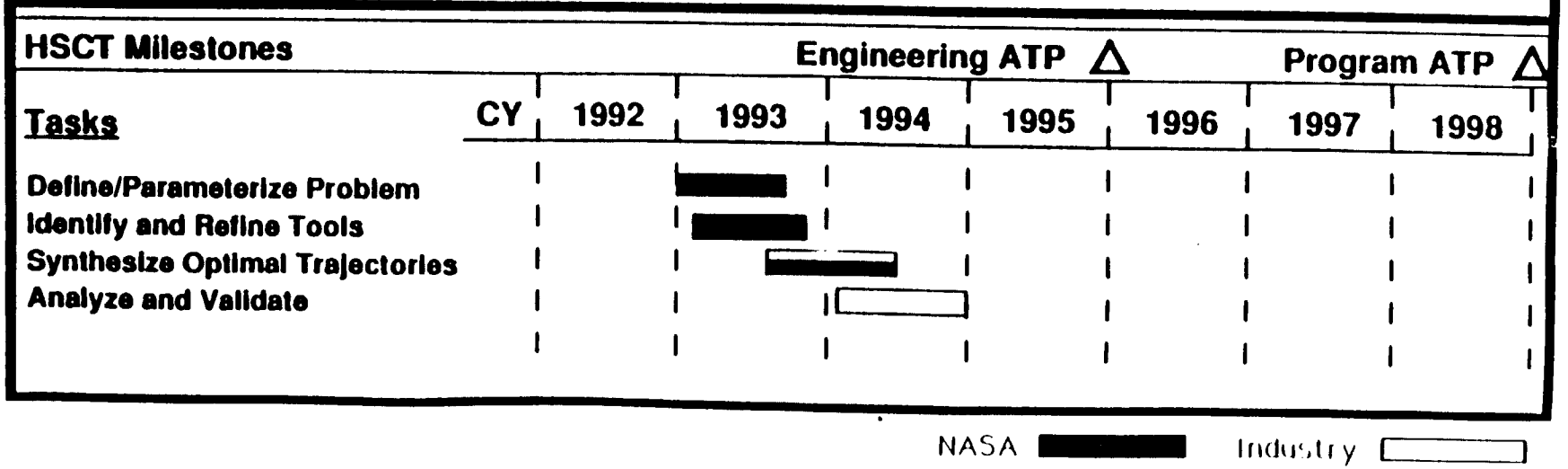


Figure 36. Technology development plan for developing constrained optimization synthesis and analysis tools.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1992	Contractor Report-Final

4. TITLE AND SUBTITLE

Design and Analysis Issues of Integrated Control Systems for High-Speed Civil Transports

5. FUNDING NUMBERS

NAS2-12722

6. AUTHOR(S)

Craig A. McCarty, John B. Feather, John R. Dykman, Mark A. Page, and John Hodgkinson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Douglas Aircraft Company
Engineering Technology and Advanced Aircraft Programs
Long Beach, California

8. PERFORMING ORGANIZATION REPORT NUMBER

H-1787

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR-186022

11. SUPPLEMENTARY NOTES

This report was prepared for PRC Inc., P.O. Box 273, Edwards, California 93523-0273 by Douglas Aircraft Company under subcontract ATD-91-DAC-7103. NASA Technical Monitor was Bruce G. Powers, NASA Dryden Flight Research Facility, P.O. Box 273, Edwards, California 93523-0273. NASA COTR for PRC Inc. Donald C. Bacon, Jr., 805-258-3484.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified — Unlimited
Subject Category 08

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A study was conducted to identify, rank, and define development plans for the critical guidance and control design and analysis issues as related to an economically viable and environmentally acceptable high-speed civil transport. The issues were identified in a multistep process. First, pertinent literature on supersonic cruise aircraft was reviewed, and experts were consulted to establish the fundamental characteristics and problems inherent to supersonic cruise aircraft. Next, the advanced technologies and strategies being pursued for the high-speed civil transport were considered to determine any additional unique control problems the transport may have. Finally, existing technologies and methods were examined to determine their capabilities for the design and analysis of high-speed civil transport control systems, and to identify the shortcomings and issues. Three priority levels – mandatory, highly beneficial, and desirable – were established. Within each of these levels, the issues were further ranked. Technology development plans for each issue were defined. Each plan contains a task breakdown and schedule.

14. SUBJECT TERMS

High-speed civil transport; Integrated control systems; Technology development plans

15. NUMBER OF PAGES

72

16. PRICE CODE

A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited