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TECHNOLOGY BENEFITS AND GROUND TEST FACILITIES FOR HIGH-SPEED CIVIL TRANSPORT DEVELOPMENT

Matthew M. Winston
Elwood W. Shields and
Shelby J. Morris, Jr.

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National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23665-5225

INTRODUCTION

Soon after the turn of the century, the first economically viable supersonic commercial aircraft may start regular service across the Pacific Ocean. Recent studies (e.g., references 1 and 2) indicate projected revenue passenger miles to the Pacific Rim area more than tripling by the year 2000. The great distances for these trans-Pacific flights make high speed transports exceptionally attractive with travel time less than half that for subsonic jets. For a new supersonic aircraft to compete in the commercial market, however, it must have much greater performance and productivity than the Concorde, the first generation supersonic transport (SST). It must also meet environmental constraints more stringent than those which have been waived for the Concorde. The new environmental and economic goals can only be achieved by incorporating numerous technological advances into the initial aircraft design. The maturation and application of these advanced technologies will require enormous amounts of ground and flight testing, not only in aerodynamics, but also in propulsion, materials, structures, and other disciplines. This paper will address the benefits of advanced technologies and the ground test facilities needed to support technology development for future high-speed civil transport (HSCT) aircraft.

Background

Numerous studies have explored future requirements for testing aerospace components, vehicles, and systems. References 3, 4, and 5 include studies conducted in the 1970's and 1980's which examined facility needs for both military and civil aerospace vehicle development. One of the more recent and comprehensive papers on the subject (reference 6) updates and expands the earlier studies and provides recommendations for facilities needed into the next century. It examines the vehicle speed range from low subsonic to hypersonic.

Most of the previous studies have focused primarily upon the needs of the aerodynamicist and has been conducted largely by and for the wind tunnel community in efforts to achieve a more faithful flow simulation and to obtain more precise measurements. The wind tunnel is and will continue (at least, for some time to come) to be the aerodynamicist's primary experimental tool. For practical reasons, however, each wind tunnel can only simulate a small portion of the flight regime and then only at sub-optimum levels of full-scale fidelity. When full-scale fidelity is essential, and can not be achieved or deduced from wind-tunnel data, it is usually necessary to obtain the required information from flight tests. Flight testing, however, is costly and not always suitable for the kinds of studies (e.g., optimizations, parametric analyses) pursued in an aircraft development program. Because of the limitations of wind tunnels and the expense and narrow application of flight test data, previous studies have, for the most part, focused on the need for new and/or improved wind tunnels together with enhanced instrumentation and test techniques.

Purpose and Scope

Previous studies have defined, in considerable detail, future ground test facility needs for a broad range of air vehicles. The purpose of this paper is to address the issue of facility needs with the focus on a single class of vehicle -- high-speed (supersonic) passenger transport aircraft. The objectives are: 1) to evaluate the potential performance benefits available to HSCT aircraft through advanced technologies, and 2) to identify the major deficiencies in test capability necessary for HSCT development which require new ground test facilities.

Technology Focus - Considering that the Anglo-French Concorde represents the first generation of supersonic transports, emphasis in this paper will be placed on the second and subsequent generations of aircraft. The second generation (currently called HSCT) is envisioned to enter service in the first quarter of the next century. The timing of later generations is highly dependent upon the success of the HSCT; hence, technology readiness and market windows for the third and later generations cannot be determined at this time. Nevertheless, it is clear that the research and development effort for second generation supersonic transports is initially focused on environmental concerns -- community noise, potentially harmful engine emissions, and sonic boom (see fig. 1). If these concerns can be successfully met, the viability of the HSCT will depend upon its ability to compete economically in the world airline market. It is the pursuit of this commercial viability via technology which will largely define both the short-term and the long-term facility needs.

Technology Benefits - How does advanced technology contribute to commercial viability, and how does improved test capability enhance new technology application? An example of technology impact can be shown by quantifying its effect on a typical configuration. A Mach 2.4 baseline aircraft concept developed by NASA and based on 2005 technology availability is given in figure 2. This configuration was developed for a design mission of 6500 nautical miles range with a 250-passenger payload. It is a tailless configuration with a double delta wing planform and four axisymmetric, single-engine, underwing nacelles. The wing planform was designed for best supersonic cruise performance while maintaining the desired low-speed characteristics. Leading-edge flaps are utilized on the outboard wing panel, and trailing-edge flaps are used across the entire available span.

To illustrate the effect of changes in the three major disciplines (aerodynamics, propulsion, and structures and materials), a five-percent change in each was arbitrarily made, and the results are shown in figure 3. It is apparent that each change has a significant impact on the configuration weight. The 5% change in lift-to-drag ratio (L/D) represents a change from 8.8 at mid-cruise to slightly over 9.2 and indicates that every 0.1 improvement in L/D is worth a reduction of almost 7,000 pounds in takeoff gross weight. In propulsion, every 0.01 (lb/hr/lbf) improvement in specific fuel consumption (SFC) is worth about 4600 pounds in takeoff gross weight. Finally, every pound of structural weight reduction provides two pounds of TOGW reduction.

However, the integration of technological advances in the separate disciplines and the importance of their interrelationships to the performance of the overall design may be more important than any one discipline advance taken alone. A structural material that is light and tolerant of the thermal flight environment may be of little use if other properties make it difficult to fabricate into an efficient aerodynamic shape. The location of engines on a supersonic configuration not only affects the aerodynamic performance but it also affects the performance of the engines. The preferred engine placement for good aerodynamic and propulsion system performance, however, may cause large structural penalties.

Facilities - Good ground testing in all three disciplines is critical in order to validate the benefits of technology and to determine the effects of these kinds of interactions. Aircraft manufacturers must be able to guarantee performance within very narrow limits to the airlines, and therefore they must be able to measure performance parameters to a high degree of precision. Precise and reliable test data will always be important to any conceptual and preliminary design process, but it is even more important to the HSCT development effort because of the limited data base of existing supersonic aircraft. This situation also makes it necessary that ground testing be done in a timely manner if the results are to be the primary basis for evaluating performance or making design changes. High utilization and productivity of any test facility, whether new or existing, is also important to the HSCT effort, and therefore points to the need to minimize setup and removal times and maintenance requirements.

Timing - With these requirements in mind, and given the years required to plan, build, bring on-line, and establish confidence in a major new facility considering the current HSCT development schedule, it is anticipated that second-generation, supersonic commercial transports will not benefit greatly from any new facilities not already well-planned or under way. Near-term environmental problems and HSCT design and development needs must be served primarily by existing major facilities supplemented by, perhaps, some minor laboratory additions and flight tests. Until it is evident that we can solve the environmental problems, the justification of any costly new facility primarily to support supersonic transport development will be difficult. However, the future facility needs discussed herein are not wholly predicated upon the success or failure of high-speed commercial transport initiatives. The major facilities which are identified as long-term needs for supersonic transport research and technology are also required to support the development of other aerospace vehicles and systems.

KEY TECHNOLOGIES FOR THE NEXT GENERATION HSCT

The target characteristics of the second generation aircraft (HSCT) are compared to those of the Concorde in figure 4. Although substantial advances in the aeronautical sciences have been made since the introduction of the Concorde, the achievement of HSCT goals requires significantly greater technology development. The enhancements provided to the next and later generations of aircraft will result from projected advances in aerodynamics (including computational fluid dynamics, CFD), propulsion, electronics, and other technology disciplines. To a greater extent than ever before, advanced materials and structures will be relied upon to achieve significant reductions in airframe and systems weights. Indeed, the application of advanced materials and structure to both engines and airframe is considered essential to a viable second-generation HSCT.

Figure 5 presents results from a recent study based on the previous Mach 2.4 baseline aircraft to assess the potential value of technological opportunities. This HSCT concept had a payload of 305 passengers and a design mission of 5,000 nautical miles, 25 percent of which was flown at a high subsonic Mach number. Figure 5 shows the benefits of advances in individual technical disciplines predicted to be available by 2005 and illustrates their collective effect on reducing aircraft takeoff gross weight. An overall decrease of 57 percent in TOGW from 1990 technology levels is indicated as being possible if the benefits of all the technologies are available and can be applied simultaneously. The need for experimental studies will continue to be significant if this is to happen. The following paragraphs discuss technologies essential to HSCT development where experimentation is expected to be utilized.

Environmental Technologies

If HSCT aircraft are to begin service early in the next century, the environmental problems require near-term solutions and currently must be addressed with existing (or almost ready) facilities. Scientific and engineering studies concerned with atmospheric emissions are being accomplished primarily through the combined efforts of the atmospheric sciences community and researchers in engine combustion technology using state-of-the-art facilities. Sonic boom reduction is being addressed with aircraft design studies supported by existing supersonic wind tunnels and with modern laboratory and field test facilities for investigating human and building responses. Studies of noise suppression devices and noise abatement schemes necessary to permit certification of second-generation HSCT aircraft under present regulations are taking place in available acoustic facilities. Reducing HSCT aircraft noise to currently permissable levels, however, presents an extraordinary challenge at the present state of aeroacoustic technology. Moreover, there are indications that all future aircraft may be required to be quieter than current noise regulations permit. If for these reasons, the need arises for enhanced ground-based experimental capability in acoustics, new test facilities may very likely be required.

Aerodynamics

Application of currently available data, facilities and airframe design methodology is considered adequate for providing evolutionary improvements in cruise aerodynamic performance. The only revolutionary aerodynamic technology expected to substantially enhance that performance and potentially provide significant economic benefits is supersonic laminar flow control (SLFC). It is, however, a yet unproven technology. Although flight test programs have been established to assess some of the installation and operational aspects of SLFC systems, the data required for design verification, development, and certification will no doubt require extensive specialized ground-based test and analysis. In addition to the need for optimum cruise aerodynamics, good low-speed performance is needed to reduce the engine thrust required (and hence, the noise) during terminal area operations . The high-lift systems required for good low speed and climb performance which have been developed and refined for subsonic aircraft are not readily adaptable to supersonic designs. Therefore, a number of candidate high-lift concepts are being considered specifically for HSCT application (figure 6), and the evaluation and selection of the best of those will require extensive ground test and analysis as well. Earlier studies (refs. 6 and 7) have recognized the need for new facilities to address both supersonic laminar flow and high-lift technology development.

Propulsion

The HSCT propulsion system must meet several stringent criteria. It must meet the primary requirements of high thrust-to-weight ratio and low cruise fuel consumption and must produce low emissions and low noise. In addition, the engines will operate in a more severe thermal environment because of the high flight speeds. Matching the engine to the inlet and nozzle and subsequently integrating the complete propulsion package with the airframe could require substantial ground testing. Although the basic facilities required for these efforts are available, some of them may need major upgrading to provide support for HSCT development.

Structures and Materials

Since every important aspect of design benefits from lower weight, disciplines which lead to weight minimization will be essential to a successful High-Speed Civil Transport. Candidate lightweight materials which can potentially meet the strength, stiffness and thermal requirements of HSCT designs have been identified. The selection of the primary airframe material will depend upon many factors, not the least of which is the design Mach number. On the other hand, the inherent thermal properties of the materials which provide the best combination of weight, strength, stiffness, damage tolerance, and repairability may very well dictate the design Mach number. The definition of material properties and structural concepts to the level of confidence required for application to civil aircraft design calls for extraordinary efforts in laboratory and field testing. The selection and application of materials to satisfy engine thermal requirements and provide the desired operational life will also require extensive investigation.

FUTURE FACILITY REQUIREMENTS

Much of the ground testing required for future HSCT development can be accomplished in existing facilities. The subsonic, transonic, and supersonic wind tunnels, engine test cells, simulators and other government and industry facilities in the U.S. have been assessed against future needs in aeronautical research and development (refs. 4, 6, and 7) and found to be adequate, assuming that necessary upgrading of facilities is accomplished where required. There are four major areas, however, where the need for new facilities has been identified (see figure 7). These are: 1) a facility suitable for testing supersonic LFC concepts, 2) a facility to test high lift concepts, 3) a facility for acoustic testing at high subsonic speeds, and 4) facilities to provide combined mechanical, internal pressure, and thermal loads testing. A detailed discussion of the rationale for and the physical attributes of (1), (2), and (3) is given in reference 6. A brief summary of all four types of facilities and their relevance to high-speed transport development is given in the following paragraphs.

Low Disturbance Supersonic Wind Tunnel

As discussed earlier, laminar flow of any appreciable amount could significantly decrease the drag on a high-speed civil transport. If laminar flow could be achieved on 30 percent of the wing and 50 percent of the tail for the configuration shown in figure 8, the wing area could be decreased by 700 square feet and the gross weight would decrease by over 40,000 pounds. The majority of the weight decrease comes from fuel savings which results in substantial economic benefits over the lifetime of the aircraft. If supersonic laminar flow is to be a viable technology on HSCT's, it will be necessary to produce a flight applicable database which can define the boundary layer transition location on representative configurations. There will also be a need for high Reynolds number wind-tunnel tests of laminar flow control systems on representative configurations. These tests require a large-scale, low-noise, low -disturbance supersonic wind tunnel. Such a facility does not presently exist. The ability of existing facilities to accurately determine full-scale transition Reynolds numbers is inadequate as shown in figure 9.

Conventional supersonic wind tunnels suffer from stream fluctuating vorticity fields and acoustic waves radiated from the nozzle wall boundary layers making them unsuitable for testing laminar flow systems. For several years, NASA research has been directed toward the development of a quiet supersonic tunnel which would provide the capability for SLFC testing. References 8 and 9 examine in detail the design and operational characteristics of such a facility. A Mach 3.5 pilot tunnel at Langley has demonstrated some success in prediction of transition Reynolds numbers on sharp cones (see fig. 10). These results and others indicate that the technology exists to design a low-disturbance supersonic tunnel similar to that shown in figure 11. There are, of course, other supersonic phenomena aside from LFC concerns where such a facility would be invaluable (e.g., flow phenomena related to supersonic maneuvering military aircraft and missiles).

Subsonic High-Reynolds Number Wind Tunnel

In addition to the terminal area performance benefits, high-lift technology is expected to contribute heavily to any final solution of the HSCT community noise problem. Substantial current effort is focused upon screening and selection of high-lift concepts suitable for providing the desired takeoff and landing performance together with the climbout performance required for effective noise abatement procedures. Evaluation of these concepts requires testing at or near full-scale Reynolds numbers. High Reynolds number facilities like the NASA National Transonic Facility (NTF) are unsuitable because the strength of model high -lift components can not withstand the high dynamic pressures generated in the test section. According to reference 6, low dynamic pressure/low Reynolds number tunnels (most of the available low-speed atmospheric tunnels) provide pessimistic estimates of system performance due to late boundary-layer transition and enhanced flow separation.

The need for a high-Reynolds number, low-dynamic pressure wind tunnel to investigate high-lift as well as other subsonic aerodynamic phenomena is not new and has been addressed in numerous past studies (see references 6 and 10, for example). In the past, the capability for achieving high Reynolds numbers at low speeds has been provided by pressurized air facilities such as the Langley Low Turbulence Pressure Tunnel (LTPT) and the Ames 12-Foot Tunnel. These facilities are not adequate, however, for many present and future needs. The limitations of test section size and required model scale preclude achievement of the necessary Reynolds number matching even at elevated pressures. Moreover, the LTPT is designed for two-dimensional airfoil testing and is not satisfactory for the variety of complete configuration tests involved in aircraft R&D programs. At least one study has been conducted (ref.10) to examine potential upgrades to the LTPT including higher pressurization, larger test section, and improved flow quality. A detailed study of a more ambitious effort has also been undertaken in an unpublished study within NASA. This study defined a large (8 x 10 - meter), low-noise, low turbulence pressure tunnel which in concept could use air, heavy gas (SF6), or cryogenic liquid nitrogen (LN2) as a test medium. Maximum Mach number would be 0.35. With air at 5 atmospheres, it could achieve unit Reynolds numbers in excess of 18 million; and with SF6 or LN2 at 5 atmospheres, it could achieve unit Reynolds numbers up to 38 million. This capability would allow testing at full-scale approach Reynolds numbers of even the largest existing subsonic transports. This 8 x 10-meter tunnel concept obviously represents a much more costly approach than the proposed LTPT upgrade. The value of the expanded test capability (figure 12) would have to be weighed against the additional expense.

Acoustic Research Facility

Noise reduction is one of the primary enabling technologies for a new high-speed transport, and it must be addressed early in the design cycle. Any ground test facility needed for acoustic research must satisfy stringent requirements. According to reference 6, a "valid acoustic state can be assured only when the true aerodynamic state of a vehicle and/or the physical phenomenon is duplicated." An appropriate acoustic test facility, therefore, must be reflection-free, of adequate size, and have low background noise while satisfying all of the other aerodynamic test requirements such as Mach number, Reynolds number, and flow quality. Although much of the desired acoustic test capability can be achieved by modifications to the Ames Research Center's 40-X-80 foot Tunnel (ref. 6), the flow velocity in that facility is limited to about 300 knots. This limitation would preclude testing at the higher subsonic Mach numbers.

Serious consideration has been given to providing the required noise research capability at the Langley Research Center. Reference 6 describes a design study for a candidate high-speed acoustic wind tunnel using either air or heavy gas (SF6) as a test medium. The design includes provisions for aerodynamic, acoustic, and aeroelastic testing by employing three interchangeable test sections. The large test section size, the acoustic design features, and the versatility of this facility could provide reliable simulations of rotary-wing and fixed-wing vehicles at speeds up to Mach 0.9. It would be the only U. S. facility adequate for supporting future acoustic research and technology across a broad speed range. The proposed design would provide capabilities superior to those of the DNW (Dutch-German Wind Tunnel) which is so heavily relied upon by U.S. and European industry and government at the present time since it is the only facility in the world with acoustic qualities and scale to provide adequate noise assessments .

Structural Test Facilities

Successful development of viable wing and fuselage structures for a future High-Speed Civil Transport (HSCT) aircraft requires verified structures technology and structural concepts that are both light weight and cost effective. Structural designs and structural analysis methods for HSCT need to be verified by testing appropriate structural elements, panel subcomponents, and built-up structural components subjected to realistic loading conditions The loading conditions for HSCT structural tests include various combinations of mechanical, internal pressure, and thermal loads needed to identify response characteristics and failure mechanisms which must be included in the structural design process. The tests are also needed to evaluate structural performance and critical design requirements such as damage tolerance and damage containment for HSCT wing and fuselage structures. The facilities should have the capability to 1) evaluate static and cyclic loading conditions that simulate flight conditions, and 2) evaluate structural integrity and damage tolerance. One test facility is needed to evaluate and study fundamental response and failure characteristics and another facility is needed to conduct hazardous tests such as those associated with damage tolerance testing of internally pressurized fuselage structure.

Current structural testing capabilities at NASA Langley Research Center are limited to room-temperature testing of panels subjected to uniaxial loads. A room-temperature, combined-load testing capability is being designed to evaluate the structural performance of panels subjected to combined mechanical and internal pressure loads typical of subsonic transport aircraft structures (See figure 13). The capability of this facility needs to be extended to include thermal loads so that panels subjected to combinations of mechanical, thermal and internal pressure loads can be evaluated. This extension will require the addition of appropriate heating capability to the facility being planned for room-temperature structural testing. This capability is needed as soon as possible for HSCT structural concept development and evaluation. It is needed by 1995 to provide for HSCT structural subcomponent tests in 1996.

A new facility is needed to evaluate the damage tolerance of built-up structural components subjected to combinations of mechanical, internal pressure, and thermal loads. The facility should have all of the support and load reaction systems necessary to conduct structural tests as well as the systems necessary to generate and control the loads required to test wing and fuselage structures to failure with damage. This facility needs to be available in 1996 or 1997 to allow structural component testing to be conducted in 1997 or 1998.

CONCLUDING REMARKS

Technology assessments on baseline HSCT configurations show that significant decreases in takeoff gross weight can be achieved if the technology goals in various disciplines can be reached. Reaching this advanced state of technology will require extensive testing in ground-based research and development facilities.

A review of future ground-test facility needs for high-speed civil transport development indicates that existing facilities (with some upgrading required) are adequate for providing a large amount of the necessary test data. New wind-tunnel facilities are needed to evaluate supersonic laminar flow and its application to this class of aircraft. New low-speed, high- Reynolds-number wind tunnels would enhance the evaluation and selection of the most effective high-lift systems for highly-swept wings. New facilities to provide accurate acoustic measurements may become essential to the design of supersonic transports to meet existing and future noise standards. In addition, new structural test facilities are required to evaluate performance and critical design requirements for high-speed transport wing and fuselage structures under combined mechanical, internal pressure, and thermal loads.

Although cost considerations were not specifically addressed in this study, it is anticipated that new facility costs will be high due to their complexity and unique requirements. Additional expense and delay of new facilities are also likely due to the environmental impact constraints placed on major construction projects.

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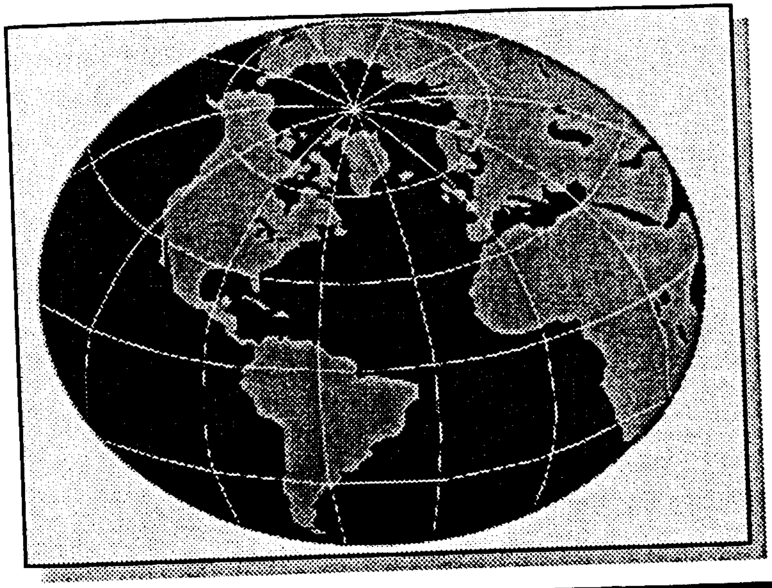


ENVIRONMENTAL CONCERNS

- Atmospheric Emissions
- Sonic Boom
- Community Noise

ECONOMIC ENHANCEMENTS

- Advanced High-Temperature Materials
- Advanced Structural Concepts
- Advanced Propulsion Systems
- Improved High-Lift & Cruise Aerodynamics
- Advanced Cockpit & Flight Management Technology

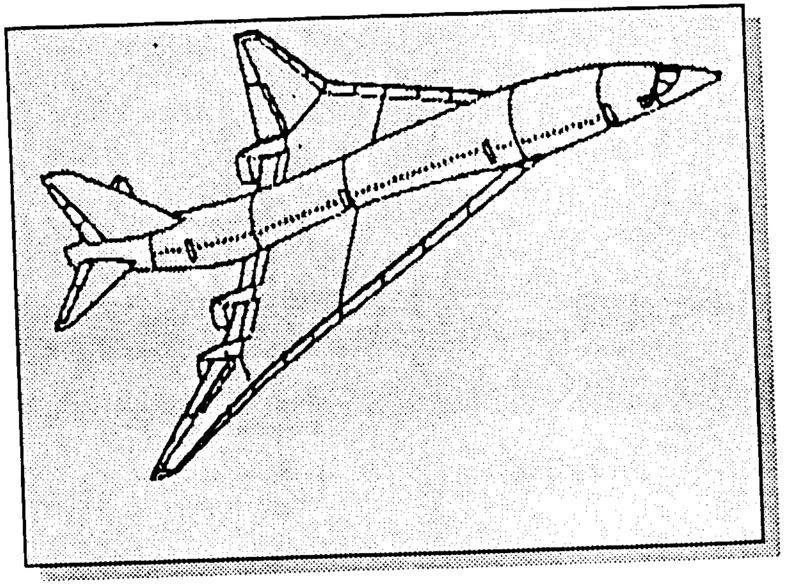


Figure 1. - HSCT research and technology focus.

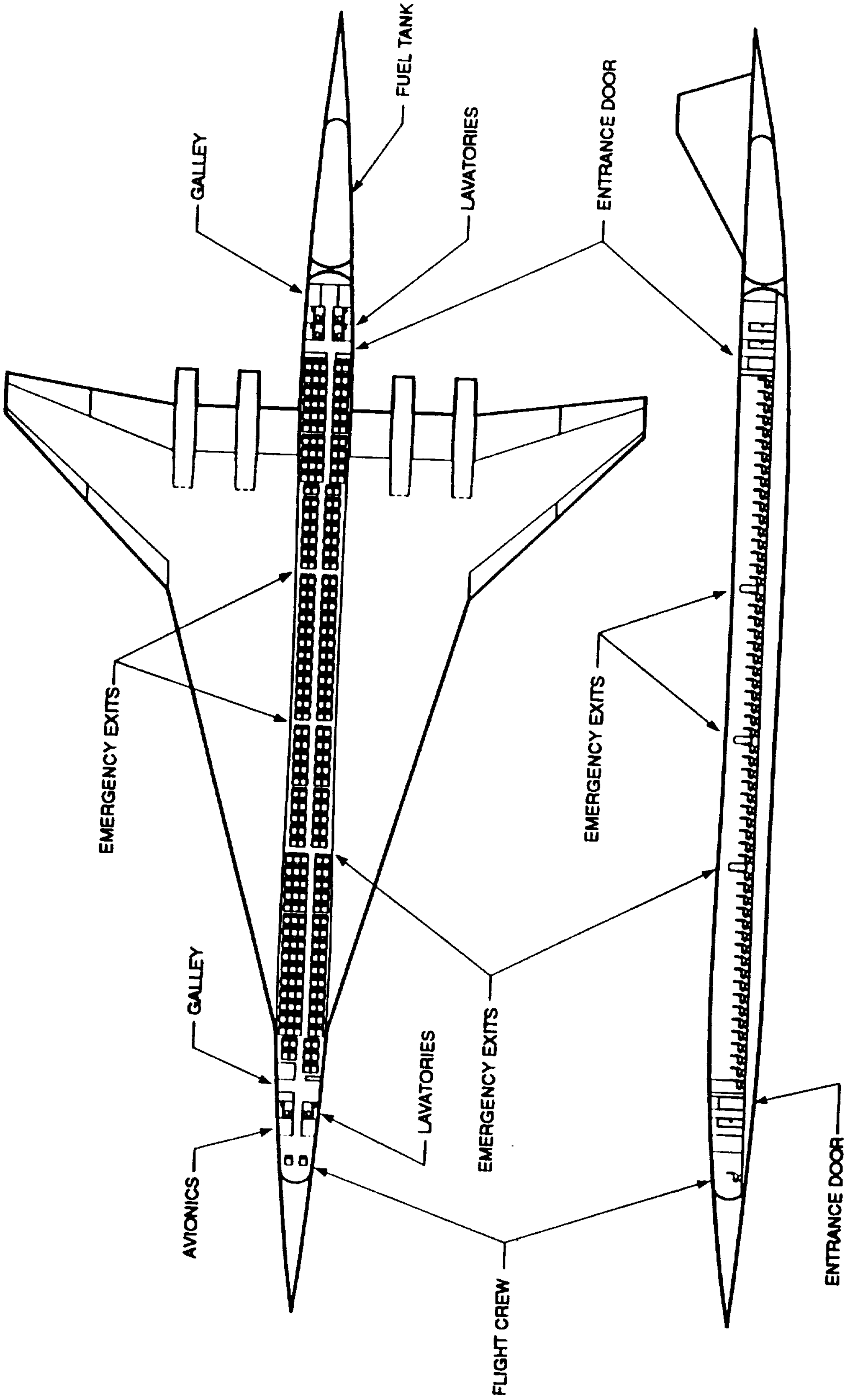


Figure 2. - NASA Mach 2.4 baseline configuration.

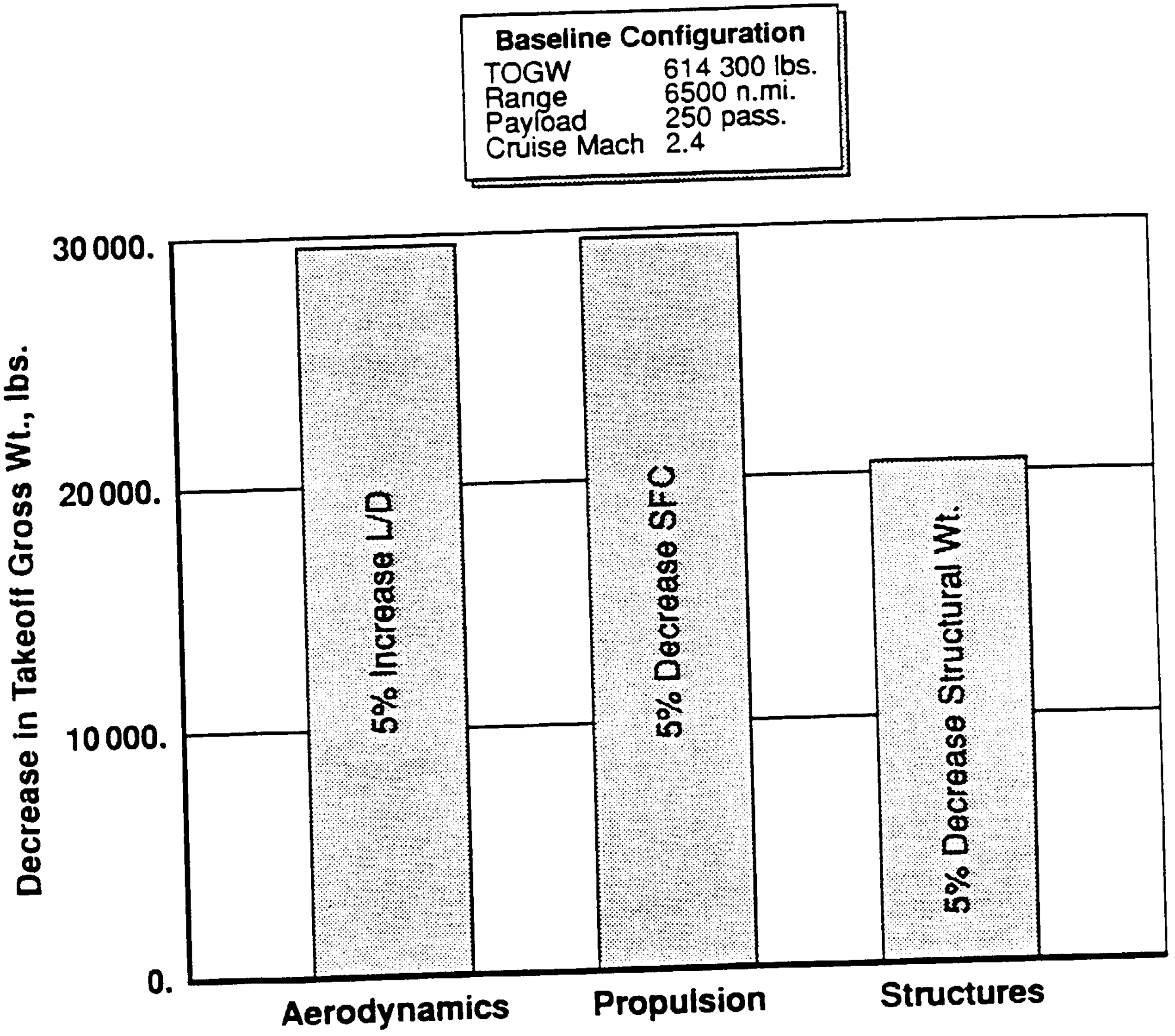
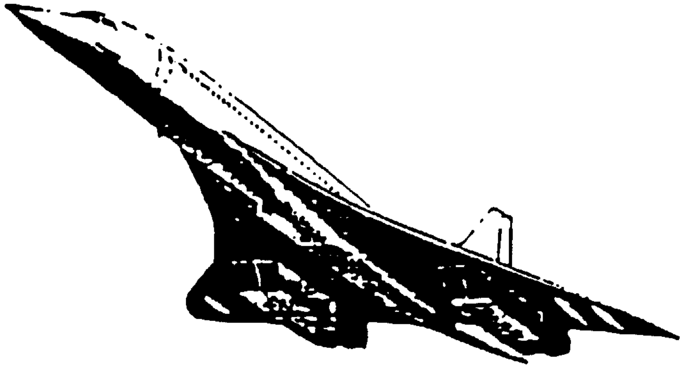
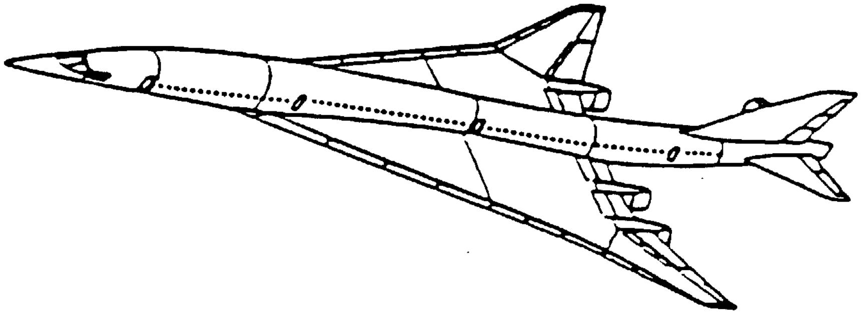


Figure 3. - Effects of advances in major technical disciplines.





Concorde		HSCT Goals
3000	Range (n. mi.)	5000-6500
100	Payload (passengers)	250-300
400,000	Weight (lb.)	750,000
87	Required Revenue (¢/RPM)	10
Premium	Fare Levels	Standard
Exempt	Community Noise Standard	FAR 36 - Stage III
20	Emissions Index (gm/Kg fuel)	3-8 (at HSCT efficiency)

Figure 4. - Supersonic transport characteristics

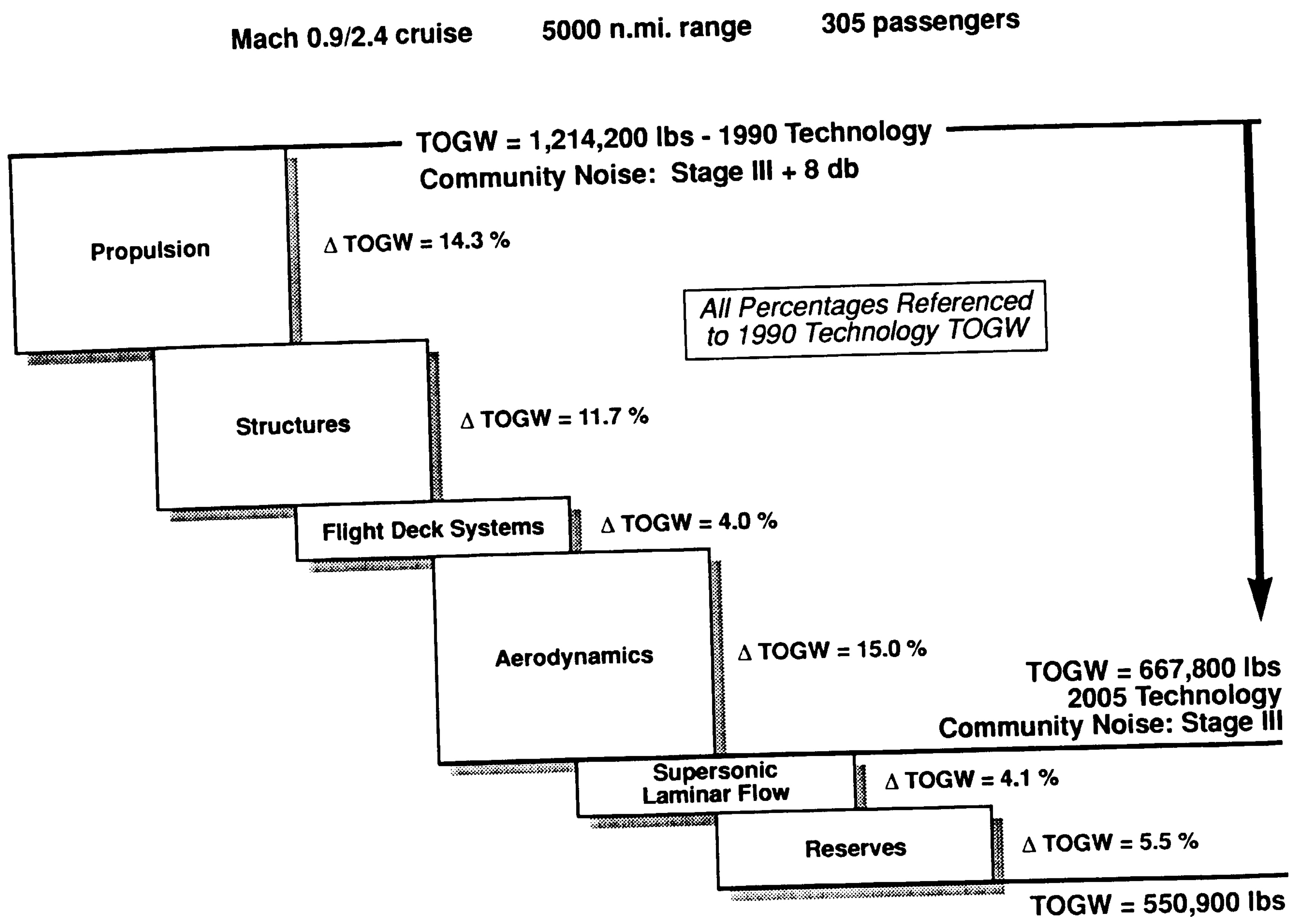


Figure 5. - HSCT technology opportunities.

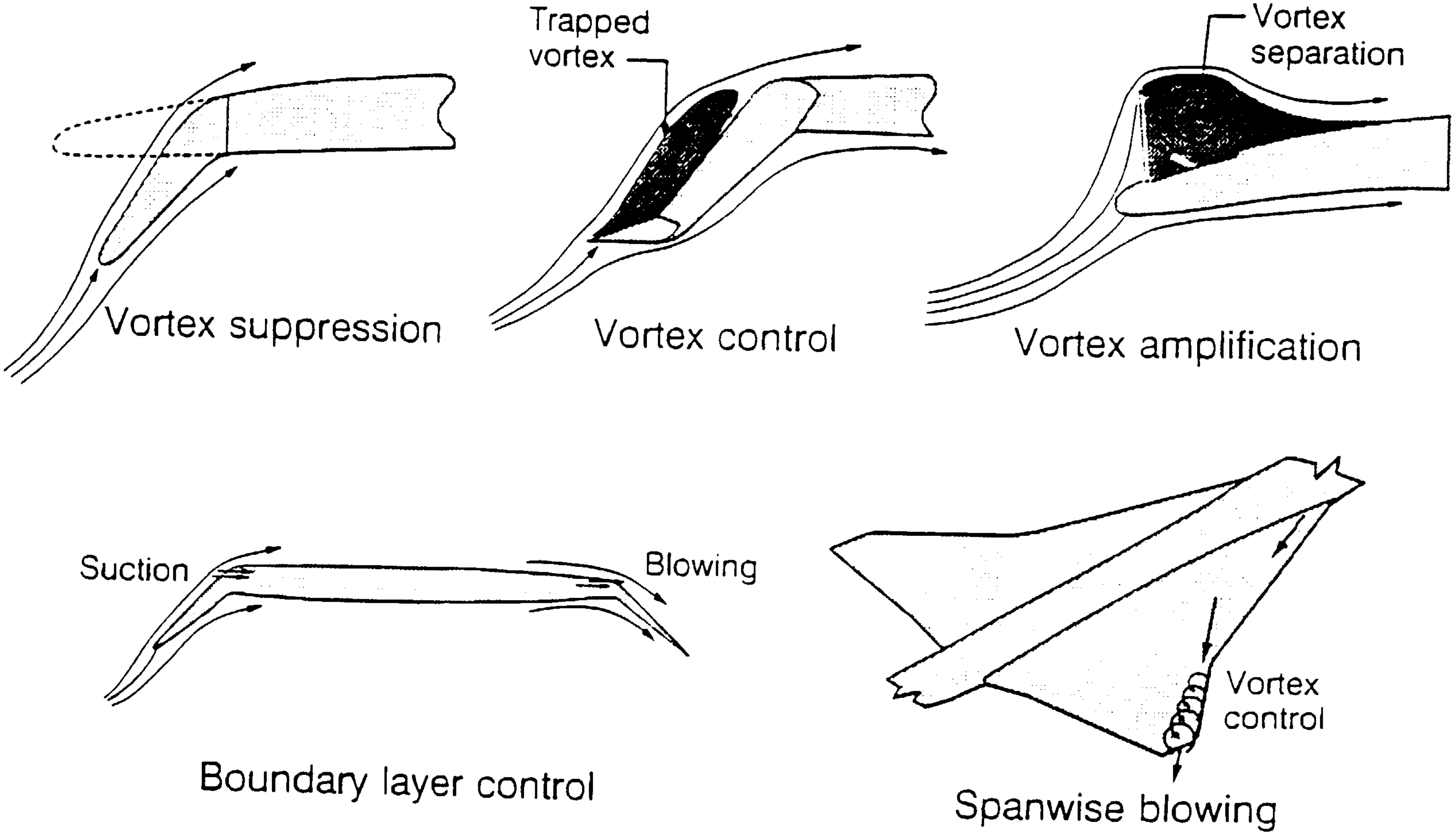


Figure 6. - High-lift system concepts.

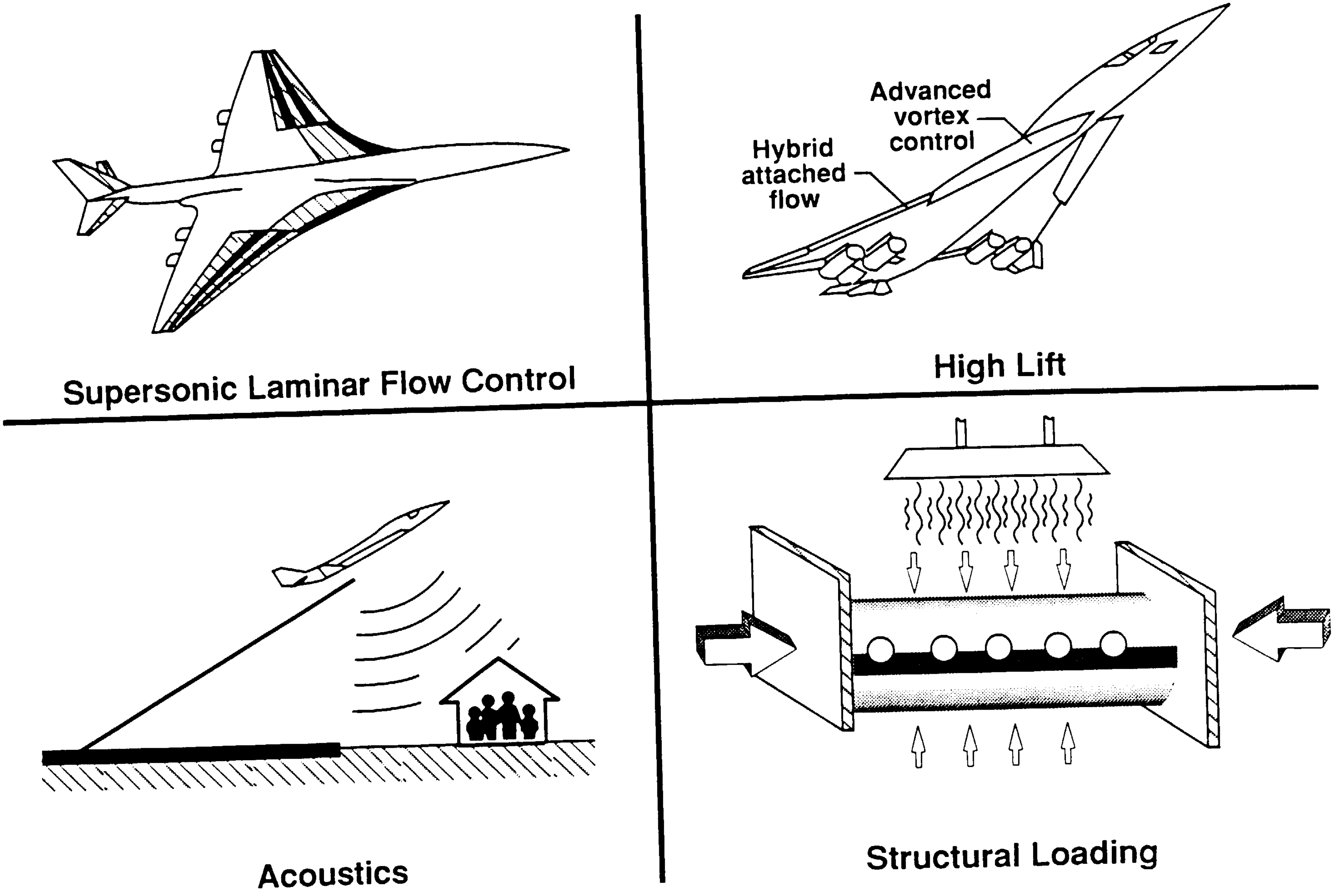


Figure 7. - Advanced technology facility needs.

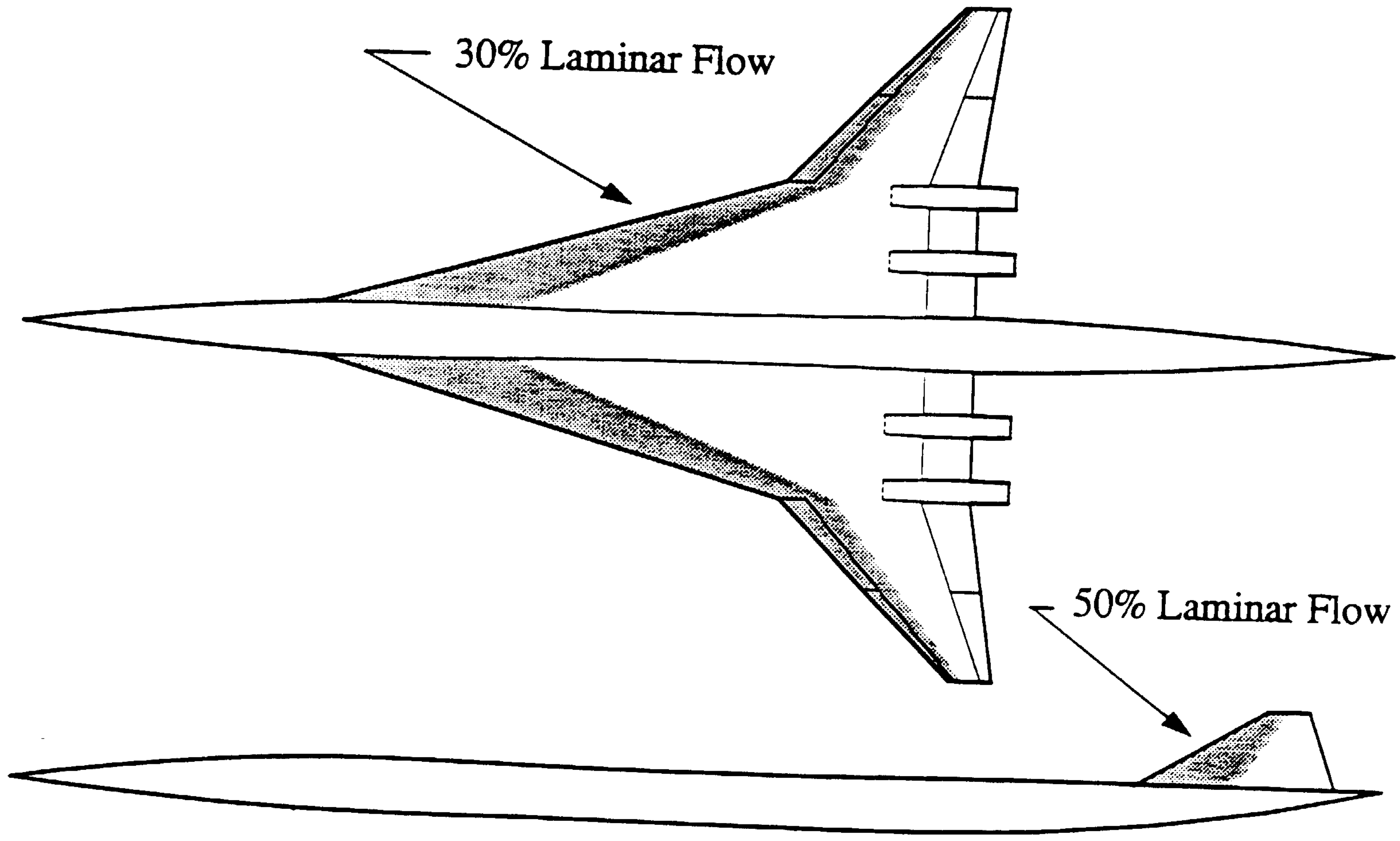


Figure 8. - Laminar flow on HSCT configuration.

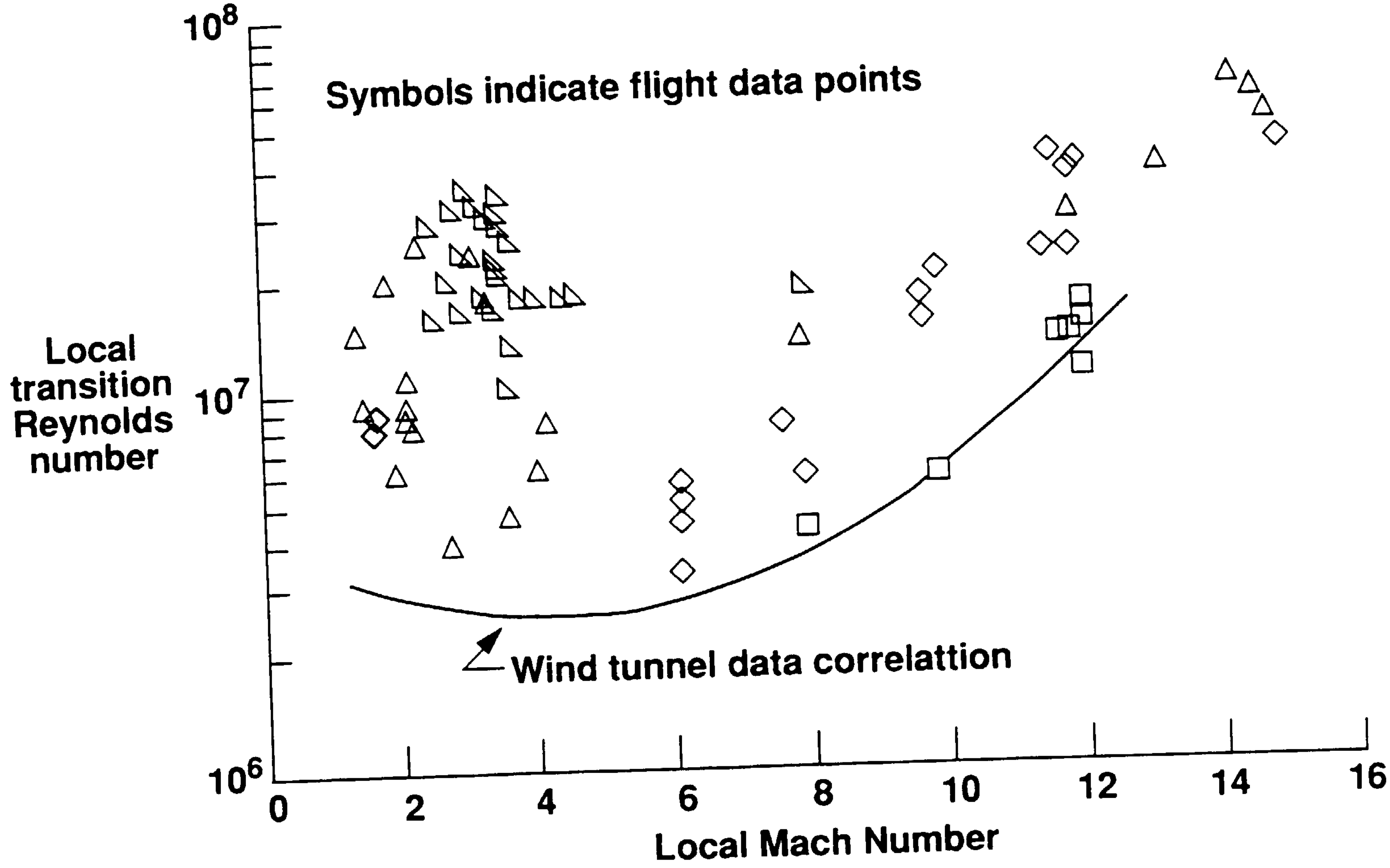


Figure 9. - Transition Reynolds numbers from wind tunnel and flight tests.

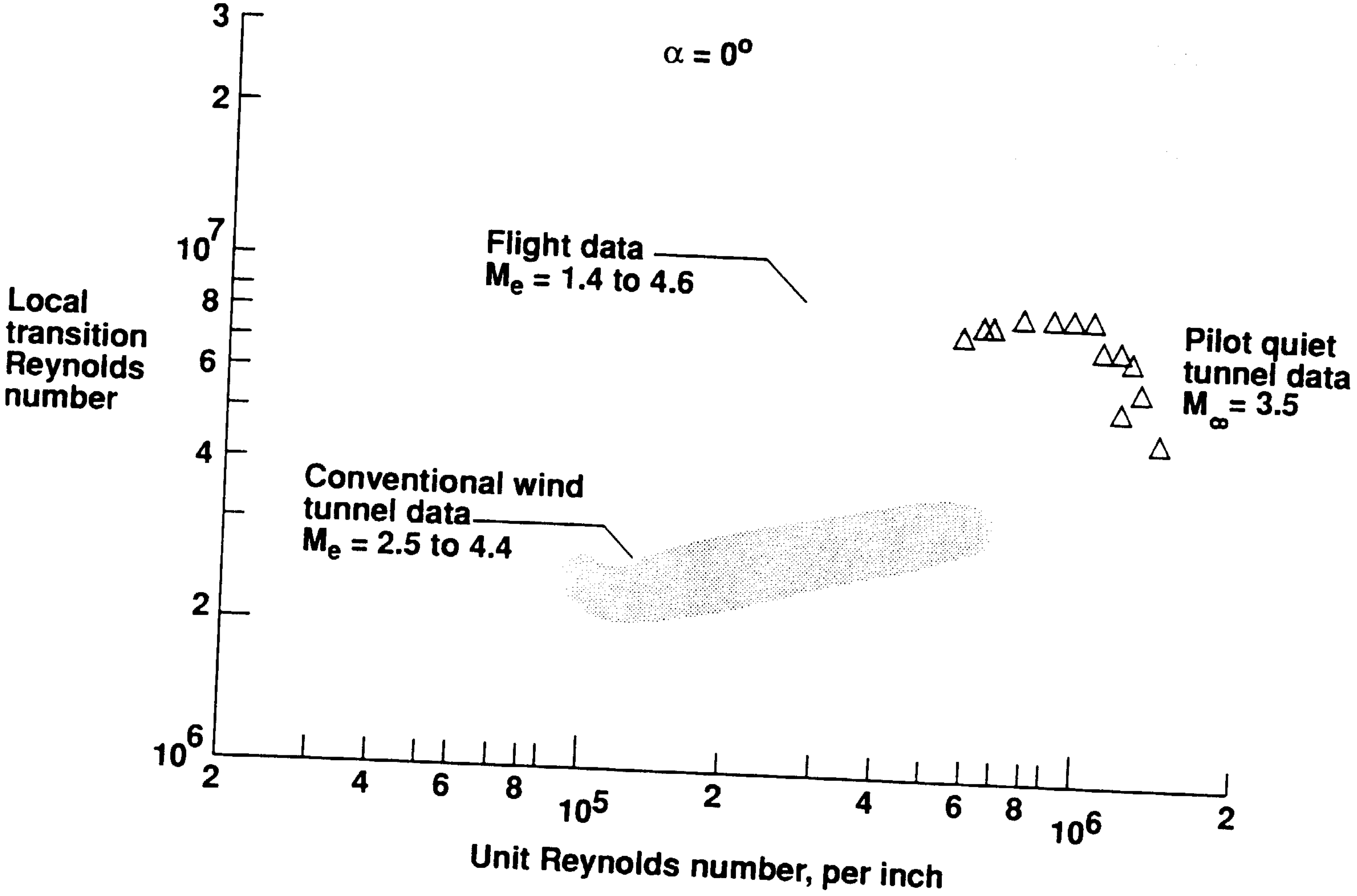
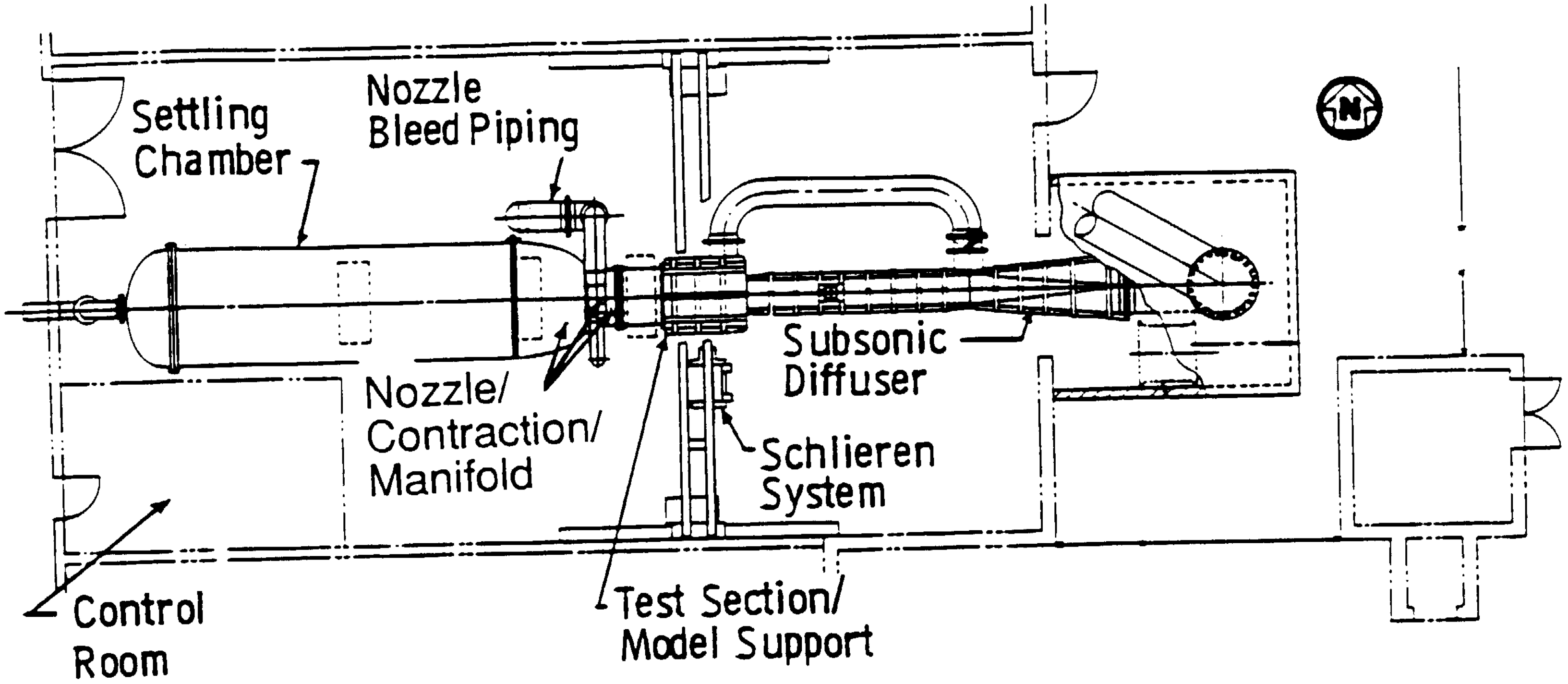
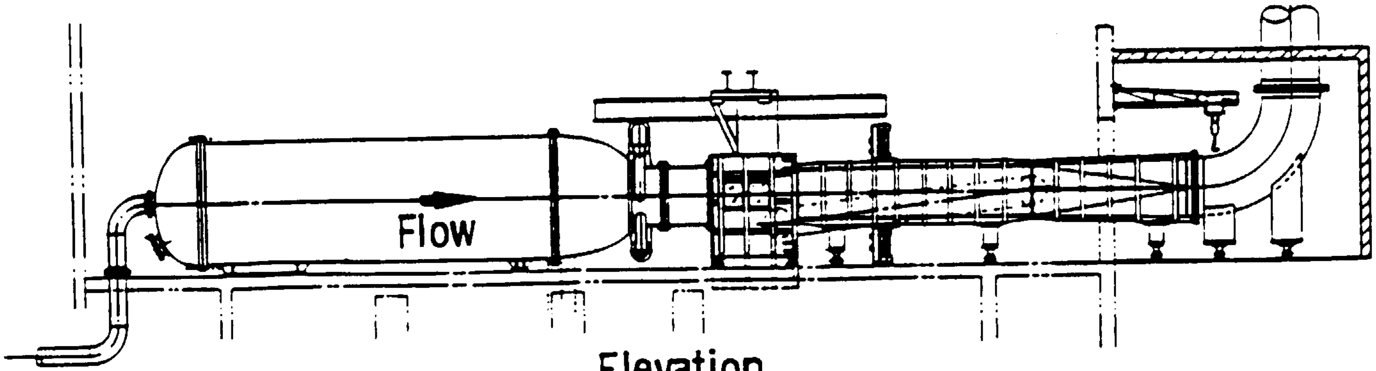


Figure 10. - Pilot quiet tunnel data comparison



Plan View



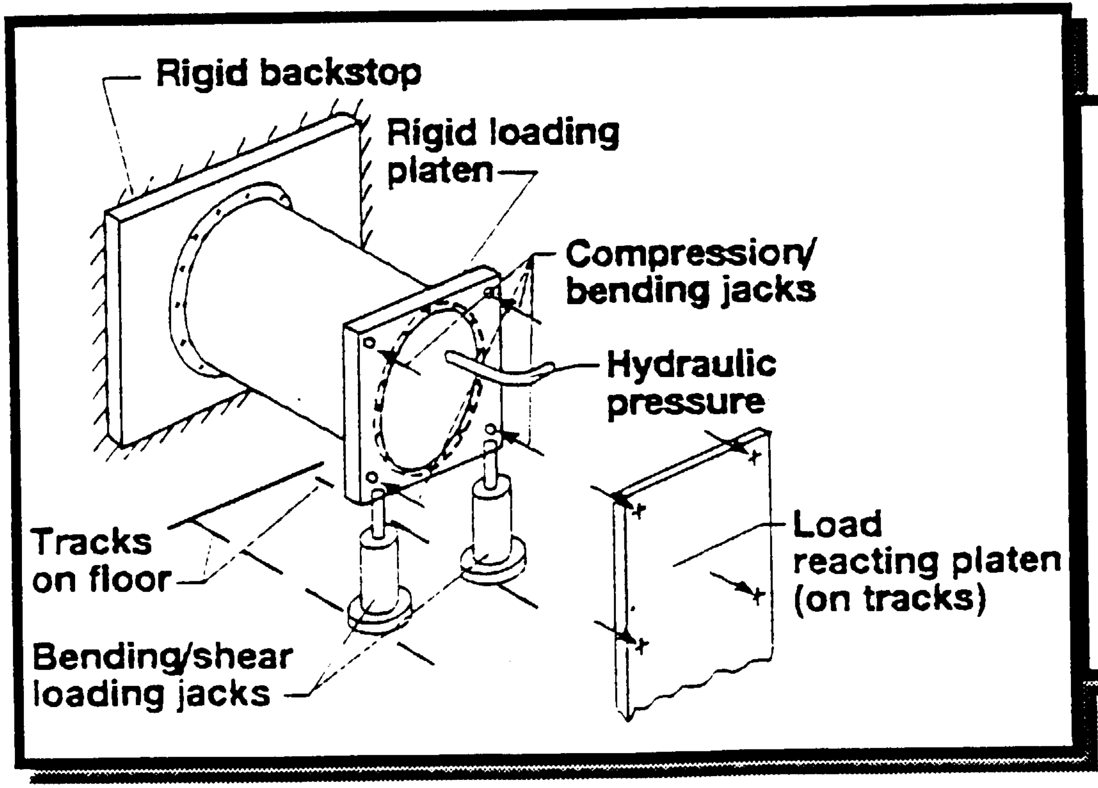
Elevation

Figure 11. - Layout of large-scale supersonic low-disturbance tunnel.

• Mach Number	0 - 0.35 (Closed) 0 - 0.24 (Open)
• Total Pressure	1 to 5 Atmospheres
• Total Temperature	100 Degrees F.
• Maximum Dynamic Pressure	300 Lb/Sq. Ft.
• Maximum Reference Chord	0.89 Meters (2.93 Ft.)
• Maximum Reynolds Number	18.6 Million (Air) 38.0 Million (LN_2 or SF_6)

Figure 12. - Characteristics of conceptual large-scale pressure tunnel.

SCHEMATIC



FEATURES

- Loading:
  - Bending/compression, 14,000 lb/in.
  - Torsion/shear, 6000 lb/in.
  - Pressure, 50 psi
- Test Articles:
  - Fuselage (48 in. dia, 90 in. long)
  - Wing (24 x 65 in. box, 90 in. long)
  - Flat/curved panels (60 in. wide, 60 in. long)

Figure 13. - Structural loads test apparatus.

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Matthew M. Winston, Elwood M. Shields and Shelby J. Morris, Jr.

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Matthew M. Winston and Shelby J. Morris, Jr.: Langley Research Center, Hampton, VA
Elwood M. Shields: Lockheed Engineering & Sciences Company, Hampton, VA

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13. ABSTRACT *(Maximum 200 words)*

The advanced technology base necessary for successful twenty-first century High-Speed Civil Transport (HSCT) aircraft will require extensive ground testing in aerodynamics, propulsion, acoustics, structures, materials, and other disciplines. This paper analyzes the benefits of advanced technology application to HSCT concepts, addresses the adequacy of existing ground-based test facilities, and explores the need for new facilities required to support HSCT development. A substantial amount of HSCT-related ground testing can be accomplished in existing facilities. The HSCT development effort could also benefit significantly from some new facilities initially conceived for testing in other aeronautical research areas. A new structures testing facility is identified as critically needed to insure timely technology maturation.

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