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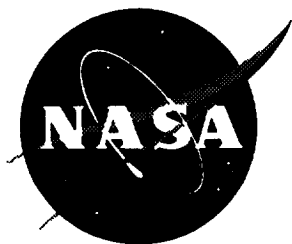
*P. 200*

# Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity

*Edited by*
Dennis M. Bushnell
*Langley Research Center, Hampton, Virginia*

September 1994

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# POTENTIAL IMPACTS OF ADVANCED AERODYNAMIC TECHNOLOGY
## ON AIR TRANSPORTATION SYSTEM PRODUCTIVITY
### (Problems, Status, and Possibilities)
### June 29 - July 1, 1993

## Tuesday, June 29

| | | |
|---|---|---|
| 7:30 a.m. | Registration Starts | |
| 8:15a - 8:30a | Welcome | Wally Sawyer |
| 8:30a - 8:45a | Introduction | Dennis Bushnell |
| 8:45a - 9:30a | Overview | Gene Covert |
| | Overview Facilitator: Michael Scott | |

**Session I:** **Problem Definition**
**Air Transportation System Efficiency -**
**Issues and Currently Envisioned Solutions**
Chairman: Christopher Cruz

| | | |
|---|---|---|
| 9:30a - 9:35a | Session Overview | |
| 9:35a - 10:05a | Airport Assessment | Robert W. Simpson |
| 10:05a - 10:35a | FAA Perspective | Ed Harris |
| 10:35a - 11:00a | Break | |
| 11:00a - 11:30a | Airline Operators | Edwin Thomas |
| 11:30a - 12:30p | NASA Flight Systems Initiative - Terminal Area Productivity | Jack Hatfield |
| 12:30 p.m. | Lunch | |

**Session II:** **Advanced Aerodynamic Configurations and Their**
**Integration into the Airport Environment**
Chairman: Jack Morris

| | | |
|---|---|---|
| 1:30p - 1:35p | Session Overview | |
| 1:35p - 2:05p | Oblique Wing Concept | Tom Gregory |
| 2:05p - 2:35p | Advanced Aircraft | John McMasters |
| 2:35p - 3:05p | Innovative Subsonic Aircraft | Robert Liebech |
| 3:05p - 3:15p | Break | |
| 3:15p - 3:45p | Thick Wing Span Loader Aircraft | Fabio Goldschmied |
| 3:45p - 4:15p | Innovative Supersonic Aircraft | Neil Driver |
| 4:15p - 4:45p | Advanced Aircraft for Airport Productivity | Steven J. Smith |
| 4:45p - 5:30p | Group Discussion | |
| 5:30 p.m. | No-Host Social, Reid Conference Center | |

## Wednesday, June 30

**Session III:** **Aerodynamic Technologies for Enhanced**
**Runway Efficiency**
Chairman: Jim Campbell

| | | |
|---|---|---|
| 8:25a - 8:30a | Session Overview | |
| 8:30a - 9:00a | High Lift/Drag-Due-to-Lift Reduction | Dennis Bushnell |
| 9:00a - 9:30a | Wake Vortex Minimization | George Greene |
| 9:30a -10:00a | Tip Vortex Control | M. Khorrami |
| 10:00a - 10:15a | Break | |
| 10:15a - 10:45a | Oscillatory Blowing for Separation Control | Israel Wygnanski |
| 10:45a - 11:15a | Circulation Control Applied to Commercial Transports | Robert J. Englar |
| 11:15a - 11:45a | Airfoil Static-Pressure Thrust: Quiet and Power-Efficient Aircraft Propulsion | Fabio Goldschmied |

**Session IV:  Aerodynamic Impact on Noise and Emissions**
Chairman:  Ken Brentner

| | | |
|---|---|---|
| 11:45a - 11:55a | Session Overview | |
| 1155a - 12:30p | Impact of Aircraft Emissions on the Atmosphere | Donald Wuebbles |
| 12:30p - 1:30p | Lunch | |
| 1:35p - 200p | Aircraft Noise Impact on Productivity | Stephen Hockaday |
| 200p - 2:25p | Engine Design and Installation for Low Noise | Robert Lee |
| 2:25p - 2:40p | Enhanced Mixing for Jet Noise Reduction | John Seiner |
| 2:40p - 3:00p | Break | |
| 3:00p - 3:30p | Airframe High-Lift Noise | Martin Fink |
| 3:30p - 4:00p | Aircraft Noise and Aircraft Capacity | Kevin Shepherd |
| 4:00p - 4:45p | Group Discussion | |

7:00 p.m.        Dinner Buffet at Capt. Georges on Mercury Blvd., Hampton


**Thursday,  July  1**

**Session V:  Advanced Aerodynamic/Structural Interactions**
Chairman:  Walt Silva

| | | |
|---|---|---|
| 8:25a - 8:30a | Session Overview | |
| 8:30a - 9:00a | Overview of Smart Structures Workshop | Jennifer Heeg |
| 9:00a - 9:30a | Structural Design Constraints of Advanced Configurations | Jim Starnes |
| 9:30a - 10:00a | Strut-Braced Aircraft | Werner Pfenninger |
| 10:00a - 10:15a | Break | |
| 10:15a - 10:45a | Span-Loader Aircraft | Roy Lange |
| 10:45a - 11:15a | Gust and Weather Constraints of Advanced Aircraft | Terry Barnes |

**Session VI:  Aircraft/Airport as a System**
Chairman:  Chris Glass

| | | |
|---|---|---|
| 11:15a - 11:20a | Session Overview | |
| 11:20a - 11:50a | General Aviation Transportation System | Bruce Holmes |
| 11:50a - 12:30p | Advanced Navigation and Personal Aircraft | Steve Crow |
| 12:30p - 1:30p | Lunch | |
| 1:35p - 2:05p | How Far Can Multidisciplinary Methodology be Taken? | Perry Newman Jarek Sobieski Gene Hou |
| 2:05p - 2:35p | Multidisciplinary Design Research at NASA Langley | Peter Coen |
| 2:35p - 2:50p | Break | |
| 2:50p - 3:20p | MDO: Key to Integrated Product/Process Development (IPPD) | Jan Tulinius |
| 3:20p - 3:50p | Future Transportation Alternatives | Bob van't Riet |
| 3:50p - 5:00p | **Workshop  Wrap-up** | |
| | Chairman:  Dennis Bushnell | |
| | Maglev (10 minutes) | Isaiah Blankson |

# WORKSHOP INTRODUCTION

## Michael A. Scott

The United States aviation industry is undergoing a major upheaval, one of the major causes of which is the shift from a military oriented cold war economy to the new reality of global economic warfare. No matter which markets the aviation industry decides to pursue they must approach the design problem using a systems viewpoint. From the beginning of the design cycle this approach requires designers from all disciplines, manufacturers, users, and regulators to communicate in a meaningful manner so that novel concepts target a real need or problem in an economically viable manner. Once a concept and a problem match, communication must continue so time and money are not wasted on unusual or novel concepts that will not be viable.

A key component of the air transportation equation is system capacity. The NASA Langley Research Center Aerodynamics Technical committee identified this as a significant problem that would perhaps benefit from a systemic approach that included advanced aerodynamic concepts. The committee hosted a workshop entitled "Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity," that began with an overview of the problem and some general directions or concepts to solve the problems by Dennis Bushnell. This was followed by Eugene Covert who presented a summary of the findings by the Committee on Aeronautical Technologies, the Aeronautics and Space Engineering Board, the Commission on Engineering and Technical Systems, of the National Research Council. These presentations provided an overview of the current situation and a set of actions that need to be taken. A compilation of the comments by both speakers follows with copies of selected view graphs used in their presentations included at the end.

The air system capacity problem is being addressed in the near term with solutions primarily of an electronic nature. The problems to be addressed are not limited to simply moving more people and cargo through an airport in less time. Problems such as safety, maintainability, operator cost(both direct and indirect), user cost, user satisfaction, profitability, legal liability, and environmental issues(noise/pollution as well as chemical) are among the major factors affecting air system capacity. Some of these problems can be solved by technical innovations but others are system related and must be addressed by

changes to the system as a whole. For those problems appropriate for technological innovation the longer term more ambitious solutions would combine aerodynamic and other technologies with electronic advances. The aerodynamic solutions include the use of flow/separation control, laminar flow control, vortex instability/excitation, among others with an ultimate goal of near bird-like all weather flight.

Many flow control techniques and other advanced aerodynamic technologies have been developed for use with military aircraft. All weather, high speed, and highly maneuverable flight are among the problems that have been addressed for fighter aircraft. If the level of effort and expertise needed to solve these problems was focused on the problems with the air transportation system of the United States new and innovative solutions could be found.

The existing air system is good but not perfect. One problem of the current system is perception, the system is perceived to be worse than it is in actuality. The systemic problems are in some cases societal in nature. A good example of a societal problem is the "cradle to grave" legal liabilities imposed on manufacturers. There are reforms proposed to address this issue such as the 15 year liability limit and torte reform in general. These solutions will help but may not completely solve the problem. A skilled lawyer is capable of convincing a jury that a crash caused by pilot error, poor maintenance, or other non-design issue is really a design problem inherent for a particular aircraft. This is especially true with higher performance/wider operating envelope aircraft that require a greater degree of pilot training and proficiency. The advent of GPS and differential GPS presents many opportunities for system improvement. Air traffic management can be more precise, completely automated landings become more feasible, and the navigation portion of private pilot training less critical since it will be easy to determine your location simply by reading a non-complicated display from a single instrument.

Once it becomes feasible for more people to safely fly small aircraft, problems such as aircraft spacing into and out of airports becomes more critical. The wake vortex hazard presented by current large aircraft may increase significantly with the 600 passenger and larger aircraft currently envisioned. If the vortexes can be prevented or reduced by flow/separation control techniques or the lifetime of a particular vortex can be shortened by excitation of vortex instability it may be possible to fly these new larger aircraft closer together than is presently possible. If these and other technologies are then applied to noise

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pollution problems one of the major restrictions on air traffic at many airports could be reduced or eliminated. If aircraft can fly more hours per day the utilization rate increases and makes both personal and cargo transportation more profitable.

Current conventional aircraft have a lift-to-drag ratio(L/D) ranging from 19 to about 23. Concepts have been proposed for many years that have L/D ratios that could go as high as 70 or more. These concepts and others need to be examined from both an aerodynamic and an operational perspective. The perfect aircraft for cruise conditions that can not land or that people can not board is useless, these types of real world aspects must be examined from the beginning.

Other examples of problems both technical and non-technical abound. For the airline industry, the high percentage of direct operating costs(DOC) solely due to the capital investment in each aircraft needs to be worked. For pilots in modern aircraft the computer is very helpful during cruise but according to some reports automation may actually increase the workload during the most critical time of a flight, take off and landing. For manufacturers the cost of advanced materials are high furthermore many very good materials are not practical for use due to problems with joints, fittings, and attachments. The "giggle factor" problem must also be addressed. People will have to be educated about any truly new and unusual aircraft design before it is fully operational. This must be a cooperative effort among manufacturers, airlines, and the government.

If a true multi-discipline approach is used and the various groups cooperate many things maybe possible. In particular, it may be possible using these or other approaches to do simultaneous multiple takeoffs and landings on a single runway. Another possibility is a clean, quiet, much higher efficiency, and affordable aircraft which is optimized simultaneously for among other metrics, cruise and terminal area operations. This type of research is long term and high risk, however, the potential returns are great. The problems are many, but so are the potential solutions.

Dennis M. Bushnell

# Timeliness of "Advanced Aerodynamics for Air Transport System Productivity"

<u>1938-1991</u>

- "Cold War" (military threats)

  - supersonic (and transonic) fighters
  - transonic transports/tankers
  - hypersonic (and sub/supersonic) missiles/rockets
  - advanced helicopters
  - "stealth" aerodynamics

- Limited transfer to civilian applications

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# Timeliness of "Advanced Aerodynamics for Air Transport System Productivity" (Continued)

<u>1991 - ?</u>

• Economic warfare

- foreign economic competition replacing military threat
- advent of very large subsonic aircraft and supersonic cruise transport aircraft favors advanced configurations
- airport productivity becoming a major issue

NASA Aeronautics Program Thrust #1

. . . "Explore new means to ensure the competitiveness of U.S. subsonic aircraft and to enhance the safety and productivity of the National Airspace System."

Dennis M. Bushnell

# Nearer Term "Solutions" to the Airport Productivity Problem(s) are Primarily "Electronic"

- Improved ATC/flt. path optimization

- "Detect and Avoid" (via on and off board sensors, adv. coms. and NAV)

  - Severe weather
  - Wake vortex hazard

Farther term solutions/optimization should involve aerodynamics/flow control (as well as electronics) to mitigate/remove performance barriers, e.g.

  - Vortex hazard mitigation

  - Efficient high-lift systems

  - Approaching "all weather" flight via envelope expansion

  - Source noise reduction

  - Chemical pollution minimization

Dennis M. Bushnell

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# Elements of the Longer Term Problems in Civil Aviation

- Economics/economic warfare      - Aircraft cost/efficiency/productivity
                                  }

                                   - Airport/runway productivity

- Enhanced demand

including additional constraints/consideration of

- Energy conservation

- Emissions

- Noise

- Safety

Dennis M. Bushnell

# Transport Aircraft

## Comparative Aerodynamic Possibilities

Cruise Lift-to-Drag Ratio (L/D)

| Configuration | All Turbulent | with Laminar Flow |
|---|---|---|
| Current Conventional | 19 | — |
| Advanced Conventional | 21 | 23 |
| Blended Wing Body | 24 | 33 |
| Strut-Braced Wings | 28 | 45 (turbulent fuselage) |
| | | 70 (all laminar) |

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Dennis M. Bushnell

# Obvious Terminal/Aero Problems Which Require Advanced Aero Research/Solutions

- Vortex hazard of large (600-900 PAX) transport aircraft (and HSCT?)

  • Half as many A/C for same no. of PAX--but may have twice the vortex hazard spacing req., ∴ may not improve airport productivity without vortex hazard mitigation?

- HSCT take-off noise

- Terminal area feasibility/ops of advanced configuration concepts (e.g. spanloaders, large strut-braced wing A/C, etc.) including simplex issues such as landing gear and treeline locations

# KEY CONCLUSIONS

## LARC WORKSHOP ON HSCT INNOVATIVE AERODYNAMICS (MARCH 1990)

- Conventional approach $L/D \sim 0\ (9)$

| Configuration | Projected Performance, L/D |
|---|---|
| "Product improvement" for conventional shapes | 0 (12) |
| Yawed wing ($M \lesssim 1.6$) | 0 (14) |
| Strut-braced arrow wing | 0 (18 to 27) |
| Enhanced favorable shock interaction, e.g., parasol wing | 0 (25% increase) |

# Status - CTOL Advanced Configuration Aero

**Strut-braced A/C ("medium" and large aircraft)**

- Advocated/Tested by Pfenninger, used in commuters at lower speeds, requires systems/sanity checks on Pfenninger's work, experiment/CFD studies, multidiscipline aspects and optimization

**Spanloaders (large A/C, includes oblique wing)**

- "Full" spanloaders for cargo applications worked in 70's, looked good for large A/C, recent studies on part spanloaders (BWB) by Liebeck, McMasters, and full spanloaders by Chapin very favorable. Additional performance improvement via aggressive propulsion integration possible, requires same spectrum of systems, experiments, CFD multidiscipline and optimization research.

## Emerging

# Era of "Designer Fluid Mechanics"

- Laminar Flow Control (Drag Reduction, General Aviation, Business Jets, CTOL, HSCT)

- Mixing Enhancement (Noise, Combustion)

- Separated Flow Control (High Lift, Diffusers, Drag Reduction)

- Vortex Control ("Super Maneuverability," Wake Vortex Hazard, Enhanced Transport of Heat, Mass, etc., Stealth)

- Turbulence Control (Drag Reduction, Mixing/Combustion)

- Anti-Noise (Acoustics, Stealth)

- Favorable Wave Interference (Drag Reduction)

- "Designer Fluids" (Via Micro/Nano Particulates)

Dennis M. Bushnell

# Some Conjectural "End Points" Applicable to Air Transportation System Productivity Enhancement Which Might Be Enabled by Clever Aerodynamics/Flow Control

- Simultaneous landings on the same runway (e.g. efficient STOL performance, ultimate limit to A/C spacing)

- Wake vortex hazard minimization via excitation of vortex instabilities

- Nearly "all weather" "bird-like" flight (via flow separation control) fly thru
  - microbursts/wind shear
  - heavy rain
  - ICING
  - cross winds

- Noise reduction (via mixing control and/or high lift/robust aero) for elimination of noise constraints/curfews on flt. path/A/C ops (except sonic boom)

- Significantly reduced emissions (via more efficient high-lift systems/red. cruise drag)

Dennis M. Bushnell

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# Purpose of this Workshop on
## "Advanced Aerodynamics
### for
## Air Transportation System Productivity Enhancement"

is to consider the longer-term possibilities for Civil Aviation in terms of

- aircraft efficiency

- aero aspects of and improvements for aircraft/runway productivity and their (synergistic?) interaction

Thesis:

- Air Transportation System productivity is so crucial to the future of Civil Aviation that aircraft and airport optimization should be worked simultaneously.

Dennis M. Bushnell

# Summary

Advanced configuration and airport/runway productivity aerodynamic research

- is long term

- is high risk

- may lead to significantly improved air transport system performance

- involves exploration/homework regarding the future possibilities in long-haul and short-haul aviation and flow control

- has application to economic "competitiveness"

# AERONAUTICAL TECHNOLOGY
# FOR THE
# TWENTY - FIRST CENTURY

A SHORT SUMMARY

BY

EUGENE E. COVERT

T. WILSON PROFESSOR OF AERONAUTICS
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

# Aeronautical Technologies for the Twenty-First Century

## Report of the Committee on Aeronautical Technologies

The Aeronautics and Space Engineering Board
The Commission on Engineering and Technical Systems
The National Research Council

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# Aeronautical Technologies for the Twenty-First Century

## Statement of Task

▲ Assist the National Aeronautics and Space Administration's Office of Aeronautics and Space Technology (OAST) in identifying and assessing the status of technologies critical to the maintenance of a strong national aeronautical sector and in assessing how well NASA's aeronautics program is meeting the identified long-term needs:

- Consider what the national and worldwide air transportation picture is likely to be 20-30 years hence taking into account the total infrastructure — airports, operations, etc.

- Identify the "high leverage" technologies required in order to give U.S. industry options for future classes of aircraft.

- In consonance with NASA's aeronautics mission as stated in the National Aeronautics and Space Act of 1958, address the appropriate role of government in developing these technologies.

# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

▲ U.S. standing in the world market for aircraft, engines, and parts is eroding:

● U.S. market share in transport aircraft dropped from 87% in 1980 to 64% in 1989.

● U.S. shipments of general aviation aircraft dropped from 17,000 in 1978 to 1,100 in 1988.

● Most major industrialized nations now participate in the aircraft industry or plan to do so in the near future.

▲ Aeronautics is a major contributor to the nation's economy:

● Every $1 billion in sales of transport aircraft produces almost 35,000 jobs.

● Civil aircraft, engines, and parts produced a $23.3 billion favorable balance of trade in 1990.

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# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

"Advanced technology cannot, by itself, ensure competitive products, but without advanced technology, market share will certainly be lost."

# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

▲ The Committee discussed the respective roles of government and industry in developing, verifying, and applying technology. One conclusion emerged clearly:

**"Without greater cooperation between commercial interests, universities, and government to define the most vital technologies and to work in a concerted fashion toward their development, the U.S. standing in civil aeronautics will continue to erode."**

▲ This conclusion, coupled with the importance that aeronautics plays in the U.S. economy, led the committee to identify four primary recommendations regarding NASA's future in aeronautics.

# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

**Recommendation #1:**

"NASA should emphasize the development of advanced aeronautical technologies in the following order: (1) advanced subsonic aircraft, (2) high speed (supersonic) aircraft, and (3) short-haul aircraft."

▲ Advanced subsonic aircraft will continue to provide the bulk of the future market, even if a viable High Speed Civil Transport (HSCT) is developed.

▲ The committee strongly believes that technological advances in subsonic aircraft are possible that could provide U.S. industry with a major competitive edge.

▲ The potential future market for HSCTs is significant:

● NASA should expand its research on upper atmospheric circulation, sonic boom, emissions, and noise, and should be on the forefront of the combustion technology R&D that is required to bring about a viable HSCT.

# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

**Recommendation #2:**

"NASA should work with aircraft manufacturers, the airline industry, and the FAA to bring about major improvements in the utility and safety of the global Air Traffic Management (ATM) system."

▲ It is in the national interest for U.S. technology to continue to lead the future development of the global ATM system using GPS, or an equivalent, as the basic technology.

▲ While the FAA is the lead agency in this area, NASA has much to contribute to a coordinated, national effort that includes ground, air, and space systems.

# Aeronautical Technologies for the Twenty-First Century

## Report Highlights

**Recommendation #3**

**"NASA should commit to a greater level of technology validation to reduce the risk of incorporating advanced technology into U.S. products."**

▲ NASA can, and should, help reduce the risk associated with incorporation of advanced technologies by expanding its flight and ground test programs:

- Help industry fill the "gap" between basic research and product-specific applications.

- Help build the necessary operational experience to speed up the incorporation of new technology into new products.

- Develop technology of first order importance for incorporation into new products.

# Aeronautical Technologies for the Twenty-First Century

## Small Improvements = Big Impacts

▲ A small decrease in the direct operating costs (DOC) of an airline can have a significant effect on the profit margin.

- A 25% reduction in fuel cost (typically 19% of DOC) produces a 4.7% decrease in DOC.

- A 25% decrease in maintenance costs (typically 14% of DOC) would produce a 3.6% reduction in DOC.

- A 25% reduction in crew costs (typically 13% of DOC) produces a 3.3% decrease in DOC.

### Net profit for a typical airline is approximately 5%.

▲

- Therefore, a 25% reduction in fuel costs would nearly double the profit for a typical airline!

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# ENVIRONMENTAL ISSUES

**General Recommendation:**

NASA, the U.S. aircraft industry, and the FAA must work together to address national and international environmental concerns both to help the United States gain a competitive edge and to avoid increasing the adverse environmental effects of aircraft on the ground and in flight.

**Specific Recommendations:**

1. Current and proposed research programs sponsored by NASA should be continued to enhance understanding of the impact of engine emissions on atmospheric ozone.

   - It is imperative that improved modeling, data collection, and verification of models of the chemistry and dynamics of the troposphere also be included in NASA's long-term subsonic aircraft program.

   - NASA is strongly encouraged to investigate worst-case scenarios for stratospheric ozone depletion to establish a basis for reasonable regulation aircraft emissions and to begin developing engineering solutions.

   - To enable a successful commercial HSCT fleet, NASA must continue or accelerate its current programs in advanced emission reduction technology related to the chemistry and dynamics of the stratosphere.

2. NASA's aggressive research and development program for aircraft noise reduction must include HSCT jet engine noise suppression, subsonic engine fan noise suppression, airframe noise reduction, and noise abatement flight operations.

3. NASA should continue its research and development program in sonic boom reduction for HSCT.

# OPERATIONAL ISSUES

**General Recommendation:**

Coordinated activity should be undertaken between NASA and the FAA to significantly increase the capacity of the worldwide aviation system, beginning with the U.S. domestic ATM system.

**Specific Recommendations:**

1. NASA should increase its current cooperative effort with the FAA, the airlines, and aircraft manufacturers to bring about implementation of the Global Positioning System (GPS) for use in the ATM system as soon as possible.

2. NASA should focus its efforts, in cooperation with the FAA and industry, to expedite

   - full integration of on-board communication, navigation, and flight management systems;

   - control and standardization of software for both on-board and ground-based computer systems;

   - development of a mission monitor to address any unacceptable developments that occur on board the aircraft, in the satellite system, or in the communication system, whether in flight or on the ground;

   - development of a satellite communication system along with a global infrastructure to ensure clear and redundant communications; and

   - refinement of inertial navigational systems, including the use of fiber optics.

# BENEFITS OF RESEARCH AND TECHNOLOGY DEVELOPMENT IN AERODYNAMICS

## Aircraft Operations

Reduced fuel consumption
 Decreased cruise drag
 Increased climb and descent lift-to-drag ratios

Reduced takeoff and landing noise


## Aircraft Design and Development

Shortened development cycle
 Improved computational capabilities
 Improved testing facilities

Technology validation

# BENEFITS OF RESEARCH AND TECHNOLOGY DEVELOPMENT IN STRUCTURES AND MATERIALS

## Aircraft Operations

Reduced cost
Reduced airframe and engine weight
Reduced maintenance requirements
Long-life materials
Design for maintenance

Enhanced safety
Predictable material fatigue
"Smart structures"

## Aircraft and Engine Design and Development

Shortened development cycle
Improved computational capabilities for materials and structures
Improved testing facilities for materials and structures

Technology validation

# AVIONICS AND CONTROLS

**General Recommendation:**

NASA should play a major role in the development and validation of the key technologies in avionics and control, including system development and integration, simulator and/or experimental flight validation, and serving in a technical advisory capacity for industry and other agencies of the government.

**Specific Recommendations:**

1. NASA should enhance its current efforts, in conjunction with the FAA, academia, and industry, to produce advances in:

   - flight path management;
   - pilot/vehicle interface (i.e., establish a cognitive engineering effort in this area);
   - avionics and controls integration;
   - control function applications; and
   - aircraft power and actuation.

# BENEFITS OF RESEARCH AND TECHNOLOGY DEVELOPMENT IN AVIONICS AND CONTROLS

## Aircraft Operations

Enhanced functionality
   Engine control
   Aerodynamic actuator control
   Greater situational awareness

Smaller crew

Enhanced safety
   Reliable automated systems
   Enhanced communication
   On-board position determination/collision avoidance
   On-board flight path management
   On-board health monitoring
   Enhanced controllability and maneuverability

## Aircraft Design and Development

Integrated systems

Technology validation

# Air Transportation System Efficiency
## Issues and Currently Envisioned Solutions
### C. Cruz

The goal of the initial session of this year's workshop was to identify the issues which adversely affect the efficiency of the current U.S. air transportation system. The session was highlighted by the presentations of four expert speakers:

Dr. Robert Simpson (Massachusetts Institute of Technology)

Mr. Edward Harris (Federal Aviation Administration)

Mr. Edwin Thomas (United Airlines)

Mr. Jack Hatfield (NASA)

Since each of these four speakers works in a different (although admittedly not sheltered) sector of the nation's air transportation system, they provided valuable insight into the shortcomings of the system. Technical, social, economic, environmental, and legal issues were all laid on the table, both for up-front discussions and for future reference by speakers in subsequent sessions. A fifth speaker, representing the airport operators' views, was scheduled to participate but was forced to withdraw at the last minute due to unforeseen circumstances.

## Systems Analysis

Dr. Robert Simpson has spent several years analyzing air transportation from the systems point of view. Dr. Simpson is a professor of aeronautics and astronautics at the Massachusetts Institute of Technology, where he also serves as the Director of the Flight Transportation Laboratory. He received his Ph.D. from MIT via a Slater Fellowship in Air Transportation, and is a world-recognized expert in air transportation systems, with a special emphasis on new technologies developed to increase the efficiency of air transportation systems. His research and analysis has covered not only U.S. systems, but also those found in many European and Asian countries.

Dr. Simpson began his presentation by stressing the importance of using a system approach in trying to improve air transportation system efficiency through the use of advanced aerodynamic technologies. The four areas which he felt needed to be addressed directly were (1) the vehicles, (2) the infrastructure, (3) the airports, and (4) air traffic control. He pointed out that significant improvements in the vehicle had been accomplished over the past 10-15 years, including increased fuel efficiency (as measured by gallons/seat-mile) and noise reduction. He stated, however, that the current infrastructure severely restricted the use of efficient aircraft. A point of major concern appears to be the lack of airports, due in a large part to the public's perception that airport operations are always characterized by unacceptable noise levels. Dr. Simpson reminded the workshop participants that the last major runway completed in the U.S was the Dallas-Ft. Worth airport (in 1964). He also stated the Munich airport took approximately 32 years to complete. Pacific rim countries, in contrast to the U.S. and Europe, are building a number of new airports. These airports are often built on swamps or islands, are connected to the "mainland" by bridges and tunnels, and bring with them such increased commerce that they often find small cities developing in close proximity to the new airports. Dr. Simpson stated that in the U.S., politics (i.e., perceived noise problems) often stop the planning and construction of new airports. He further stated that the last time he traveled from Boston to Chicago, it took him 2 hours and 5 minutes to fly from Boston to Chicago, and 2 hours and 25 minutes to drive from O'Hare to his motel. He proposed that the best place to put an airport in the Chicago area would be 5 miles out into Lake Michigan connected to the city by a tunnel.

Dr. Simpson next addressed the problems which are directly related to air traffic control. The limiting factor of the current system, he stated, is the number of approach operations per hour, which is currently a function of the weather. He stated that the current "hub" approach used by today's airlines is a direct result of FAA regulations. For example, up to 50 approach operations might be scheduled over a period of only 45 minutes, followed by a 30 minute break, and then a rush to get those same 50 airplanes back off the ground. Dr. Simpson indicated that because of deregulation, several airlines schedule high density approach times which actually overlap those of other airlines, and a view from FAA computers screens which track incoming aircraft often looks like a swarm of locusts descending on a city. He further pointed out that, at the Dallas-Ft. Worth airport, as many as 100 landings per hour are scheduled at an airport which has a maximum capacity of only 80 landings per hour.

Dr. Simpson stated that air traffic controllers are often forced to attempt to do the impossible, trying to juggle preferred routings and miles-in-trail requirements while keeping the airplanes on schedule. In closing, he stated several areas in which aerodynamic technology could contribute greatly to increased system efficiency. First, he indicated the need for higher approach capacities, in particular through the performance of two near-simultaneous landings on the same runway (currently a single runway can be used for simultaneous landing and take-off). Second, he stressed the need to address the noise level on take-off (engine noise) and approach noise . He reminded the workshop of the importance of noise reduction; in fact, he stated that a number of people world-wide had been killed in riots over airport openings. He then moved on to reiterate the need to develop a  device to generate wake vortex instability, in an attempt to ensure that the vortex breaks up within a mile aft of the aircraft. Finally, he indicated the growing need for a short-haul VSTOL aircraft.

## FAA  Perspective

Mr. Edward Harris is the Director of Systems Capacity and Requirements for the Federal Aviation Administration. His experience includes that of a naval aviator, an air traffic controller, and the Director of the FAA Technical Center in Atlantic City. He holds a pilot's license for several classes of aircraft, including a helicopter pilot's license.

Mr. Harris began by characterizing the duties of today's air traffic control managers as "coping with the day's activities with the hand you're dealt". He stated that there are currently 664 certified airports in the U.S., 52 of which are considered major airports, and 35 of which have a significant impact of the performance of the overall air transportation system. He indicated that 62 of the 100 largest airports in the U.S. currently are planning/building runway additions and/or extensions. He also stated that the FAA was currently researching new methods of routing, sectorization, stratification, and multiple approach paths in an effort the increase system efficiency. Mr. Harris presented statistics which showed that the number of delays (15 minutes or longer) has decreased from 337,700 in 1988 to 280,800 in 1993. The nature of the delays has also changed. In 1984, for example, the number of delays in the air were approximately equal to the number of delays on the ground. Today, however, the delays are restricted to the terminal area, whenever possible.

Mr. Harris stated that the U.S. is not going to build many  new  airports  in the foreseeable future, and that it currently takes 5-8 years to get a new runway in place at a n existing airport. He also echoed Dr. Simpson's

sentiments concerning the political obstacles which fight airport construction (both new airports and the expansion of current airports). The only alternative, he stated, is to make better use of existing concrete. One possibility is to utilize abandoned military bases. Another approach would be to develop ways to put more airplanes in the same space with greater safety. Mr. Harris mentioned wake vortices as a major problem - FAA regulations require 5 miles or 3 minutes between take-offs, and any runways within 2500 ft. of each other are considered the same runway for wake vortex avoidance purposes. He stated the need to increase the number of optimum altitudes, to improve the speed range of existing aircraft (as most of the planes flying in 2010 are out there today), agility on landing, to reduce airframe/engine noise, and to optimize airframe geometry. Stating these needs in different words, he indicated that the U.S. needed (1) large capacity aircraft that take up little space, (2) fast aircraft that can fly slowly, (3) efficient aircraft at less efficient altitudes, and (4) powerful aircraft that operate quietly.

## Airline Operator's Perspective

Mr. Edwin Thomas serves United Airlines both as a DC-10 flight officer and as the Flight Systems Program Manager in the Flight Operations Division. His responsibilities include the coordination of the development of new equipment and procedures (i.e., operations, flight tests, research, and development) for current and future UAL fleets. Mr. Thomas has extensive experience in flight systems, flying quality, and human factors development and testing. He received his B.S. in engineering sciences from the United States Air Force Academy and his M.S. in aeronautics and astronautics from Purdue University. He is a graduate of the USAF test pilot school and a member of the Society of Experimental Test Pilots.

Mr. Thomas specified four items which he felt were required to increases the efficiency of the U.S. transportation system, namely:

> (1) more autonomy
>
> (2) less restrictions
>
> (3) minimum delays
>
> (4) equivalent safety

He felt that all four of these could be accomplished if the airlines were allowed to fly "free flight" trajectories. These trajectories would be characterized by dynamic flight planning, optimum wind routes, cruise climb, optimum descent, and company input to priorities and delays. He was quick to point out the quantitative effects of the inefficiencies in the current U.S. air transportation system, as outlined by acting FAA administrator Del Balzo in April 1993:

- one major carrier lost $300 million in 1992 due to system delays

- the system experienced 8.5 million minutes of inflight or taxi delay

- 14 thousand hours of delay were experienced at the departure gate

- $108 million was lost due to altitude and speed restrictions and inefficient routings

Mr. Thomas indicated that there were several systems that were currently being developed or evaluated for development which would facilitate "free flight trajectory" planning, including the Aeronautical Telecommunications Network (ATN), the Global Navigation Satellite System (GNSS), Automatic Dependent Surveillance (ADS), and Air Traffic Management (ATM). He stated that the development of these systems (and related research) should provide solutions to six needs which are currently vital to a highly efficient air transportation system in the United States:

(1) conflict probe to identify need for restriction of avoidance maneuver

(2) resolution algorithm and guidance

(3) wake vortex detection and avoidance

(4) dynamic flight planning software

(5) better wind model or far-field wind sensor

(6) ability to sense and avoid turbulence and hail (not just rain)

# Terminal Area Productivity - NASA Perspective

Mr. Jack Hatfield began his NASA career in 1960, shortly after receiving his B.S. in electrical engineering from the University of Virginia. Mr. Hatfield has performed graduate work in physics and electronics at both the University of Virginia and at the College of William and Mary. His early research at NASA was in the field of communications theory. He has performed extensive research in the area of advanced cockpit technology and related human factors issues. As head of the Cockpit Technology Branch, he is responsible for leading the low-visibility landing and surface operations element of the Terminal Area Productivity Program (TAPP) and the synthetic vision research portion of the Phase II Flight Deck Systems Program of the NASA's High-Speed Research effort.

Mr. Hatfield opened by stating that a major goal of the TAPP is to achieve clear weather capacity in instrument weather conditions. NASA's hopes to meet this goal by using airborne and ground-based technology to increase capacity (while maintaining safety standards) by reducing separation requirements. As previous speakers had noted, Mr. Hatfield indicated that approximately two-thirds of the top 100 U.S. airports are attempting to construct new runways. He then stated that, while more runways per airport is one part of the solution, increasing the number of landings per runway is vital to improving terminal area productivity. He noted that today's aircraft "in trail" standards do not account for the physical behavior of vortices and that gaps due to light aircraft trailing heavier aircraft are large contributors to inefficiency.

Mr. Hatfield then commended the FAA for pushing the development of the infrastructure which will be needed to accomplish increased productivity, including a telecommunications network, a differential GPS satellite system, automation systems, and an integrated terminal weather system. He then outlined NASA's approach to reducing aircraft separation requirements : (1) modification of existing miles in trail standards, (2) development of new lateral spacing standards, and (3) development of a new flight management system. Mr. Hatfield then indicated that NASA would also continue to support CTAS development, automation aids to improve landing frequency, simulation techniques, and flight tests - all in an effort to produce a efficient system for air traffic management. Mr. Hatfield cited technologies such as electronic maps, synthetic vision, and satellite-based navigation as indicative of systems which need to be developed to achieve higher productivity goals by the end of this century.

# Session II "Advanced Aerodynamic Configurations and Their Integration into the Airport Environment"

## by S. J. Morris

The National Aeronautics and Space Administration (NASA) has recently been directed (references 1 and 2) to "focus on expanding high-speed and subsonic research directly related to civil aviation ... ." One of the questions that could arise from this effort is: Is there a new aircraft configuration which could enhance the productivity of the air transportation system? In other words, is there an aircraft configuration that could do for the present air transportation market what the original Boeing 707 (the so-called Dash 80) did to the air transportation market of the early 1960's. This new configuration, if it exists, should fit into existing airports and require a minimum of changes in the present system infrastructure.

Recently (June 1993), a workshop was held at the NASA Langley Research Center to explore possible new commercial aircraft configurations and other questions. A very select group of distinguished scientist and engineers were invited to give summary presentations in their various fields of expertise. The individuals selected to present papers in this session were Tom Gregory of NASA Ames, who discussed the oblique wing supersonic concept, John McMasters of The Boeing Company, who discussed advanced subsonic aircraft, Robert Liebeck of the McDonnell Douglas Company, who also discussed advanced subsonic aircraft, and Neil Driver (NASA Langley retired) of Eagle Engineering, who discussed advanced supersonic aircraft. Fabio Goldschmied (retired) and Jan Rosham (University of Kansas) were also invited but were unable to attend. The focus of all of these presentations was a search to identify any new commercial aircraft configuration which could revolutionize the passenger aircraft market. Most of the material in this summary was taken from these presentations (references 4, 5, 6, and 7).

The possible benefits of such a configuration can be seen in figure 1, which is derived from information taken from reference 3. Figure 1 shows the estimated fare in dollars per passenger nautical mile for a conceptual model of an existing 412-passenger transport (labeled "existing" in the figure), an

advanced all-turbulent conceptual aircraft with an increased aspect-ratio wing and a capacity of 800 passengers, an advanced laminar flow conceptual aircraft with an 800-passenger payload, and a very-advanced flying wing-body conceptual aircraft also with an 800-passenger payload. The net fare reduction potential is about 45 percent. This is a very substantial benefit if it can be achieved in an aircraft which is operational practical and acceptable to the passenger and to the environment. The purpose of this chapter is to examine some alternative subsonic and supersonic commercial aircraft configurations which might provide some benefits over existing configurations and to document what is known about these configurations. The reader should be warned that some of these configurations are very novel and many have unique problems and/or operational characteristics. These configurations are not offered as solutions to the challenges of designing a replacement for the modern commercial transport, but as a menu of possible configurations which need future consideration.

## SUBSONIC AIRCRAFT CONFIGURATIONS

A very interesting study of possible alternate configurations for subsonic commercial aircraft is presented in references 3 and 4. This study methodically examines the benefits of various degrees of advanced technologies. The technologies are identified in figure 2 which is taken from reference 3. These potential technical improvements are quantified according to the projected benefit available from each technical area. For example, the projected benefits are 35 precent improvement in the cruise lift-to-drag ratio, 40 percent in cruise specific fuel consumption (SFC), 20 percent in the weight of the propulsion system, 40 percent improvement in the structural weight of the aircraft, and from 10 percent to 50 percent improvement in the weight of the various systems. These projected improvements are remarkable because as shown in figure 3, there has been only a 15 percent improvement in the aerodynamics (cruise Mach times lift-to-drag ratio) of modern subsonic transport aircraft compared with the 1950's Boeing 707 designs. The parameter chosen for comparison is the product of the Mach number times the lift-to-drag ratio. If the cruise lift-to-drag ratio had been compared alone, the improvement would have been even smaller. This is somewhat of an unfair comparison, since some of the

aerodynamic benefits (i. e. the new supercritical wing designs) that could have been used to improve the cruise lift-to-drag ratio were often used to thicken the wing, which would reduce the aircraft's structural weight and thus improve the load carrying characteristics of the aircraft. The reader should note, however, that references 3 and 4 presents concepts which offer large potential improvements projected for modern subsonic transport aircraft. However, the economic, operational, and environmental acceptability of these improvements must be demonstrated before they will be accepted into the airline's fleets. Figure 4 shows a comparison of the McDonnell Douglas (M/D) DC-10 and the MD-11, which has a somewhat improved engine and a significantly improved lift-to-drag ratio. The fuel burned per seat is reduced by 33 percent and the cruise lift-to-drag ratio is improved by 27 percent (from 14.2 to 18.1). Figure 5 compares the MD-11 with the Super Stretch Advanced Derivative (AD) configuration, which has a passenger capacity of 368 passengers compared with the MD-11 capacity of 293 passengers. The AD also has an improved wing with an increased aspect ratio (the AD's aspect ratio = 11 versus an aspect ratio of 7.5 for the MD-11). The AD has a projected lift-to-drag ratio of 21.2 without laminar flow or riblets and 24 with them. The projected fuel burned per seat is reduced by 23 percent for the AD compared with the MD-11. Figure 6 compares the Super Stretch Advanced Derivative (AD) with the so-called Synergistic Technology Transport (STT), which represents an accumulation of all of the available technologies which can be incorporated in a conventional planform configuration. The STT has an improved engine, a new wing with an aspect ratio of 17.5 and a vastly reduced overall empty weight. The fuel burned per seat is reduced by 68 percent when compared with an AD configuration without laminar flow or riblets. Finally, figure 7 compares the effect of a completely new configuration. In figure 7, a radically new Blended Wing-Body (BWB) configuration is compared with the more conventional planform, equivalent technology, STT configuration. The BWB configuration offers a projected cruise lift-to-drag ratio of up to 33.3 compared with 23.1 for the much more conventional, but still very technologically-advanced STT configuration. The fuel burned per seat is improved by about 25.7 percent for the BWB compared with the STT. Currently, NASA is funding a more in-depth look at the advantages and disadvantages of these configurations. It should be clear that significant improvements can be made over the existing commercial aircraft now in the

airlines' fleets.  The airlines must be convinced that they can make a profit on these proposed aircraft if these new designs are ever to reach production.

A cross section of an 800-passenger conventional aircraft (figure 8) is shown in figure 9.  An isometric of a comparable 800-passenger Blended Wing Body (BWB) is shown in figure 10.  The cross section of this BWB configuration is shown in figure 11. The characteristics of a slightly different (more recent) version of the 800-passenger BWB configuration is summarized in figure 12. Work is continuing on these designs at the present time .

There are other alternative solutions to the search for a new configuration for a revolutionary new subsonic commercial transport.  The fact that there may be more than one solution for this design problem should be no surprise, since it is well documented that two very different solutions to the same aircraft design problem has occurred in the past.  In fact, figure 13 (reference 5) demonstrates that the Boeing B-47 and the AVRO Vulcan B2 are very different solutions to a similar demand for a medium bomber.  Note the take-off gross weights were almost the same, but the configurations were completely different.  Both these aircraft performed the mission very competently.  The conventional solution to a new design problem is to "evolve" the new aircraft from an existing configuration. This process is illustrated in figure 14 (reference 5).  In this figure, the process of developing a 600+-passenger aircraft from an existing Boeing 747-400 design is demonstrated.  This is a very conservative approach and is not to be ignored. The results of this process are illustrated in figure 15.  Note that the new conceptual has a full-twin deck fuselage, an increased wing span, and larger engines.  An alternate approach using the wing airfoil technology illustrated in figure 15 is also possible.   The proposed wing technology would allow a much thicker wing (by using boundary layer control) at the same cruise Mach Number. In other words, this technology would allow thicker wings by delaying the drag divergence for these wings.  This technology could allow a thick wing with a reduced sweepback which would allow a design approach as illustrated in figure 16.  The resulting configuration and the design process are shown in figures 17 and 18.  This novel aircraft configuration, which is sized for 600 to 800 passengers, could offer a viable alternative to the more conventional configuration shown in figure 15.  One of the concerns with the configuration shown in figures 17 and 18 is the 300-foot wing span, which could create landing

and take-off problems at some airports. An alternative configuration which offers a solution to this concern can be developed from the wing configuration information shown in figure 19. This figure (reference 5) presents a summary of the "induced drag efficiency factor" or Oswald's wing efficiency factor for many different and novel wing designs. This demonstrates that a significant reduction in induced drag could (perhaps) be achieved for a novel new approach to the wing layout. An argument comparing the results of this approach and a more conventional approach is illustrated in figure 20. The resulting configurations are illustrated in figure 21 and the features for the very innovative new configuration is illustrated in figures 22 and 23. The culmination of this process could produce the huge aircraft shown in figure 24, which could hypothetically carry 1250 passengers. This gigantic aircraft is configured to land on water to avoid the rather obvious problems with a conventional airport landing/takeoff.

Many other subsonic commercial aircraft configurations have been proposed in the past. Some of these alternative configurations are illustrated in figure 25 from reference 8. The spanloader configurations deserve special mention because of the attention they received in the CLASS studies (references 8 and 9) of the late 1970's and early 1980's (see figures 25 and 26). Finally the Russians have studied large subsonic aircraft in depth and are currently operating the largest subsonic aircraft in the world: the An-225 "Mriya" (reference 10) which has a gross weight of 1,322,750 pounds and a maximum payload of 551,150 pounds.(figure 27). Another Russian conceptual cargo aircraft design, which is also shown in reference 11, is illustrated as figure 28. This novel aircraft which features a removable pod to enhance cargo-handling is designed to carry a payload of 1,100,000 pounds. This conceptual aircraft has a wing span of 400 feet, a wing area of 19,500 square feet, and a gross weight of 2,866,000 pounds.

The conclusion that the reader could reach from the above information is that there are many novel subsonic configurations, which offer the potential of revolutionary changes in subsonic commercial aircraft. For example the potential improvement in lift-to-drag ratio of the configurations presented in reference 3 are summarized in figure 29. This demonstrates a potential doubling, and more of this critical measure of aerodynamic efficiency is available

if the marketplace demands the effort. In our present world the marketplace is "King".

## SUPERSONIC AIRCRAFT CONFIGURATIONS

A survey of possible new commercial aircraft configurations cannot be complete without the inclusion of the proposed new concepts for a new supersonic commercial aircraft. NASA has studied possible supersonic commercial aircraft configurations for many years and, of course, the British and the French have developed and operated the technically brilliant "Concorde." This aircraft (figure 30) should stand as a baseline for comparison with any suggested new configuration. NASA has done a very exhaustive study of various supersonic planforms, which is summarized in reference 12. This reference, along with reference 13, gives an excellent overview of the past NASA efforts. NASA is presently pursuing a modern supersonic commercial design effort in cooperation with Boeing and McDonnell Douglas. A status report on this effort was recently presented at an AIAA Aircraft Design Conference (August 1993) in Monterey, California (reference 14). The reader should also be aware of the political and environmental factors that have influenced this program in the past and which are well documented in reference 15. A summary of the various planforms examined by NASA is shown as figure 31, which is taken from reference 12. Many of these configurations were tested in the wind tunnels. The Boeing 2707-200 of 1966-vintage is shown in figure 32, and 1971-vintage Boeing 2707-300 is shown in figure 33. Note the 2707-300 no longer has the variable-sweep wings of the 2707-200. The logic behind the change in planform is well documented in reference 13. More recent studies, sponsored by NASA, have attempted to improve on the Boeing 2707-300. For example, figure 34 taken from reference 12 shows a 1975-vintage configuration (called the MDC-AST) , which was suggested by McDonnell Douglas. The configuration is compared with the Boeing 2707-300. One measure of the goodness of a supersonic configuration is the cruise lift-to-drag ratio of the configuration. A study, summarized in reference 16, has attempted to present a roadmap of the achieved lift-to-drag ratio of several supersonic aircraft configurations (some of which are conceptual and some represent existing hardware) and to quote some proposed goals. The result of this effort is shown as figure 35. The Concorde,

as shown in this figure, has a lift-to-drag ratio at the Mach 2 cruise condition of about 7.3. The B-70, at its Mach 3 cruise condition, had a lift-to-drag ratio of about 7 and the YF-12 had a lift-to-drag ratio, at cruise Mach numbers above 3.0, of about 6.9. Two proposed lines of cruise lift-to-drag ratio versus Mach number are presented in this figure as "goals" or challenges for future research and an area of results from some "good" paper studies is also shown in this figure. The reader should be warned that the "goal" constraints are very subjective and somewhat controversial.

There have been other planform designs suggested for efficient supersonic cruise, including the very novel oblique-wing studies (see reference 17, for example). The lift-to-drag ratio versus Mach number shown in figure 36 demonstrates the motivation for this work, and the oblique-wing test vehicle shown in figure 37 demonstrates the degree to which this planform has been studied. Typical conceptual designs using this technology are shown as figures 38, 39 and 40, which are taken from the presentations by Tom Gregory and Neil Driver (references 6 and 7).

Finally it may be useful to mention the designs which have been suggested for a sub-scale research vehicle which could perhaps serve a dual purpose of first performing a proof of concept research vehicle for the future supersonic transport and secondly perhaps serve as a prototype for a modern supersonic business jet aircraft. One of the proposed conceptual research aircraft is shown in figure 41. The goal of this prototype research vehicle would be to develop an advanced supersonic transport which might have the characteristics shown in figure 42. This vehicle could offer formidable competition to long-range subsonic aircraft.

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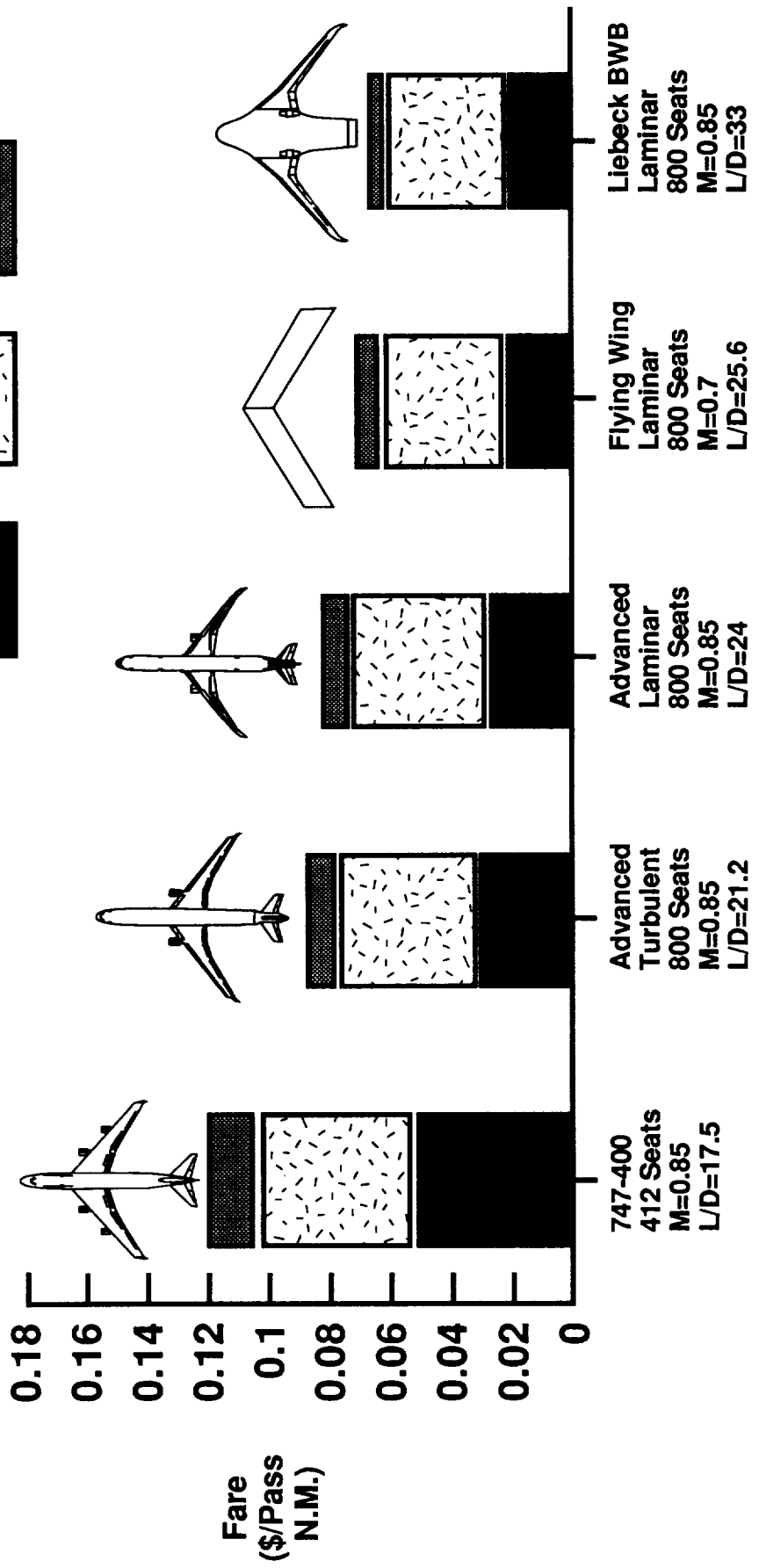
Figure 1. Comparison of the Estimated Fares for Various Large Subsonic Conceptual Aircraft.

Legend:
- DOC $/Pass-NM
- IOC $/Pass-NM
- Profit $/Pass-NM

Fare ($/Pass N.M.) axis: 0, 0.02, 0.04, 0.06, 0.08, 0.1, 0.12, 0.14, 0.16, 0.18

747-400
412 Seats
M=0.85
L/D=17.5

Advanced Turbulent
800 Seats
M=0.85
L/D=21.2

Advanced Laminar
800 Seats
M=0.85
L/D=24

Flying Wing Laminar
800 Seats
M=0.7
L/D=25.6

Liebeck BWB Laminar
800 Seats
M=0.85
L/D=33

50

| Technology | Improvement (%) |
|---|---|
| **Aerodynamics (L/D)** | 35 |
| • High AR, LFC, turbulent drag reduction, etc. | |
| **Propulsion (SFC)** | 40 |
| • VHBR, materials, aerodynamics, etc. | |
| **Propulsion (weight)** | 20 |
| • Improved materials | |
| **Structures (weight)** | 40 |
| • Improved materials | |
| **Systems (weight)** | |
| • Distributed avionics (using optics) | 50 |
| • Hydraulics | 25 |
| • Mechanical controls | 80 |
| • Environmental - Ducts | 40 |
|      - Pumps/APU | 25 |
| • Landing gear | 10 |
| • Furnishings | 15 |
| • Operating items | 10 |
| **Maintenance** | 25 |

Figure 2. Technologies Available To Improve Subsonic Commercial Aircraft.

51
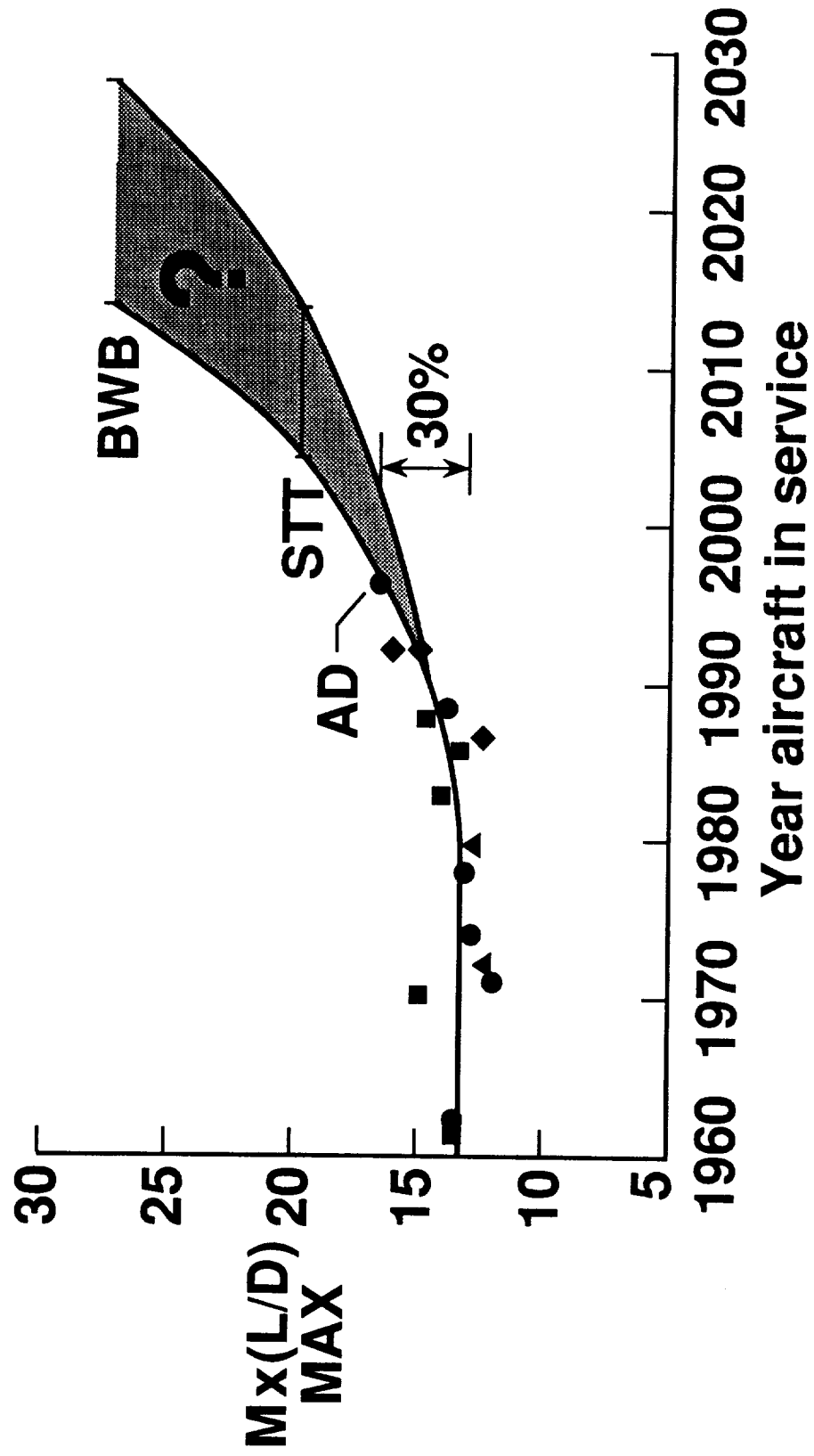
Figure 3. Past Improvements in the Aerodynamic Efficiency Of Commercial Subsonic Aircraft.

**DC-10**
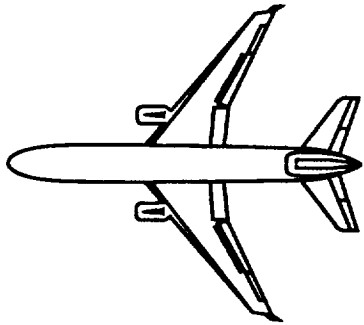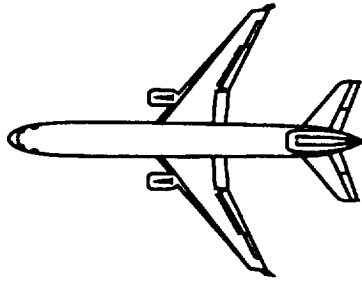
|  | | **MD-11** |
|---|---|---|
| Design range (N MI) | 5,800 | 7,000 |
| Passengers (3 class) | 231 | 293 |
| Cruise Mach | 0.82 | 0.82 |
| Engines | CF6-50C2 | PW4000/CF6-80C2 |
| Wing span (ft) | 165 | 170 |
| Length (ft) | 183 | 201 |
| Wing area (ft²) | 3,647 | 3,647 |
| Aspect ratio | 7.5 | 7.5 |
| TOGW (lb) | 572,000 | 605,500 |
| L/D | 14.2 | 18.1 |
| Fuel burn/seat at 3,000 N MI | Base | Base |

Figure 4. Comparison of the McDonnell Douglas DC-10 and The MD-11.

53

**MD-11**

**Super stretch advanced derivative**

| | MD-11 | Super stretch advanced derivative |
|---|---|---|
| Design range (N MI) | 7,000 | 8,500 |
| Passengers (3 class) | 293 | 368 |
| Cruise Mach | 0.82 | 0.85 |
| Engines | PW4000/CF6-80C2 | Same as MD-11 (VHBR TBD) |
| Wing span (ft) | 170 | 211 |
| Length (ft) | 201 | 236 |
| Wing area (ft2) | 3,647 | 3,900 |
| Aspect ratio | 7.5 | 11 |
| TOGW (lb) | 605,500 | 738.000 |
| L/D | 18.1 | 21.2 (24 with LFC/riblets) |
| Fuel burn/seat at 3,000 N MI | Base | -23% (-28%) |

Figure 5. Comparison of the MD11 and The Super Stretch Advanced Derivative (AD) Configuration.

## Super stretch
## Advanced Derivative (AD)

## Synergistic Tecthch
## Technology
## Transport (STT)
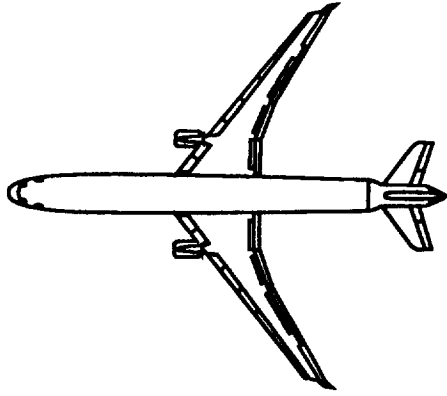
| | Super stretch Advanced Derivative (AD) | Synergistic Technology Transport (STT) |
|---|---|---|
| Design range (N MI) | 8,500 | 8,500 |
| Passengers (3 class) | 368 | 368 |
| Cruise Mach | 0.85 | 0.85 |
| Engines | PW4000/CF6-80C2/RB211-524L | VHBR |
| Thrust (klb) | 61.5 | 30.6 |
| Wing span (ft) | 211 | 188 |
| Length (ft) | 236 | 236 |
| Wing area (ft2) | 3,900 | 2,020 |
| Aspect ratio | 11 | 17.5 |
| TOGW (lb) | 738.000 | 367,200 |
| OEW (lb) | 340,100 | 192,700 |
| L/D | 21.2 | 23.1 |
| Fuel burn/seat at 3,000 N MI | BASE | -68% |
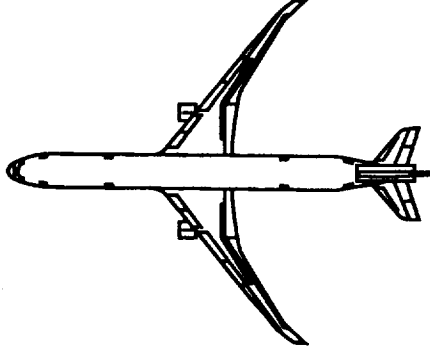
Figure 6. Comparison of The Super Stretch Advanced Derivative (AD) and The Synergistic Technology Transport (STT).

55

## Synergistic Technology Transport (STT)
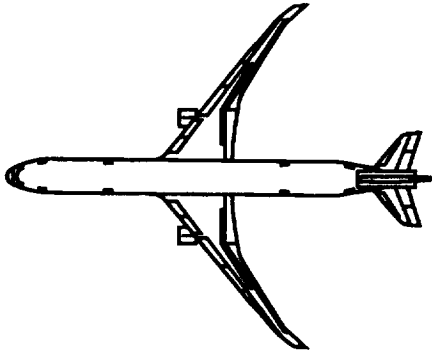
## Blended Wing-Body (BWB)
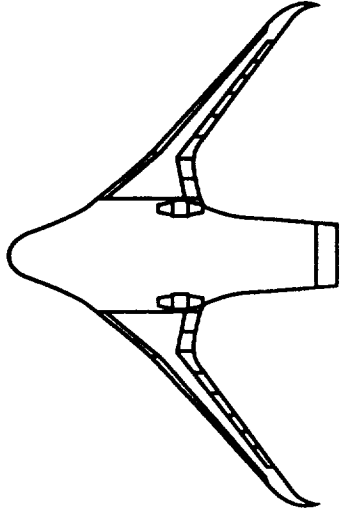
| | Synergistic Technology Transport (STT) | Blended Wing-Body (BWB) |
|---|---|---|
| Design range (N MI) | 8,500 | 8,500 |
| Passengers (3 class) | 368 | 368 |
| Cruise Mach | 0.85 | 0.85 |
| Engines | VHBR (3) | VHBR (2) |
| Thrust (klb) | 30.6 | 30.9 |
| Wing span (ft) | 188 | 260 |
| Length (ft) | 236 | 167 |
| Wing area (ft2) | 2,020 | 4,500 |
| Aspect ratio | 17.5 | 15.0 |
| TOGW (lb) | 367,200 | 338,800 |
| OEW (lb) | 192,700 | 195,300 |
| L/D | 23.1 | 33.3 |
| Fuel burn/seat at 3,000 N MI | -68% | -25.7% |

Figure 7. Comparison of The Synergistic Technology Transport (STT) and The Blend Wing Body (BWB) Configurations.
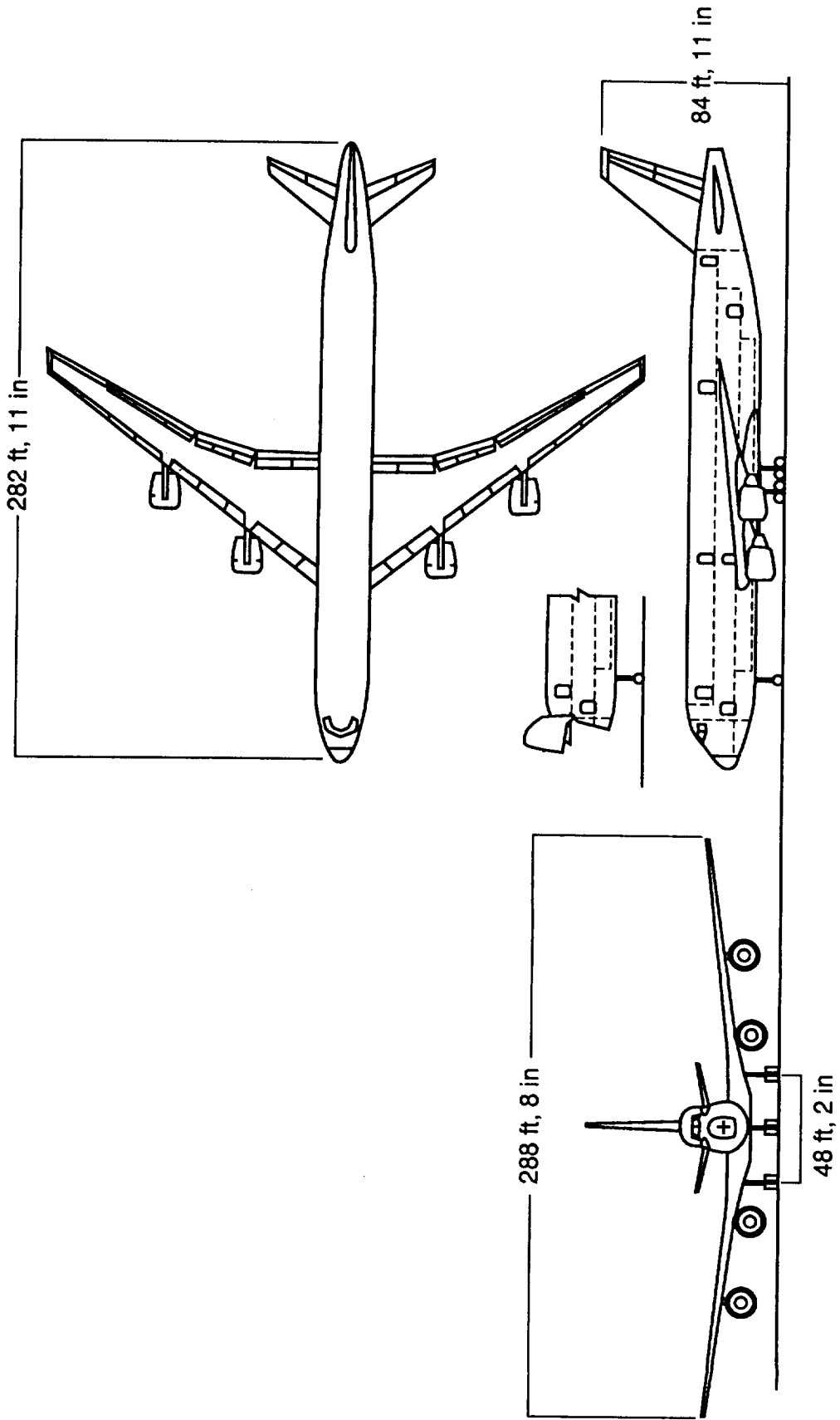
Figure 8. A Conceptual 800-Passenger Conventional Aircraft.

282 ft, 11 in

84 ft, 11 in

288 ft, 8 in

48 ft, 2 in
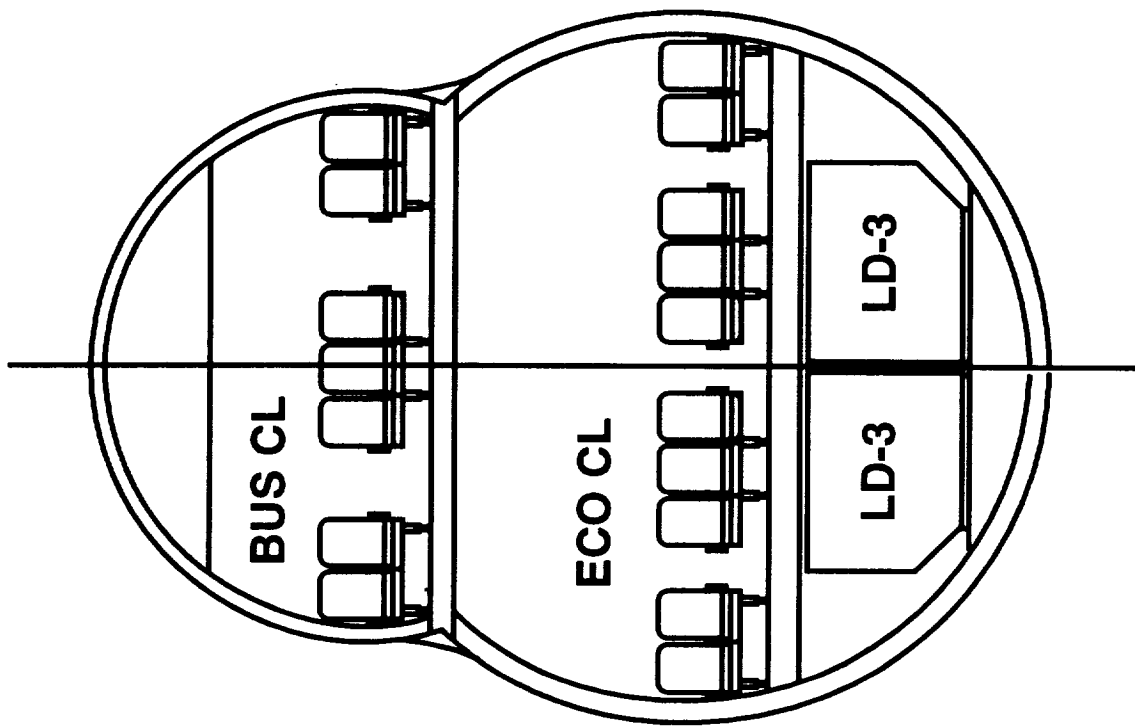
Figure 9. A Cross-Section Of the 800-Passenger Conventional Aircraft of Figure 8.

58
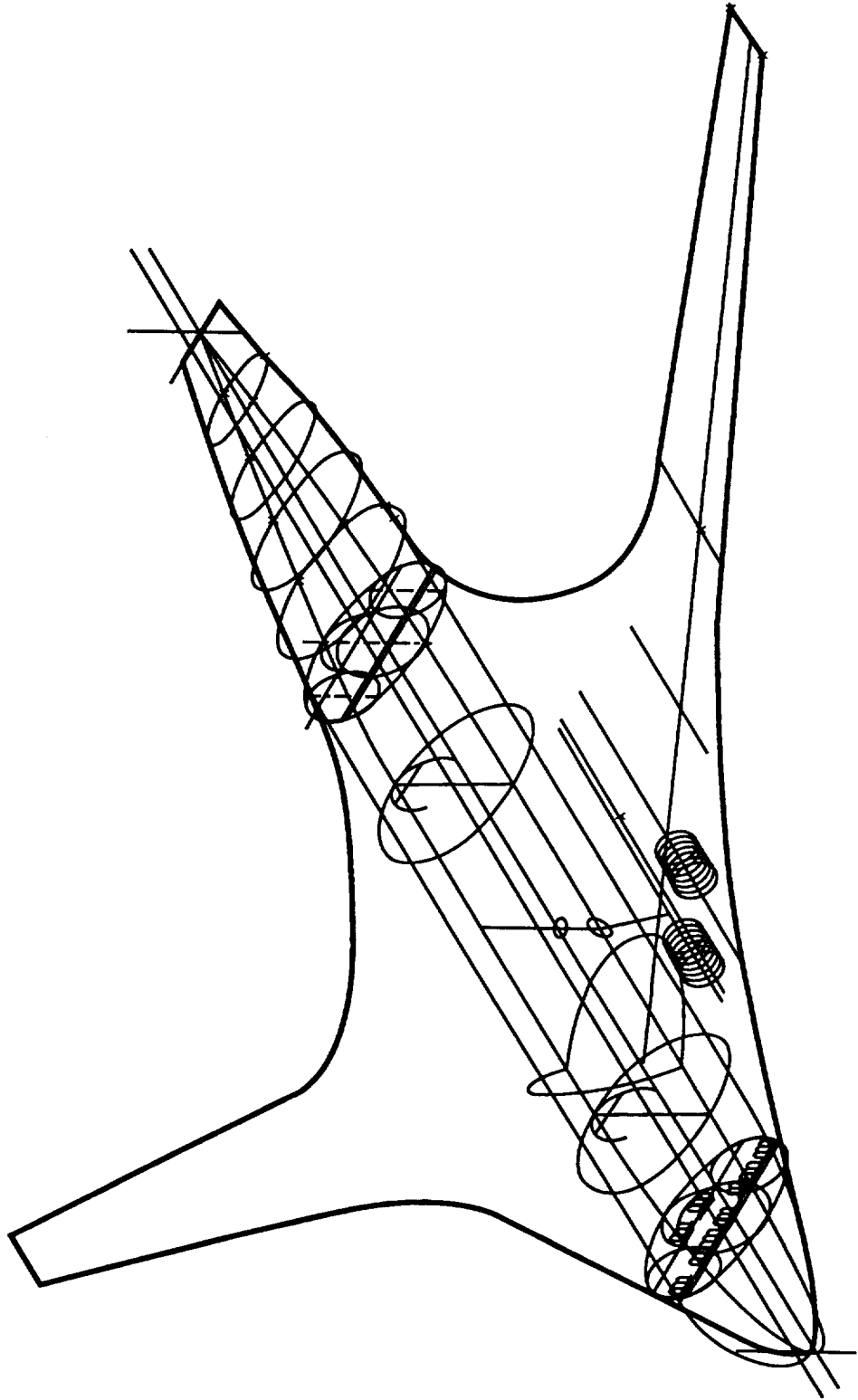
Figure 10. An Isometric View of an 800-Passenger Blended Wing Body Aircraft.
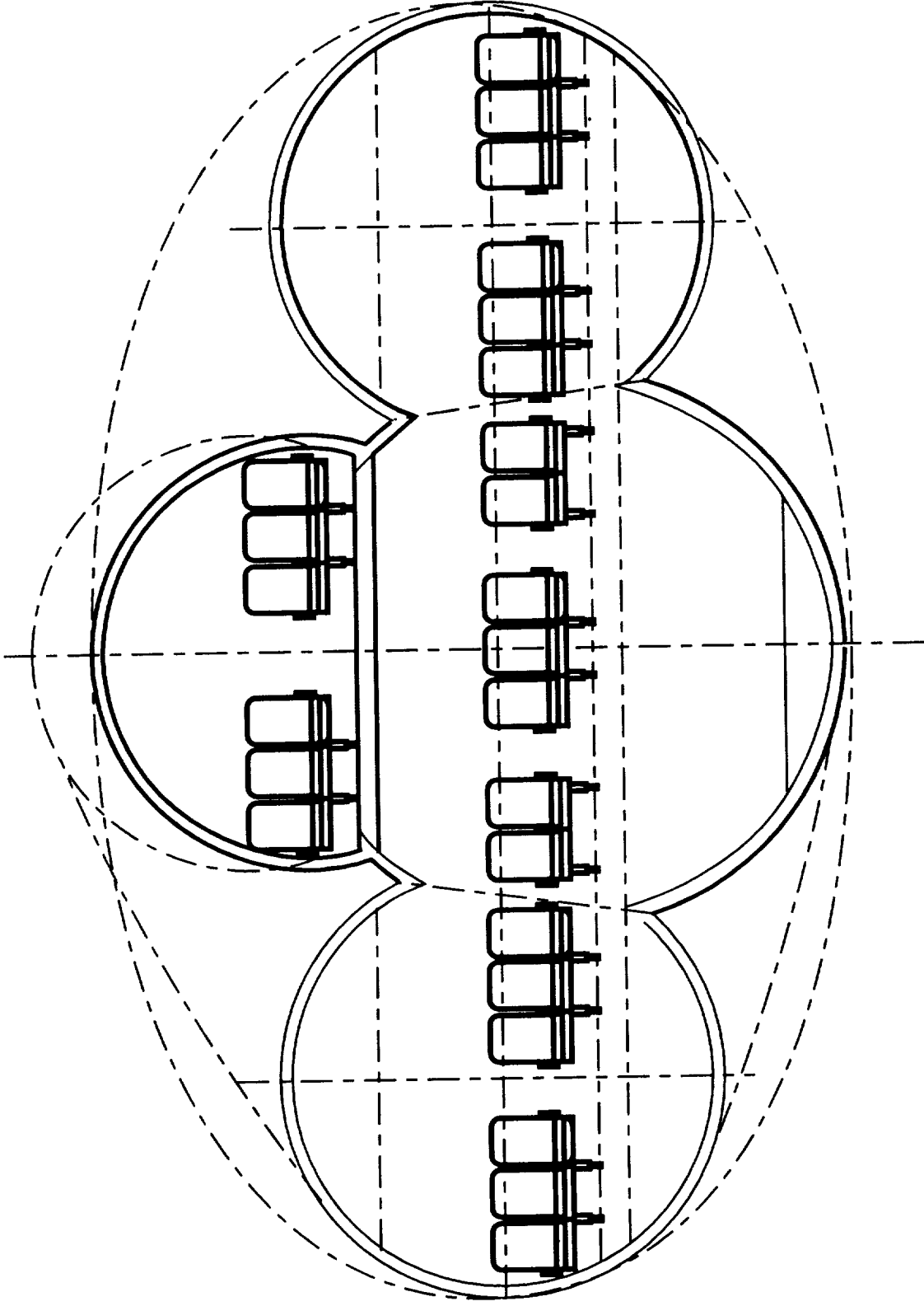
Figure 11. A Cross-Section of the 800-Passenger Blended Wing Body Aircraft.

# BLENDED-WING-BODY, BWB CONCEPT

| | | |
|---|---|---|
| Range | = 7,100 nm | 800 passengers mixed class |
| TOGW | = 800,000 lbs | 4 - 60,000 lb class ADP's (fan reversing) |
| Wing Area | = 10,000 ft2 | Initial cruise altitude 35,000 - 45,000 ft |
| Wingspan | = 320 ft | Composite non-cylindrical pressure vessel |

Fin and high bandwidth rudder

Split flap drag rudders/elevons

Single element Fowler flaps & roll/DLC spoilers

Buried ADP's with boundary layer swallowing

Structural mode control body flaps

Kink tailoring flap

Slat (kink & flapped areas)

Double deck center cabin

Single deck outer cabins
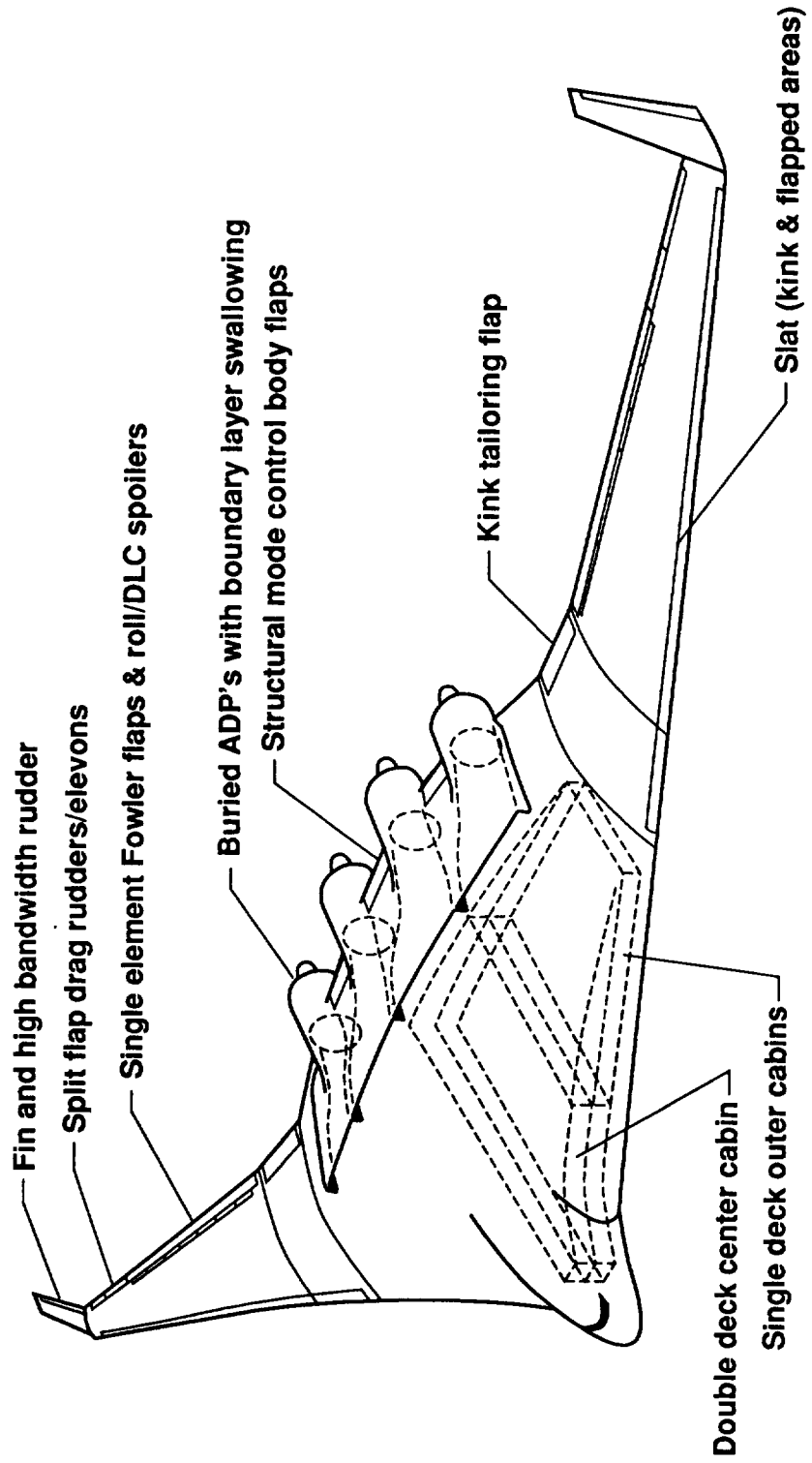
Figure 12. The Characteristics of the 800-Passenger Blended Wing Body Aircraft.

61

Boeing B-47H
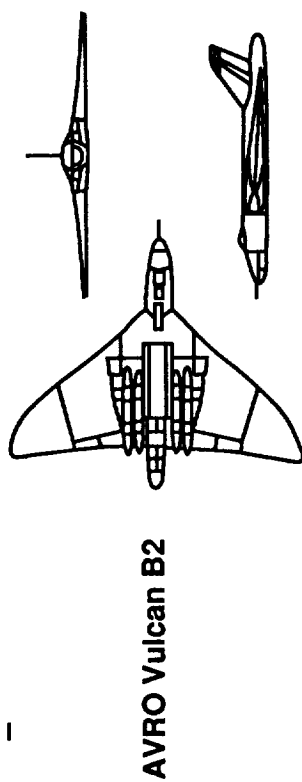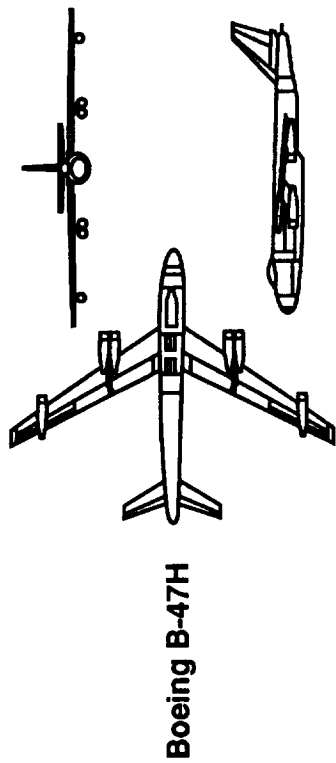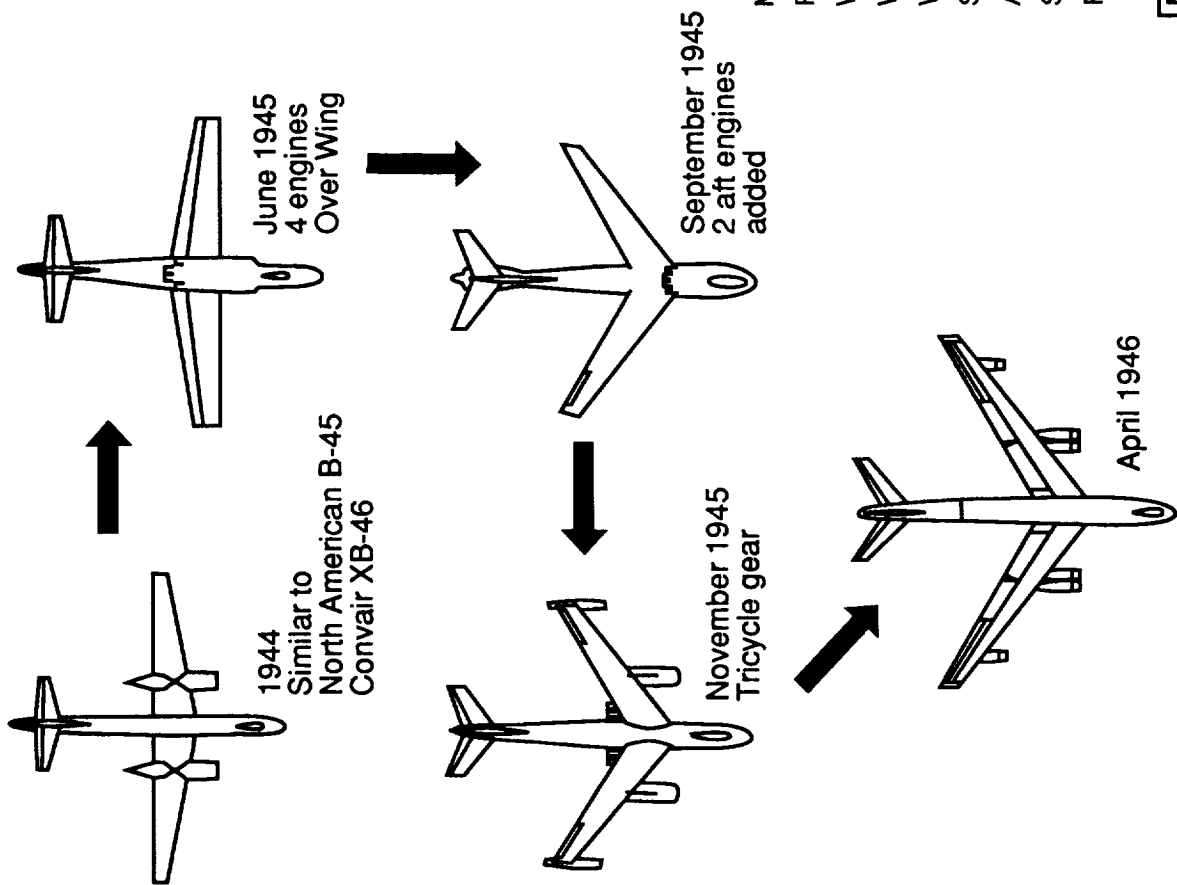
AVRO Vulcan B2

| | | Boeing B-47H | AVRO Vulcan B2 |
|---|---|---|---|
| Max. take-off weight | $W_{TO}$ | 202,000 | 200,000 |
| Ref. wing area | S | 1,400 | 3,964 |
| Wetted surface area | $S_{wet}$ | 11,300 | 9,600 |
| Wing span | b | 116 | 111 |
| Wing loading | $(W/S)_{TO}$ | 144 | 50.5 |
| Span loading | $(W/b)_{TO}$ | 1,741 | 1,801 |
| Aspect ratio | AR | 9.6 | 3.1 |
| Skin friction coefficient | $C_f$ (assumed) | 0.0030 | 0.0030 |
| Parasite drag area | $f(C_f*S_{wet})$ | 34.0 | 29.0 |
| | $dC_D/dC_L^2$ (c=0.8 assumed) | 0.041 | 0.128 |
| Max. lift-drag ratio | $(L/D)_{max}$ | 15.8 | 16.4 |
| Max. lift-drag at L/D Max. | $CL(L/D)_{max}$ | 0.77 | 0.24 |

Figure 13. A Comparison of Two Very Different Aircraft Designed For Similar Missions.

1944
Similar to
North American B-45
Convair XB-46

June 1945
4 engines
Over Wing

September 1945
2 aft engines
added

November 1945
Tricycle gear

April 1946

XB-47 Development Models

Increase size to accommodate 600+ passengers

94 ft,

300 ft

292 ft

273 ft

**Model 747-XL**

Hang-ups or Show-staoppers?
- Taxiway limits
- Runway limits
- Gate limits
- Community noise
- Wake vortices
- Material size/availability
- Emergency evacuation

An alternative configuration paradigm needed? (See following figures.)
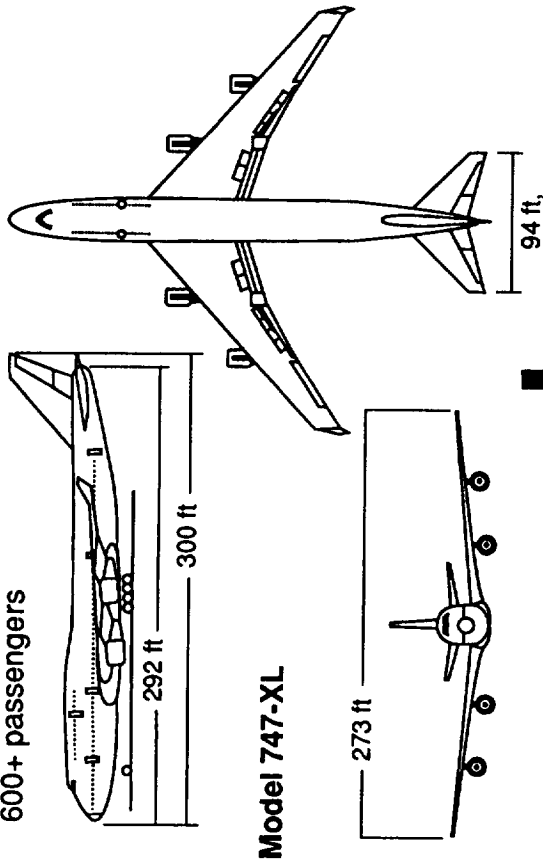
Too long. Reduce length to that of original 747-400

225 ft, 1 in

231 ft, 9 in

**Model 7??**

212 ft, 2 in

What you get if you follow the now traditional 707/747 recipe in configuring a new large transport

42 ft

138 ft, 9 in

39 ft, 8 in

130 ft, 9 in

**Model 707-120**

Increase size to accommodate 400+ passengers

63 ft

72 ft, 8 in

231 ft, 9 in

225 ft, 1 in

**Model 747-400**

212 ft, 2 in

Figure 14. Demonstration of The Evolutionary Process In Aircraft Design.

63

Boeing Model 747-400

225 ft, 2 in

231 ft, 10.25 in

212 ft, 2 in
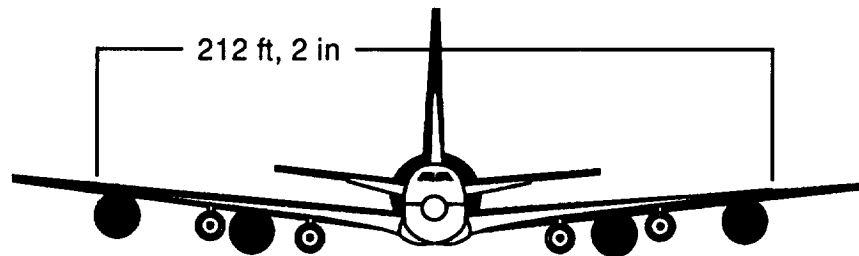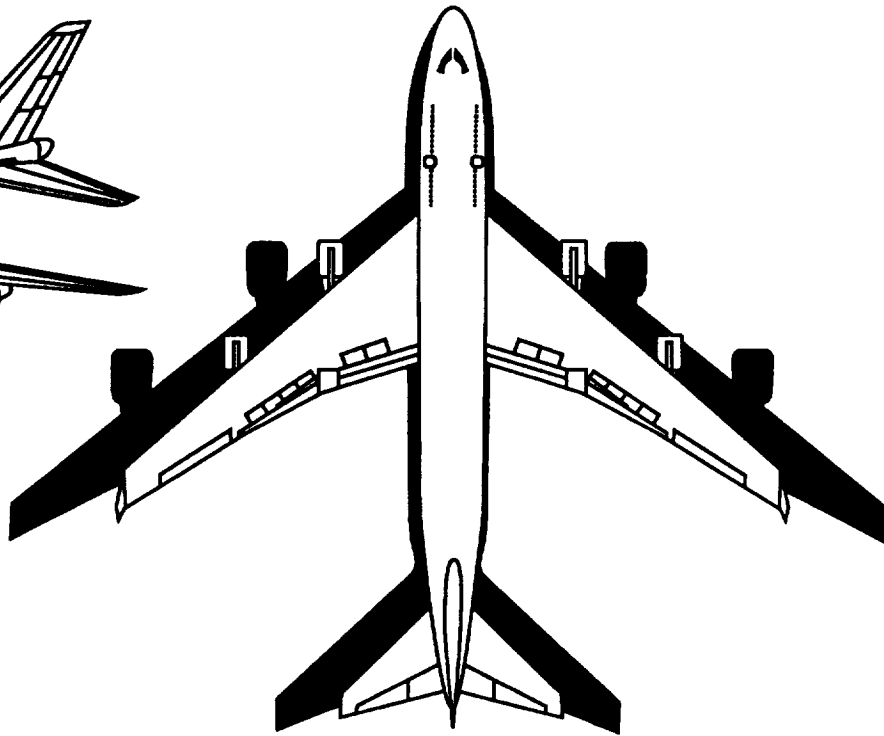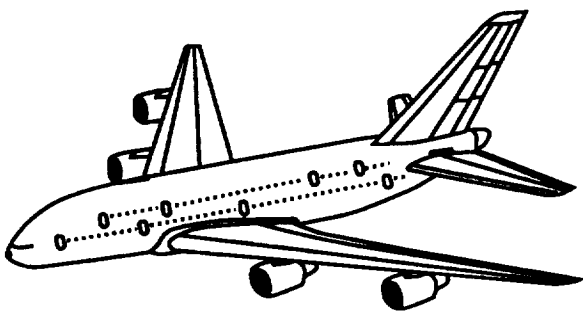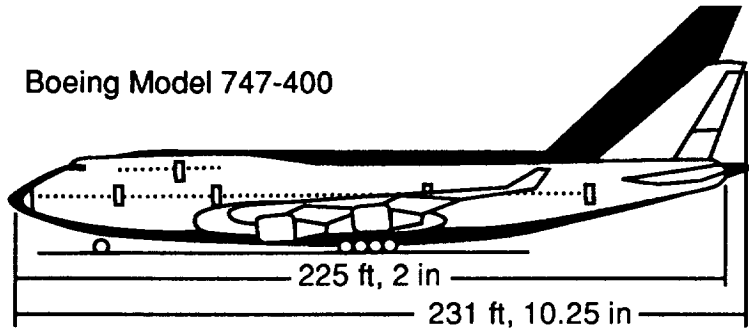
Figure 15. Results of The Evolutionary Approach To Aircraft Design.
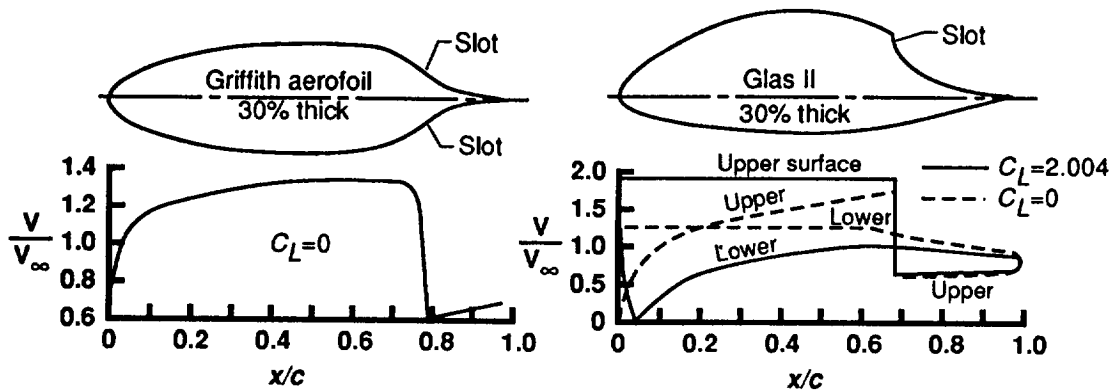
Thick low-drag aerofoils with suction slots (Ref. 7)
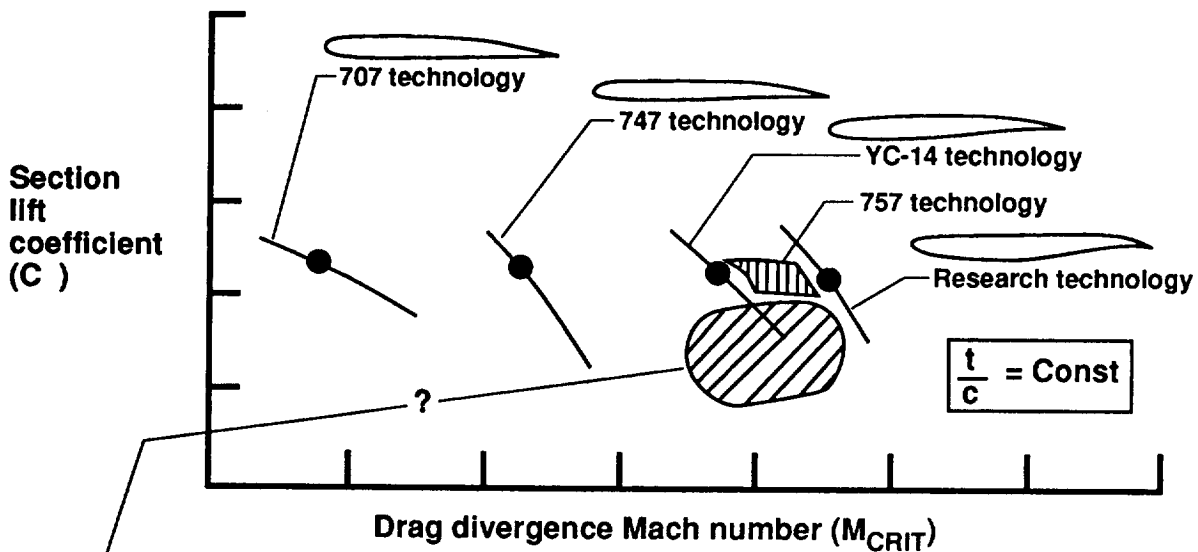


Cruise condition, Mach - 0.82
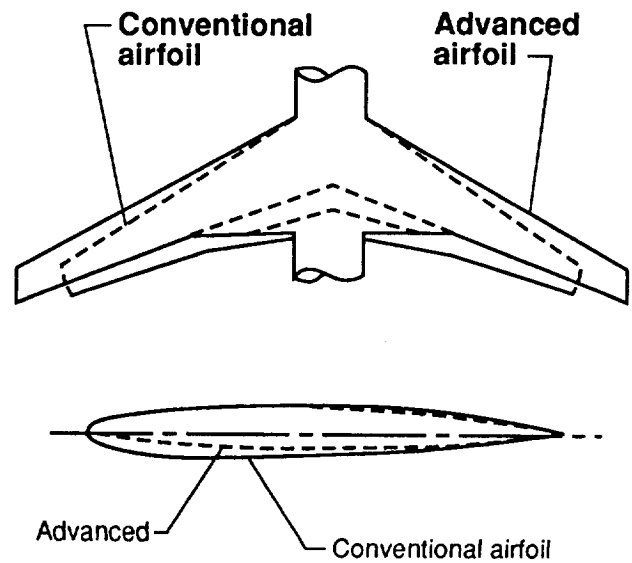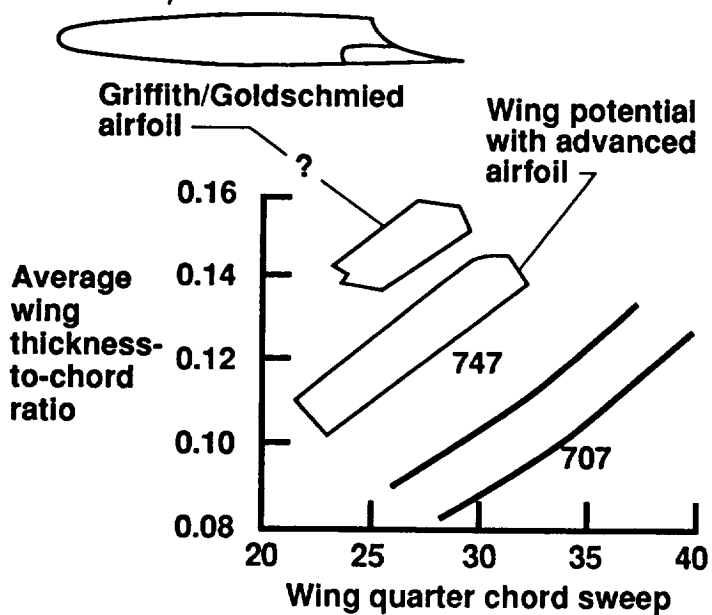


Figure 16. A More Radical Approach to Aircraft Design.

65

## A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT PLANE?
### (Greater than 600 passenger capacity)

**Based on 707/747 configuration paradigm?**

**Possible new configuration paradigm?**
(Unique to this class of airplane)

LARGE SIZE PRESENTS MAJOR PROBLEMS BUT OFFERS MAJOR OPPORTUNITIES
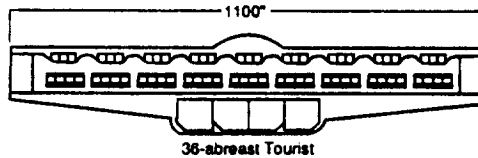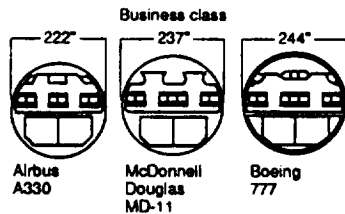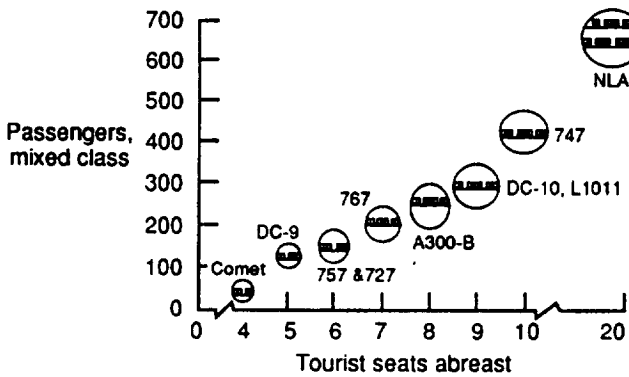
POSSIBLE TECHNOLOGIES AVAILABLE

- Taxiway limits
- Runway limits
- Gate limits
- Community noise
- Wake vortices
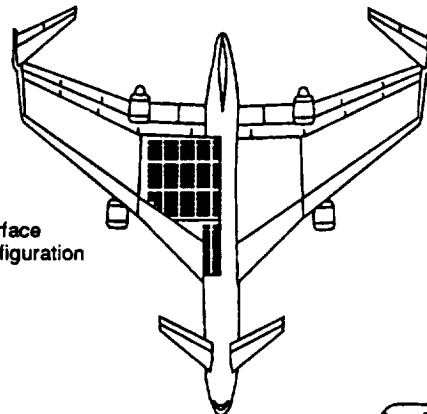- Material size/availability
- Emergency evacuation

BUT:

- Laminar flow control becomes more attractive for large, long-range airplanes

- Large wing size for given thickness/chord ratio yields wing approaching passenger height in absolute thickness

- Griffith.Goldschmied airfoil
- Slotted cruise airfoils
  - Hybrid laminar flow control
- Composite structures (anisotropic materials)
  - Active controls (Fly-by-wire, fly-by-light)
- Very high bypass ratio, very high thrust turbofan engines (GE 90, etc.)
- B-2 bomber experience demonstrates feasibility of an all-wing configuration
- CFD tools available to deal with complex configurations, non-planar wings, complex aeroelastics, etc.

- Active controls/control configurated vehicles

- Composite structures

- Advanced manufacturing techniques

WITHOUT AIRPORT CONSTRAINTS, A VERY LARGE AIRPLANE WANTS TO BE A SPAN-LOADER (A "FLYING WING")

- A "wing" is easier to laminarize than a fuselage

- Conventional fuselage wetted area can be traded for wing area:

  - increases chord
  - increases thickness
  - provides space for passengers seated laterally rather than vertically (multi-decks)
  - may ease emergency evacuation
  - requires less powerful high-lift system
    - reduces airframe noise
    - reduces cost to manufacture and maintain

*B 747-XL*

BUT:

Using conventional technology the wing becomes very large in both span and chord

- Violates all airport constraints, even with large foldable wing-tips

- Suffers from same wingskin limits as current NLA if metal structure used.
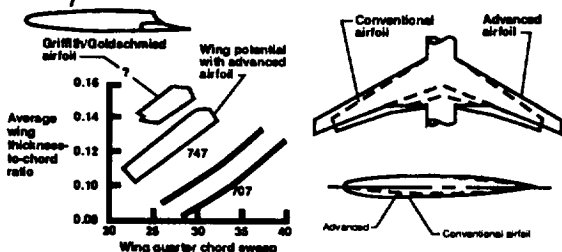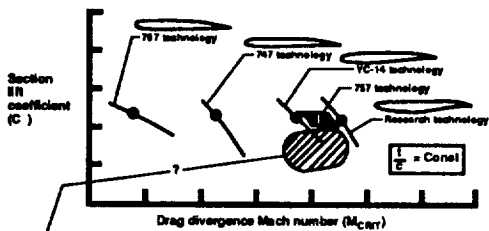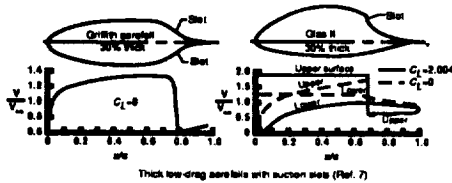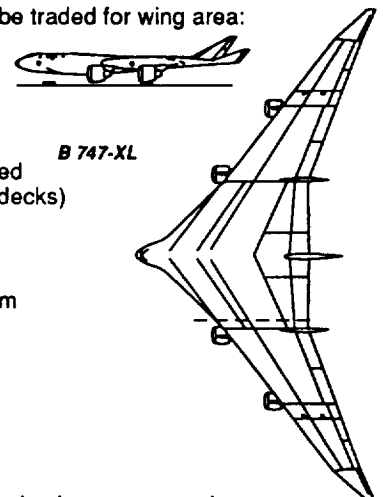
Figure 17. Some Design Concerns.
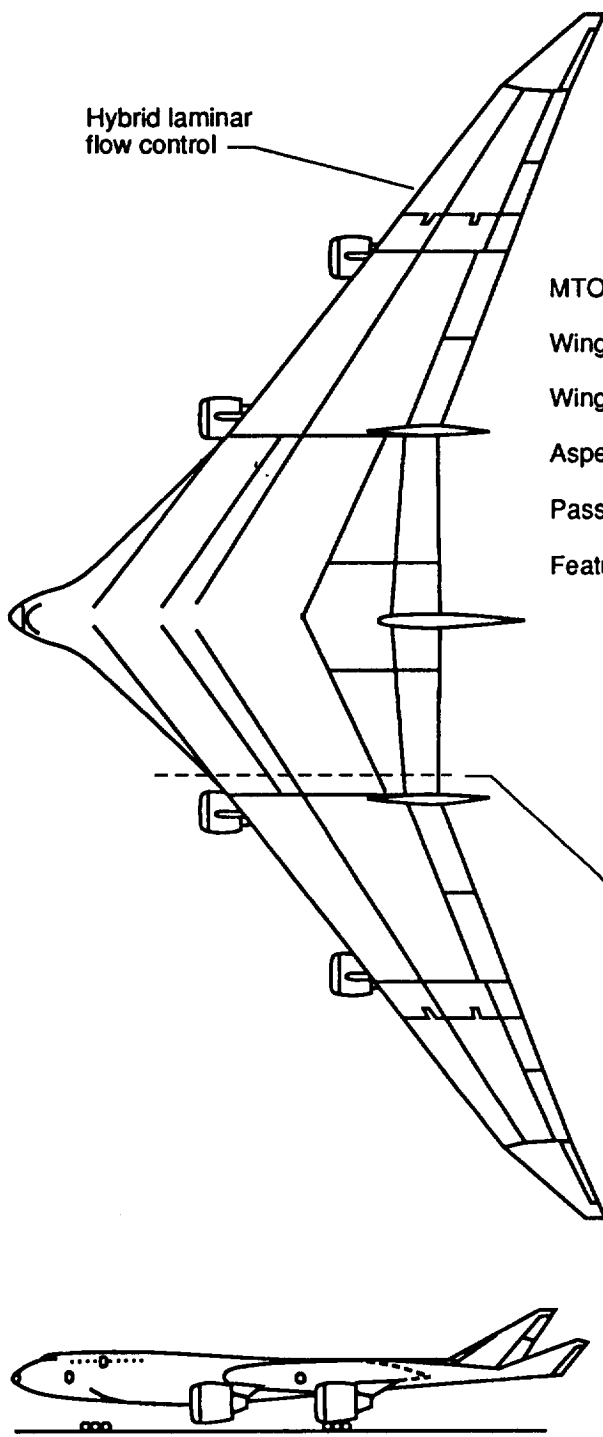
Hybrid laminar
flow control

## B 747-XL

Concept Study

| | |
|---|---|
| MTOW: | 1,400,000 lbs. |
| Wing span: | 300 ft (170 ft. folded) |
| Wing area: | 9,000 ft (trap) |
| Aspect ratio: | 10 |
| Passengers: | 600-800 (50 abreast seating) |
| Features: | • Griffith/Goldschmied airfoil inboard<br>• Hybrid Laminar flow control (with Krueger bug shield leading edge high-lift device<br>• Flat panel, multi-panoramic view/ entertainment system interior<br>• Largely composite structures<br>• 4x95,000 lb. thrust very high by-pass ratio turbofan engines |
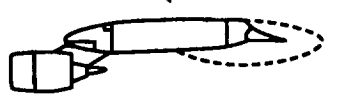
Griffith/Goldschmied
airfoil inboard

From the desk of John McMasters December 1991

Figure 18. Alternate Design Which Could Solve The Concerns Of Figure 17.

# e = induced drag efficiency factor

| End view (front or rear) | | Plate view |
|---|---|---|
| | e = 1.36 Biplane | |
| | 1.33 X-wing | |
| | 1.32 Branched wing tips (pfeathers) | |
| | 1.38 End plates | |
| | 1.46 Box wing (biplane w/ ed plates) | |
| | 1.05 Jointed wing | |
| | 1.45 C-wing | |
| | 1.20 Tip-plated winglets | |
| | 1.41 Winglets | |
| | 1.03 Dihedral (large) | |

**End view (front or rear)**                    **Plate view**
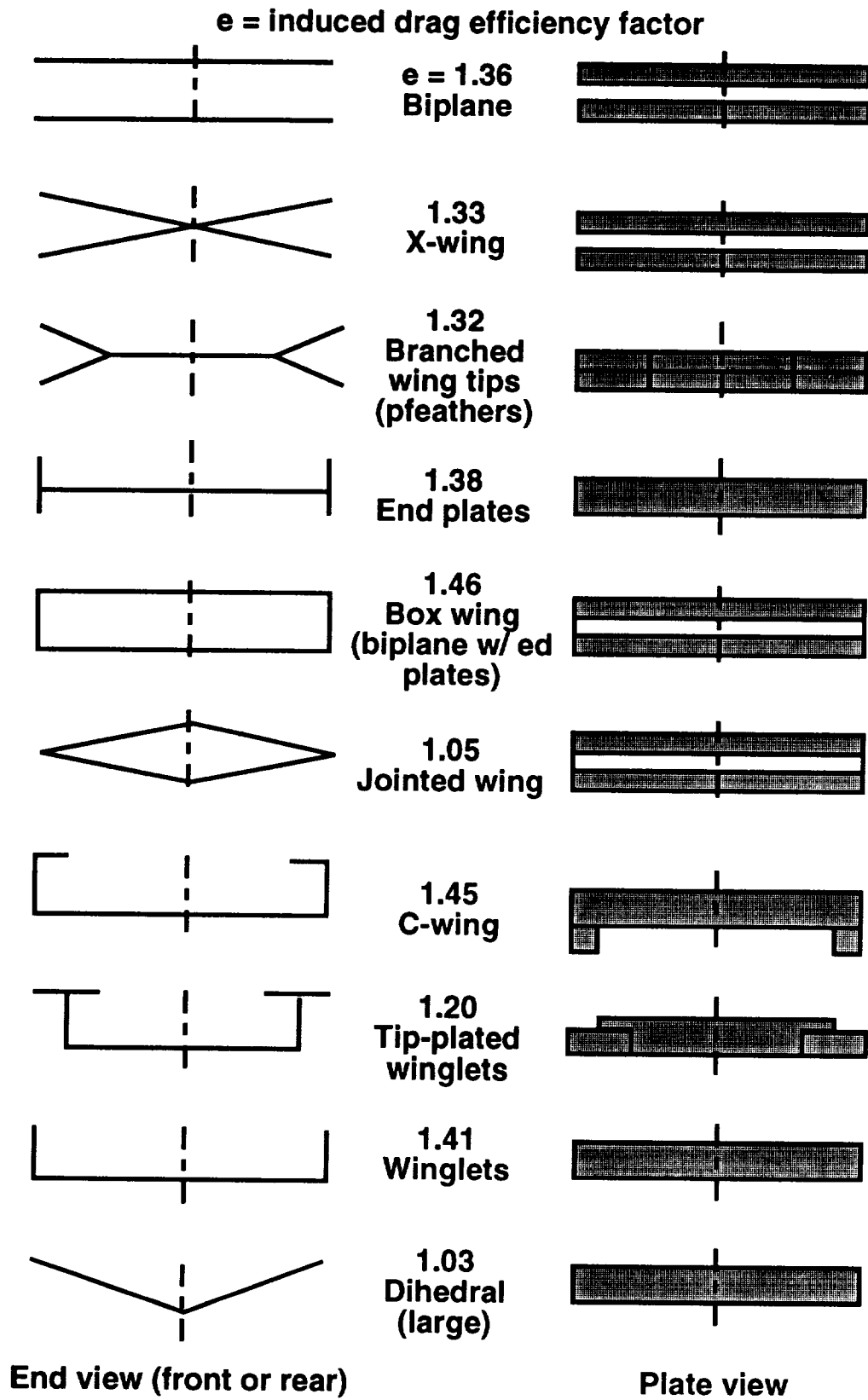
Figure 19. Theoretical Calculations of The Induced Drag Efficiency Factor (e) for Various Non-Planar Wing Configurations.

68

**A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT PLANE?**
(Greater than 600 passenger capacity)

Based on 707/747 configuration paradigm?

Possible new configuration paradigm?
(Unique to this class of airplane)

LARGE SIZE PRESENTS MAJOR PROBLEMS BUT OFFERS MAJOR OPPORTUNITIES

POSSIBLE TECHNOLOGIES AVAILABLE

- Taxiway limits
- Runway limits
- Gate limits
- Community noise
- Wake vortices
- Material size/availability
- Emergency evacuation

BUT:

- Laminar flow control becomes more attractive for large, long-range airplanes

- Large wing size for given thickness/chord ratio yields wing approaching passenger height in absolute thickness

- Griffith.Goldschmied airfoil
- Slotted cruise airfoils
  - Hybrid laminar flow control
- Composite structures (anisotropic materials)
  - Active controls (Fly-by-wire, fly-by-light)
- Very high bypass ratio, very high thrust turbofan engines (GE 90, etc.)
- B-2 bomber experience demonstrates feasibility of an all-wing configuration
- CFD tools available to deal with complex configurations, non-planar wings, complex aeroelastics, etc.

Cross-section Configuration Comparison

Passengers, mixed class

700
600
500
400
300
200
100
0

NLA
747
DC-10, L1011
767
A300-B
DC-9
Comet
757 &727

0  4  5  6  7  8  9  10  20

Tourist seats abreast

Business class

222"  237"  244"

Airbus A330
McDonnell Douglas MD-11
Boeing 777

1100"

36-abreast Tourist

WITH REALISTIC CONSTRAINTS
&
SYNERGISMS OF NEW TECHNOLOGIES

Large 3-Surface Spanloader Configuration
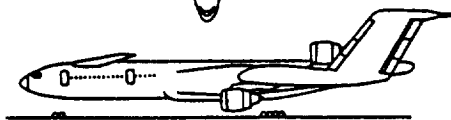
Figure 20. Comparison Of The Different Approaches To Aircraft Design.

69
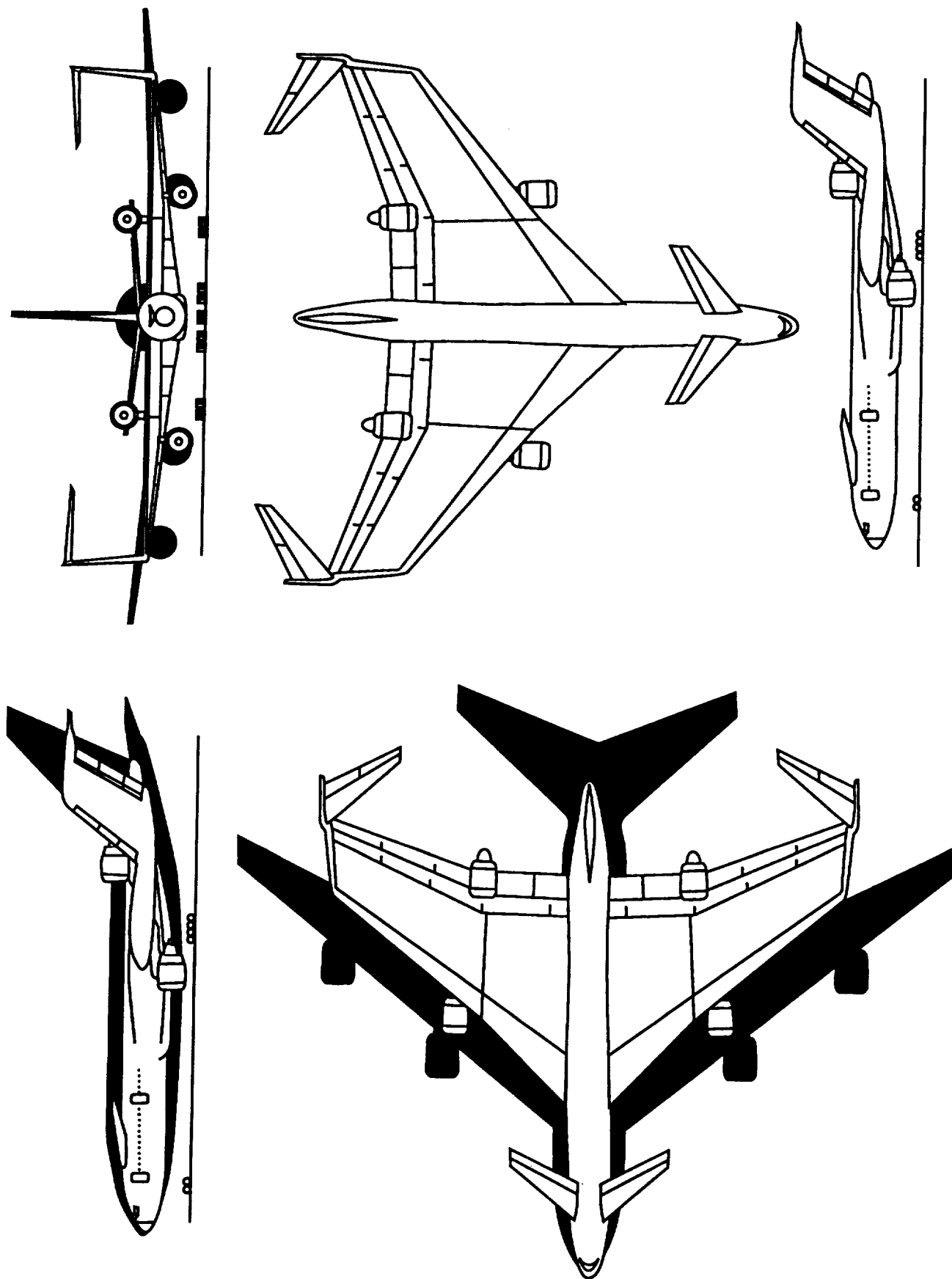
Figure 21. A Conventional Configuration and A More Radical Configuration.

Two engines forward and two aft provide good loadability and wing provides shielding of fan noise from upper aft mounted engines.

Non-planar "C-Wing" when swept, staggers lifting surfaces so that horizontal "winglets" produce a downward lift component replacing a conventional horizontal stabilizer while limiting physical wing span without serious loss of induced drag efficiency.

Stabilizing surface during cruise becomes control surface when flaps are extended and produce an increase in effective wing span replacing need for folding wing tips for taxiway and gate clearance.

Large wing area provides thickness for spanwise distribution of payload and reduces high-lift requirements.

3-surface configuration provides wider allowable c.g. range. Foreplane acts as a control surface during cruise and becomes part of the high lift system when flaps are extended.

Combination of tailored composite structure and active control provides control of structural dynamics (flutter, etc.)

Aft-swept "winglets" mounted aft provide directional stability.

Slotted transonic cruise airfoil outboard.

Hybrid laminar flow control on wing and vertical surfaces.

Inconventionally thick Griffith/Goldschmied airfoil inboard.

36 abreast seating for 400+ passengers. Goldschmied airfoil geometry allows emergency evacuation through aft wing spar with escape slides over the wing flaps.

Figure 22. The Main Features For The More Radical Configuration.

71
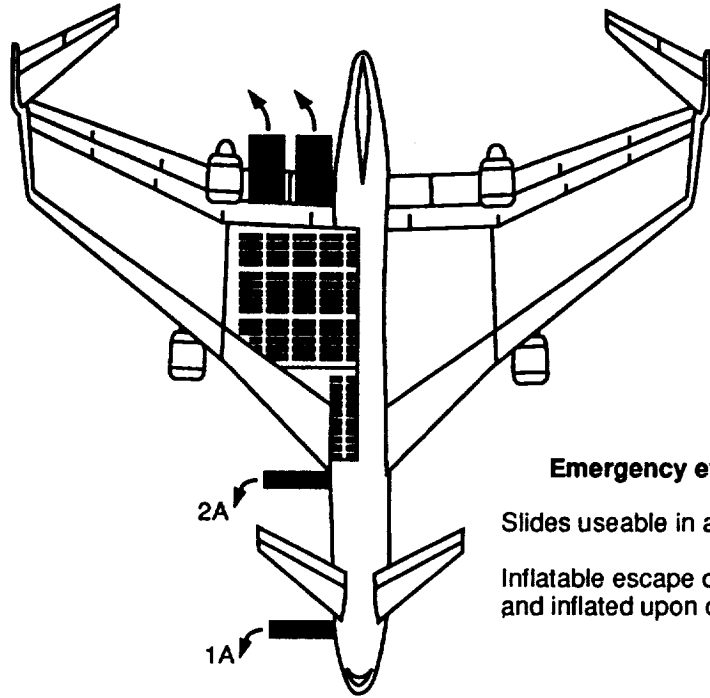
**Emergency evacuation**

Slides useable in all landing gear conditions

Inflatable escape device automatically deployed and inflated upon opening door

Business class

222"
**Airbus A330**

237"
**McDonnell Douglas MD-11**

244"
**Boeing 777**

1100"
**36-abreast Tourist**

NLF suction surface

Suction ducts
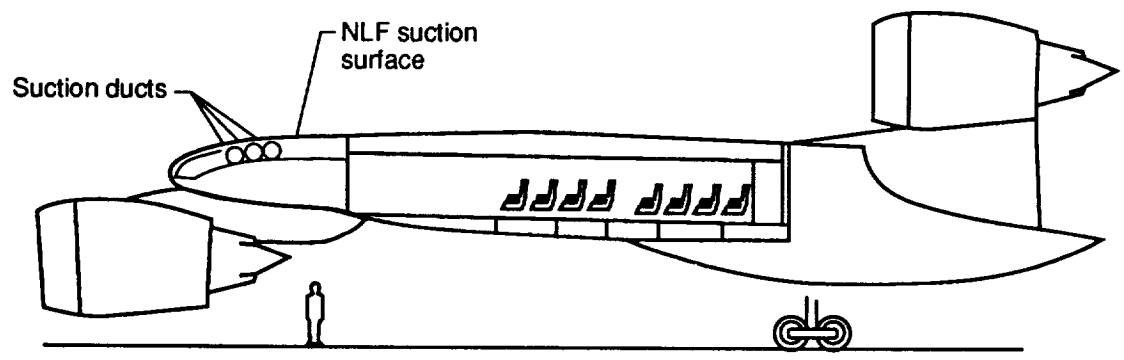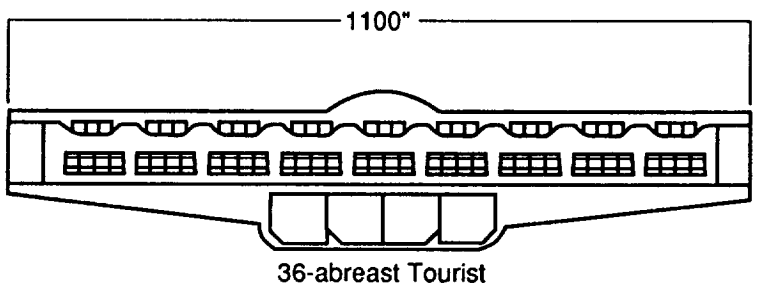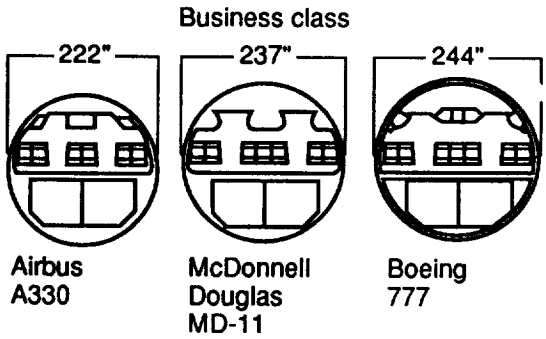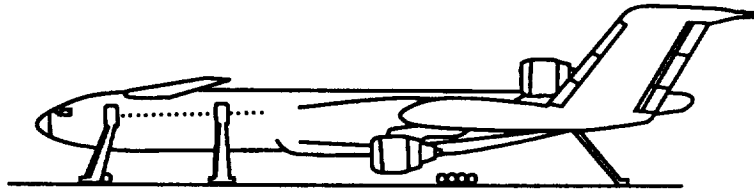
Figure 23. Additional Features For The More Radical Configuration.

Wing Span: 400 ft.

Wing Area: 0.65 acres

Max Take-off Wt.: 2,547,000 lbs.

Power: 6 x GE 150 Turbofans
(@ 151,000 lbs. thrust each)

Passengers: 1,250

Crew: 40

Scale (ft.)

waterline

Boeing Model 747-400

waterline
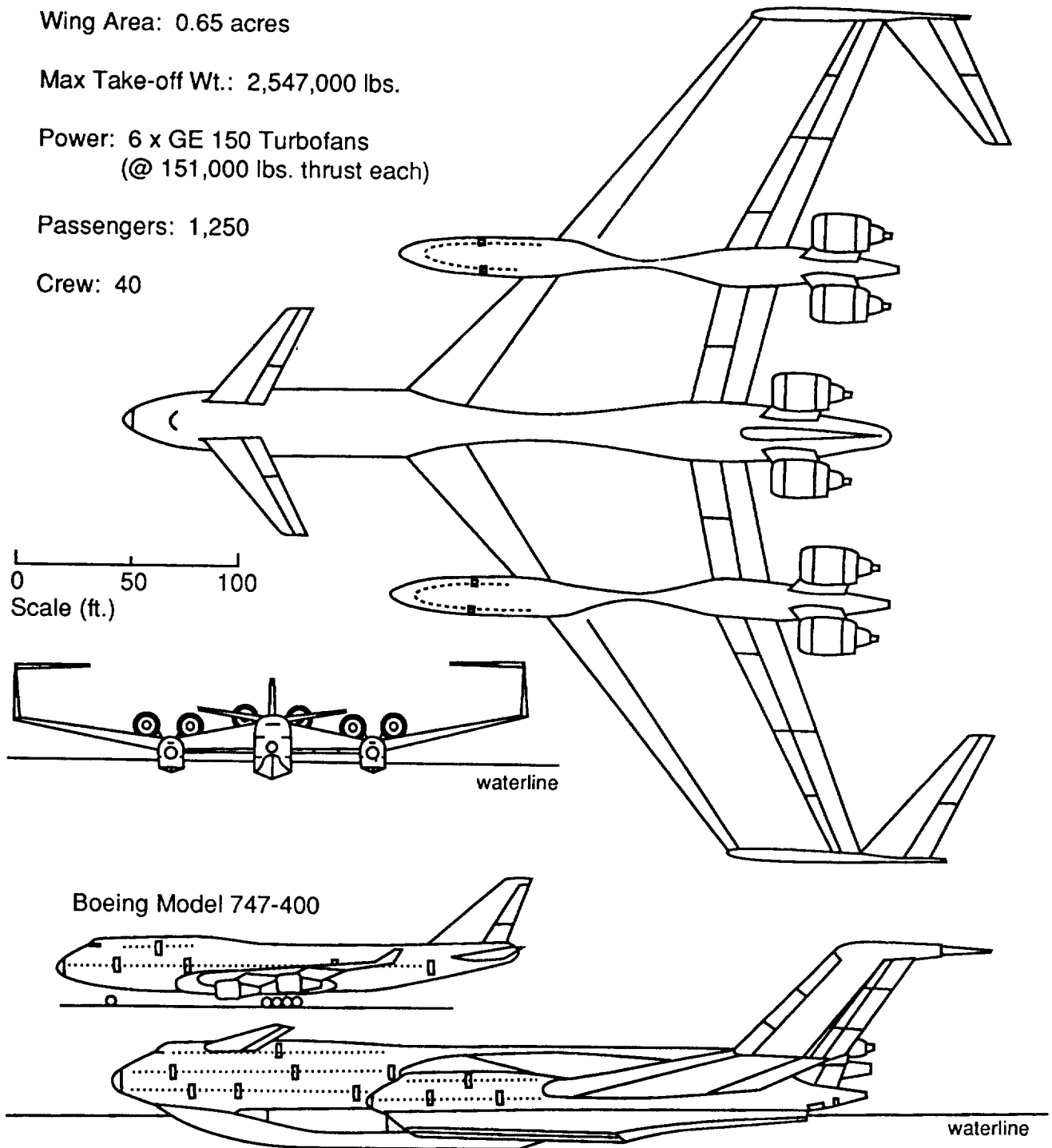
Figure 24. Alternative Configurations.
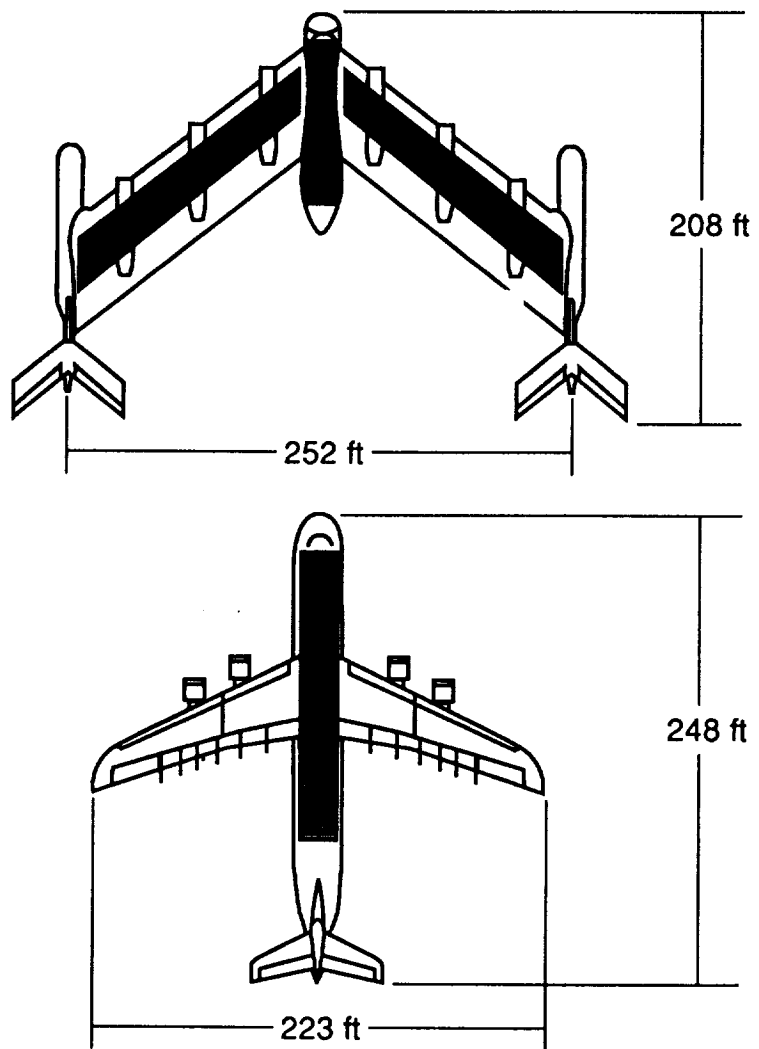
Figure 25. Typical Spanloader Configurations.
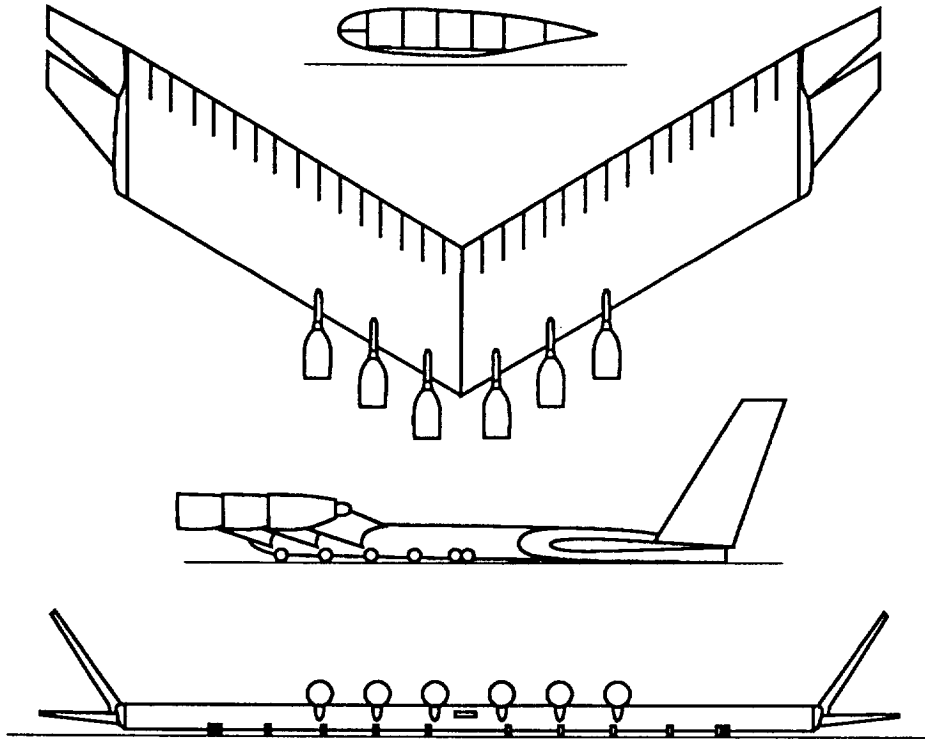
| TOGW | 2,354,000 lb. |
| OEW | 687,936 lb. |

| Wing area | 26,933 $ft^2$ |
| Aspect ratio (EFF) | 7.73 |
| Sweep | 30° |
| t/c | 0.19 |
| Cruise Mach | 0.78 |
| Engines BPR | 9.5 |
| SLST | 93,000 lb. |

Figure 26. An Additional Spanloader Concept.
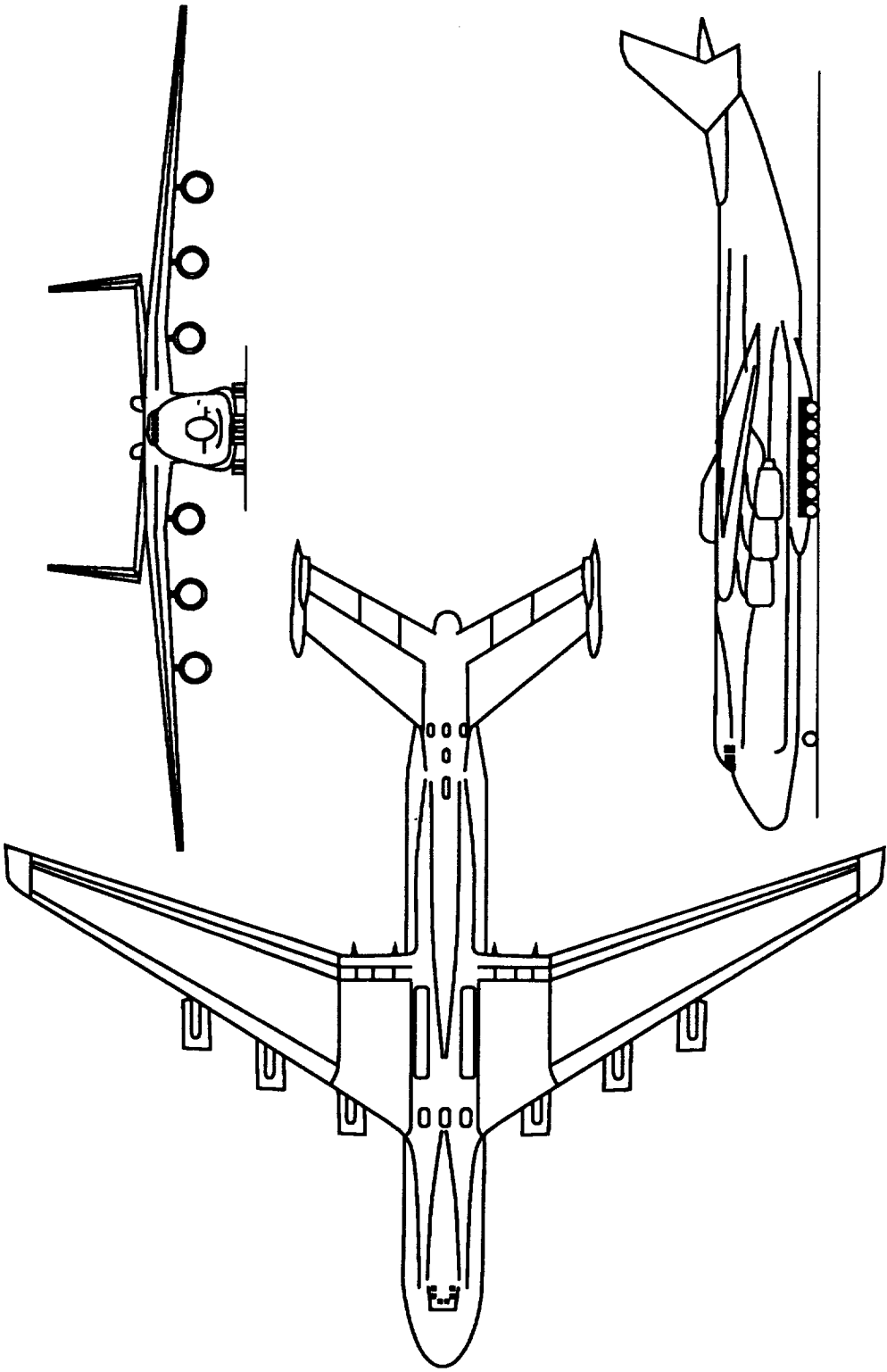
Figure 27. The World's Largest Aircraft; The 1,322,750 pound Russian AN-225 "Mriya".
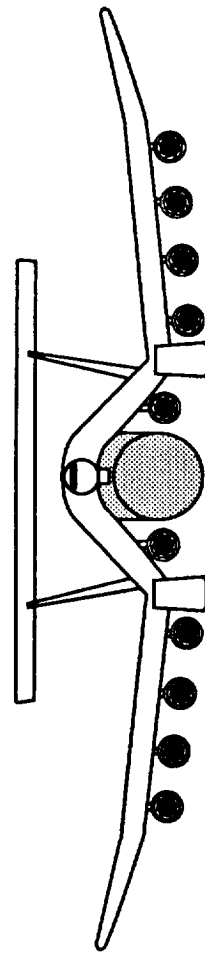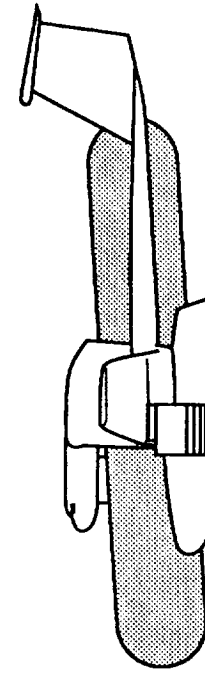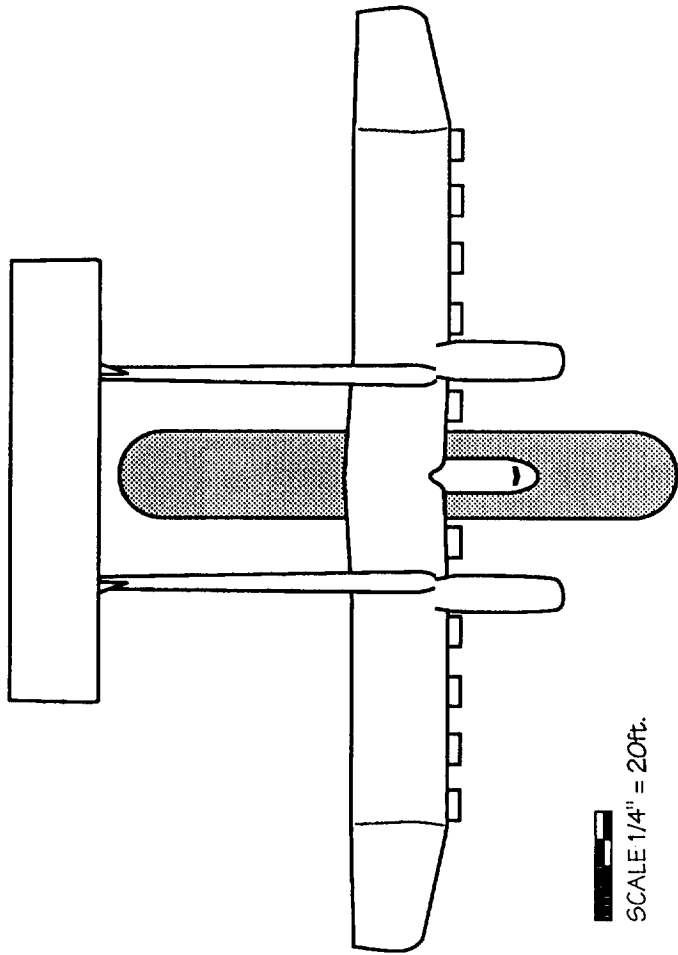
Figure 28. A Conceptual Russian Cargo Aircraft.

SCALE 1/4" = 20ft.
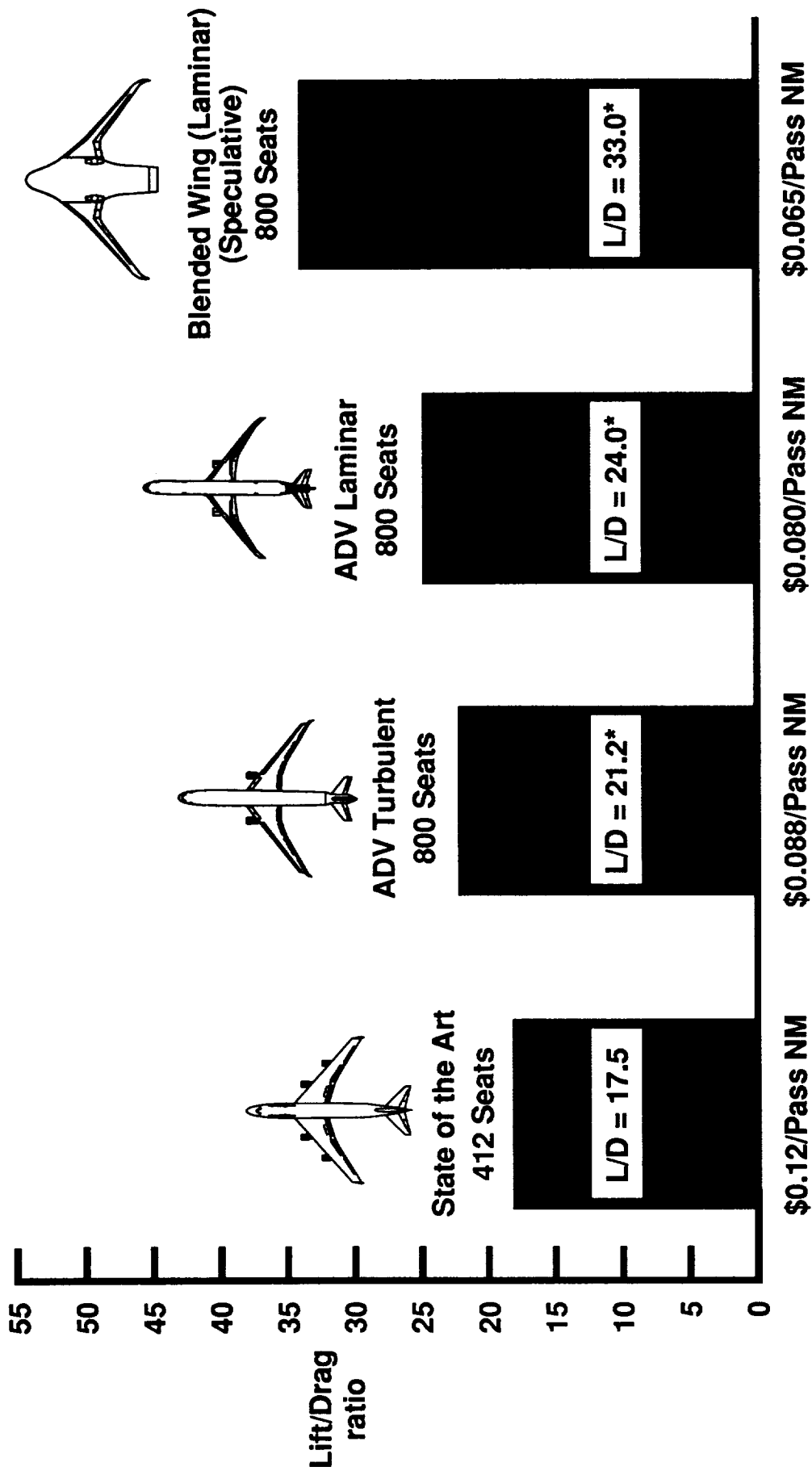
Figure 29. Summary Of the Potential Improvements In Subsonic Lift-To-Drag Ratio.
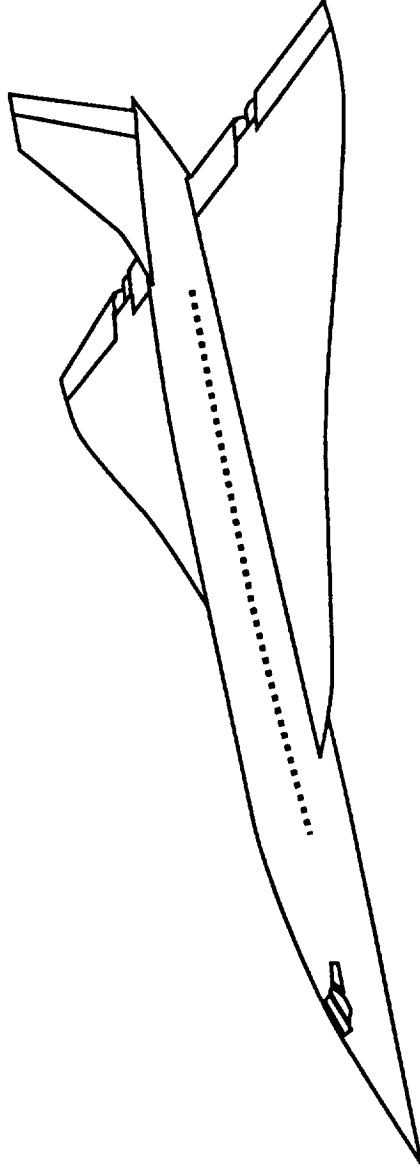
Figure 30. The British/French Supersonic "Concorde".

SCAT 4

SCAT 8

SCAT 14

SCAT 16

SCAT 19

SCAT 3

SCAT 7

SCAT 13

SCAT 15-F

SCAT 18-2

SCAT 2b

SCAT 6b

SCAT 12

SCAT 15-2.6

SCAT 18-1

SCAT 2a

SCAT 6a

SCAT 11

SCAT 15-2.2

SCAT 17-2

SCAT 1

SCAT 5

SCAT 9

SCAT 15-3

SCAT 17-1
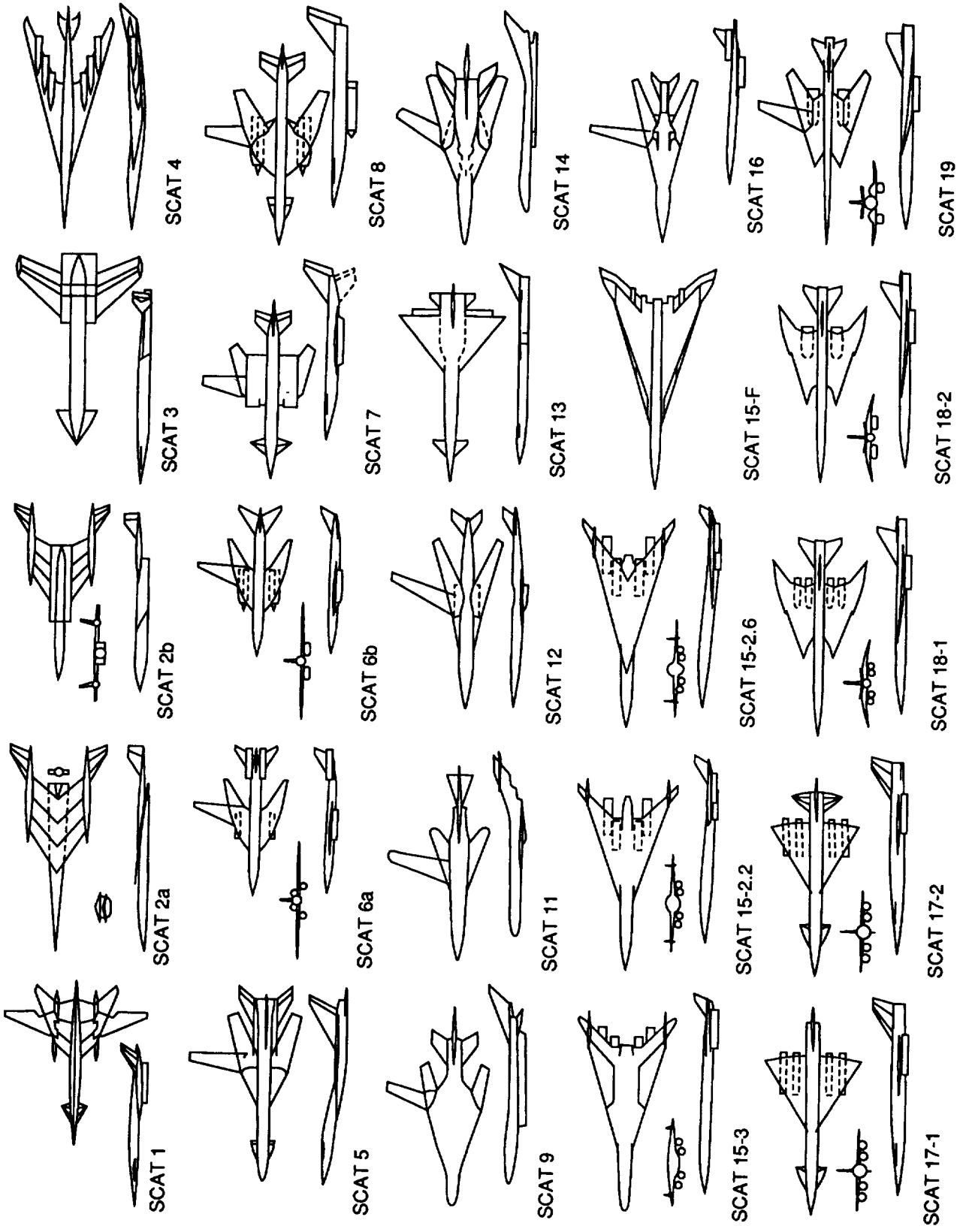
Figure 31. A Summary Of the Various Supersonic Planforms Studied By NASA.

80
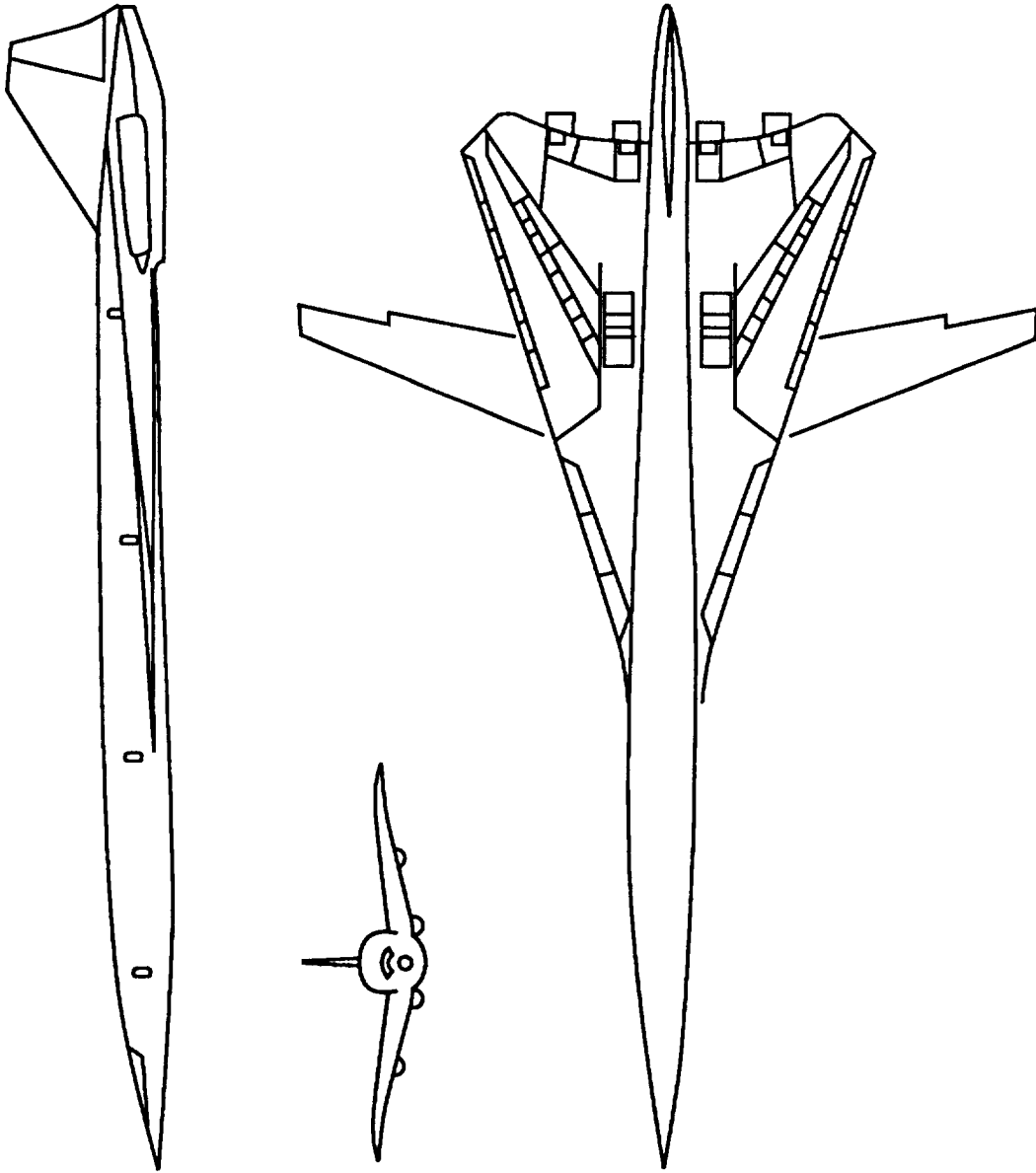
Figure 32. The 1966-Vintage Boeing 2707-200.
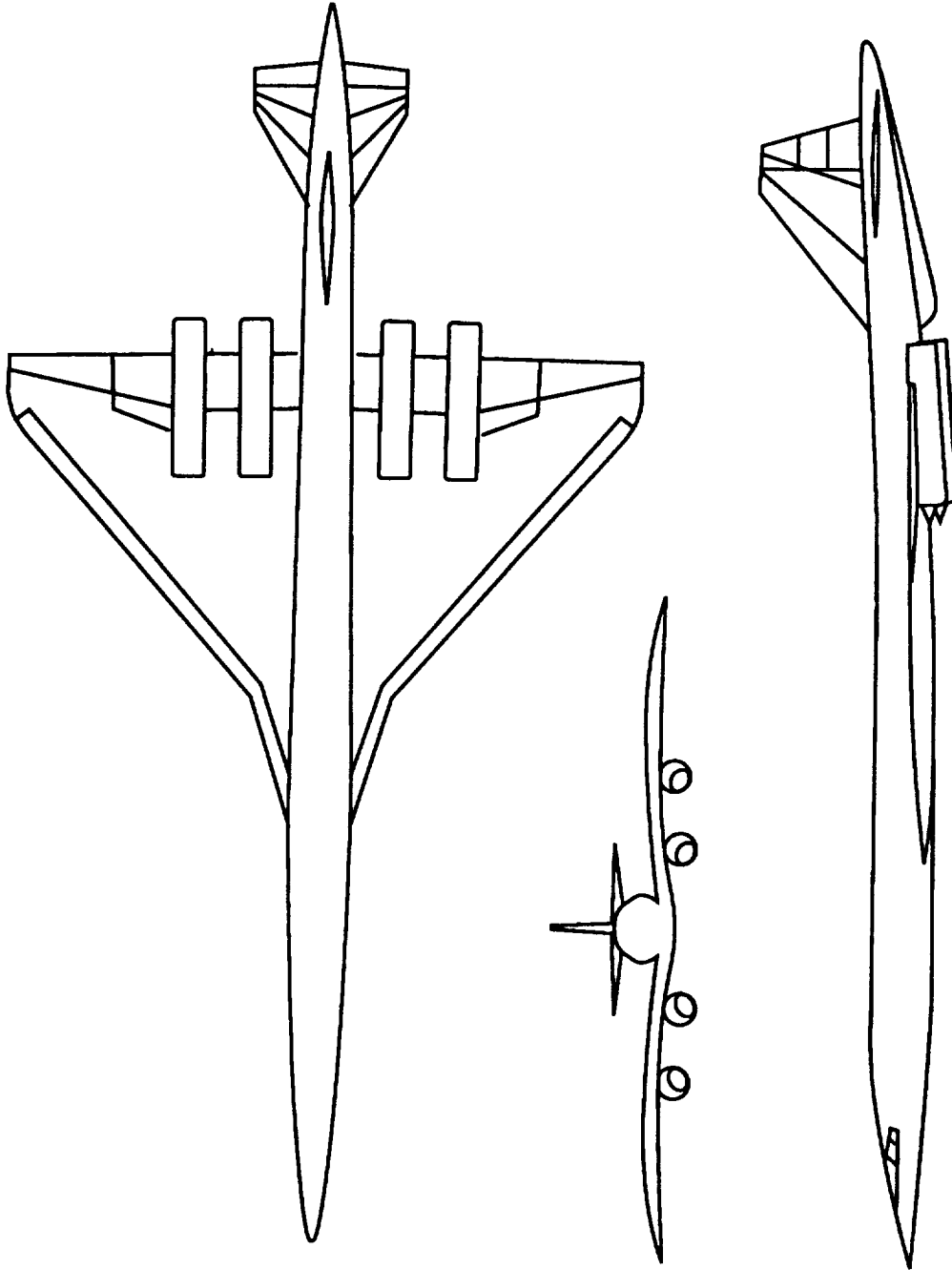
Figure 33. The 1971-Vintage Boeing 2707-300.

MDC-AST

B-2707-300
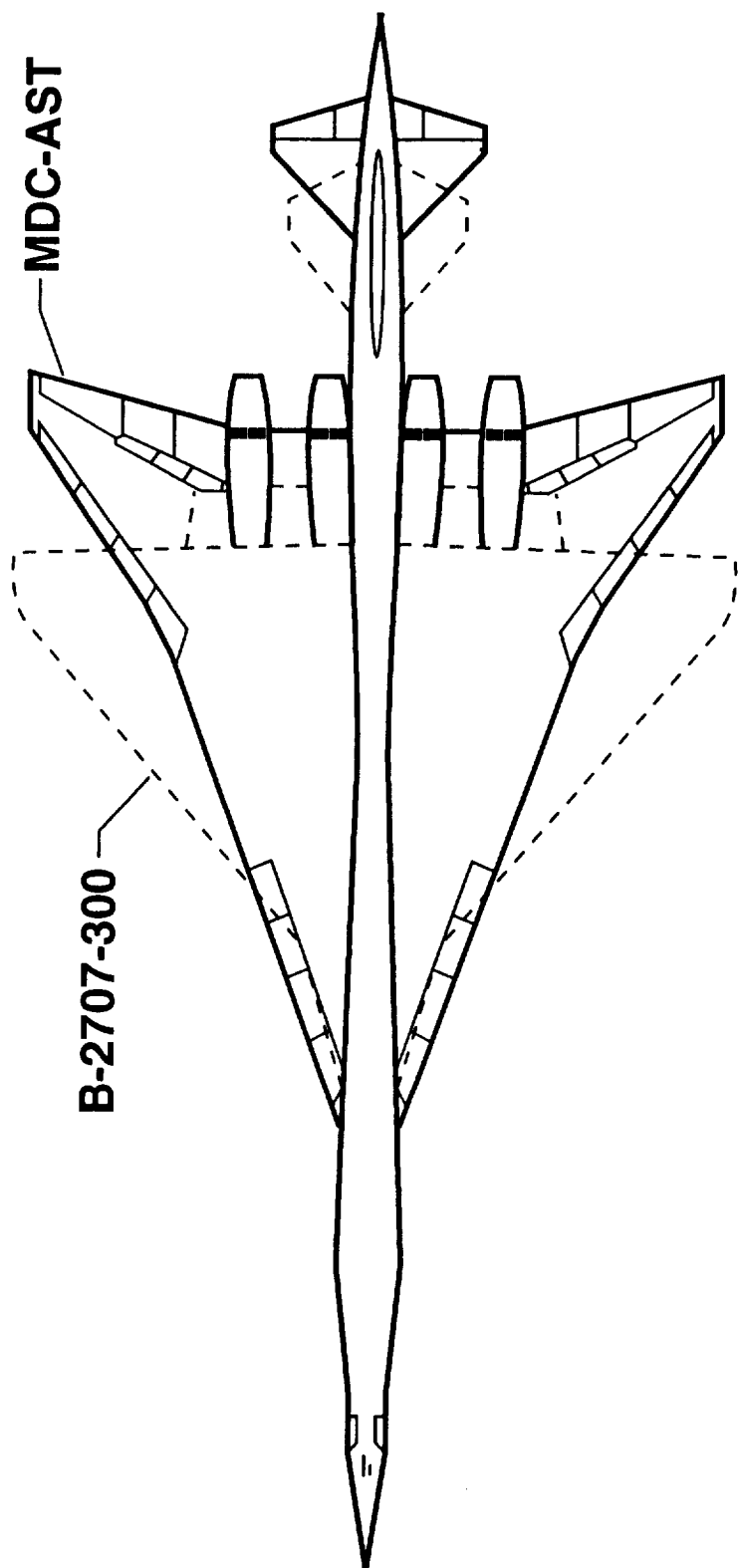
Figure 34. The 1975-Vintage MDC-AST.

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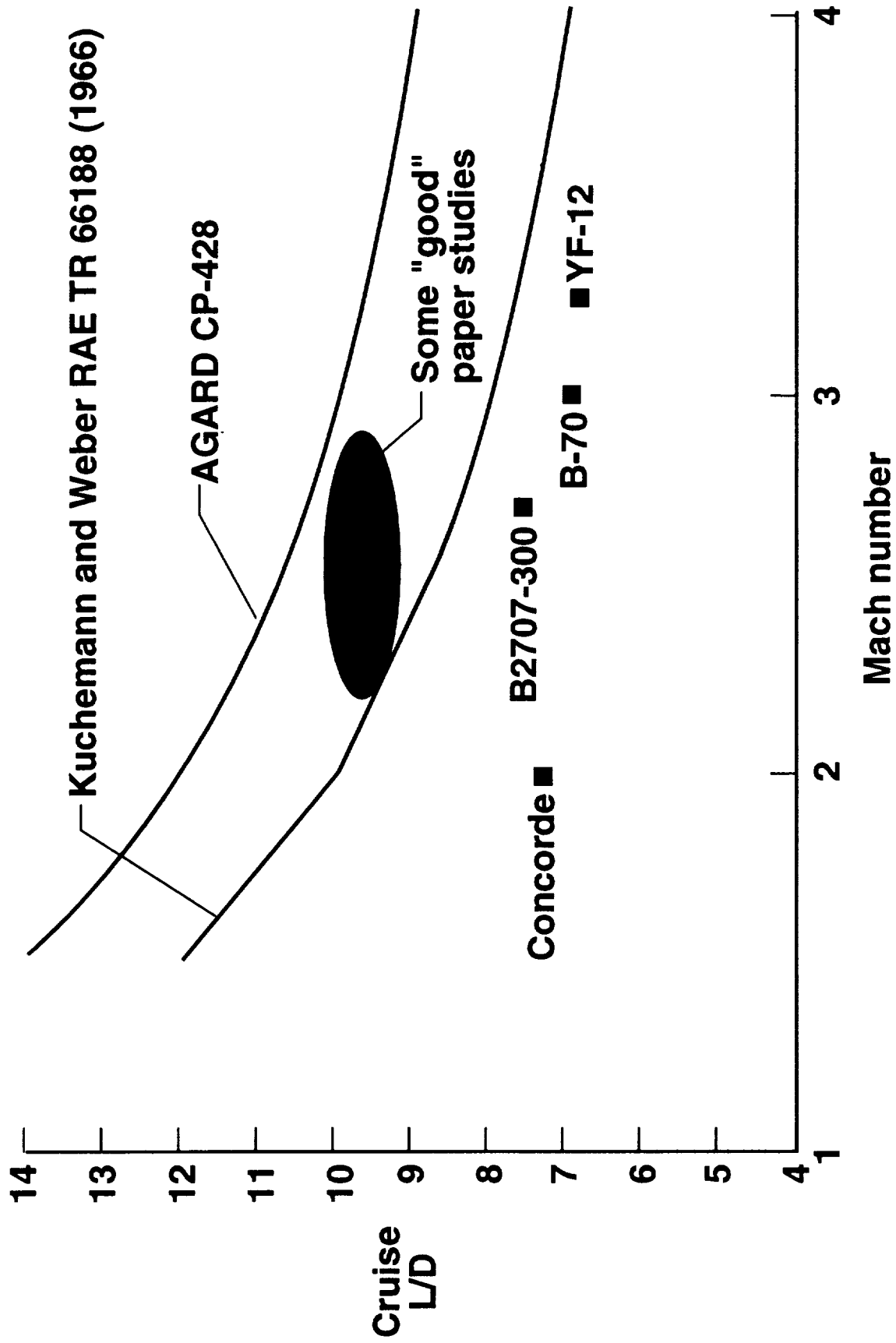
Figure 35. A Survey of Some Supersonic Cruise Aircraft's Lift-to-Drag Ratios.
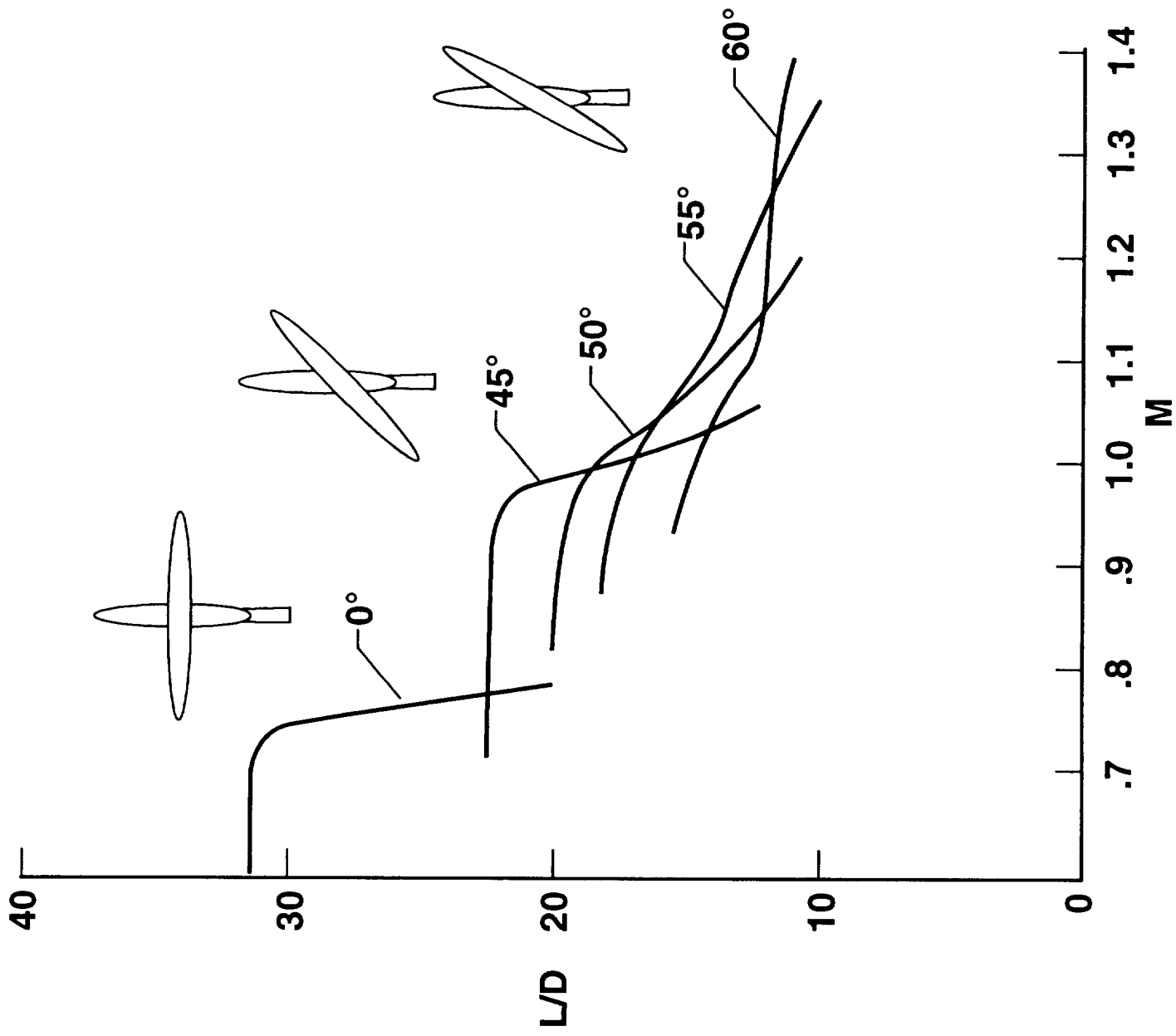
Figure 36. A Summary of Oblique-Wing Model Test Lift-To-Drag Ratios.
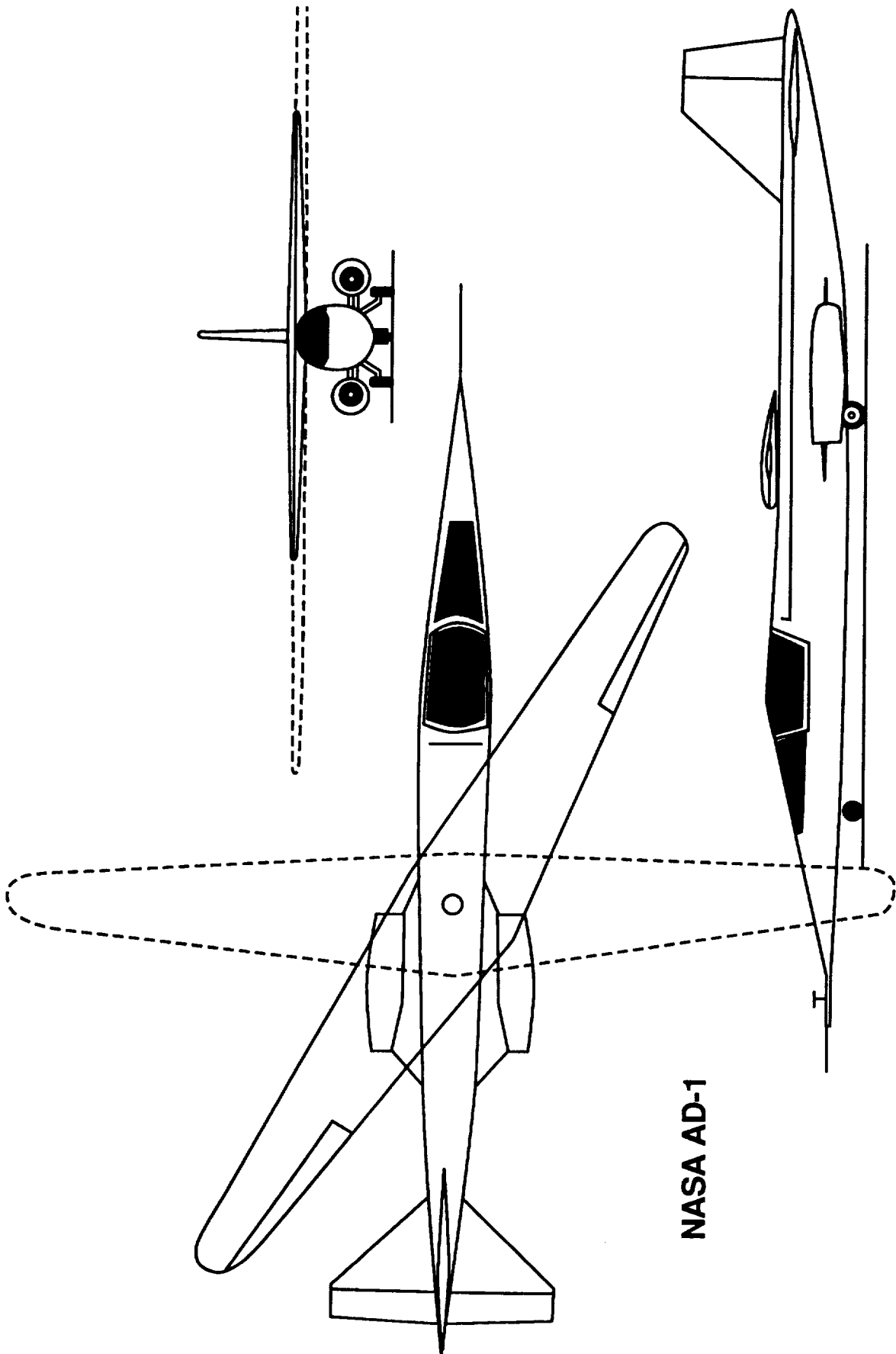
NASA AD-1

Figure 37. A Oblique-Wing Test Vehicle.
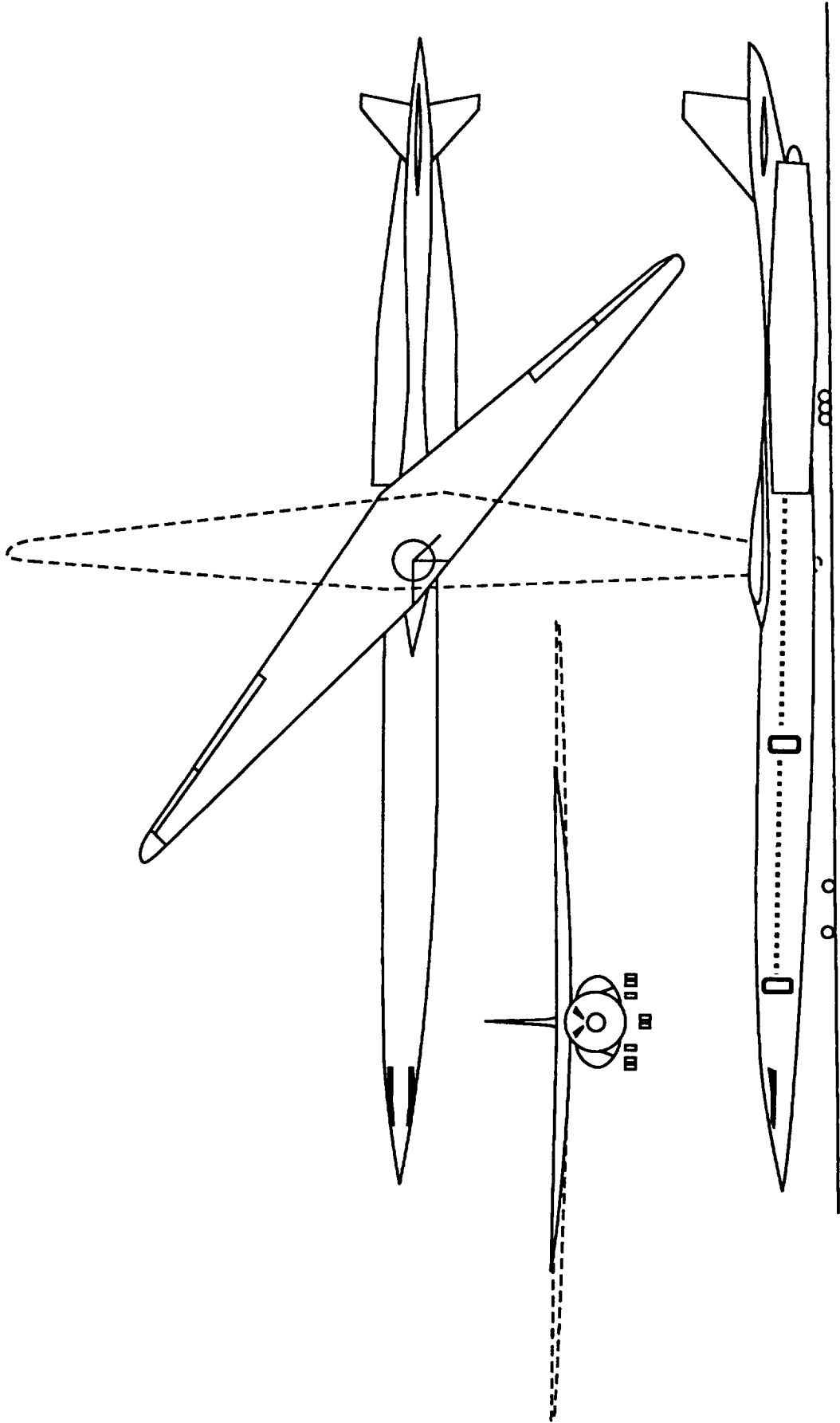
Figure 38. A Typical Oblique-Wing Conceptual Aircraft.

300 Pax, Mach 2.4

Features:
- Single slotted flap
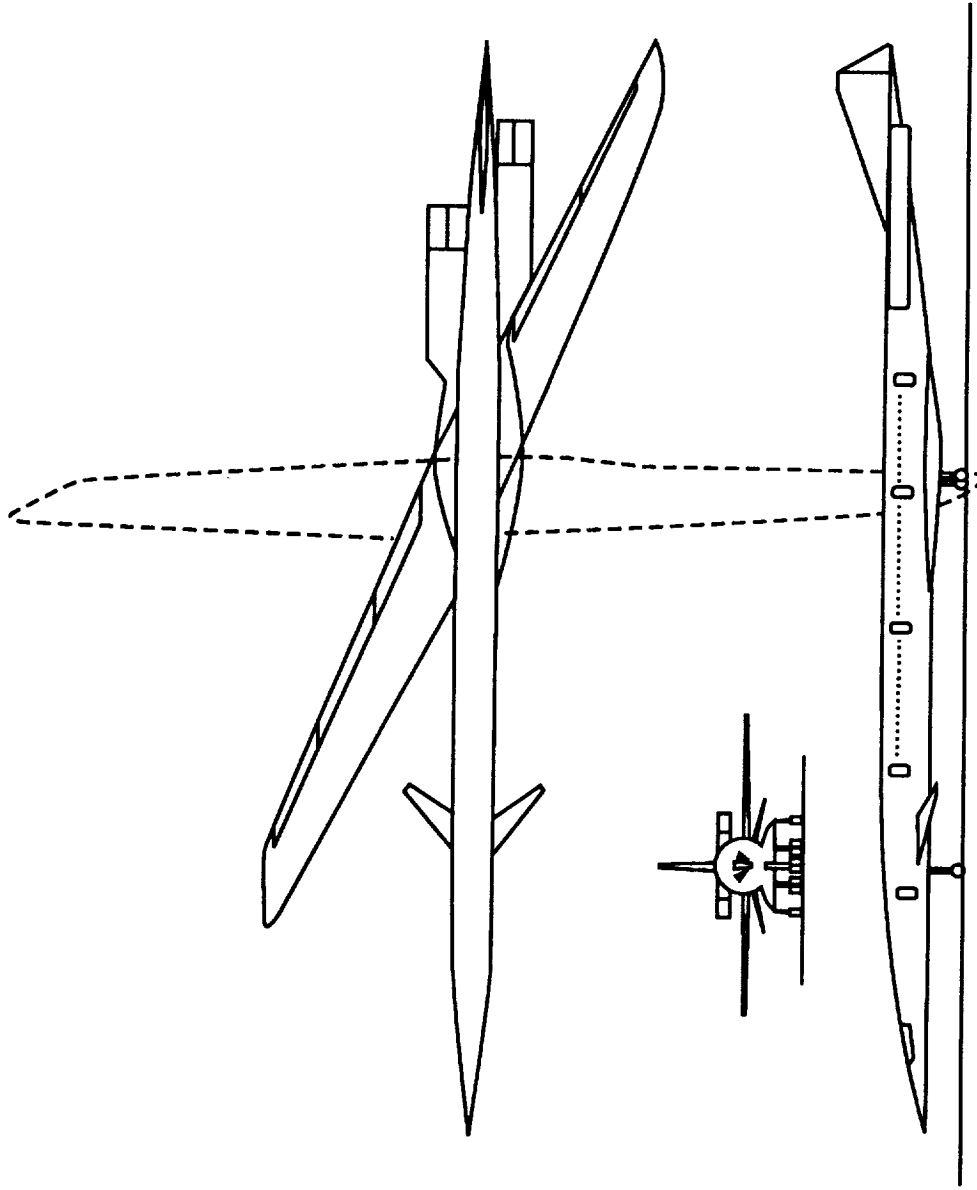- Small AC shift
- Gear independent of wing
- All fuel in wings
- Low wave drag

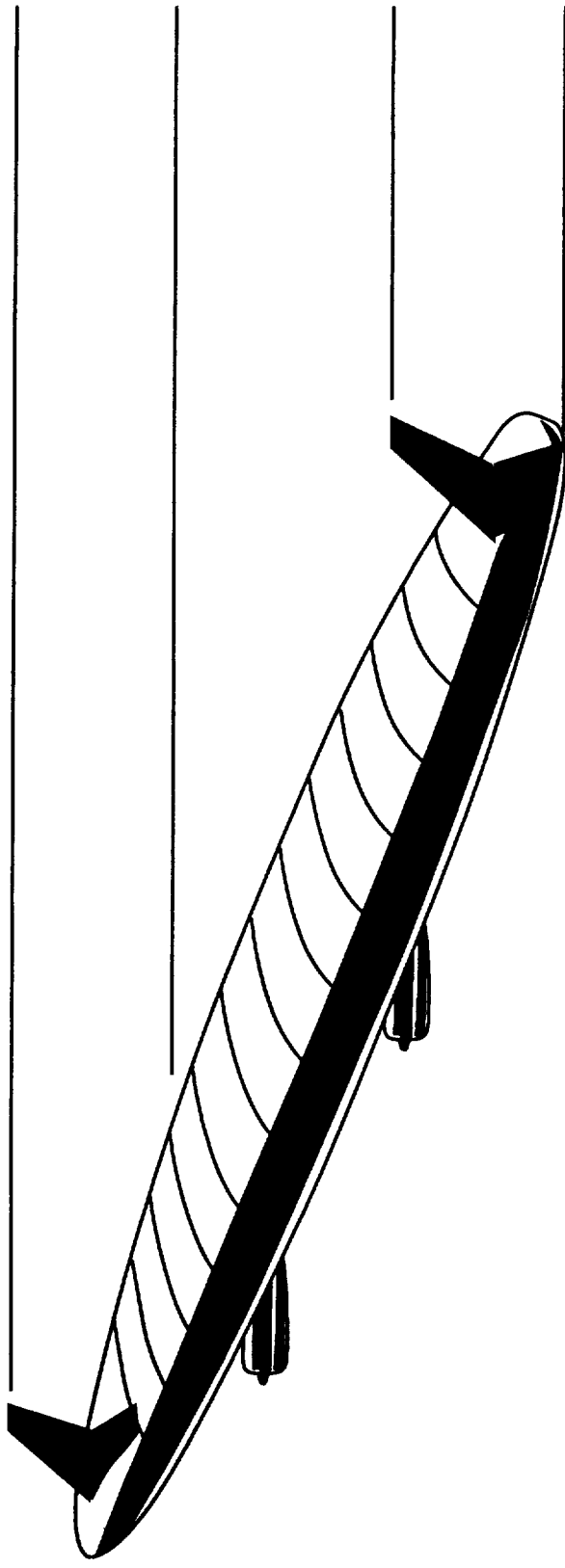Figure 39. Another Oblique-Wing Conceptual Aircraft.

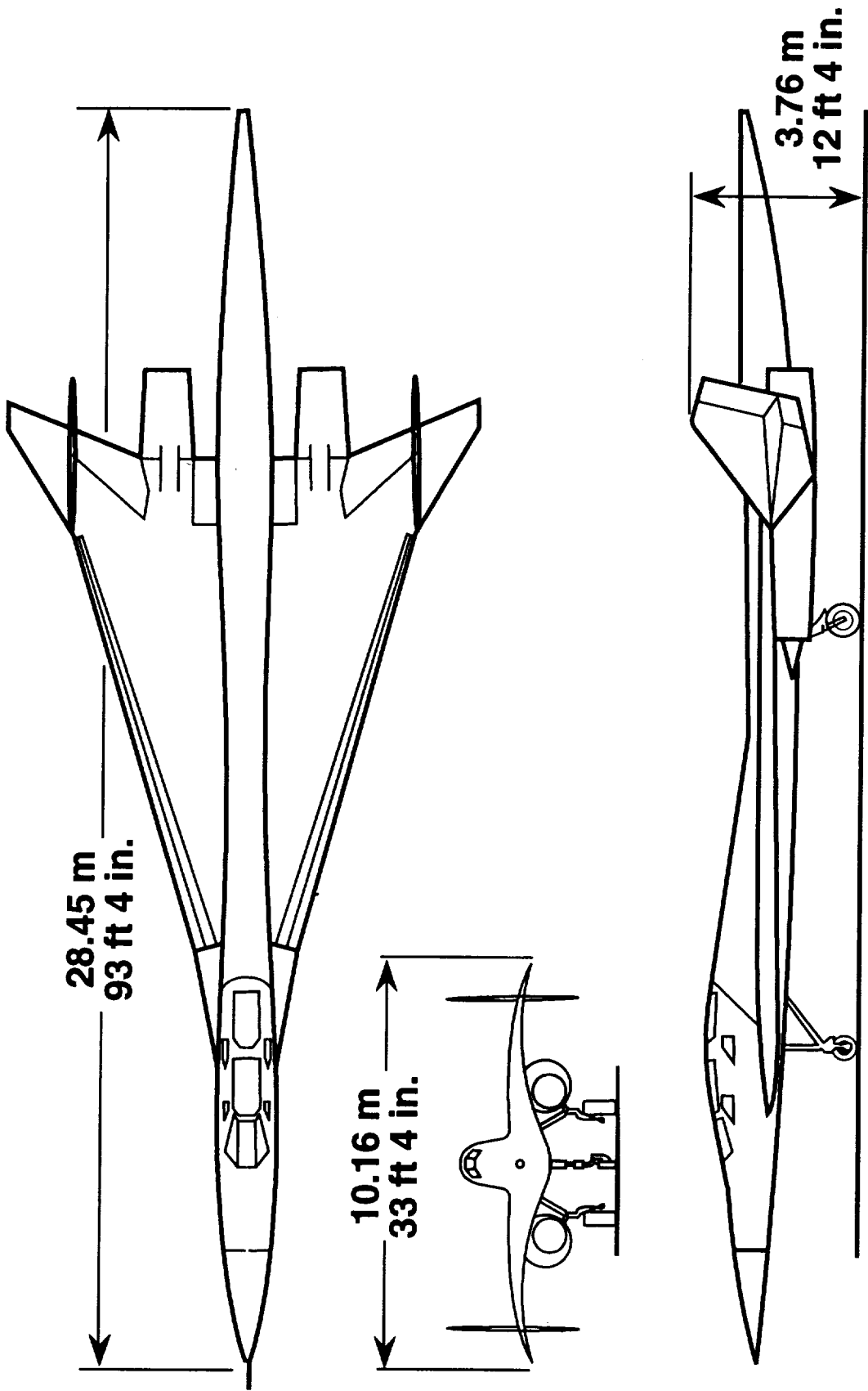Figure 40. An All-Wing Oblique-Wing Conceptual Aircraft.

Figure 41. Proposed Supersonic Research Vehicle.

28.45 m
93 ft 4 in.

10.16 m
33 ft 4 in.

3.76 m
12 ft 4 in.

# N-wave sonic boom 1.0 lb/ft or less

- Takeoff gross weight $\leq$ 400 000 lbs

- Can be tailless

- R $\leq$ 4800 NMiles

- $P_L \leq$ 260 passengers

- $\Delta P \leq$ 0.6 lbs/ft$^2$ with finite times

Figure 42. Considerations For A Future Advanced High Speed Civil Transport (HSCT).

# Aerodynamic Technologies for Enhanced Runway Efficiency
by
James F. Campbell

New aerodynamic technologies are needed to improve the take-off, landing, and cruise performance for the next generation of subsonic and supersonic advanced transport aircraft. Technology developments are required to increase L/D and maximum lift, evaluate flow control concepts, reduce and eliminate the wake vortex hazard, provide propulsion integration options, and develop more capablilies for design tradeoffs with structures, propulsion, noise and emissions studies. The six presentations in this session provide a sample of advanced aerodynamic studies that can address some of the issues of this complicated aerodynamic environment, and suggests many opportunities for applications. The titles of the talks and the speakers were:

"High Lift/Drag-Due-to-Lift Reduction" by Dennis Bushnell, NASA Langley Research Center.
"Wake Vortex Minimization" by George Greene, NASA Langley Research Center.
"Stability of Longitutlinal Vortices" by Mehdi Khorrami, High Technology Corporation.
"Oscillatory Blowing, A Tool to Delay Boundary Layer Separation" by Israel Wygnanski, University of Arizona.
"Circulation Control Technology for Application to Advanced Transport Aircraft" by Robert J. Englar, Georgia Tech Research Institute.
"Airfoil Static-Pressure Thrust: Quiet and Power-Efficient AircraftPropulsion" by Fabio Goldschmied, Consulting Engineer.

The principle points covered in each talk are summarized and a sample of the figures is presented.

## High Lift/Drag-Due-to-Lift Reduction ... Bushnell:

Bushnell reviewed technologies that could impact the high lift and drag-due-to-lift aerodynamics for new transport aircraft. This effort was undertaken because of the critical need to increase $C_{L_{max}}$ and L/D characteristics for advanced CTOL and high-speed transports at take off and landing.

He noted that high lift was the principle issue for the design of an advanced CTOL aircraft in a new NASA program. The objectives of high-lift research, shown in figure 1, were to have simpler high-lift systems with higher $C_{L_{max}}$ and L/D. The impact of improved high-lift technologies would allow reduced engine thrust during takeoff and lower approach speeds during landing, which would lower sideline and community noise. Additional impacts would result in smaller wing area and less-complex flap elements, which could lower wing weight, increase aspect ratio, and increase wing loading. He showed that Airbus had been successful at meeting this objective; it achieved a higher lift using single-slotted trailing-edge flaps than most transports obtained using double- and triple-slotted flaps.

Bushnell observed that while high-lift technologies were developed for military applications, there is a need to better exploit these advances for civilian transport systems. He used the Circulation Control Wing concept as an example of generating transport high lift, where it's application may reduce part count, system weight, and wake vortex hazard.

Technology advances in areas like flow separation control can lead to significant payoffs for new CTOL aircraft, particularly for maximum lift. Bushnell suggested that it was important to pursue technologies to control flow separation, such as low-profile vortex generators for high-lift three element airfoils. Flow separation control concepts are reviewed in reference 1, and longitudinal vortex control techniques in reference 2.

A variety of techniques for reducing drag-due-to lift were presented which included, modifying the planar and non-planar vortex sheets, extracting energy or thrust from the tip vortex, altering

the wing tip boundary condition, eliminating the wing tips, and improving propulsion integration. He commented that some of these should be evaluated for their beneficial effects on reducing wake vortex hazard.

<u>Wake Vortex Minimization ... Greene</u>:

Greene gave a review of wake vortex minimization efforts. This work was presented because of the need to reduce the adverse effects of an airplane wake as a hazard to following aircraft, which dictated spacing at airports.

Greene stated that considerable research was undertaken in the 1970's to help reduce the adverse effects of an airplane wake, but that the assumptions in this early research were that maximum vortex velocities were associated with the wake hazard without concern for the whole vorticity throughout the flow field. Since then, an improved understanding has emerged to show the powerful effect inboard vortices have on the primary (tip) vortex, and the importance of atmospheric coupling. Both of these effects, illustrated in figure 2, were important factors for minimizing the influence of the wake; one was concerned with minimizing the effects of vorticity generated at the wing trailing edge, and the other with designing the wake to couple with the atmosphere more quickly. He noted that the potential benefits of applying this new knowledge were a design with reduced vortex strength, increased vortex core diameter, enhanced coupling to atmospheric turbulence, and early initiation of crow instability, all of which were safer for following aircraft.

Greene made several observations concerning atmospheric coupling. It generally did not matter what kind of airplane you had, the vortex lifetime was determined by the interaction with the atmosphere and the ground. In addition, the calculations showed that the interaction was a function of both atmospheric and aircraft parameters, and because of this the atmospheric coupling may produce non-intuitive results. Small amounts of turbulence caused the wake to decay much quicker; however, large airplanes couple more slowly with the atmosphere because their vortices last longer and are stronger, so that super-heavy airplanes will still have vortex hazard. Some of these points can be found in reference 3.

<u>Stability of Longitudinal Vortices ... Khorrami</u>:

Khorrami presented a study on the stability of longitudinal vortices. This work was motivated by the need to destabilize and breakup the highly stable trailing line vortices generated by large commercial aircraft that created a wake hazard for following aircraft, which reduced flight frequencies at major airports.

Mean velocity components from a Batchelor vortex were used to perform a viscous linear stability analysis of a trailing line vortex, from which two new viscous instability modes were identified, one axisymmetric and the other asymmetric. In addition, he found that these viscous disturbances were long-wave instabilities with maximum growth rates which were substantially smaller than the inviscid modes, and that these occurred over wide range of wavelengths and Reynolds numbers.

Khorrami wanted to determine velocity profiles that were the most destabilizing, so he applied his stability analysis to multiple cell vortices, where he found that their growth rates for unstable disturbances were substantially greater than those of single cell vortices. A sample calculation shown in figure 3 is a plot of growth rate of the unstable axisymmetric disturbances as a function of wavenumber for a two cell vortex.

The results this study suggested that the key to controlling the break up and dissipation of an airplane's trailing vortices was to induce at least a two cell structure in them, and that the axisymmetric instability mode was the most likely to succeed. The desired velocity distribution

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might be achieved by using blowing or suction to alter axial velocity component near the wing tip. The results have been published in references 4 and 5.


## Oscillatory Blowing, A Tool to Delay Boundary Layer Separation ... Wygnanski:

Wygnanski presented a study on the effects of oscillatory blowing as a means to delay boundary layer separation. This research was undertaken because of the need to develop boundary layer control concepts that prevent flow separation from transport wings at high lift conditions.

The effects of oscillatory blowing of two thin two-dimensional wall jets were investigated with one slot located at the leading-edge and the other at the flap shoulder located at 75% of the chord. Experiments were carried out on a hollow, NACA 0015 airfoil having a trailing-edge flap deflectable to 40°. The steady blowing momentum coefficients could be varied independently of the amplitudes and frequencies of the superimposed oscillations.

A sample result of the effect of trailing-edge blowing on lift and drag is shown in figure 4 for 20° flap defelection. Oscillatory blowing achieved the same lift increase and drag reductions as steady blowing (no oscillations) at considerably lower values of jet momentum. Similar results were obtained with 40° flap defelection. Surface pressures and velocity measurements over the flap region demonstrated that the flow was attached. Wygnanski suggested that a physical mechanism appeared to be that oscillatory blowing enhanced the momentum transport of coherent structures through the wall jet which invigorated fluid near the surface.

In a further experiment Wygnanski showed that oscillatory blowing from the airfoil leading-edge was not as effective as the same blowing applied to the flap shoulder. The results of blowing at the trailing-edge flap shoulder are published in reference 6.


## Circulation Control Technology for Application to Advanced Transport Aircraft ... Englar:

Englar described an investigation to apply Circulation Control technology to advanced transport aircraft. This research effort was undertaken because of the need to develop new high-lift systems that create the same or higher lift with fewer parts, than current multi-element mechanical high-lift airfoils.

Englar showed that the Circulation Control Wing (CCW) concept had been developed through prior tunnel and flight studies and showed sigificant payoffs for high lift generation with few parts. However, in order to take maximum advantage of pnematic benefits, some specific transport application-related issues had to addressed, such as being able to vary airfoil geometry between high lift cruise. As part of the current research program, an advanced dual-radius CCW configuration was developed and tested in GTRI Model Test Facility Research Wind Tunnel. In order to delay leading-edge stall onset at the high-lift condition, Englar selected leading-edge blowing instead of a krueger flap, and used Navier Stokes equations to computationallly evualate CCW airfoil designs and capabilities. Experimental lift values were obtained approaching 8.0 at zero incidence.

To evaluate the effects of applying the CCW characteristics to a subsonic commericial transport aircraft, Englar used a B737 whose baseline geometry and aerodynamic characteristics were from a wind tunnel study. The sketch in figure 5 shows the mechanical wing flaps that can be replaced with a 0 to 3 parts per wing for dual-slot CCW, which represented a reduction in complexity. In addition, lift increased more than a factor of three for the 737/CCW at the highest blowing rate. He showed that the lift and drag characteristics for the CCW resulted in significant performance benefits, one of which was improved takeoff and landing performance. For example, the 737/CCW provided greatly reduced takeoff and landing speeds and distances, reduced noise footprint in the terminal area, and produced steeper climbout and approach paths due to short and landing capability. Results of this study are published in reference 7.

Goldschmied presented the concept of airfoil static pressure thrust to achieve efficient thick wings aerodynamics. This research was undertaken because of the need to develop boundary layer control concepts that prevent flow separation from thick transport wings.

He evaluated the use of suction slots to keep flow attached on upper-surface and rear of thick airfoils, and reported on a flight test program performed on a 31.5% thick GLAS II laminar flow airfoil, shown in figure 6. The experiment achieved an L/D ratio of about 46 over wide range of lift values. He described that the axial static pressure force on a subsonic airfoil was the difference between wake-drag and skin-friction drag. For conventional airfoils this force was a drag, opposing the flight motion; however, with boundary-layer control this force coulld be transformed into a very substantial thrust counteracting up to 90% of the skin-friction drag.

The wing technology appeared to offer about 25% drag reduction due to interactions between aerodynamics and propulsion, especially for thick wings; he showed an application to a thick wing spanloader configuration in the previous session. Results of this study are published in reference 8.

## Concluding Remarks

A number of aerodynamic technologies were presented that offer the possibility of significant improvements for advanced subsonic and supersonic transport aircraft. These include flow separation control, laminar flow control, drag-due-to-lift reductions by a variety of techniques, wake vortex minimization, tip vortex control and destabilization, oscillatory blowing to delay boundary layer separation, circulation control for high lift and integrated control surfaces, and airfoil static pressure thrust.

High-lift technologies have been developed for many years for military application; these need to be better exploited for civilian transport systems.

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7. Englar, R. J.; Smith, M. J.; Kelly, S. M.; and Rover, R. C. Development of Circulation Control Technology for Application to Advanced Subsonic Transport Aircraft. AIAA 93-0644, January 1993.
8. Goldschmied, F.: Airfoil Static-Pressure Thrust: Flight-Test verification. AIAA 90-3286, September 1990.
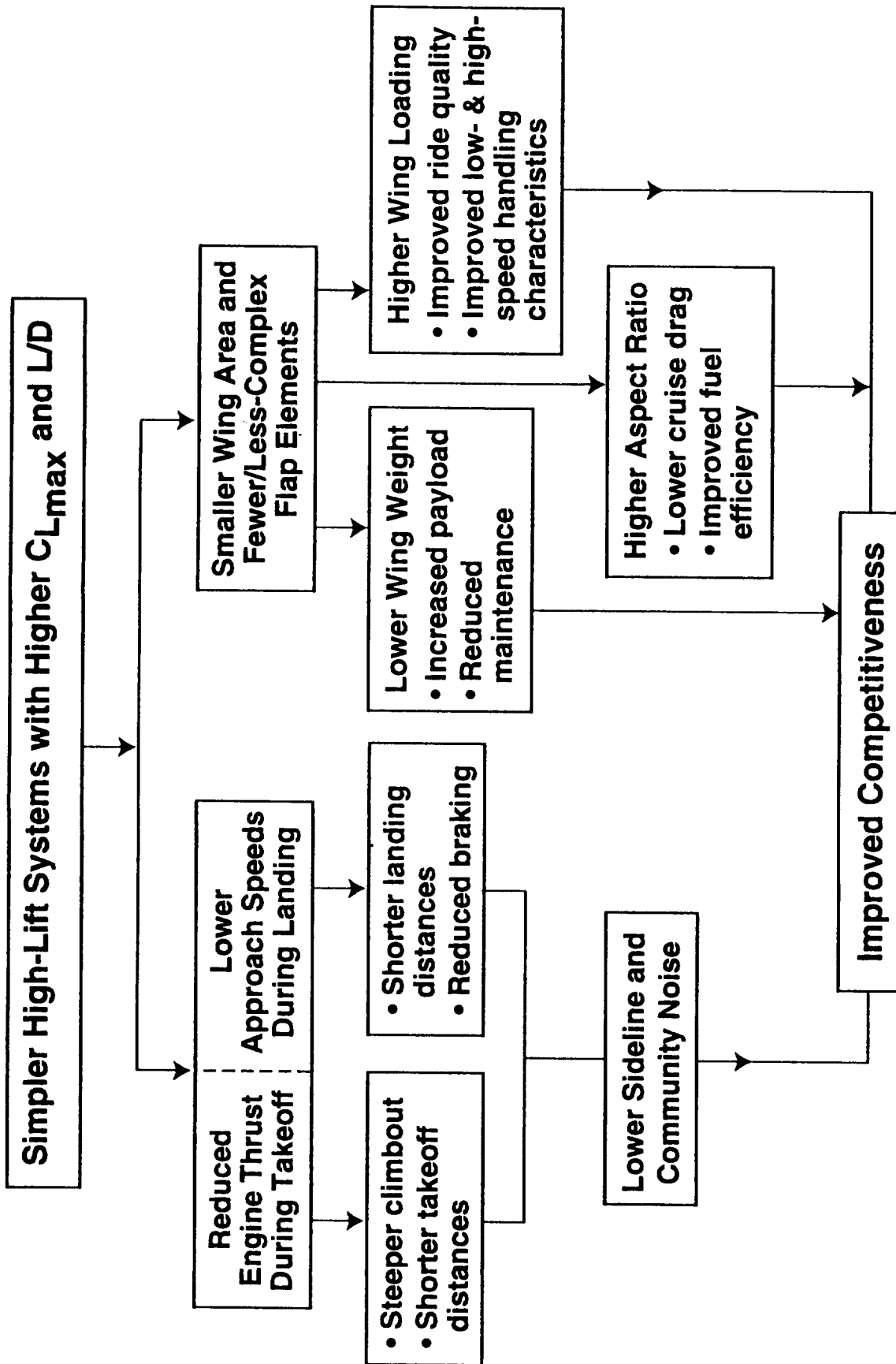
Figure 1.- Objective of high-lift research

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C-2

Atmospheric
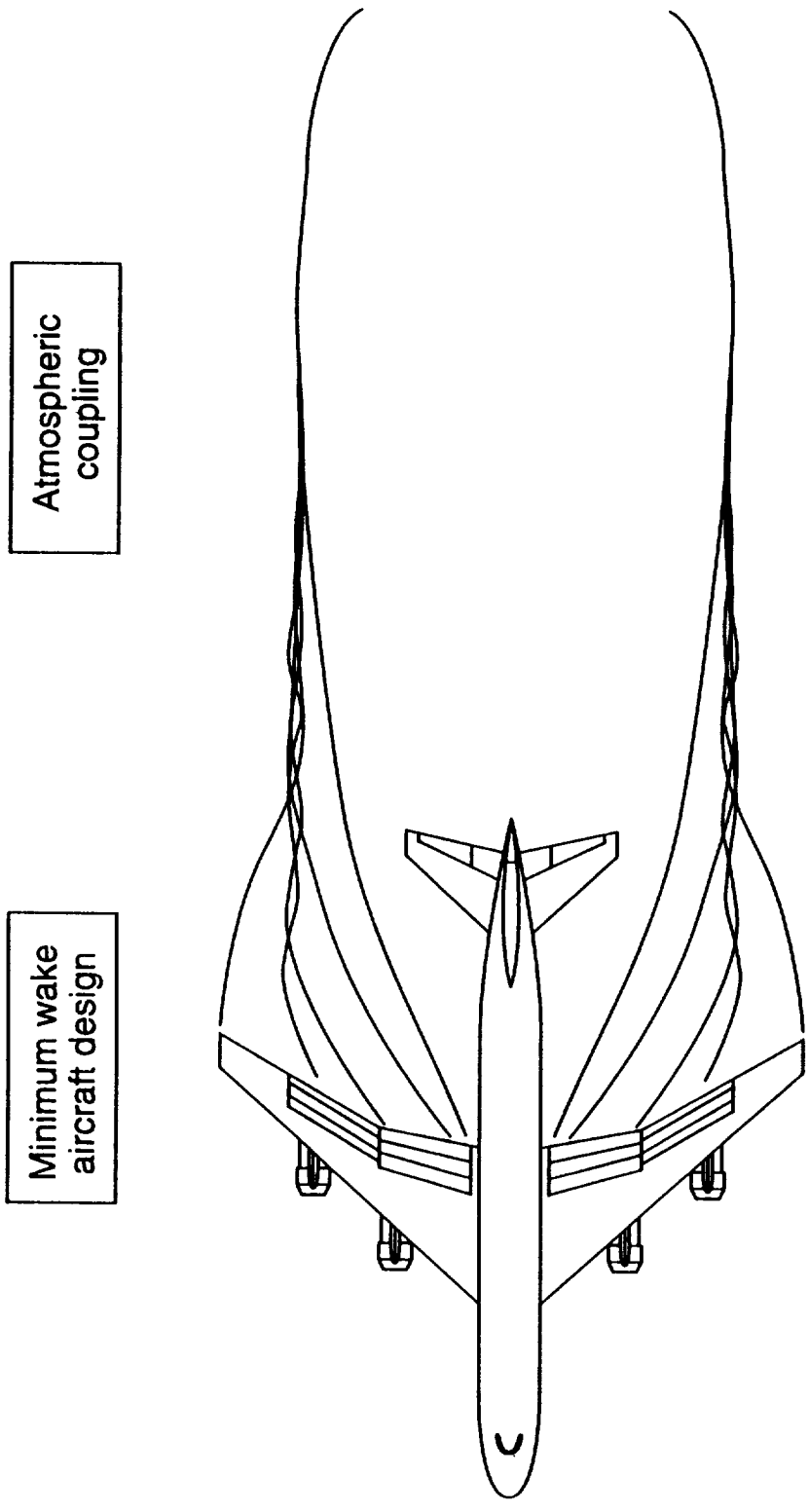coupling

Minimum wake
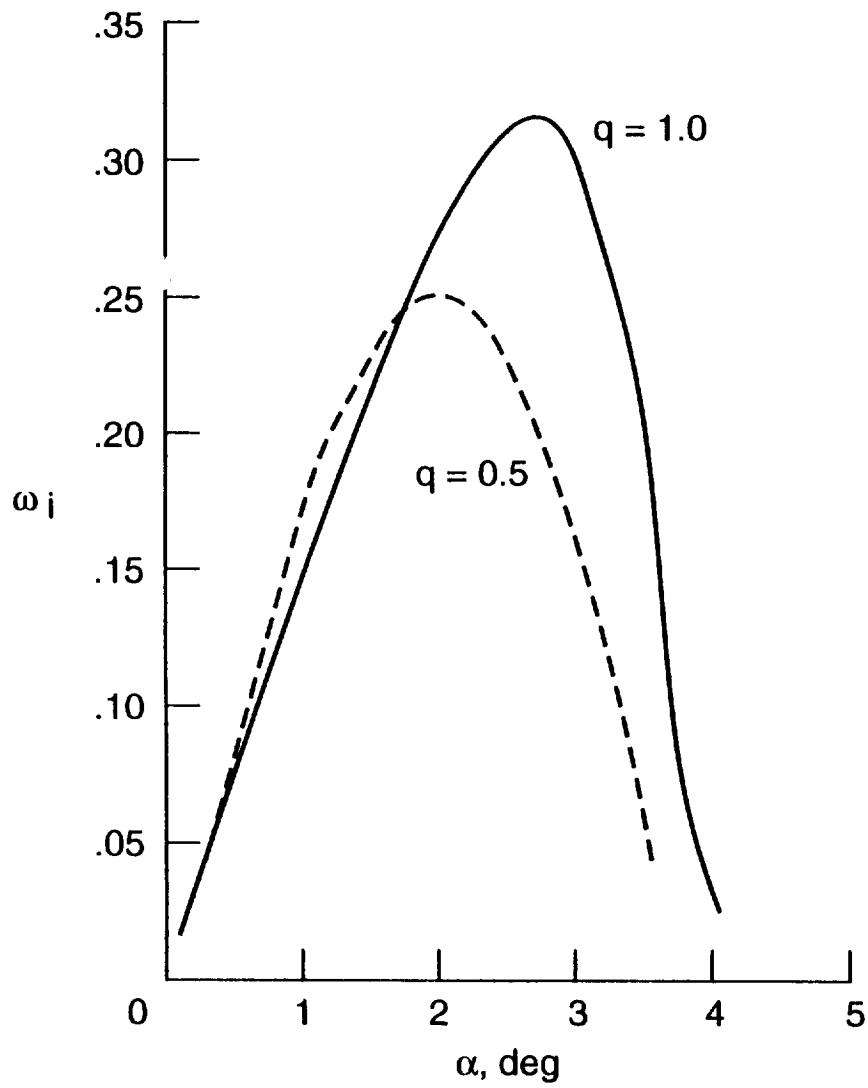aircraft design

Figure 2.- Wake minimization factors.

Figure 3.- Variation of the growth rate of unstable axisymmetric disturbances as a function of wavenumber for a two cell vortex for two values of swirl ratio; $R_e = 10^4$.
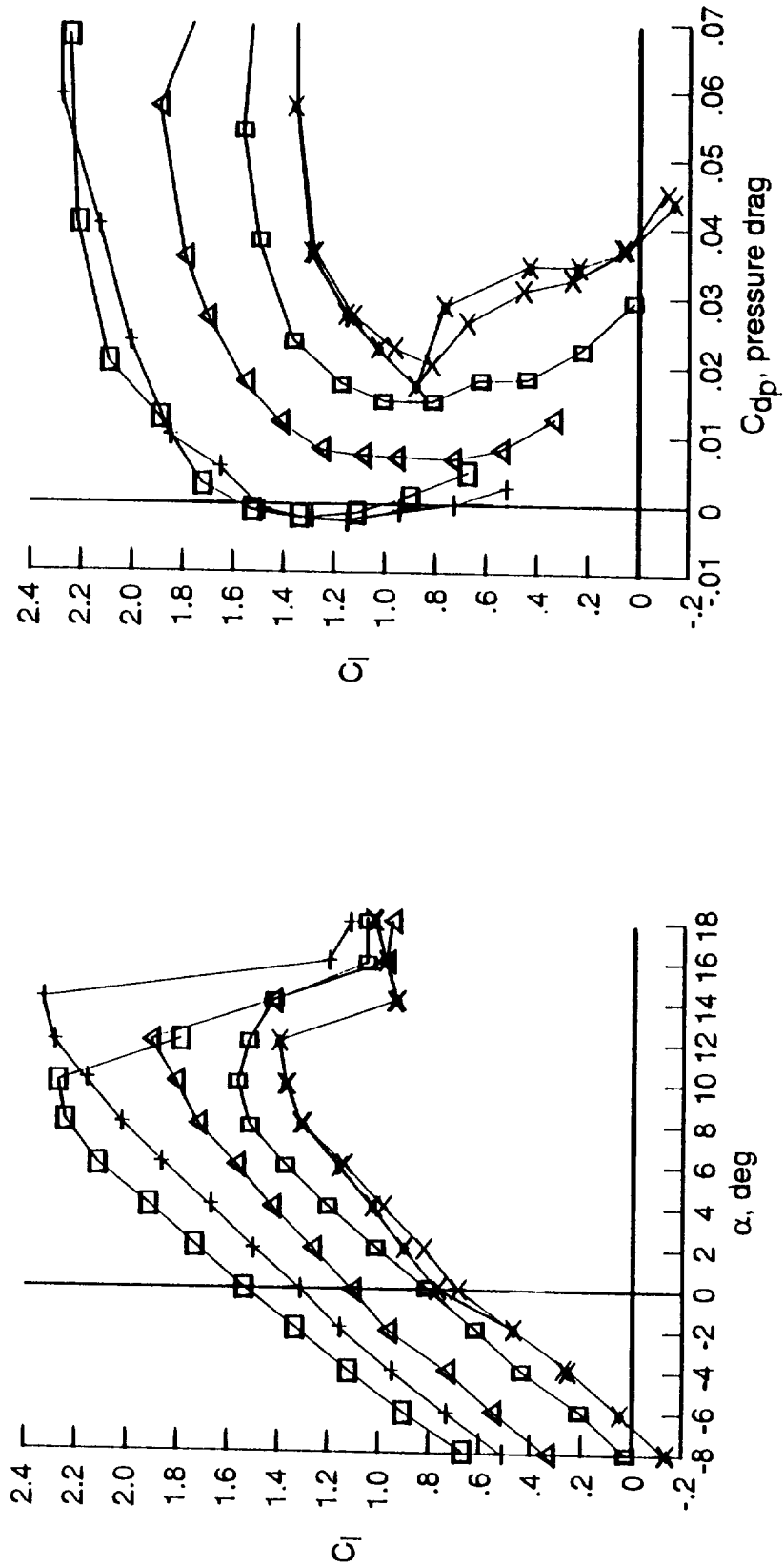
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Figure 4.- Effect of oscillatory blowing on lift and form drag of an NACA 0015. $\delta_f = 20^c$. $R_c = 0.15 \times 10^6$.
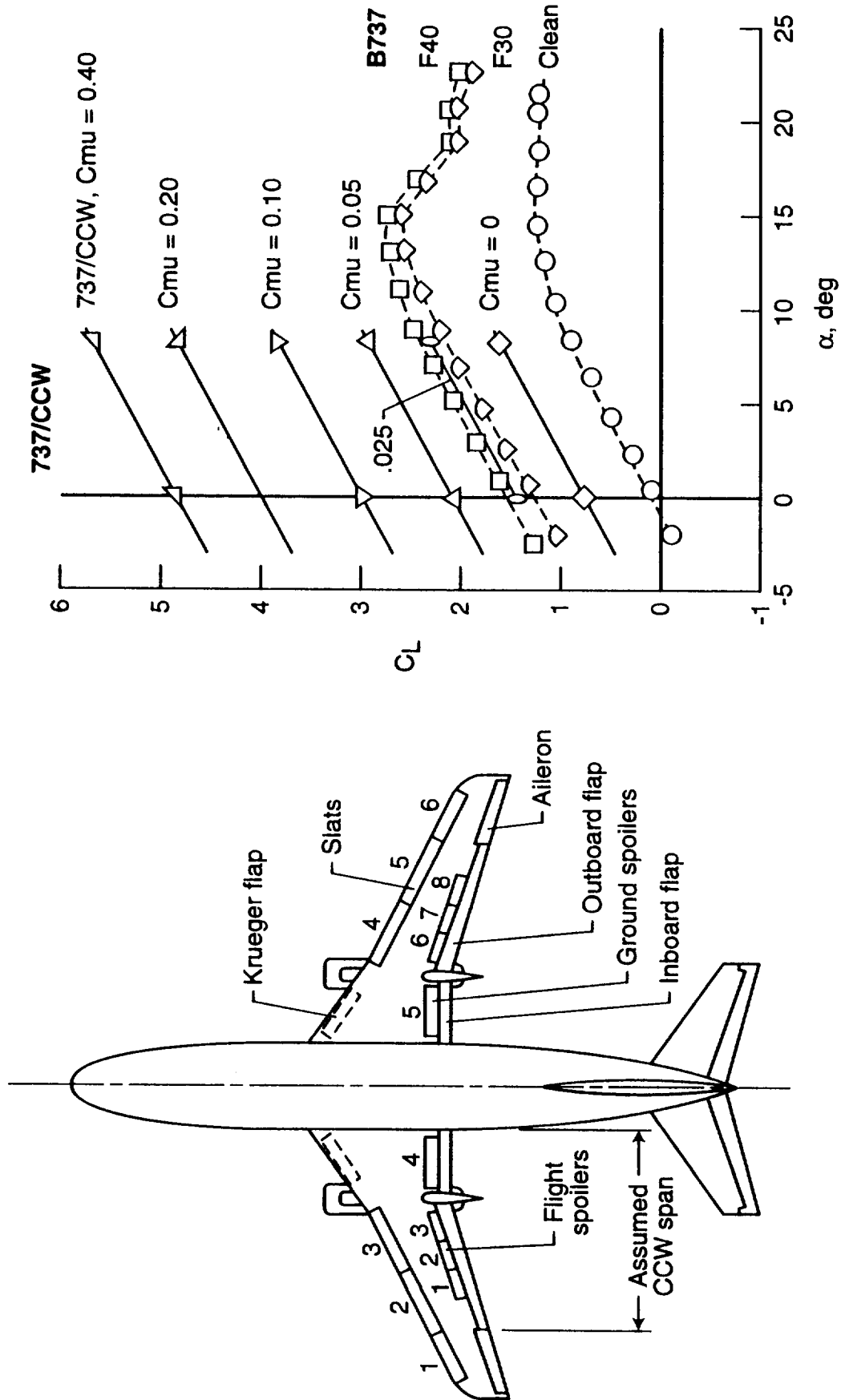
# B737 Lift Curves
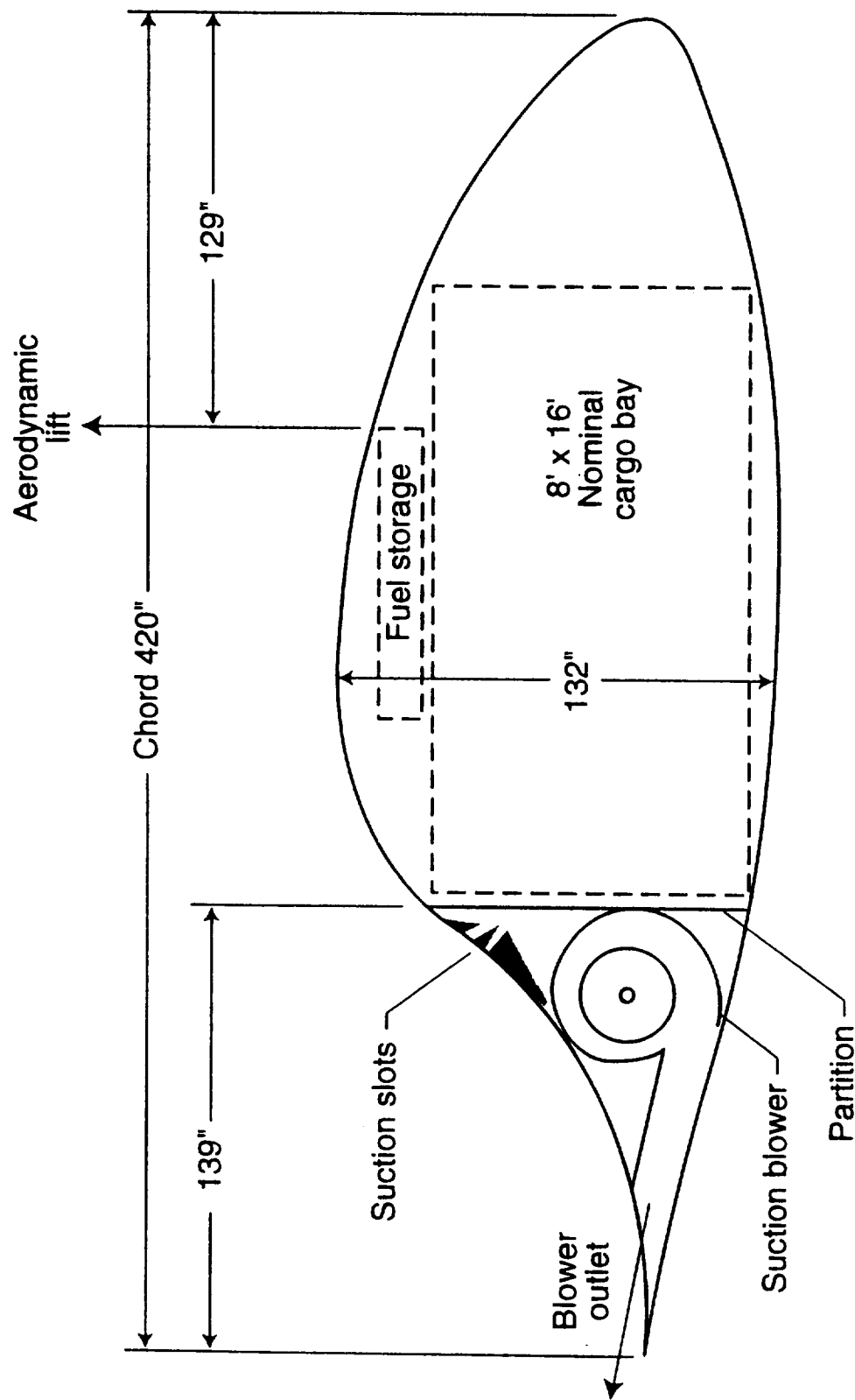


Figure 5.- Boeing 737 and 737/CCW high-lift systems.

Aerodynamic lift

129"

Chord 420"

Fuel storage

8' x 16' Nominal cargo bay

132"

139"

Suction slots

Blower outlet

Suction blower

Partition

Figure 6.- Layout of Glass II modified 31.5%-thick laminar airfoil with 35.0 foot chord

# Aerodynamic Impact on Noise and Emissions

## Session IV

### Kenneth S. Brentner

## Introduction

In the past, the aircraft noise and emissions were of secondary concern to the aircraft designer. The primary responsibility for noise certification compliance fell on the engine manufacturer. Treatments and fixes were added to the configuration to meet noise criteria. Even though noise has typically not been considered seriously in the initial design stages, figure 1 shows that considerable progress has been made in noise reduction throughout the history of commercial aviation. Aircraft noise and emissions reduction are still extremely important for both certification and competitiveness. An aircraft unhindered with operating restrictions or curfews is more productive since it can be more fully utilized. With a projected doubling of air travel in the beginning of the next century, the total noise exposure will rise even though individual aircraft may be quieter than those in today's fleet. The effect of aircraft emissions may increase substantially with this increase in air traffic. Hence aircraft noise and emissions will become an even bigger concern than now.
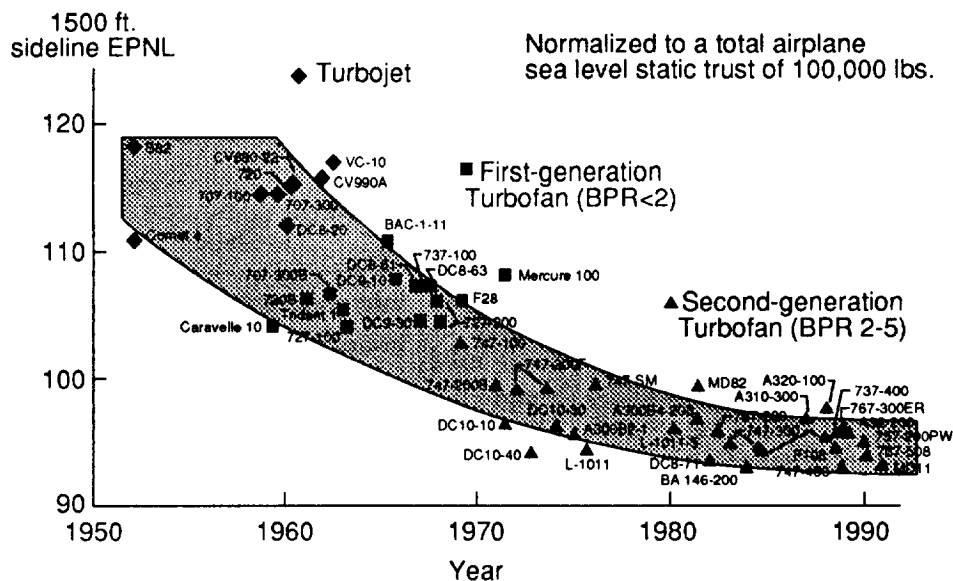


Figure 1. Progress in aircraft noise reduction. (Seiner)

Advanced aerodynamics have an important role to play in the necessary reduction of aircraft noise and aircraft emissions. Clearly aerodynamic advances can be applied directly in the development of new engine technology, resulting in quieter, more fuel efficient, and cleaner burning engines. Yet even larger gains are possible if the aircraft design utilizes advanced aerodynamics directly for the purpose of noise reduction. One way to do this is to trade some of the increases in performance for additional noise reductions. Another way to reduce noise exposure is to take advantage of flight path optimization made possible through robust aerodynamics and "bird-like" flight. Many opportunities for acoustically improved propulsion integration and low noise airframe design also exist in the unconventional configurations presented in this workshop. These configurations have the potential for both large performance gains and decreased noise.

For this session six speakers where invited to discuss: 1) the importance and impact of aircraft noise and emissions; 2) the role advanced aerodynamics can play in decreasing noise; and 3) the potential noise characteristics of several of the unconventional configurations that have been proposed. A list of speakers together with the section of this chapter associated with their presentation is given in Table 1.

| Speaker | Affiliation | Primary Section |
|---|---|---|
| Donald Wuebbles | Lawrence Livermore National Laboratory | Impact of Aircraft Noise and Emissions: Impact of Aircraft Emissions |
| Stephen Hockaday | California Polytechnic State University | Impact of Aircraft Noise and Emissions: Aircraft Noise Impact on Productivity |
| Robert Lee | General Electric Aircraft Engines (retired) | Aircraft Noise Problems and Opportunities for the 21ᵃ Century |
| John Seiner | NASA Langley Research Center | Jet Noise Reduction |
| Martin Fink | Engineering Consultant | Airframe High-Lift Noise |
| Kevin Shepherd | NASA Langley Research Center | Aircraft Noise and Airport Capacity |

Table 1. Speaker list for Session IV - Aerodynamic Impact on Noise and Emissions

Each of these speakers gave an excellent presentation in their area of expertise. The purpose of this chapter is to give a synopsis of the presentations together with the associated discussions. A brief appendix with a written version of the presentation given by Martin Fink will follow at the end of the chapter.

## Impact of Aircraft Noise and Emissions

The importance of aircraft noise and emission reduction can only be understood through a recognition of the impact of these undesirable byproducts of aircraft operation. This understanding will help point to areas where advanced aerodynamics can offer relief to these problems. This section will first consider the impact of aircraft noise and then the effect of aircraft engine emissions on the environment.

### Aircraft Noise Impact on Productivity

Several groups are directly or indirectly impacted by aircraft noise. The most obvious group affected directly by noise is the airport community. These people must deal with aircraft noise on a daily basis and are the most vocal group objecting to both daily operations and increases in operations. Residential property values in the airport vicinity usually are decreased due to aircraft noise exposure. Local and national governments provide regulations, monitor compliance, and certify aircraft in an attempt to minimize the impact on the community, yet each of these activities has significant costs. Governments also have the additional expense of legal fees associated with defending regulations and prosecuting violators.

The airport sponsor incurs legal expenses related to aircraft noise as well, but there are several other direct costs. Airport sponsors are also impacted by aircraft noise through higher planning and construction costs, increased operational costs and delays in airport improvement implementation. Few new major airports are envisioned even though air traffic is expected to grow substantially. This is a direct result of community opposition to aircraft noise. Even expansion of present airports can be difficult because the airport communities resist any increase in noise exposure.

The impact on airlines is similar in many ways to that on airport sponsors. The increase of stringent local noise regulations, nighttime curfews and noise budgets limit the full utilization of the airline fleet. This loss of potential revenue is a cost that must be added to the increased acquisition cost of quieter new aircraft and the expense of retrofitting current aircraft to meet the newer standards. Airlines must also be concerned that flight safety can be compromised to some extent during noise abatement flight procedures. Aircraft manufacturers have increasing competitive pressures to meet foreign noise restrictions while certification time and costs tend to be

increasing. Finally, the traveling public must pay for many of these noise related expenses through increased ticket costs, ticket taxes and surcharges, and less convenient and less frequent flight times.

Clearly the costs directly or indirectly attributable to aircraft noise must be very large, yet it is very difficult to quantify these costs. Professor Hockaday is attempting to provide such a quantification in the near future. Never-the-less, as quieter aircraft and flight operations are developed each of the affected groups will realize a benefit. In fact, the feasibility and profitability of new aircraft will depend heavily on noise reductions. Advanced aerodynamics can play a major role in reducing the aircraft noise.

## Impact of Aircraft Emissions

The first studies on the effects of aircraft emissions on the global atmosphere were done in the early seventies. These studies focused on the impact that a fleet of supersonic transport aircraft flying in the stratosphere would have on the ozone and climate. Aircraft engine emissions from subsonic aircraft flying in the troposphere were studied briefly in the mid-seventies but have been essentially ignored over the last 20 years.

Understanding the impact of emissions on the ozone is important since it is a key absorber of ultraviolet radiation in the atmosphere. Ozone prevents biologically harmful radiation from reaching the surface of the earth, thus a significant change in the amount of stratospheric ozone can have an impact on people and the biosphere. Ozone is also a greenhouse gas and as such can have an effect on the global climate. Ninety percent of the ozone is in the stratosphere and the other ten percent of the ozone is in the troposphere. The bottom line is that it is most desirable to keep as much ozone as is possible in the stratosphere and have no significant increases in the troposphere (in order to limit direct ozone contact with humans and the ecosystem).

Aircraft emissions tend to increase the tropospheric ozone and decrease the stratospheric ozone. The magnitude of these effects is uncertain. The primary emissions of concern are nitrogen oxides, $NO_x$ (both NO and $NO_2$). Hydrogen oxides, $HO_x$ (primarily in the stratosphere) and sulfur dioxide are also of some concern, however, carbon monoxide and hydrocarbon emissions are not thought to be very important. Since 1990 a study of aircraft emissions has been underway to determine what the emission goals for a high speed civil transport (HSCT) should be. It has been estimated that the current subsonic fleet adds approximately 134 billion kilograms of $NO_x$ per year to the troposphere. By the year 2015, it is projected that this will increase

by a factor of 2 to 2.5 due to subsonic aircraft alone. The largest amounts of emissions are found primarily in the northern hemisphere, mostly in North America, Europe and the Middle East. These emissions are mostly in the upper troposphere with some extension to the lower stratosphere.

Current aircraft technology HSCT engines operate with emission index of about 15 for $NO_x$ but advanced technology engines may bring the emission index as low as 5. The emission index, EI is the number of grams emission per kilogram of fuel burned. HSCT aircraft will generally increase the emission, but their emissions will be primarily in the stratosphere rather than the troposphere. Thus the $NO_x$ will react with oxygen and hence cause a reduction in stratospheric ozone. Emission of $NO_x$ is significantly less for a HSCT cruising at Mach 1.6 than for one that cruises at Mach 2.4. Studies show that the effect of a 594 aircraft , Mach 1.6 HSCT fleet will result in a .1 to -.2 percent average global change in ozone. For a 500 aircraft, Mach 2.4 HSCT fleet, the global change in ozone will be on the order of -.2 to -.6 percent. These results are based on a emission index of 5 and would be higher if this cannot be achieved. It is unknown at this time what change will be acceptable to policy makers, but it is known that a 1 percent reduction in ozone results in about 2 to 5 percent increase in the detrimental effects of ultraviolet radiation - such as skin cancer, etc.

Very few calculations of the effect of subsonic aircraft have been done to date. What is known however is that the largest subsonic aircraft emissions occur in the high latitudes. There also are some indications, both from atmospheric measurements and from models that current aircraft are having some effect on the upper tropospheric ozone. Subsonic aircraft $NO_x$ emissions are expected to cause an increase in ozone, while supersonic aircraft are expected to cause a decrease in ozone. Current models show that the increase in ozone due to subsonic aircraft will compensate somewhat for HSCT aircraft. Several uncertainties must be resolved in the current models before a full understanding of the effect of aircraft is resolved, but current subsonic aircraft are believed to be increasing tropospheric $NO_x$ by as much as 30 percent or more.

## Aircraft Noise and Airport Capacity

Current aircraft noise certification requirements, which limit the noise levels of new transport aircraft, allow heavier aircraft to generate higher noise levels. In contrast, noise limits at some individual airports are independent of aircraft weight. Restrictions which favor smaller, quieter aircraft prompt a question regarding the impact on capacity. This section presents an analysis of the relationships between aircraft size, noise levels, and the number of aircraft events and noise exposure. No attempt is made to

address operational constraints and market forces which determine the fleet mix. This section is a condensed version of reference 1.

## Individual Airport Considerations

A relationship between aircraft size and aircraft noise can be inferred from the FAA certification requirements for new aircraft (stage III). After some simplifying assumptions, the relationship between aircraft weight and takeoff noise is found to be a 4 dB change per halving or doubling of the weight. Thus

$$\text{Single event noise level } L, \text{ dB} \propto 13.3 \log_{10}(W) ,$$

where $W$ = aircraft weight. For this analysis, the number of passengers passing through an airport is used as a measure of airport utilization. Passenger payload as a function of current aircraft size can be modeled as a linear regression of the aircraft weight on the logarithm of the number of passengers. This yields the relation (correlation coefficient = 0.955)

$$\log_{10}(W) \propto 1.582 \log_{10}(P_{ac}) ,$$

where $P_{ac}$ = Number of passengers per aircraft.

Coupling this relationship to the 4 dB per doubling of aircraft weight shown above leads to the conclusion that noise levels increase by 6.33 dB per doubling of passenger payload:

$$L, \text{ dB} \propto 21.04 \log_{10}(P_{ac}).$$

Noise exposure around airports is normally assessed by means of a metric based upon the equal energy hypothesis. For example, a reduction of noise exposure by 3 dB may be achieved by reducing the level of each aircraft flyover by 3 dB or by halving the number of flyovers. Thus for a given aircraft type, noise exposure increases 3 dB for each doubling of the number of events.

$$\text{Noise Exposure, dB} \propto L + 10 \log_{10}(N)$$
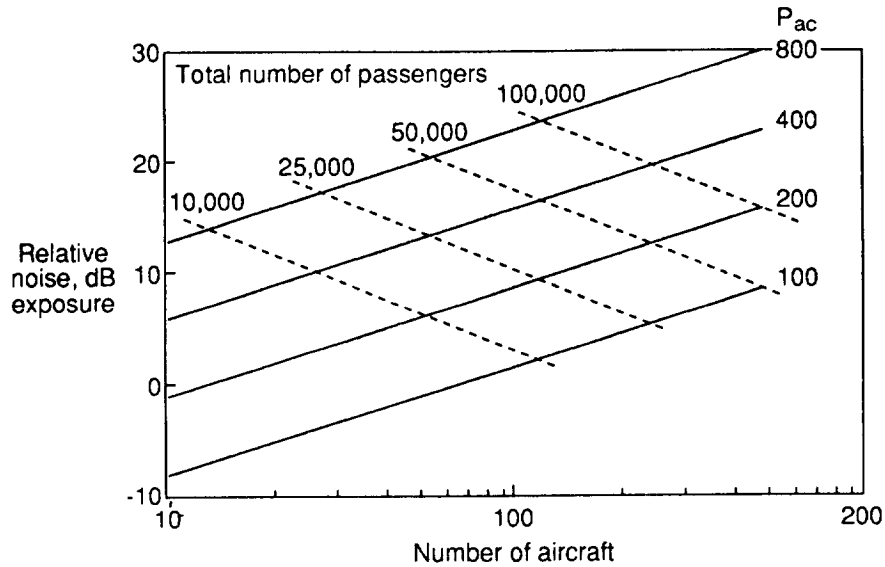
where $N$ = Number of aircraft events.

Figure 2.  Relative noise exposure as a function of number of aircraft and aircraft passenger payload ($P_{ac}$) for takeoff condition; dashed lines indicate contours of constant numbers of passengers. (Shepherd)

Figure 2 illustrates the relationship between relative noise exposure and the number of aircraft events for various sizes of aircraft. The slope of the $P_{ac}$ curves is 3 dB per doubling of the number of aircraft events, and the separation between the curves is 6.33 dB for each doubling of the number of passengers per aircraft.  Also plotted in figure 2 are curves showing the total passengers carried.  It is now possible to examine the effects on noise exposure of large numbers of small aircraft compared to small numbers of larger aircraft. For example ten thousand passengers can be carried by 100 aircraft, each with a payload of 100 passengers, or by 25 aircraft each carrying 400 passengers. The use of the larger aircraft results in approximately 7 dB greater noise exposure than that obtained from the more numerous small aircraft operations.  It is clear that, for any arbitrary number of passengers to be transported, the use of smaller aircraft results in the least noise exposure for takeoff conditions.  The noise exposure for take-off is given by:

$$\text{Noise exposure, dB} \propto 10 \log_{10} (N \times P_{ac}) + 11.04 \log_{10} (P_{ac})$$

where $N \times P_{ac}$ is the total number of passengers. This expression indicates that noise exposure increases by 3 dB for each doubling of passenger throughput, with a penalty of 3.3 dB for each doubling of aircraft payload (passengers per aircraft).

The foregoing discussion was based on the aircraft noise certification requirements at the centerline measurement point on takeoff. The allowable noise levels for the approach condition are also weight dependent, without variations based on the number of engines. A similar relation of noise exposure as a function of the number of noise events for various aircraft sizes is shown for the approach condition in figure 3. For approach conditions, the single event noise level increases 4.05 dB for each doubling of the number of passengers per aircraft. Noise exposure as a function of the total number of passengers and aircraft size can be expressed by:

$$\text{Noise Exposure, dB} \propto 10 \log_{10} (N \times P_{ac}) + 2.24 \log_{10} (P_{ac})$$

Hence for approach conditions, noise exposure increases 3 dB for each doubling of the total number of passengers, with a penalty of 0.7 dB for each doubling of aircraft payload. As was noted for the takeoff condition, the noise exposure is a minimum for the smallest aircraft. However, the noise benefit resulting from the selection of small aircraft is clearly far greater for takeoff conditions than for approach conditions.

It can, therefore, be concluded that noise exposure around an airport is minimized if the passengers are carried by large numbers of small aircraft rather than small numbers of large aircraft.

## Total Air Transportation System Considerations

It can be argued that the foregoing analysis is legitimate when applied to an individual airport, but takes no account of the longer ranges that the larger, noisier aircraft are generally capable of flying. It seems reasonable that an aircraft having a given passenger payload and range should be allowed to be noisier than one with the same payload and half the range. The latter would require twice as many operations to be equally productive, and thus should be 3 dB quieter in order to have equivalent noise exposure. In this example noise exposure is used in a global sense, rather than necessarily being applied to an individual airport. A linear regression of the logarithm of current aircraft weight on the logarithm of passenger-miles (the product of aircraft range and number of passengers) yields a slope of 0.795 (correlation coefficient = 0.982).
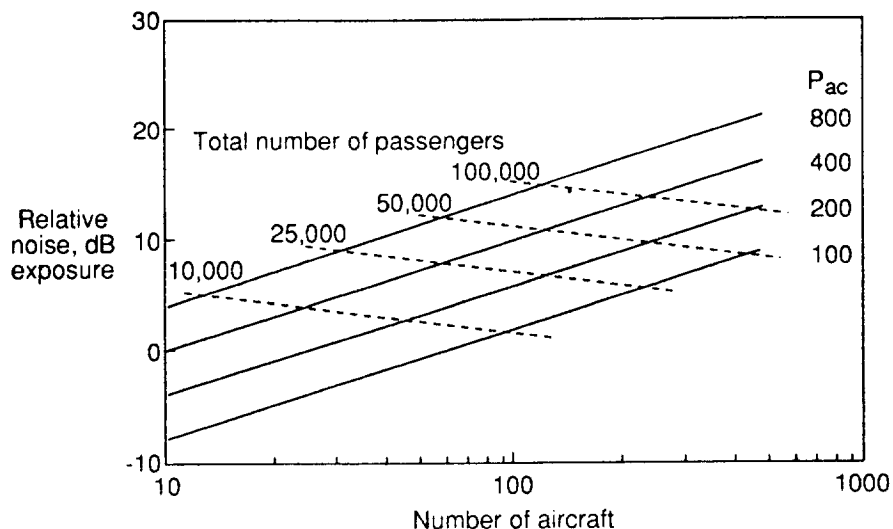
$$\log_{10} (W) \propto 0.795 \log_{10} (PM_{ac})$$

Figure 3. Relative noise exposure as a function of the number of aircraft and aircraft passenger payload ($P_{ac}$) for approach conditions; dashed lines indicate contours of constant numbers of passengers. (Shepherd)

where $PM_{ac}$ = Passenger-Miles per aircraft. When the above result is coupled with the observation that noise on takeoff increases 4 dB per doubling of weight, it is concluded that takeoff noise increases 3.18 dB per doubling of aircraft passenger-miles. Thus

$$L, dB \propto 10.57 \log_{10} (PM_{ac})$$

The effect of the number of aircraft events and the aircraft size (expressed in passenger-miles) on noise exposure is illustrated in figure 4. It is clear that, in terms of total system noise exposure on takeoff, there is a very minor incentive to operate aircraft with the lowest passenger-miles. The curves of figure 4 are given by:

$$\text{Noise exposure, dB} \quad 10 \log_{10} ( PM_{ac} \times N) + 0.57 \log_{10} (PM_{ac})$$

Thus, noise exposure increases 3 dB per doubling of the total number of passenger-miles ($PM_{ac} \times N$), with a penalty of 0.2 dB per doubling of passenger-miles per aircraft.

For approach conditions, noise increases 2.33 dB per doubling of aircraft weight. When this is combined with the relationship between aircraft weight and aircraft
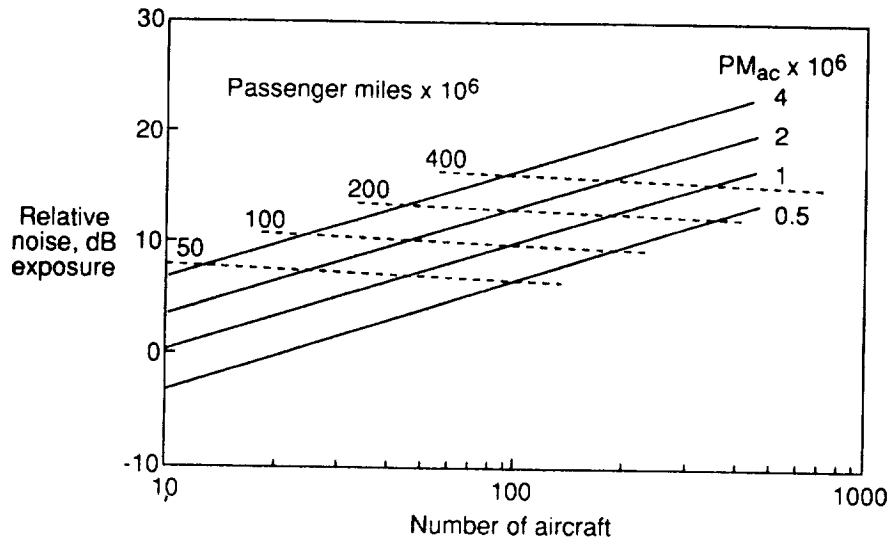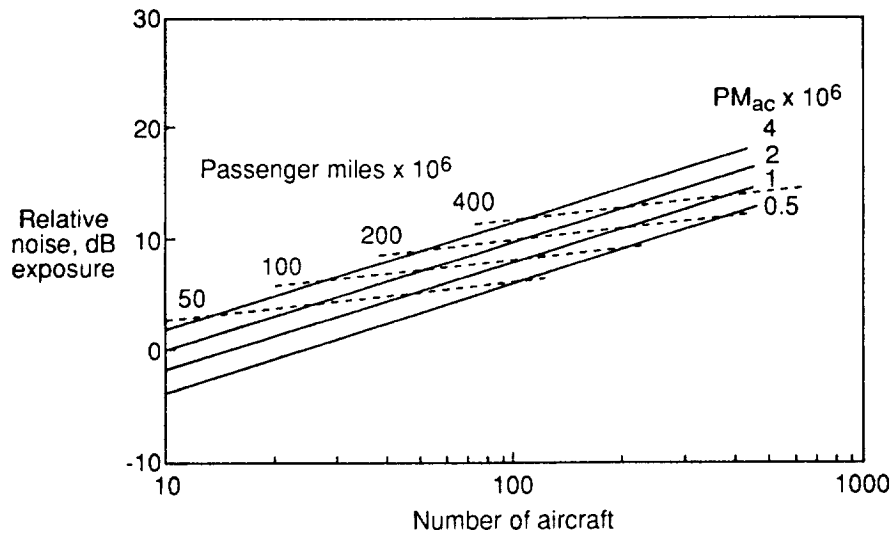
Figure 4. Relative noise exposure as a function of aircraft and the product of passenger payload and range $(PM_{ac})$ for takeoff conditions; dashed lines indicate contours of constant passenger-miles. (Shepherd)

passenger-miles, it is found that noise increases by 1.8 dB per doubling of passenger-miles. Thus it turns out for approach, the total system noise is given by

$$\text{Noise exposure, dB} \propto 10 \log_{10} (PM_{ac} \times N) - 3.85 \log_{10}(PM_{ac})$$

and as illustrated in figure 5, the total system noise exposure is minimized by the use of aircraft with the largest passenger-miles. Noise exposure increases 3 dB per doubling of the total number of passenger miles, with a penalty of 1.2 dB per halving of passenger-miles per aircraft.

When noise exposure throughout the air transportation system is considered, takeoff noise is not affected by the size of aircraft used to transport a fixed number of passengers a fixed number of miles. Noise exposure under approach conditions is minimized if the passengers are carried by small numbers of large aircraft rather than large numbers of small aircraft.

## The Role of Advanced Technology

Growth of the air transportation system will undoubtedly require increased numbers of aircraft operations at existing airports. If the fleet mix remains unchanged, noise exposure will simply increase by 3 dB for each doubling of the number of operations.

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Figure 5. Relative noise exposure as a function of aircraft and the product of passenger payload and range ($PM_{ac}$) for approach conditions; dashed lines indicate contours of constant passenger-miles. (Shepherd)

These conclusions are based on the assumption that the level of technology and the relationships between aircraft noise, weight, range and payload remain unchanged. Given a desire for greater air traffic and a desire for reduced airport noise exposure, there is still a need for advances in source noise reduction, aerodynamic performance and flight procedures to minimize noise reaching the ground. Advanced aerodynamic and acoustic technology must be used to essentially change the slopes of the curves. The noise penalty associated with larger aircraft is certainly undesirable from the viewpoint of increasing airport capacity. Without significant source noise reductions noise minimization then tends to even further exacerbate the capacity problem. Hence the role of advanced aerodynamics and acoustic technology is to lead to advanced (and possibly quite unconventional) aircraft designs which minimize or eliminate the penalty associated with larger aircraft at individual airports.

## Aircraft Noise Problems and Opportunities for the 21 Century

Now that the impact of acoustics and emissions has been clearly established and the importance of the fleet mix has been considered, the next step is to examine the noise challenges for the aircraft fleet in the next century. The current fleet of aircraft is rapidly making the transition to an all stage III fleet, meaning that every aircraft must meet the FAA noise regulations, FAR part 36, which will prohibit stage II aircraft from

operating in the United States. This change is already resulting in a noise benefit, which will be offset by the increase in the number of flights required to meet the growing demand.

## The Proper Target

What is an acceptable level of noise exposure? This question must be answered before the challenges of noise reduction can be seriously addressed. While current regulations give some guidelines, they are probably not the proper targets by which aircraft should be designed for the year 2015. There are three criteria which we would like new aircraft to meet. First, we would like to have a noise exposure of no more than 55 to 65 LDN to minimize the annoyance from aircraft noise. The LDN metric is an average measure which takes into account both the level of noise from individual events, the number of noise events and the frequency of the events. The EPA has recommended that an noise exposure level of 65 LDN would probably be acceptable, but this is probably the upper limit. Second, we want the single event exposure, which is currently the basis for aircraft noise certification, to be at a sufficiently low level. Washington National airport has had a nighttime curfew to protect the community from sleep interference. This curfew limited operations above 72 dBA. Recently a very thorough study has been completed in the United Kingdom which found that single noise events which were below about 80 dBA were not much of a problem for sleep interference. Hence a level of about 75 dBA, or the roughly equivalent level of 88 EPNdB should be a useful target. Finally, these targets need to be reduced by 5 to 10 dB for areas that have received little or no previous exposure, thus making the challenge even greater.

The next question is "Will a fleet of stage III aircraft meet these goals?" The answer is clearly no. Large, long range, four engine aircraft are allowed to operate at up 106 EPNdB according to the stage III certification requirements. This is 18 dB over the desired 88 EPNdB goal. Another indication that a stage III fleet will not be adequate is that several airports, both in the U.S. and abroad, already have noise restrictions or nighttime curfews which are more stringent than the certification requirements. Burbank, California is an example of a smaller airport which currently only allows stage III aircraft, yet the 65 LDN exposure level is high enough that many complaints are received. This is coupled with the reality that the number of airline passengers is expected to double in the next 10 to 15 years. Hence even if a stage III fleet were acceptable today, improvements are necessary to offset the increase in noise due to a greater number of flights. In planning for future aircraft, we must question the basis for

the current regulations which permit larger aircraft to make more noise. Our targets really should be based upon what is truly acceptable to society rather than be aimed directly at the regulations. In our present hub and spoke system many smaller airports have not had as much noise exposure as the hub airports, yet these smaller airports will be required to handle more traffic if the number of travelers doubles. Hence the proper target for aircraft noise will need to be significantly lower than the current certification requirements.

## Potential Benefits from Advanced Technology

Advanced technology, and especially advanced aerodynamics technology can be used to make very substantial noise reductions. Advanced configurations of the type proposed in this workshop can offer very large improvements in cruise L/D – two to three times that of current commercial aircraft. These gains in cruise L/D are achieved at the same time as fifty percent reductions in take-off gross weight (TOGW). These improvements should result directly in significant noise reductions in two ways. First, an aircraft with substantially increased cruise L/D and reduced TOGW should have reduced noise as a result of reduced engine size. Such an advanced configuration might be expected to reduce fuel burn by as much as 35 percent. This would have a significant favorable impact on direct operating cost (DOC) and emissions as well. Secondly, if the aerodynamic performance improvements are utilized to carry more passengers, a noise exposure benefit should be realized through a reduction in the number of flights for the same number of passengers.

It is important to remember that except for the passengers, noise is offensive primarily during the take-off and approach segments of the flight profile. Improved L/D at cruise does not necessarily correlate to an equal increase during take-off, therefore particular attention must be paid to the take-off performance to ensure that noise gains can be realized. Improved take-off L/D also provides another chance for noise exposure reduction. The noise exposure footprint can be minimized by increasing the climb rate. Recent experience from the HSCT program has demonstrated that improved high-lift on take-off can help to reduce the noise exposure significantly. Approach noise must also be considered in the configuration design stage to ensure that the airframe high-lift noise does not become unnecessarily high. Many opportunities exist for reduction of this noise source through advanced configuration design. This will be discussed in more detail in a later section.

Now consider an example of how much noise reduction can realistically be achieved. Let our aircraft have a TOGW of 780,000 pounds. Stage III certification regulations

allow the aircraft 106 EPNdB on take-off, which is 18 dB higher than the goal of 88 EPNdB. Aircraft with current engine technology are already about 4 dB below the rule, however, so only 14 dB needs to be found. Without too much trouble next generation engines with moderately high bypass ratios, say 8 to 10, should help reduce the engine noise by another 3 dB. Advanced aerodynamic technology should be able to reduce the take-off noise by 2 to 3 dB through reduction in take-off thrust and by 3 to 6 dB through improved take-off L/D and high-lift performance. An extra 3 to 5 dB reduction can be achieved by giving up some gain in DOC – through the use of longer nacelles, more treatment etc. These back of the envelope estimates show that 15 to 21 dB reduction seems very reasonable. Table 2 summarizes these estimates.

| Stage III limit for 780,000 lb., 4 engine aircraft | 106 EPNdB |
|---|---|
| current engine technology | - 4 dB |
| higher bypass ratio engines | - 3 dB |
| required thrust reduction | - 2 to - 3 dB |
| improved high-lift, increase climb rate | - 3 to - 6 dB |
| trade some DOC for extra noise reduction | - 3 to - 5 dB |
| Potential noise level | 91 to 84 EPNdB |

Table 2. Estimate of noise reduction for a advanced transport aircraft. (Lee)

Opportunities exist for noise reduction through the application of advanced technology in engine design as well as aircraft configuration design. With unconventional aircraft configurations, such as span loaders, blended wing-body, oblique wing, etc., it is really a whole new ball game and many possibilities exist. It will be crucial that engine sizing and matching to the aircraft will be based not only on performance considerations, but noise considerations as well. An optimal noise design should be possible with close engine/aircraft system integration.

There are several research topics which are worthwhile as engine noise reduction technologies. Aircraft engines will benefit from many of the same advances that can be applied to the airframe. With high bypass ratio turbofan engines, fan noise is the dominant noise source, hence reductions in fan noise will result in overall engine noise

reduction. Research in fan source noise reduction will be facilitated by use of modern computational fluid dynamics. Designs which have been put aside might even be reconsidered, given a new and more complete understanding of the flow physics made possible with CFD. Variable geometry inlets may offer very significant noise reductions. These will probably have some cost, in terms of performance, weight penalty, and DOC, yet they offer 10 to 15 dB in potential noise reduction. Active noise control is also a very promising technique for fan noise reduction. Low velocity jet noise reduction may also prove to be important for moderately high bypass ratio engines ( BPR 10 to 12). Recent work in the HSCT program has shown that source noise reduction is possible while improving take-off performance.

Finally, the economics are important. Advanced aerodynamics technology allows a great deal of flexibility for trading improvements in direct operating costs for lower noise. The cost of lower noise may be higher aircraft weight, performance losses, increased fuel costs, additional complexity and maintenance costs and added development costs. These all add to the operating cost and acquisition cost, but advanced technology can minimize and even eliminate these costs. The benefit of lower noise is reduced growth constraints, potential gains in volume and market share, increased aircraft utilization and reduced airport fees and costs. Hence the aircraft value is increased and a greater return on investment is possible.

## Jet Noise Reduction

Up to this point there has been very little discussion of individual noise sources on modern aircraft. There are actually several important noise sources on a transport aircraft, as shown in figure 6. These include fan noise, from both the fan inlet and exhaust; airframe noise, from the airframe boundary layer, cavities, high-lift devices and landing gear; and jet noise from the core jet engines The relative importance of each of these noise sources depends upon the configuration and operating regime of the particular aircraft. In this section we will consider jet noise and jet noise reduction strategies. Keep in mind however that for high bypass ratio turbofan engines, the fan noise will dominate the engine noise, while for very large aircraft the airframe noise may be comparable to engine noise on approach.

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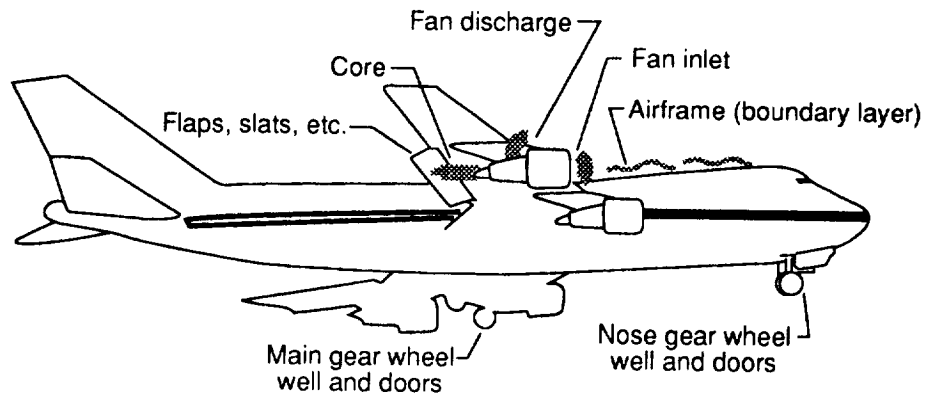
Figure 6. Jet aircraft noise sources. (Seiner)

## Jet Noise Sources

Jet noise must be discussed based on the velocity of the jet since the characteristics of supersonic and subsonic jets are quite different. In both subsonic and supersonic jets there exist large scale, coherent turbulent structures and fine grain, small scale turbulence. This turbulence is responsible for what is known as mixing noise. Mixing noise is the only component of subsonic jet noise. In supersonic jets the large coherent structures are the dominant mixing noise source while the fine grain turbulence is a relatively inefficient noise source. When the turbulent eddies in the shear layer move at supersonic speeds the Mach wave emission mechanism is present in supersonic jets. The Mach wave emission mechanism can produce noise on the order of up to 1 percent of the total mechanical energy of the jet. This is one hundred to one thousand times more efficient that a subsonic jet.

Supersonic jets also have to contend with the possibility of shock noise for engines not designed to be completely shock free. Also subsonic aircraft in cruise can have supercritical pressure ratios and produce shock noise, hence designers historically have had to design tailcones, etc. to handle shock noise in cruise. Shock noise can take two distinct forms - broadband shock associated noise and screech. Broadband shock associated noise is due to turbulent eddies convecting through and interacting with the shock cell structure of the jet. Screech is an acoustic feedback mechanism in which the acoustic energy propagates back to the nozzle region and sets up a resonant condition in the jet flow. When screech exists it is the dominant noise source. Shock waves in the jet could be utilized to enhance the mixing of the flow, but conventional

wisdom suggests that shocks should be completely avoided for commercial aircraft due to the substantial increases in noise which accompany the onset of shocks in the jet.

## Suppression Techniques

Any consideration of jet noise reduction technology must be made along side a consideration of engine performance. The role of advanced technology has been to reduce the performance penalty for a given level of noise reduction. Mass augmentation is a method of noise reduction which trades weight flow for reduced jet velocity. Since noise is proportional to a high power of the jet velocity this is an effective method of noise reduction. The subsonic jet noise problem has been dealt with primarily through mass augmentation by increasing the engine bypass ratio. High pumping ejectors can be used in supersonic cruise aircraft, but there is a limit to what can be achieved.

Another technique for jet noise reduction is frequency shifting. The idea here is to push the noise frequencies above about 3 kHz where the noise is not weighted as heavily in the noise metric. This can be done with high aspect ratio nozzles. Enormous aspect ratios of about 600 to 900 are required, but these may actually be achievable in certain situations. Lobed mixers also take some advantage of frequency shifting, in addition to enhancing the mixing of hot and cold flows to reduce the jet velocity. Tube jet suppressors utilized frequency shifting with very substantial reductions in noise, and unfortunately a very large performance penalty as well. Plugged nozzles with a high radius ratio also take advantage of frequency shifting to offer promising noise reductions.

A third method used for noise suppression is to enhance the mixing of the jet with either a low speed, secondary flow or the quiescent air. Mixing lower temperature, slower moving air with the jet reduces the jet velocity and the length of the source region. Hence eddy Mach wave emission has less distance over which to radiate noise. Enhancing the mixing is primarily a supersonic jet noise suppression technique because the increase in turbulence level due to mixing will usually result in a significant increase in subsonic jet noise. Therefore a lined ejector is needed to absorb the subsonic mixing noise.

Mixing can be enhanced passively, through the use of mechanical devices in the jet stream, such as mixers, or through modification of the nozzle geometry. For example in an elliptic nozzle, as the shear layer develops, there is a large distortion of the jet column as it evolves due to a slight difference in the distribution of the momentum thickness at the exit of the nozzle. This distortion engulfs large amounts of fluid and

the jet highly distorts from the elliptical shape into a round shape. The supersonic portion of the jet is reduced, hence there is less distance over which the turbulent structures are convecting supersonically and radiating noise through Mach wave emission. An unsuppressed nozzle can produce 7 to 8 EPNdB noise reduction relative to a round nozzle with only 1 percent performance loss. A rectangular convergent-divergent nozzle has enhanced mixing in the same way and can produce 5 dB suppression just from its rectangular shape. An ejector by itself will actually minimize mixing, therefore some type of mixing mechanism must be introduced. Mixing can also be enhanced through streamline curvature in curved ducts. The pressure gradient destabilizes the flow and thus promotes much greater mixing. Streamline curvature could possibly be used in conjunction with high-lift devices, such as blown flaps, but otherwise may require too much curvature.

Active control can also be used to enhance mixing. In subsonic jets tones can be injected to excite the jet resulting in a large increase in spread rate and decrease in jet velocity. Broadband noise will also be increased. The enhanced mixing generates increased turbulence and more noise - which must be eliminated with liners. In supersonic jets the story is different because mixing trades the efficient Mach wave emission noise source for the much less efficient fine grain turbulent mixing noise.

Unlike engine inlet liners, engine exhaust liners must absorb broadband noise in a high temperature environment. Development of such liners is an important research area. Research on liners with flow injection has shown promising noise reduction characteristics and the blowing could also be used for transpiration cooling.

## Opportunities for Noise Control with Advanced Configurations

The very large, advanced configurations discussed in the workshop offer many opportunities to reduce noise which are not practical with current aircraft. A blended wing-body or span-loader configuration offers potential since the propulsion system can be integrated into the body rather than simply be hung under the wing. Consider the advanced technologies illustrated in the schematic in figure 7. The engine exhaust in this configuration is over the back of the fuselage, thus it is shielded from direct line of sight from the ground. The high velocity jet is augmented with a low temperature bypass flow. The bypass flow is needed to push the jet off the flat surface. Acoustic treatment panels can be installed directly on the fuselage surface downstream of the engine and if necessary a lined ejector with transpiration cooled liner could be used as well. The placement of the engines relative to each other is also important. Noise reductions of several dB can be gained in every direction, even below the aircraft,
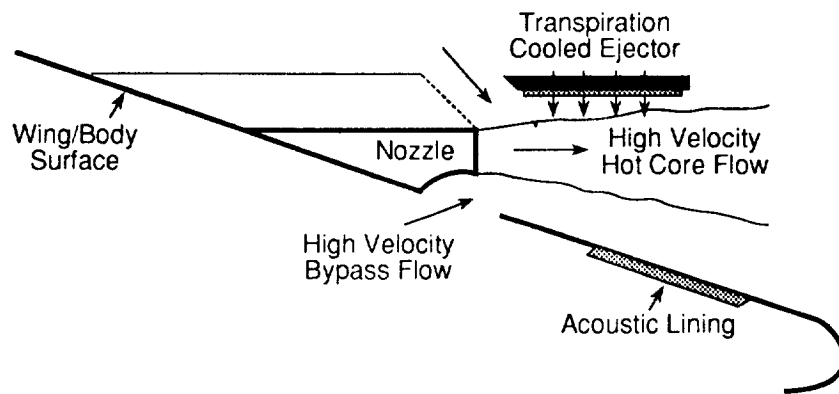
Figure 7. Schematic of potential applications of advanced technology for jet noise reduction. (Seiner)

through jet by jet shielding. This jet by jet shielding is planform dependent and should be considered early in the preliminary design. It is clear that even though individual technology areas may be approaching a point of diminishing returns for further improvements, advanced often unconventional aircraft configurations, approached using a systems design philosophy rather than separate individual disciplines, offers significant benefits in both performance and jet noise reduction.

## Airframe High-Lift Noise

When aircraft propulsive system noise has been greatly reduced, another kind of noise is observed during aircraft flyover. This is airframe noise, the noise caused by motion of the aircraft surfaces through the air. With landing gear and high-lift devices retracted, airframe noise is caused by the turbulent boundary layer moving past trailing edges of wings and stabilizing surfaces. High-lift devices during climb out, and landing gear and high-lift devices during approach, increase the airframe noise. Another type of airframe noise, powered-lift noise, is generated when engine exhausts are directed over the wing's trailing edge flaps to increase the lift at low flight speeds. This interaction will generate additional noise. This section tries to describe the effect of new types of airframe shapes on airframe noise generated by airflow and exhaust flow during takeoff and approach

One purpose of advanced aircraft concepts is to reduce the operating cost by increasing the maximum lift-drag ratio during cruise. Increased lift-drag ratio during climb and approach should allow use of engines with lower thrust, which would reduce

the propulsive system noise at those flight conditions. Airframe noise might then set the noise certification limits. Some of the advanced aircraft concepts probably would be unable to trim the large pitching moments associated with elaborate flaps that provide high maximum lift coefficient but radiate high annoyance noise spectra. Single and double-slotted trailing-edge flaps with few spanwise segments are quieter, and generate a lower annoyance spectrum shape, than multiple spanwise segment double or triple-slotted trailing-edge flaps. Those advanced aircraft concepts would coincidentally generate relatively low annoyance airframe noise. For this reason, each type of configuration is discussed separately below.

## Airframe Noise Sources

### Noise impact of increased laminar flow

The effects of aerodynamic changes on noise are not always obvious. For example, consider what would happen to clean airframe noise if the wings of commercial airplanes were built with suction boundary layer control to achieve laminar flow over much of the upper and lower surfaces. Airframe flyover noise from a clean airframe is dominated by broadband noise from the wing. Mean square acoustic pressure of this noise is proportional to the product of turbulent boundary layer average thickness at the trailing edge and wing span. Suppose that the product of the reduced boundary layer thickness and span was only half that of the original wing. Then the overall sound pressure level would have been decreased by 3 dB as is shown in figure 8. This reduced noise was caused by halving the boundary layer thickness. The frequency at the peak amplitude of the noise spectrum varies inversely with boundary layer thickness at the trailing edge, with the peak frequency generally occurring at less than 200 Hz. Halving the boundary layer thickness doubles the frequency which would increase the A-weighted noise by 5 dBA. Although the absolute level of noise would be reduced by 3 dB, the annoyance weighted noise would be increased by 2 dB. What at first had seemed like an improvement has worsened the annoyance.

The story becomes more complicated when the effects of atmospheric attenuation are included. Noise is more strongly attenuated at higher frequencies. If the aircraft is high enough above the ground when it overflies the measurement position, atmospheric attenuation might reduce the high frequency part of the noise spectrum enough to bring the annoyance weighted noise down to less than that for the original situation. This example shows that it is not always obvious whether a given change in airframe design will improve or worsen the resulting noise annoyance.

## Installation noise

Placing high bypass ratio turbofan engines under aircraft wing surfaces increases the downward radiated broadband noise. This increase is caused by several effects. These are: 1) reflection of upward radiated high frequency engine noise by the wing; 2) wing lift fluctuation noise and trailing-edge noise caused by convection of fan-exhaust-jet shear-layer turbulence past the wing cutout's trailing edge; and 3) trailing-edge-flap side-edge noise caused by interaction between the fan-exhaust-jet shear-layer turbulence and the airflow around the side of the adjacent trailing-edge flap segments.

## Trailing-edge flap noise

The noise caused by trailing-edge flaps is known to be produced by at least two different processes. The first is the generation of lift fluctuations along the flap span, caused by turbulence shed by the upstream wing surface. This generates the lower frequency, lower annoyance part of the flap noise spectrum. The other is caused by convection of turbulence around the flap side edges, and produces the broad, higher frequency, higher annoyance part of that spectrum. Single-slotted trailing-edge flaps
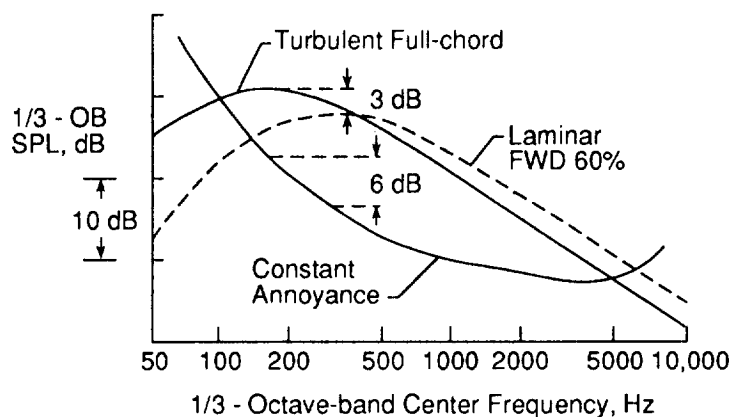
Figure 8. Effect of laminar flow on airframe noise. (Fink)

radiate strong noise only at low frequencies because they usually have only one flap panel on each semispan.

### Landing gear noise

In the past, commercial transport aircraft were designed with single-wheel landing gear, two wheels on one axle, or four wheels on a two-axle wheel truck. The largest commercial transports now being designed may have more than four wheels per landing-gear assembly. Placing two wheels on the same axle merely doubled the downward-radiated noise from that of one wheel. However, putting an axle with two wheels closely behind another axle with two wheels to make a four-wheel landing-gear truck caused the noise spectrum to decay less rapidly at high frequencies. That is, putting landing-gear wheels in the turbulent wake of other wheels increases the noise at the moderate and high frequencies which annoy people.

## Analysis of Advanced Configurations

Now that we have look briefly at the sources of airframe noise, we will consider individual advanced configurations from the viewpoint of airframe noise.

### Thick-wing spanloader aircraft

Spanloaders are flying wing aircraft which carry their payload within a high thickness ratio wing. Because these aircraft wouldn't have separate horizontal stabilization and control surfaces, they probably could not trim the large pitching moments produced by elaborate, high maximum lift coefficient, multiple chordwise-segment trailing-edge flaps. Use of simple single-slotted trailing-edge flaps, rather than complicated flaps, would change the flap noise spectrum and significantly reduce the most annoying contribution to airframe noise during climb-out and approach.

Spanloaders have wings with higher thickness ratio, and therefore thicker boundary layers at the trailing edge, than those of conventional wings. The use of many single-slotted trailing-edge flap segments distributed along the entire span for longitudinal and lateral control will further thicken the boundary layer at the trailing edge. Thickening the boundary layers at the trailing edge would increase the absolute level of noise but would shift its spectrum to lower, less annoying frequencies. Spanloaders therefore are likely to have lower annoyance-weighted noise levels in straight-line flight than conventional aircraft. However if a spanloader uses split-flap drag rudders to turn, the unsteady flow over their blunt bases would cause added noise during turning flight. An oblique wing aircraft is essentially a spanloader aircraft and would have the same airframe noise advantages.

## Strut-braced natural laminar-flow wings

Strut-braced wing aircraft would likely have very high aspect ratio wings and struts with laminar flow. The struts would have much smaller chord than that of the wing, and a high thickness ratio airfoil section. Both the airframe noise from the wings and the struts would suffer a noise penalty due to the shift in peak frequency of the noise into the more annoying part of the spectrum. Also the struts essentially add to the number of trailing edges over which the boundary layer passes, even though the struts would not have trailing edge flaps.

## Blended wing-body aircraft

Blended wing-body configurations would have a very high aspect-ratio sweptback outer wing chosen for extensive chordwise laminar flow at cruise, blended into a wide flat fuselage. The outer wing panels would have the same combination of leading-edge and trailing-edge high-lift devices as those of a conventional aircraft, and the landing gear would resemble those of a conventional aircraft. However, the very high aspect ratio of the wing panels would not tolerate the high pitching moments of elaborate trailing-edge flaps. Current design concepts are limited to single-element Fowler trailing-edge flaps, which should be relatively quiet. Airframe noise of the takeoff and approach high-lift configurations probably would be somewhat quieter than that of conventional aircraft. Propulsive system installation noise probably would be reduced since the trailing-edge flaps would not need cutouts for turbofan engine exhaust gases. This is because the engines would most likely be installed within the long-chord thick region where the outer wing and the wide fuselage are blended. The propulsive system exhaust gases therefore would not interact with sharp trailing edges or with the side edges of trailing-edge flaps.

## Joined-wing aircraft

The joined-wing aircraft concept combines a low-mounted positive-dihedral sweptback wing joined near its tip to a high-mounted forward-swept negative-dihedral horizontal tail. This combination can give favorable structural bracing and favorable subsonic aerodynamic interference. Because trailing-edge flaps would be mounted on both sets of surfaces, it seems likely that simple full semispan, single or double slotted, trailing-edge flaps could be used. Joined-wing aircraft probably would be quieter in climbout and landing approach than conventional aircraft.

## Non-Planar Three-Lifting-Surface Aircraft

This type of aircraft, described at the workshop as a C-wing, uses a canard followed by a sweptback wing of relatively high thickness ratio. The wing has vertical winglets with inward-pointing horizontal control surfaces at their upper tips. Use of three sets of

horizontal surfaces allows the induced drag to be reduced below that of conventional two-surface aircraft. The thick wing achieves high lift-drag ratio by use of a Goldschmeid airfoil section. Here, nearly all of the upper-surface recompression is achieved abruptly at a suction slot which prevents flow separation. The airflow taken in at this suction slot is compressed and the expelled along the upper surface near the wing trailing edge. The resulting upper-surfaced-blowing powered-lift noise might be controlled through the use of frequency shifting.

### Supersonic transports

Conventional supersonic transports tend to have much higher leading-edge sweep back and a more highly tapered wing planform than those of subsonic transports. Their airframe noise during subsonic cruise in the clean configuration would be generated in a similar manner as a conventional subsonic aircraft, except that the normalized spectrum shape would be different. The large variation of boundary-layer thickness from the wing root to the tip produces a broader spectrum than that for a less sharply tapered planform. Annoyance due to airframe noise radiated from the landing gear and simple trailing-edge flaps would greatly exceed that caused by the greater high-frequency content of airframe noise from the supersonic transport's more highly tapered wing planform.

### Summary

Aircraft airframe noise, like the other aircraft noise sources can potentially be reduced through advanced aerodynamic technology and advanced aircraft configurations. Most of the advanced configurations discussed in the workshop may coincidentally, rather that intentionally, reduce the airframe noise levels. Clearly if airframe noise is given proper attention in the preliminary design reduction relative to current aircraft should be achievable. (This section is based on a written version of Martin Fink's presentation which can be found in the appendix for this chapter.)

## Concluding Remarks

This section has shown the importance of aircraft noise and aircraft emissions. Fortunately, many of the same advances that may be used to dramatically improve aircraft performance, relative to current transport aircraft, will also reduce noise and emissions. Improving the cruise performance of the aircraft would make the use smaller engines possible and hence reduce the amount of emissions and the noise. Noise reductions in turn allow the aircraft to be utilized more, thus increasing the productivity of the aircraft and the airport. It seems likely that the target goals for aircraft noise, which are significantly below current certification requirements, should be

acceptable to the communities in which airports are located. It also seems clear that significantly quieter aircraft are possible - but only through the use of an interdisciplinary, systems design approach in which aircraft noise is considered and given importance at each stage of the design process. Advanced aerodynamics make this possible.

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## Appendix

Martin Fink submitted the following written paper for the workshop. It is included here with the figures at the end.

# AIRFRAME HIGH-LIFT NOISE

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## INTRODUCTION

When aircraft propulsive-system noise has been greatly reduced, another kind of noise is observed during aircraft flyover. This is airframe noise, the noise caused by motion of the aircraft surfaces through the air. For aircraft with landing gear and high-lift devices retracted, airframe noise is caused by the turbulent boundary layer moving past trailing edges of wings and stabilizing surfaces. High-lift devices during climb-out, and landing gear and high-lift devices during approach, increase the airframe noise. To use a phrase originated (Ref. 1) by Dr. Jay C. Hardin of NASA Langley Research Center, airframe noise is the ultimate noise barrier.

In 1976 and 1977 I developed a noise component method (Ref. 2) for predicting airframe noise, with funding from the FAA. It calculated the predicted noise radiation from each major component of the airframe as sketched in Fig. 1 (clean wing, horizontal and vertical stabilizing surfaces, leading-edge slats, trailing-edge flaps, and landing gear) and summed these contributions. That method was later modified and adopted for use by NASA (Ref. 3) and ICAO, not because it was rigorously correct but because it was easy to use and was less wrong than other methods then available. As of a few years ago (Ref. 4), it remains the state-of-the-art. The new aircraft concepts discussed herein were not part of the database with which this prediction method was tested.

Another type of airframe noise which was then being examined was powered-lift noise. This is the noise generated when turbofan engine exhausts are directed over the wing's trailing-edge flaps to increase the lift at low flight speeds for short-field operation. Noise prediction for such configurations is summarized in Ref. 5. This concept proved to be too noisy for civil aviation. However, the need for improved fuel

economy and reduced propulsive-system noise has led to the development of turbofan engines with higher bypass ratios. Such engines have larger fan exit diameters, at the same thrust. When these engines are mounted under the wings of new transport aircraft, as sketched in Fig. 2, the fan exhaust flow is likely to interact with the trailing edge of the wing cutout and the side edges of trailing-edge flaps. This interaction will generated additional noise.

This paper tries to describe the effect of new types of airframe shapes, such as those described at this workshop, on airframe noise generated by airflow and exhaust flow during takeoff and approach.

## ADVANCED AIRFRAME CONCEPTS

### General Comments

The purpose of advanced aircraft concepts is to reduce the operating cost by increasing the maximum lift-drag ratio during cruise. This would allow transporting the payload with less fuel. The resulting increased lift-drag ratio during climb and approach should allow use of engines with lower thrust, which would reduce the propulsive-system noise at those flight conditions. Then airframe noise might set the noise certification limits.

During climbout at low altitudes, the engines may have reduced thrust levels. The landing gear would be retracted, and the trailing-edge flaps would be set to moderate deflections. Advanced aerodynamic shapes might have high enough airspeed at this condition so that airframe noise from the flaps could set the takeoff noise limit. During approach, engine thrust levels might be low enough so that noise at the ground would be dominated by airframe noise from the landing gear and the highly deflected trailing-edge flaps.

Some of the advanced aircraft concepts probably would be unable to trim the large pitching moments associated with elaborate flaps that provide high maximum lift coefficient but radiate high-annoyance noise spectra. Single and double-slotted trailing-edge flaps with few spanwise segments are quieter, and generate a lower-annoyance spectrum shape, than multiple-spanwise-segment double or triple-slotted trailing-edge flaps (see the Appendix of this paper). Those advanced aircraft concepts would coincidentally, rather than intentionally, generate relatively low-annoyance airframe noise. For this reason, each type of configuration is discussed separately below.

### Increased Chordwise Extent of Laminar Flow

The effects of aerodynamic changes on noise are not always obvious. For example, consider what would happen to clean-airframe noise if the wings of commercial airplanes were built with suction boundary layer control to achieve laminar flow over much of the upper and lower surfaces. The boundary layer would become turbulent ahead of the region of pressure recovery over the aft 35 to 40 percent chord. Such airframes would have increased wing span to increase the aspect ratio. That would reduce the induced drag by about the same fraction that boundary-layer control had reduced the form drag, for increased maximum lift-drag ratio.

Airframe flyover noise from a clean airframe is dominated by broadband noise from the wing. Mean-square acoustic pressure of this noise is proportional to the product of turbulent boundary layer average thickness at the trailing edge and wing span. Suppose that the product of the reduced boundary-layer thickness and increased span was only half that of the original wing. Then, as sketched in Fig. 3, the overall sound pressure level (OASPL) would have been decreased by 3 decibels (3 dB). That is, overall noise would be reduced, which is good.

However, this reduced noise was caused by halving the boundary-layer thickness. The frequency at peak amplitude of the noise spectrum varies inversely with boundary-layer thickness at the trailing edge. This peak frequency generally occurs at less than 200 Hz, which is not very annoying. Halving the thickness doubles that frequency. A curve showing the variation of A-weighted noise level with frequency is also shown in Fig. 3. For this example, doubling the peak frequency would increase the A-weighted noise by 5 dB(A). Although the absolute level of noise would be reduced by 3 dB, the annoyance-weighted noise would be increased by 2 dB. What at first had seemed like an improvement has worsened the annoyance as perceived by the human mind.

The story becomes more complicated when the effects of atmospheric attenuation (not shown in this figure) are included. Noise is more strongly attenuated at higher than at lower frequencies. If the aircraft is high enough above the ground when it overflies the measurement position, atmospheric attenuation might reduce the high-frequency part of the noise spectrum enough to bring the annoyance-weighted noise down to less than that for the original situation. The object of this example has been to show that it is not always obvious whether a given change in airframe design will improve or worsen the resulting noise annoyance.

### Thick-Wing SpanLoader Aircraft

SpanLoaders, sketched in Fig. 4(a), are flying-wing aircraft which carry all of their payload within a high-thickness-ratio wing. Because these aircraft wouldn't have separate horizontal stabilization and control surfaces, they probably could not trim the large pitching moments produced by elaborate, high maximum-lift-coefficient, multiple-chordwise-segment trailing-edge flaps. Use of simple single-slotted trailing-edge flaps, rather than complicated flaps, would change the flap noise spectrum. This change would significantly reduce the most annoying contribution to airframe noise during climb-out and approach.

SpanLoaders have wings with higher thickness ratio, and therefore thicker boundary layers at the trailing edge, than those of conventional wings. Also, the use of many single-slotted trailing-edge flap segments distributed along the entire span for longitudinal and lateral control will further thicken the boundary layer at the trailing edge. As implied in the discussion of noise from wings with part-chord laminar flow, thickening the boundary layers at the trailing edge would increase the absolute level of noise but would shift its spectrum to lower, less annoying frequencies. SpanLoaders therefore are likely to have lower annoyance-weighted noise levels in straight-line flight than conventional aircraft. However, it is likely that spanloaders, like the Northrop flying-wing aircraft of the early 1940's, would use split-flap drag rudders in order to turn. The unsteady flow over their blunt bases would cause added noise during turning flight.

### Strut-Braced Natural-Laminar-Flow Wings

Another approach for reducing aircraft drag during cruise is to use a greatly reduced wing chord and increased wing span. Then the wing airfoil section can be chosen to provide large chordwise extents of laminar flow on both the suction and pressure surfaces at the cruise flight condition, without use of powered boundary-layer control. The resulting wing planforms probably would have very high aspect ratio. Their wing structure might be unable to support the airloads unless external struts, as sketched in Fig. 4(b), were used. Airframe noise from the wing would be predicted in the same manner as that discussed under "Increased Chordwise Extent of Laminar Flow."

The struts would have much smaller chord than that of the wing, and a high-thickness-ratio airfoil section. Airframe noise from the strut would be calculated in the same manner as is discussed under "Thick-Wing SpanLoader Aircraft" except that the struts would not have trailing-edge flaps. The small chord would result in a much higher peak frequency of broadband noise, which might put the strut's noise at high-annoyance frequencies.

### Oblique-Wing Aircraft

Small oblique-wing demonstrator aircraft (Ref. 6) have used a continuous straight wing that extends across the fuselage and is pivoted at the fuselage centerline. As sketched in Fig. 4(c), the wing would be unswept at takeoff and landing. After takeoff, the complete wing would be rotated about its pivot so that the wing panel on one side of the fuselage is swept forward and the other panel is swept back. Disadvantages include coupled longitudinal and lateral oscillatory response to gusts and control inputs, and possible mechanical problems in fairing the wing into the fuselage to improve airflow at all sweep back angles. Commercial transports using this concept would be very large flying-wing aircraft in which the passengers would be contained within the wing. Takeoffs and landings would be made with the wing at moderate sweep, to avoid excessive wing span within the airport.

Airframe noise in low-speed flight (climb-out and approach) would be correctly predicted because the configuration then would be that of a low-subsonic-speed aircraft with a high aspect ratio unswept wing. Such wings can have high maximum lift coefficients with relatively simple low-noise trailing-edge flaps. Therefore, their absolute and annoyance-weighted airframe noise in takeoff and landing should be lower than that of sweptback-wing aircraft which need complicated, noisier trailing-edge flaps. If turbofan engines were mounted within ducts within structure, then another noise advantage of oblique-wing aircraft would be reduced noise due to interaction of the propulsive system and airframe.

### Blended Wing-Body Aircraft

Blended wing-body configurations as sketched in Fig. 4(d), would have a very high aspect-ratio sweptback outer wing chosen for extensive chordwise laminar flow at cruise, blended into a wide flat fuselage. The outer wing panels would have the same combination of leading-edge and trailing-edge high-lift devices as those of a conventional aircraft, and the landing gear would resemble those of a conventional aircraft. However, the very high aspect ratio of the wing panels would not tolerate the high pitching moments of elaborate trailing-edge flaps. Current design concepts are limited to single-element Fowler trailing-edge flaps, which should be relatively quiet. Airframe noise of the takeoff and approach high-lift configurations probably would be somewhat quieter than that of conventional aircraft.

However, propulsive-system installation noise probably would be reduced. The trailing-edge flaps would not need cutouts for turbofan engine exhaust gases if the

engines were installed within the long-chord thick region where the outer wing and the wide fuselage are blended. The propulsive-system exhaust gases therefore would not interact with sharp trailing edges or with the side edges of trailing-edge flaps.

### Joined-Wing Aircraft

The joined-wing aircraft concept, described in Ref. 7 and sketched in Fig. 4(e), combines a low-mounted positive-dihedral sweptback wing joined near its tip to a high-mounted forward-swept negative-dihedral horizontal tail. This combination can give favorable structural bracing and favorable subsonic aerodynamic interference. Because trailing-edge flaps would be mounted on both sets of surfaces, it seems likely that simple full-semispan single- or double-slotted trailing-edge flaps could be used. Joined-wing aircraft probably would be quieter in climbout and landing approach than conventional aircraft.

### Non-Planar Three-Lifting-Surface Aircraft

This type of aircraft, describes at this Workshop meeting as a C-wing, uses a canard followed by a sweptback wing of relatively high thickness ratio. The wing has vertical winglets with inward-pointing horizontal control surfaces at their upper tips. Use of three sets of horizontal surfaces allows the induced drag to be reduced below that of conventional two-surface aircraft. The thick wing achieves high lift-drag ratio by use of a Goldschmeid airfoil section. Here, nearly all of the upper-surface recompression achieved abruptly at a suction slot which prevents flow separation. The airflow taken in at this suction slot is compressed and the expelled along the upper surface near the wing trailing edge. The resulting upper-surfaced-blowing powered-lift noise can be calculated as described in Ref. 5.

### Supersonic Transports

Conventional supersonic transports (Fig. 4(f)) tend to have much higher leading-edge sweep back and more highly tapered wing planforms than those of subsonic transports. Their noise during subsonic cruise in the clean configuration would be calculated in the same manner as that for conventional subsonic aircraft, except that the normalized spectrum shape would be different. As sketched in the left side of Fig. 5, taken from Figure 4 of Ref. 3, the large variation of boundary-layer thickness from the wing root to the tip produced a broader spectrum than that for a less sharply tapered planform. An empirical equation for the normalized spectrum shape at zero taper ratio was given in Ref. 3.

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Comparisons of predicted spectra with those measured by NASA for an 0.015-scale wind-tunnel model of a supersonic transport in the cruise and landing configurations were shown in Fig. 11 of Ref. 3. These calculated spectra for both configurations, and data for the model in the landing configuration, are shown on the right side of Fig. 5. The landing configuration was about 5 dB noisier over most of the frequency range. That is, annoyance due to airframe noise radiated from the landing gear and simple trailing-edge flaps would greatly exceed that caused by the greater high-frequency content of airframe noise from the supersonic transport's more highly tapered wing planform.

The concepts of the supersonic transport, the oblique-wing aircraft, and the SpanLoader were combined in one of the configurations examined in Ref. 8. In this design concept, the SpanLoader would have an unswept wing during low-speed flight such as climb and approach. Its engine nacelles and vertical fins would be pivoted to remain streamwise as the wing was yawed at low transonic flight speeds to become swept behind the bow shock wave at the supersonic cruise Mach number. Its airframe noise during climb and approach could be predicted in the same manner as for a conventional SpanLoader, and should be relatively low.

INSTALLATION NOISE

Placing high-bypass-ratio turbofan engines under aircraft wing surfaces increases the downward-radiated broadband noise. This increase is caused by several effects, including three that are sketched in Fig. 6. These are (1) reflection of upward-radiated high-frequency engine noise by the wing, (2) wing lift-fluctuation noise and trailing-edge noise caused by convection of fan exhaust-jet shear-layer turbulence past the wing cutout's trailing edge, and (3) trailing-edge-flap side-edge noise caused by interaction between the fan-exhaust-jet shear-layer turbulence and the airflow around the side of the adjacent trailing-edge flap segments.

Detailed experimental studies of these noise processes were conducted at Boeing during design of the Boeing 757. The resulting data correlations, and discussions of noise mechanisms, were given 10 years ago in Ref. 9 for zero flight speed. Effects of forward flight on this increased noise are described in Ref. 10.

MODIFICATION NEEDED FOR AIRFRAME NOISE PREDICTION METHOD

The airframe noise prediction method of Refs. 2-4 was developed when very little flyover noise data were available. Usually, the data consisted only of spectra measured at peak amplitude rather than spectra measured over a range of direction

angles. Also, some of the available equations for predicting directivity of noise generated by different flow processes were valid only in the limit of very low subsonic Mach number. Analytical solutions which correctly predict the effects of subsonic Mach number are now available, and should be included in the prediction method. Some of these needed changes to prediction of airframe noise directivity were discussed by Patricia Block, then of NASA Langley Research Center, in Ref. 3.

Also, the noise caused by trailing-edge flaps is now know to be produced by at least two different processes, sketched in Fig. 7. One is the generation of lift fluctuations along the flap span, caused by turbulence shed by the upstream wing surface. This generates the lower-frequency, lower-annoyance part of the flap noise spectrum. The other is caused by convection of turbulence around the flap side edges, and produces the broad higher-frequency higher-annoyance part of that spectrum. Single-slotted trailing-edge flaps radiate strong noise only at low frequencies because they usually have only one flap panel on each semispan.

Noise from trailing-edge flaps was represented in Ref. 2 by use of two empirical normalized spectra. These are plotted in Fig. 8, taken from Fig. 23 of Ref. 2. One normalized spectrum was used for single and double-slotted flaps. The other, which remains strong over a wiser range of frequencies, was used for triple-slotted flaps. Double-slotted flaps are now know to produce spectra anywhere within those two limiting shapes, depending on the number of spanwise flap panels. Until a better prediction method can be developed, the noise spectrum for both double-slotted and triple-slotted trailing-edge flaps should be predicted conservatively by using the empirical equations of Ref. 2·for triple-slotted flaps. Much of this additional predicted noise probably would be strongly attenuated by atmospheric absorption.

The method of Ref. 2 was developed when commercial transport aircraft had either single-wheel landing gear, two wheels on one axle, or four wheels on a two-axle wheel truck. The largest commercial transports now being designed may have more than four wheels per landing-gear assembly. Placing two wheels on the same axle merely doubled and downward-radiated noise from that of one wheel. However, putting an axle with two wheels closely behind another axle with two wheels to make a four-wheel closely behind another axle with two wheels to make a four-wheel landing-gear truck caused the noise spectrum to decay less rapidly at high frequencies. That is, putting landing-gear wheels in the turbulent wake of other wheels increases the noise at the moderate and high frequencies which annoy people.

There are some indications that the noise spectrum radiated by airframes with four-wheel landing-gear trucks is strong at frequencies higher ( and therefore more

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annoying) than those predicted by the method of Ref. 2. That prediction was based on acoustic data for model landing gear at Reynolds numbers much less than those for jumbo-jet landing gear at approach flight speeds. It is reasonable to expect that noise radiation from bluff bodies in the wake of other bluff bodies should vary with Reynolds number. This portion of the method of Ref. 2 should be updated to match the contribution to flyer noise spectra caused by those landing gear during approach flight.

Similarly, airframe noise due to extended spoilers was not included in Ref. 2 because data for such configurations were not available. Such data now exist, and should be used as the basis for a semi-empirical prediction.

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# 1. NOISE - RADIATING AIRFRAME COMPONENTS

VERTICAL TAIL

CLEAN WING

HORIZONTAL TAIL

SLATS

FLAPS

MAIN LANDING GEAR

NOSE LANDING GEAR

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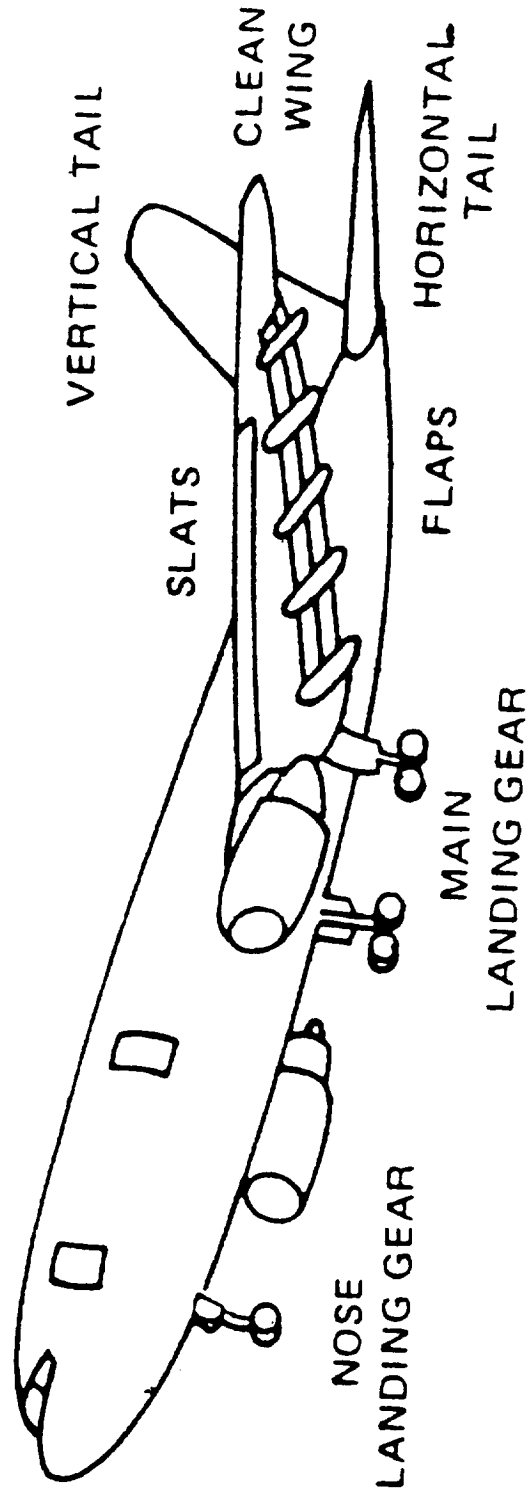
2. INTERACTION OF EXHAUST JET WITH FLAPS



FLAP SIDE EDGES

FLAP CUTOUT
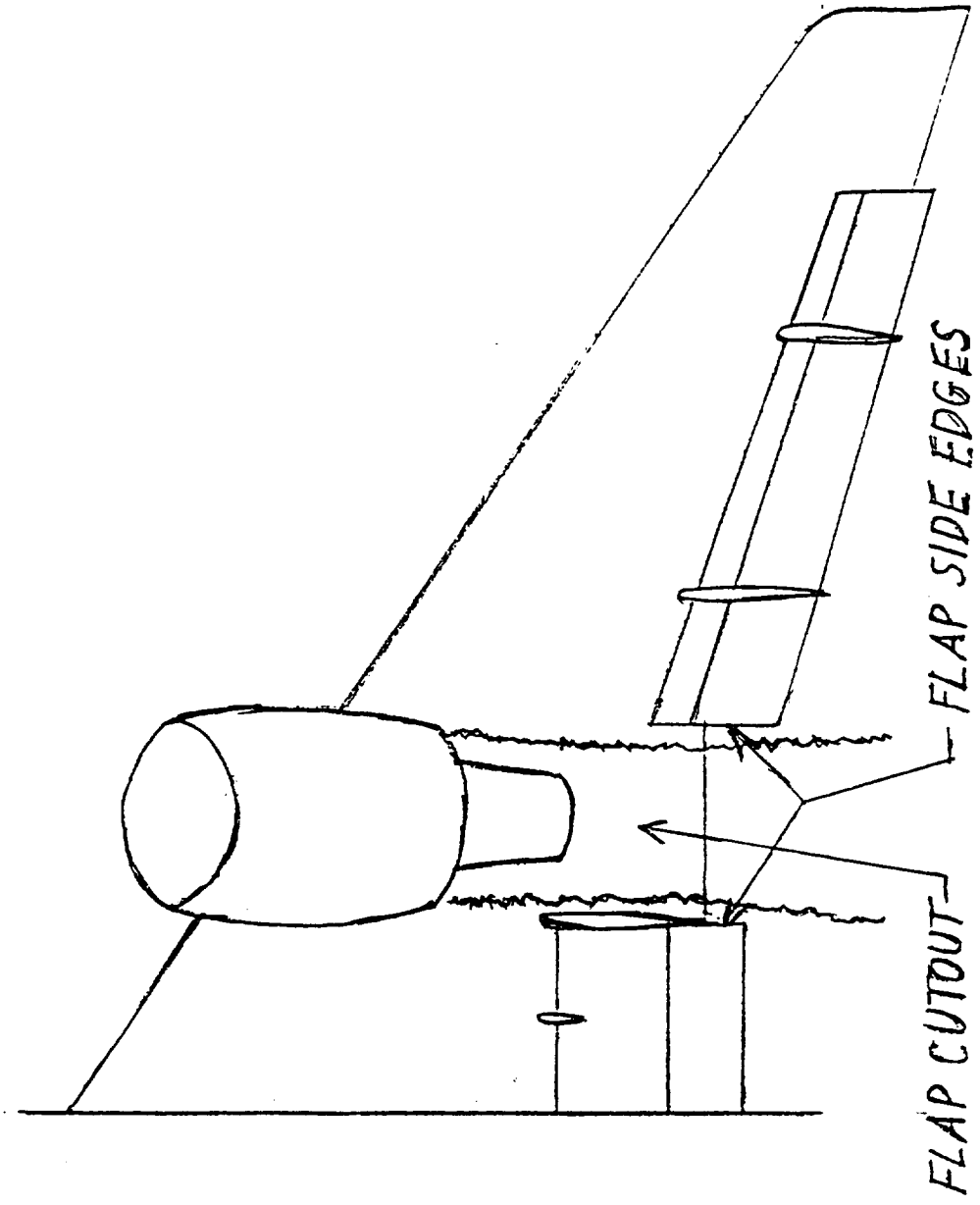
## 3. EFFECT OF LAMINAR FLOW ON AIRFRAME NOISE

*HALF THE BL THICKNESS AT TRAILING EDGE*
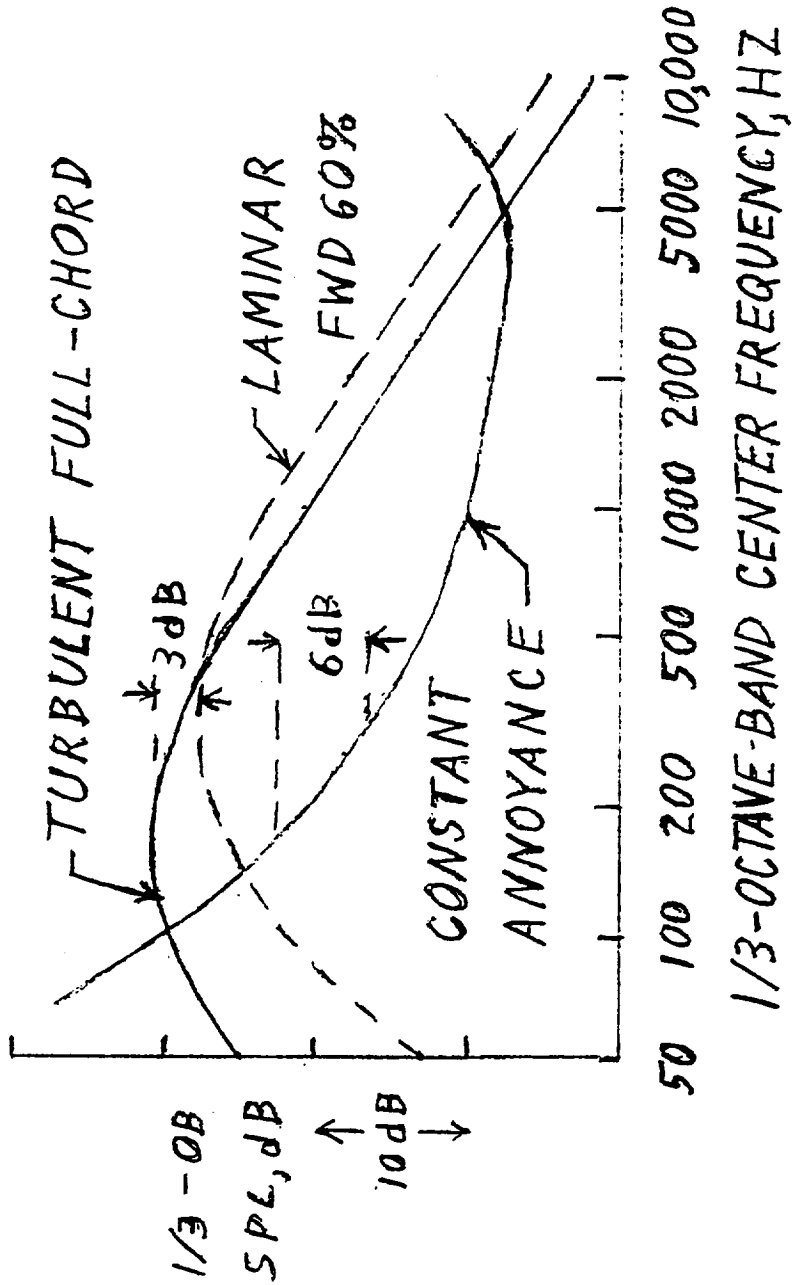
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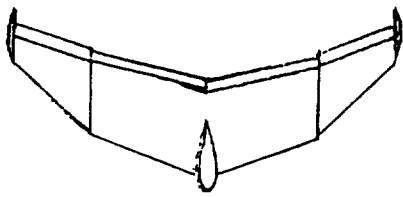
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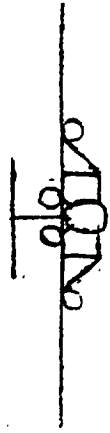
(b) STRUT-BRACED
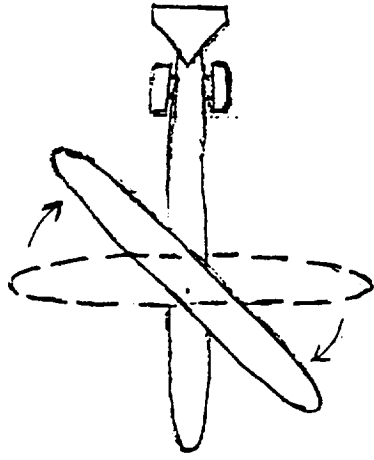
(c) OBLIQUE WING
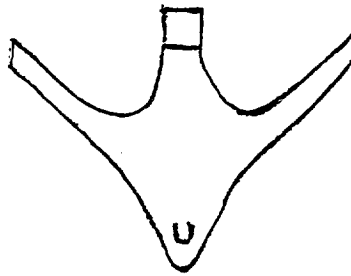
(d) BLENDED WING
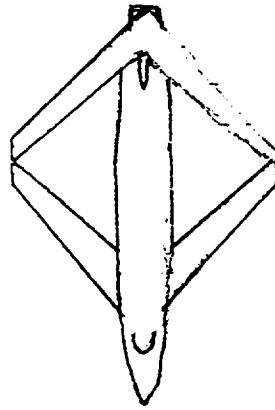
(e) JOINED WING
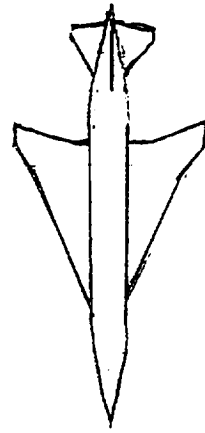
(f) SUPERSONIC TRANSPORT

# 5. AIRFRAME NOISE PREDICTION FOR SST



PREDICTED EFFECT OF TAPER

ACOUSTIC WIND TUNNEL
0.015 SCALE SST MODEL
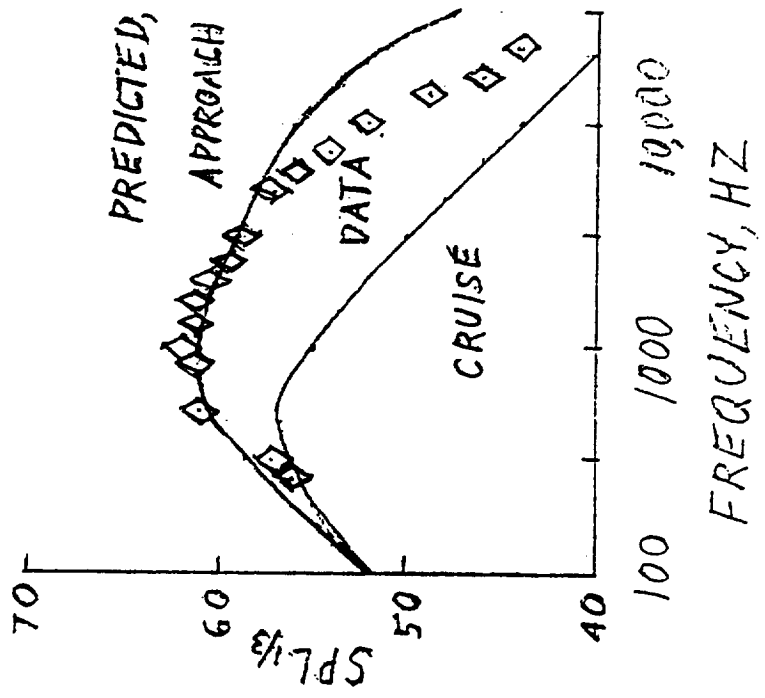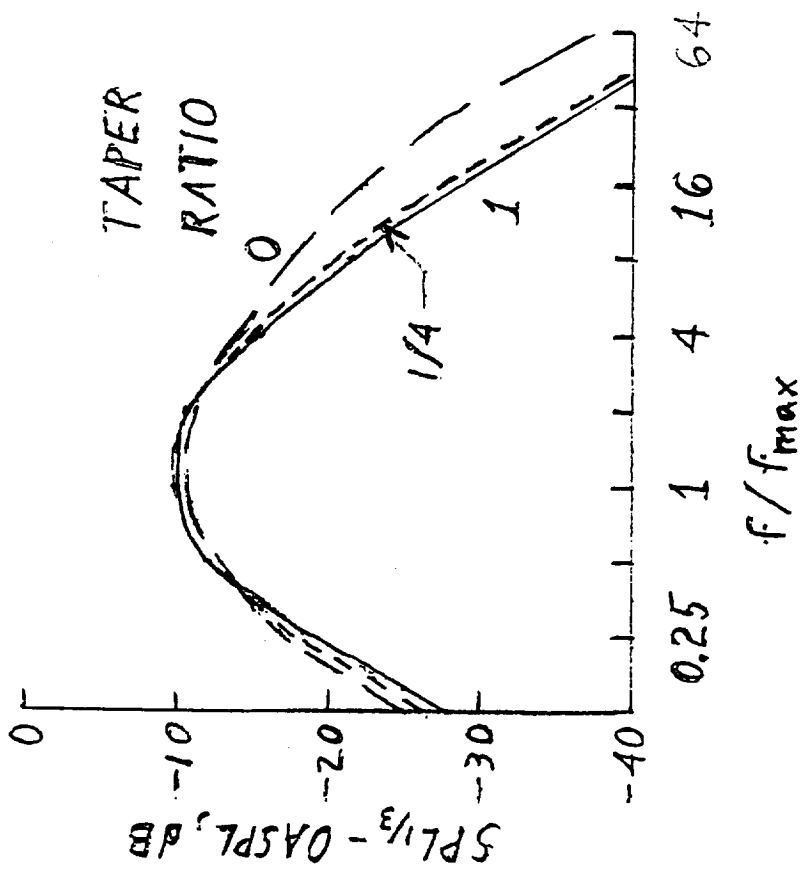
# 6. INTERACTIONS OF ENGINE EXHAUST WITH AIRFRAME WING AND FLAPS



REFLECTION

INDUCED AIRLOADS

TRAILING-EDGE FLAP
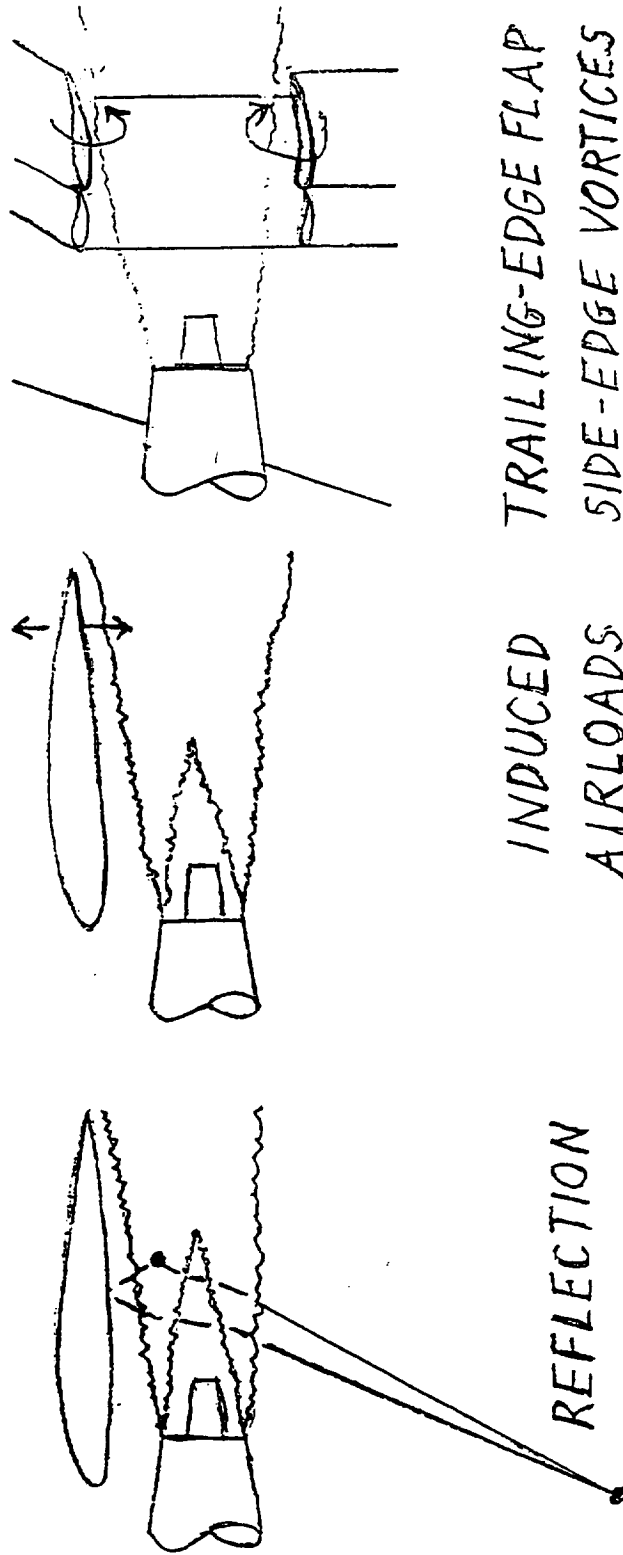
SIDE-EDGE VORTICES

## 7. TRAILING-EDGE FLAP NOISE PROCESSES

VANE

FLAP

WING

WING

BOUNDARY LAYER
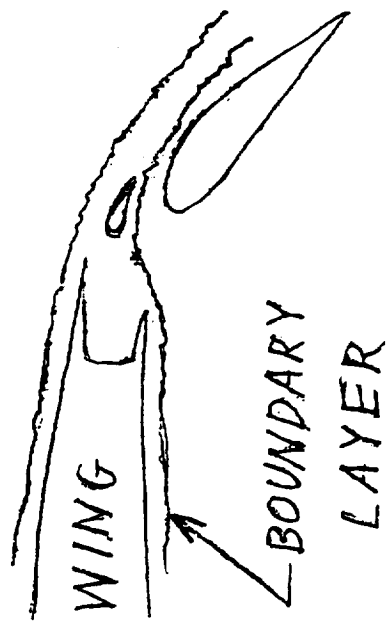
LIFT DIPOLE ALONG
VANE AND FLAP SPAN
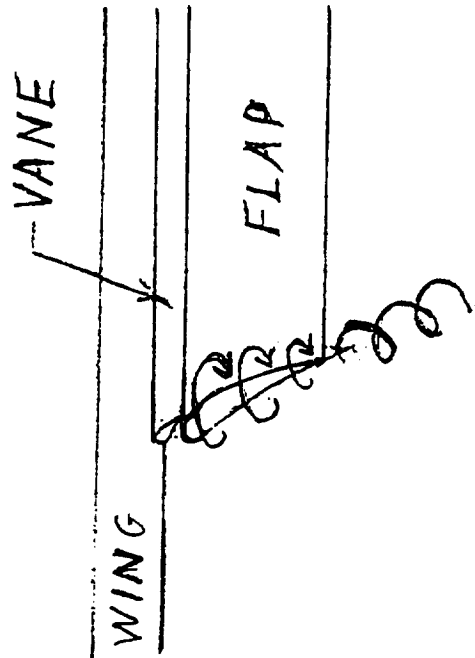
DIPOLES FROM VANE AND
FLAP SIDE-EDGE VORTICES

# 8. NORMALIZED SPECTRA FOR TRAILING-EDGE FLAPS
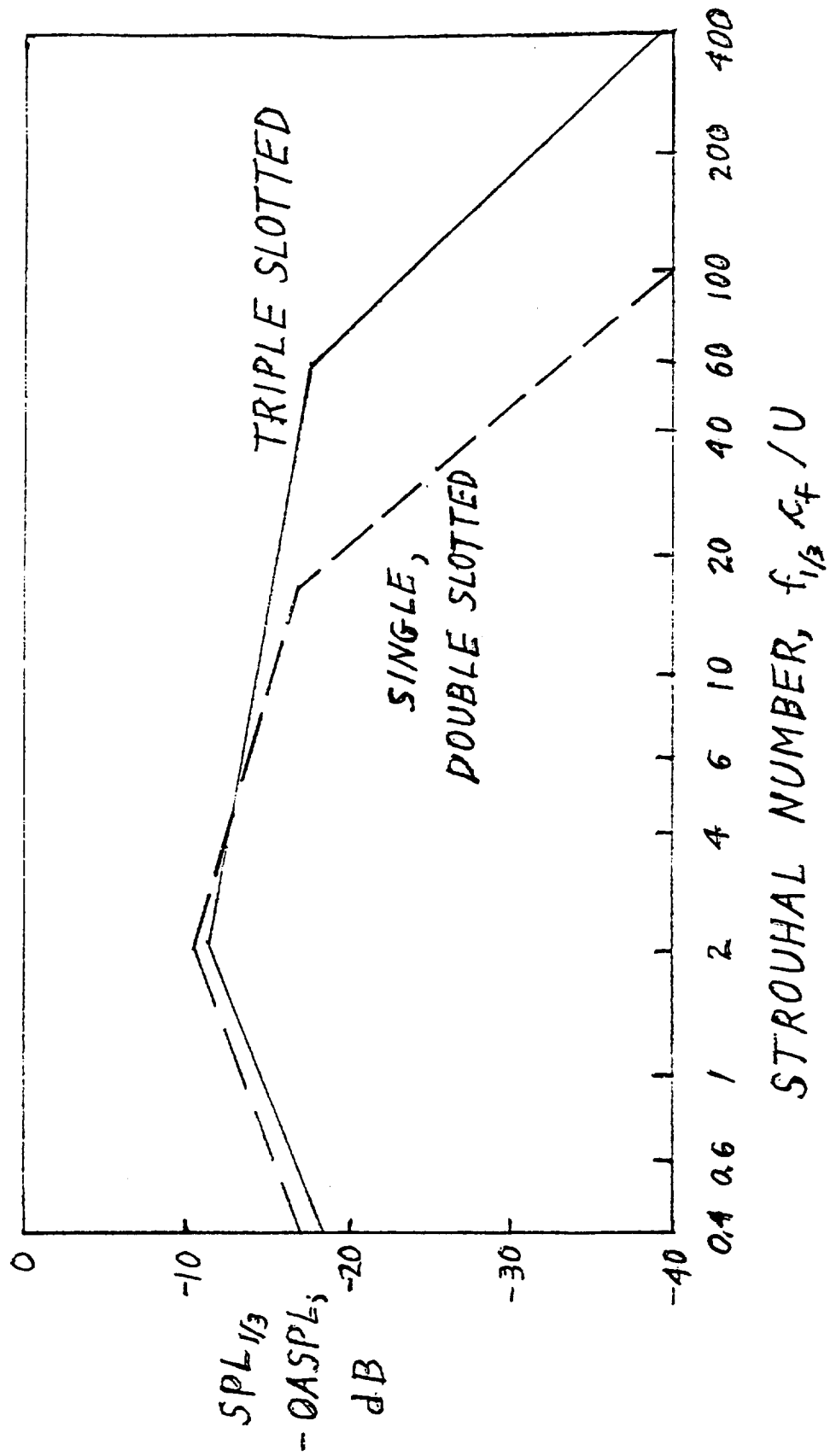
By Walter A. Silva

Introduction

   The goal of this session was to identify critical aerodynamic/structural interactions that could significantly impact advanced configurations, runway efficiency and/or airport operations of the future.
   The session was initiated with the comment that structures can make or "break" a given configuration. This is because the structures/structural dynamics experts have to deal with loads, manufacturing (economics, maintainability, reliability), fatigue, flutter, gust response, and ride comfort. Each one of these categories can be a major driver in the design of any given configuration.
   It is important to remember, however, that, in the spirit of the workshop, important advances in just one discipline can mean the difference between success and failure of a given configuration. For example, in the 1930's, the German all-metal forward-swept wing was proven to be a flawed concept as the wing divergence loads proved to be excessive. In the 1980's, however, thanks to advancements in the materials and flight controls disciplines, the forward-swept-wing aircraft, the X-29, was built and successfully flight tested. The use of composites for aeroelastic tailoring and sophisticated control system design for maintaining stability of an inherently unstable aircraft resulted in a successful design. As such, it is the hope of this session chairman that this workshop has served to identify critical areas of research that can turn a problematic design into a successful transport aircraft of the future.
   The agenda for this session was as follows:
      - Overview of Smart Structures Activities  by Jennifer Heeg (LaRC)
      - Structural Design Constraints of Advanced Configurations
        by Dr. J. H. Starnes, Jr. (LaRC)
      - Strut-Braced Aircraft by Dr. Werner Pfenninger (Vigyan, Inc.)
      - Span-Loader Aircraft by Roy Lange (retired, presented by S. J. Morris,LaRC)
      - Gust and Weather Constraints of Advanced Aircraft by Terry Barnes (FAA)

The format for this session writeup consists of summaries of each of the presentations with some of the actual viewgraphs included. The complete presentations, however, are available upon request from this session chairman.

Overview of Smart Structures Activities  by Jennifer Heeg

   An overview of the Smart Structures Workshop, sponsored by the Langley Smart Structures Technical Committee, was presented by Jennifer Heeg and is hereby summarized.
   The different categories of structures are presented in VG1-1 (viewgraph 1 of presentation 1). Smart structures are defined as structures that are actuating, sensory, controllable, and active. The different types of adaptive materials include piezoelectrics, shape memory alloys, magnetostrictives, and photoelectrics. Piezoelectrics deform under an electrical load and they generate an electrical load when deformed. Shape memory alloys deform when exposed to heat while magnetostrictives and photoelectrics respond to magnetic fields and light, respectively.
   In terms of applications, some recent accomplishments within the acoustics discipline include the active control of extensional and flexural waves on beams, the active control of interior cabin noise using piezoceramic materials, and neural network optimization of force inputs for active structural acoustic control. There are plans to assess the impact of

smart structures on engine noise, nacelle aeroacoustics, integration of wing and engine acoustics, interior noise, and community impact noise.

Application of smart structures in the field of aeroelasticity has resulted in the suppression of wing flutter for a simple two-degree-of-freedom wind-tunnel model using piezoceramic materials. Future work includes experimental panel flutter supression using shape memory actuators and experimental flutter suppression of a three-dimensional elastic wing using piezoelectric actuators.

In the electronics arena, research is being performed on the application of fiber optics and piezoelectric materials for sensing stresses and strains in structures.

If the smart structures technology matures succesfully, one of the potential payoffs is the development of a mission adaptive wing (MAW). A MAW would increase the drag rise Mach number of a given configuration, resulting in significant increases in efficiency.

The major challenges for smart structures are the development of a high-strength bonding agent for attachment of the smart material to the substrate, a needed increase of 3 to 10 times the current force levels, and improved material properties.


Structural Design Constraints of Advanced Configurations by Dr. J. H. Starnes, Jr.

The conventional transport structural design considerations are shown in VG2-1. These constraints have been defined primarily for metallic (usually aluminum) structural concepts. The 20,000 ground-air-ground cycles addresses fuselage and wing fatigue constraints. It should be mentioned that the general structural requirements, shown in the third bullet of the viewgraph, will apply to any new configuration as well.

For new, or emerging, transport designs, some of the structural design considerations are presented in VG2-2. These include a longer service life, possibly around 80,000 flight hours or 20,000 more flight hours than current transports provide. It is hoped that innovative structural concepts will aid in reducing structural weight while still supporting the applied loads and satisfying all structural design constraints. Some of these advanced materials include composites such as graphite epoxy.

It is imperative that fabrication processes be understood and optimized in order to reduce structural costs. Advanced analysis techniques need to be exploited and optimized as well in order to reduce the design-cycle time. An important step towards reducing most of these design and fabrication costs is to increase the interaction, or communication, between the different disciplines such as structures and aerodynamics early in the design phase.

Current airframe material selection choices include both metallic and composite materials. Metallic materials are widely used on existing aircraft, derivative aircraft and on new aircraft designs while composites have, in the past, been used only selectively for some structural components. The reasons for this are clear. Metallic primary structures (wing and fuselage) have enjoyed over 50 years of successful applications to transport aircraft. There exist many experienced designers that are very familiar with these materials and, as a result, company design manuals have been institutionalized. Metallic materials are ductile and are, therefore, more forgiving so that lower-fidelity analyses can be used on a preliminary basis. The failure mechanisms are well understood and the fabrication costs are known and predictable resulting in reduced economic risk.

Composite primary structures, on the other hand, are quite different. There is, to date, very limited experience in the application of these materials to transport aircraft since most of the applications have been for military aircraft. Some company design manuals, however, are evolving based on the military aircraft design experiences. Designing a composite structure is quite different from designing a metallic structure. Composite materials are brittle and, therefore, less forgiving of design uncertainty which means that the analyses must be of relatively high fidelity. The failure mechanisms of composites

are not well understood and fabrication methods are evolving although fabrication costs are not yet accurately predictable. This results in greater economic risk on the side of the manufacturer.

But what, if any, are the benefits of this increased economic risk ? For one thing, composite structures can provide a significant weight reduction: 25 to 30% for retrofit designs (such as replacing empennage only, for example) and more than 40% for resized aircraft. Composites do not suffer the corrosion or fatigue problems that plague metallic structures although damage tolerance is still a problem. Reduced fatigue problems implies that the 20,000 ground-air-ground cycles limit can be raised substantially. Composite structures allow advanced aircraft to have higher aspect-ratio wings than would be possible with metallic structures and to tailor structures to any structural design constraint.

Figure VG2-3 shows the composite structural components of the Boeing 777 and figure VG2-4 shows other aircraft that are partly or completely made of composites. It is important to note the scale difference in this figure as building larger composite structures presents a tougher economic problem.

Some of the current concerns with composite structures are as follows. Composite structures fail differently than metallic structures therefore techniques must be developed to understand and deal with failures. The cost of composite materials is more than conventional aluminum alloys. Fabrication and assembly cost predictions for composite structures are not as reliable as for metallic structures. Manufacturing infrastructure for composite structures is still evolving. Cost is more important than performance in today's transport economic environment. Keeping all these things in mind, it is very disturbing that foreign competitors are very active in composite structures. Therefore, if we are to be competitive, we must resolve the aforementioned concerns.

In the future, it is expected that composite structures will be used for conventional transport primary structures. Also, tailored composite structures will enable advanced transport aircraft with non-derivative configurations. Metallic materials will, of course, still be used where appropriate and where the composite/metallic combination makes the most sense. The cost of fabricating and assembling composite aircraft structures will become accurately predictable as experience is obtained. Finally, structural and aerodynamic design processes will become more integrated.


Strut-Braced Aircraft by Dr. Werner Pfenninger

The development of the strut-braced aircraft concept was influenced primarily by structural, aerodynamic and materials considerations. Conventional transports, with the typical cantilevered wings, reach an aspect ratio limit as they grow in size. The strut-braced concept, by essentially off-loading the root of the wing, extends this aspect ratio limit. Strut-braced aircraft actually allow for double the structural take-off gross weight for the same amount of structure. Although one of the concerns with strut-braced designs is the buckling of the struts, modern materials might alleviate this problem. Figure VG3-1 shows a 20-year old strut-braced laminar flow control (LFC) long range transport concept.

Since the strut off-loads the root portion of the wing, the chord of the wing at the root can be substantially smaller since the bending moments that it sees are reduced. Reducing the root chord of the wing then permits the application of laminar flow control technology as well as being able to design to a higher critical Mach number. Use of LFC technology reduces the friction drag of the aircraft, thereby improving the L/D substantially, by as much as 20% more than for cantilevered wings even when accounting for the parasitic drag of the strut.

Again, because the root of the wing of a strut-braced aircraft is thinner than for a cantilevered wing, it is easier to satisfy area-ruling design constraints for a strut-braced

aircraft. This means that the strut-braced concept allows for a more favorable transonic design of the aircraft.

One important design consideration is the aerodynamic interference between the strut and the wing as well as blockage at higher subsonic speeds. Figure VG3-2 presents the cutout that is required to reduce the blockage at higher subsonic speeds.

In the mid-50's, a model was built and tested with a 35 degree sweep and a 9.5 aspect ratio which supported the characteristics mentioned thus far. Of importance is the higher L/D value that can be obtained by using strut-braced wings as shown in figure VG3-3.

One concern that has been raised in the past is a potential difficulty in parking the vehicle at an airport gate with such high aspect ratios. One solution to this potential problem would be to park other smaller aircraft underneath the high strut-braced wings.

Since the strut-braced concept results in a reduced wake-vortex hazard, this implies an improvement in runway efficiency.


Span-Loader Aircraft by Roy Lange (presented by S. J. Morris)
(See "Review of Unconventional Aircraft Design Concepts", R. H. Lange, Journal of Aircraft, Volume 25, Number 5, May 1988, Pages 385-392.)

What is a span-loader aircraft ? In a span-loader aircraft, the weight (or passenger load) is distributed along the span of the wing to more evely match the loads on the wing and reduce the point stresses encountered around standard fuselage configurations. One obvious problem, however, is that a very wide landing configuration is required to maintain this load balance which means that the span-loader may not fit on most existing airport runways.

Another difficulty is that a thick airfoil is needed to adequately accomodate the cargo. Airfoil thicknesses on the order of 20% would be about the order of magnitude required. One potential solution would the Goldschmeid airfoil, which has boundary layer control to improve the performance.

Based on previous studies it was shown that a span-loader concept can result in a 20% decrease in operating empty weight, 8% decrease in block fuel, 10% decrease in gross weight, 9% decrease in thrust, 15% decrease in acquisition cost, and 10-12% decrease in DOC(direct operating cost) at a Mach number of .75 and a range of 3300 miles.

A Boeing concept, referred to as a Boeing 759, had a take-off gross weight (TOGW) of 2,350,000 lbs., could carry a payload of over 1,000,000 lbs., had a wing-span of 350 ft., and a wing area of 26,000 square ft. (5 times the area of a B747). So, although these were extremely large aircraft, the savings came from more efficient operation in the air.

One difficulty that has been pointed out with span-loaders is that these aircraft would typically load from the wing tip. This presents an inefficient operational problem when one has to unload one cargo and load another cargo in. The combination of loading/operational requirements and landing/take-off requirements may indicate the need for specially dedicated airfields, quite possibly the airfields that are currently being surplused by the armed services.

Although structurally the span-loader is an efficient design, the bulk of its problems arise in operations and operations support.


Gust and Weather Constraints of Advanced Aircraft by Terence J. Barnes (FAA)

This presentation addresses first the effects of advanced aicaft configurations on airport productivity and, secondly, the effects of airport productivity on aircraft configurations. The latter will address primarily the effects on structural design.

Beginning with the effects of advanced aircraft configurations on airport productivity, some of the problems that need to be addressed are those of aircraft size and weight

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which affect the resultant wake vortex and, therefore, the level of turbulence in a given area. In addition, certification of advanced configurations must also include, amongst many other issues, cross-wind and tail wind limits, roll and yaw control, tire ground speeds, and aircraft response to the turbulence that exists in the atmosphere or in the air space. May include consideration of cross-wind gear to give more flexibility.

As an example, one can look at aircraft response to turbulence due to a gust in the vertical direction. The basic equations are presented in VG5-1. The aircraft gust response due to vertical turbulence is shown to be a function of the lift-curve slope, gust velocity, the forward velocity, the gust alleviation factor and the wing loading. Some of these parameters you can control or modify but some you cannot. For example, inspection of the lift curve slope indicates that aspect ratio is a major driver of lift-curve slope which means that this parameter is different for straight-wing and swept-wing configurations and can, therefore, be controlled. The forward speed and wing loading can also be modified. One cannot, however, control or alter the turbulence in the atmosphere.

An advanced configuration that includes canards presents new problems. The FAA put forward criteria that were used to certify the Beech Starship and other foreign aircraft. These criteria are now rules in the small airplane FAR. The basic problem was to determine how to handle gust response and gust criteria. In the FAA regulations, there are two options for dealing with gust criteria. One is to fly an airplane through a 1-cosine gust shape and the other option is to use a formula which looks very much like that shown on FAR 23.333 (see VG5-2). The FAR 23.333, however, was based on flight measurements of conventional configurations and was therefore not appropriate for a canard configuration. The reason is that the canard tends to pitch up the aircraft before the main wing enters the gust. Therefore, the criteria selected was that the canard configuration fly through a 1-cosine gust function.

Shown in VG5-3 is a typical response of a canard configuration to a 1-cosine gust function. As can be seen, the forward wing reaches its maximum load point before the main wing, causing a slight nose-up pitch which results in the main wing load peaking after the forward wing. Therefore, must be careful with canard configurations.

Now taking a look at the operations point-of-view, VG5-4 is taken from an article written by Bill Hendricks, Director of the FAA Office of Accident Investigation. This means that increased speed results in higher structural loads. If the airplanes are required to speed up to fill slots, some airplanes are flown at speeds higher than the manufacturer predicted for normal operation. Increased traffic results in more flights through turbulence. This implies that with more turbulence and more restrictive air space, the pilots have less room to maneuver around that turbulence. This reflects what was mentioned by the United Airlines representative (earlier in the workshop) who suggested operational flexibility to minimize those structural concerns. This means that, from the FAA's standpoint, there is a need to build a loads data base to understand what the air traffic system and the "hub and spoke" system are doing to the aircraft structure. There is also a need to get information back to the pilots regarding the turbulence situation.

What is the FAA doing to minimize the impact of these concerns on the current operating environment ? First, there is an attemp to increase the gust design criteria with flaps extended. This is not welcome by the manufacturers but the FAA believes that they have data to show that this might be necessary. Secondly, they are collecting loads parameters on commercial transports in the U.S. hub-and-spoke system. And, finally, they are working to develop an updated, near real-time system for turbulence reporting.

Looking at the first of those developments, some time histories (see VG5-5) show gust speeds at around 60 ft/sec. These gust speeds exceed the values of the gust criteria in the regulations which at cruise speed is 50 ft/sec and with flaps deflected it is 25 ft/sec. There are several other time histories, but not all are presented. Instead, the results are summarized as follows. In 9 out of 10 of the time histories, the flaps are deflected and the range of gust speeds is from 50 to 70 ft/sec. So an obvious question is that if the design criteria is 25 ft/sec for flaps deflected but the aircraft is experiencing 50 to 70

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ft/sec gust velocities, why didn't the airplane fall out of sky? There are two reasons for this. The first is that the design gust speed (25ft/s) is combined with the flap structural design speed and these gusts occured at normal operating speeds which are lower than the structural design speed. The other reason is the 1.5 safety factor. How much can this safety factor be reduced before structural safety is put at risk? This is the reasoning for the proposal to increase the gust design speed with flaps deflected. A compromised gust design speed with flaps deflected of 40 ft/sec was reached figuring that, in combination with normal operating speeds, increasing from the 25 ft/sec speed to 40 ft/sec would be adequate. But manufacturers have removed this proposed modification from the plan that was submitted to Washington, D.C.

The second element of the effort to minimize impact is to measure loads parameters in flight on our current transports. There is a program already underway on USAir Boeing 737-400 (one recorder) actually collecting data. The FAA will be placing another recorder on another B737-400 and then four recorders on a B757 (USAir). This program will gradually be expanded to include the placement of recorders on the MD-80. The FAA is currently looking for airline volunteers to participate in this program. Research is also being performed to determine the minimum amount of instrumentation required to perform a similar operation on commuters. Many commuters do not require the flight data recorder, therefore there are no electronics suitable for feeding into a loads recorder. This research is summarized in a paper put together by Mr. Barnes along with the research center at the FAA entitled "The New FAA Flight Loads Monitoring Program", AIAA 91-0258.

Some of the data that is expected to be obtained is shown in VG5-6 which is in the altitude range of 30-35K ft. plotting exceedances per nautical mile of CG acceleration and the solid black line is from NACA TN 4332 which is the basis for many manufacturer's fatigue analysis. It can be seen that measured data from some B747s in operation in Europe show that these are actually recording lower CG accelerations than would be predicted by using the NACA TN 4332. The TN was considered to be fairly severe data and was developed initially for design of missiles but is very widely used for transport fatigue design.

But at an altitude range of 5-10K ft. (VG5-7), the recorded data exceeds predicted values. It is believed that this is a direct result of how the aircraft are operated at these altitudes, influence primarily by air traffic control and crowding.

The final development involves the automated reporting of metereological data by aircraft. The goal is to disseminate metereological data to all users essentially in real time and develop a worldwide turbulence map. There is an interim system in operation called the MDCRS (Metereological Data Collection and Reporting System). This program is a combined effort of the FAA, the National Weather Service, and Aeronautical Radio Inc. The ultimate goal is to combine it into the Aeronautical Telecommunications Network. The way the system works is that each airplane (see VG5-8), wherever it is flying, reports a parameter to the ground. This parameter is a measure of the level of turbulence at that point in space and time. It is important to be able to differentiate between aircraft motion and atmospheric motion, of course. This parameter could be in terms of m/sec, or a derived gust velocity, or a relative level of turbulence (mild or strong). These parameters are sent to a ground station where the three-dimensional information (altitude and geographic location) would be stored and analyzed. Access to this database would allow pilots to plan their route accordingly, if they had the freedom to do so.

Turbulence data acquisition, over many years, has resulted in justifying a reduced gust design criteria for airplanes in the clean configuration in the cruise mode. Manufacturers of the most recent transport configurations are being allowed to use this reduced gust design criteria based on the type of statistical data that was collected at cruise altitudes. This results in a 10-20% reduction of design gust loads on the airplane. But archaic air traffic control mode and ridiculous "hub and spoke" schedule, then what is being gained in design criteria will be lost in fatigue. A plea was made from the FAA to modulate the

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hub-and-spoke schedule and also to modernize the air traffic control system to give the pilots more flexibility.

Some of the questions asked:
1). With regards to the flaps extended problem, are all those cases at or below 10K feet altitude and in the terminal area maneuvering ? Do we know anything about the turbulence in the atmosphere at those locations ? Are we dealing with wake vortices ?

All that is known at this point is that these cases are with flaps deflected, which tends to indicate that they are fairly close to the airport. We do not know if we are dealing with atmospheric turbulence or wake turbulence. However, we do know that pilots are being forced to fly through turbulence, which they would rather not do and there is also a large number of airplanes in the vicinity.
2). Is the turbulence mapping a real-time data base or a curve-fitting procedure ?

It is a near real-time turbulence mapping with a time interval of a couple of minutes at a given location. It would either be sent automatically to airplanes or airplanes could interrogate the system to get the information. Serves as sampling information to aid in flight planning.
3). How difficult would it be to certify a strut-braced aircraft ?

No problem certifying any aircraft. Including a strut-braced aircraft. Recently certified the Airbus A320 with active flight controls, completely reevaluated the structural criteria, and for the first time allowed for a variable safety factor below 1.5 based on system structure interaction and the frequency of failures of active controls; from 1.5 to 1.25 (at low probability of system failure).

Conclusions by Walter A. Silva

It is clear from this session that structural design is a rapidly-evolving discipline with a potential to significantly impact existing and future aircraft configurations. Advanced aircraft configurations that were at one time proposed but subsequently rejected need to be revisited and analyzed in light of the structural design concepts mentioned in this session.

For example, how might the design of a strut-braced aircraft be impacted if the struts are made of composites which are lighter than metals but possess high strength as well as infinite fatigue life ? How might this strut-braced design also be impacted by the use of smart structures at the wing tips (feathers) that could adapt, in an optimal fashion, to different flight conditions and even different turbulence levels ?

It is also clear from this session that any rule which at one time was considered to be a "hard and fast" design rule may not be so hard or fast tomorrow as technologies evolve. This is evidenced by Mr. Barnes (FAA) presentation where, at the end, he mentions that the FAA has certified the Airbus A320 and allowed a variation in the 1.5 safety factor based on the reliability of active controls. This is clearly groundbreaking work and it behooves the U.S. industry (and its partners) to actively pursue and exploit those areas that could lead to a highly competitive product such as the A320. If the A320 had not broken new ground in terms of new certification requirements, would it be as competitive as it is ? That is, if the Airbus people had not decided to apply state-of-the-art technologies to their aircraft but had instead proceeded with a "same as usual" approach, there is a good chance that their product would not be what it is today.

It is very hard to ignore, once again, the example of the forward-swept wing aircraft. What was once a failed aircraft built out of metal became a successful vehicle when built with composites and active controls. Success requires that we take the risk involved with new and sophisticated technologies. If we just do what we have always done, we will simply stay where we have always been.

# TYPES OF STRUCTURES



Sensory

Actuating

Smart

Controllable

VG1-1

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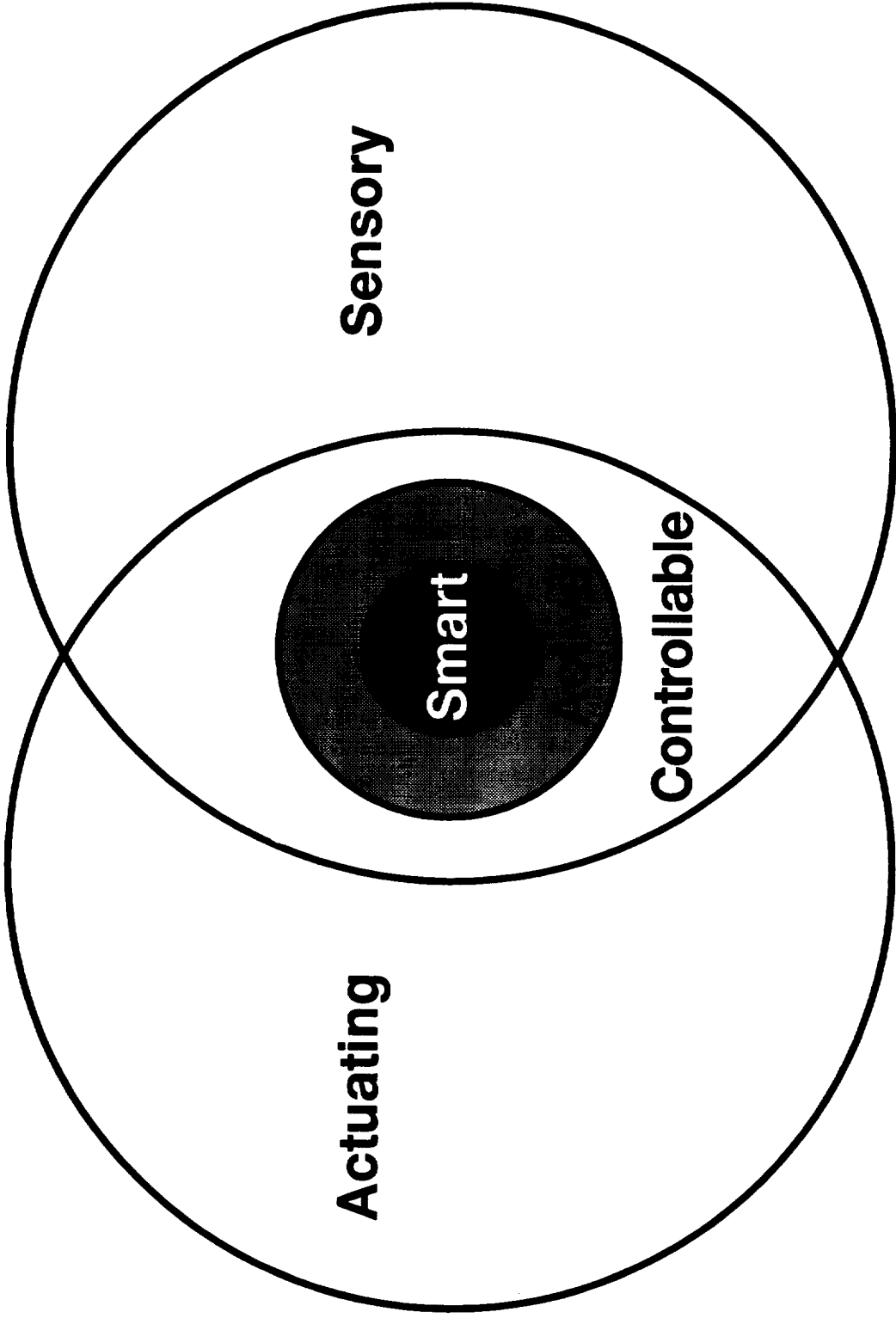
# CONVENTIONAL TRANSPORT STRUCTURAL DESIGN CONSIDERATIONS

- Metallic riveted stiffened-skin structural concepts

- Typical transport general requirements
  - 60 000 flight hours
  - 20 000 ground-air-ground cycles
  - 20-year economic service life

- General structural requirements
  - Be lightweight and span the space
  - Support the applied loads
  - Satisfy the structural design constraints
    - Do not fail
    - Do not buckle below a prescribed load
    - Do not fatigue
    - Do not flutter
    - Do not corrode
    - Be damage tolerant
    - Etc.

VG2-1

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# EMERGING TRANSPORT STRUCTURAL DESIGN CONSIDERATIONS

- General requirements
  - Longer service life
- Innovative structural concepts
  - Reduce structural weight
  - Support the applied loads
  - Satisfy structural design constraints
- Advanced materials
  - Exploit advanced composites and metallic materials
- Cost-effective fabrication processes
  - Reduce structural costs
- Computer-aided design and analysis
  - Reduced design-cycle time
- Structures-aerodynamics interactions
  - External loads
  - Influence of structural response and design on aerodynamic performance

# 777 LIGHTWEIGHT COMPOSITE STRUCTURE

777 composite structure:

- Toughened materials for improved damage resistance and damage tolerance
- Designed for simple, low-temperature bolted repairs
- Corrosion and fatigue resistant
- Weighs less (composite empennage saves over 1,500 lb compared with prior aluminum structure)

- ▨ Toughened graphite
- ■ Graphite
- ■ Hybrid
- □ Fiberglass

Rudder

Elevator

Fin torque box

Leading and trailing edge panels

Wing-to-body faring

Inboard and outboard spoilers

Stabilizer torque box

Floorbeams

Flaps

Flaperon

Wing landing gear doors

Outboard aileron

Outboard flap

Engine cowlings

Wing fixed leading edge

Trailing edge panels

Strut fwd and aft fairings

Main landing gear doors

Nose radome

Nose gear doors

VG2-3

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# COMPOSITE AIRCRAFT STRUCTURES SIZE COMPARISON

Beech Starship

McDonnell Douglas AV-8B

McDonnell Douglas F-18

Boeing 747

Douglas DC-10

Boeing 737

VG2-4

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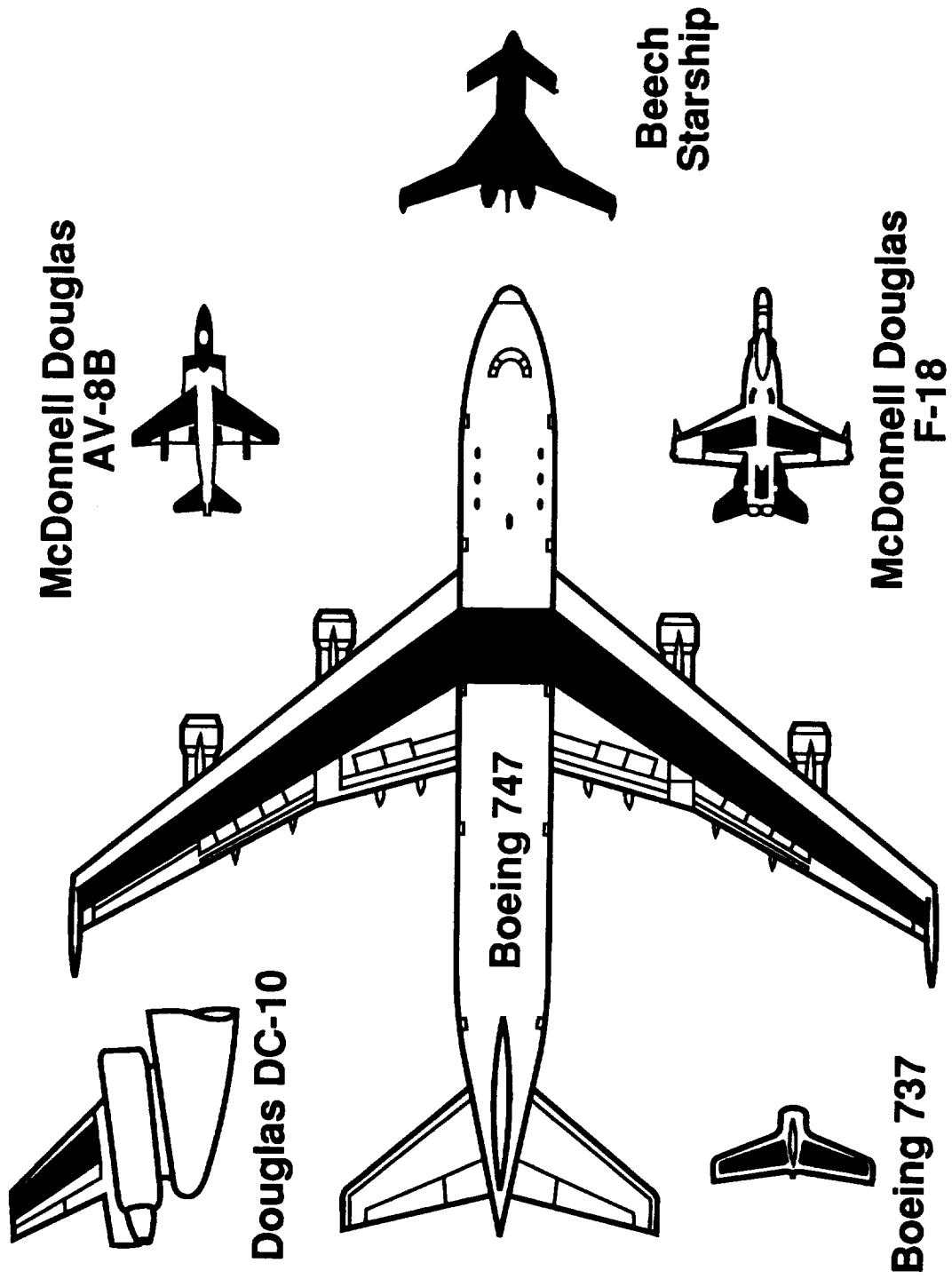
$w_o = 400\ 000$ kg
Payload = 120 000 kg
$b = 125$ m    $b^2/S = ?$
$s = 960$ m$^2$
L/D = 48 to 50, $M_{cruise} = .7$
Range = 11 000 nml

W. Pfenninger
March 1975

Split wing tips with active control for induced drag reduction and load alleviation

Laminar areas: Wing, empennage, struts, fuel nacelles possibly part of fuselage and engine nacelles

Jury-strut

Suction laminarized graphite struts for wing bending-and torsion load alleviation

Main engine in rear fuselage

c.g.
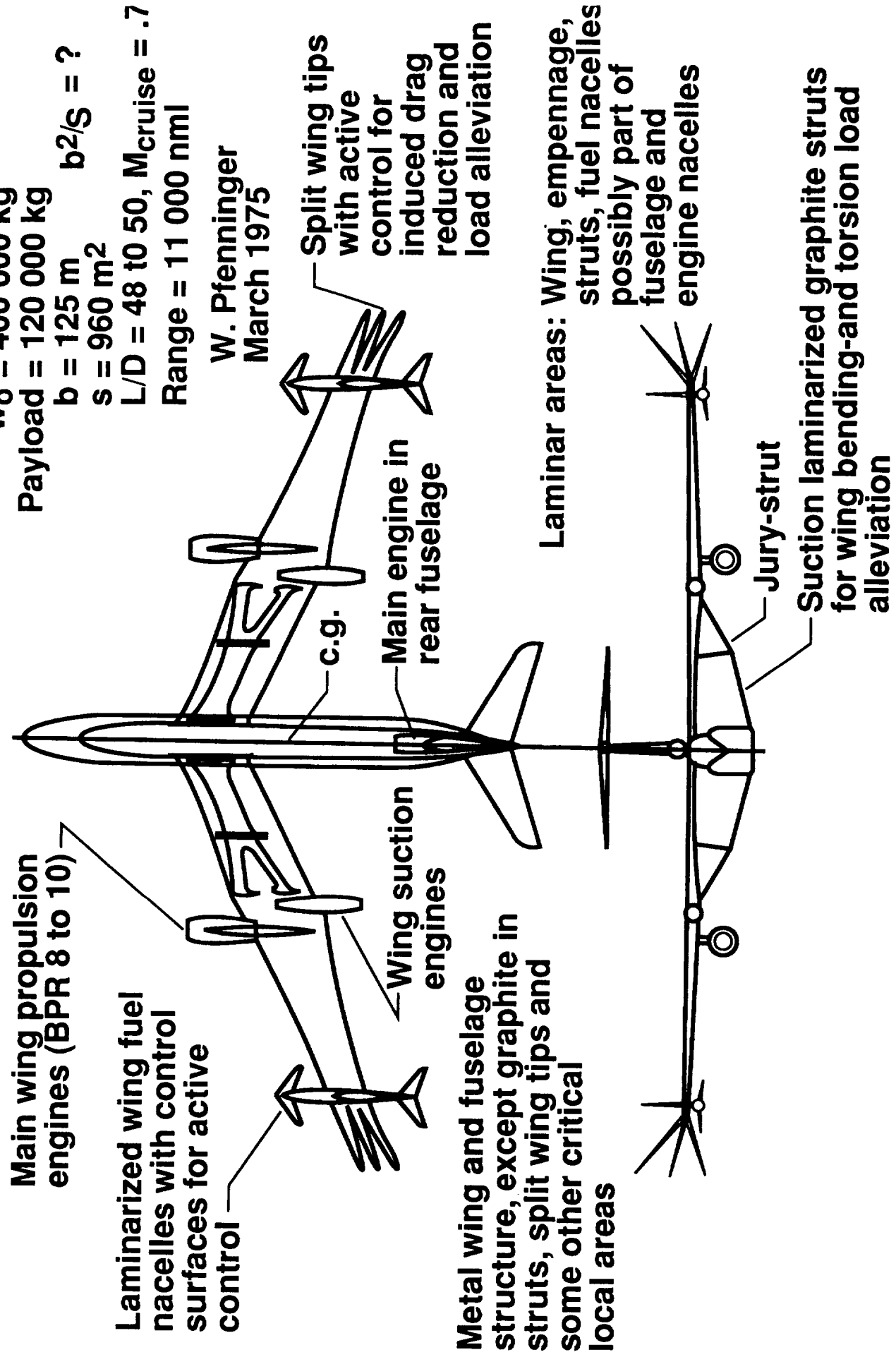
Main wing propulsion engines (BPR 8 to 10)

Laminarized wing fuel nacelles with control surfaces for active control

Wing suction engines

Metal wing and fuselage structure, except graphite in struts, split wing tips and some other critical local areas

VG3-1

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Lower Surface with cutout and same pressure distribution as isolated wing without cutout

Wing

$\varphi$ = sweep angle

Strut mean-line streamline around isolated wing (no cutout)

Cutout f on lower wing surface with the same pressure distribution on lower wing surface in the presence of the strut as on isolated wing without cutout

Experimental results (K. Rogers, Northrop Boundary Layer Research Group)

Lower surface of isolated wing (no cutout)

M-COS $\varphi$

f

a

$t_{st}$

$c_{st}$

$\dfrac{f}{t_{st}/2}$

1.0

0

1.0

$a/C_{st} \sqrt{1-(M\,COS\varphi)^2}$

VG3-2

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Double-braced wing, $b^2/S$ = 16.85

Single-braced wing, $b^2/S$ = 12.10

Cantilevered wing, $b^2/S$ = 7.50

$W_o$ = 400 000 kg
$W/S$ = 400 kg/m²
Wing 70% laminar

$L/D = f(C_L)$ for cantilevered, single- and double-braced M = 0.85 LFC transports

VG3-3
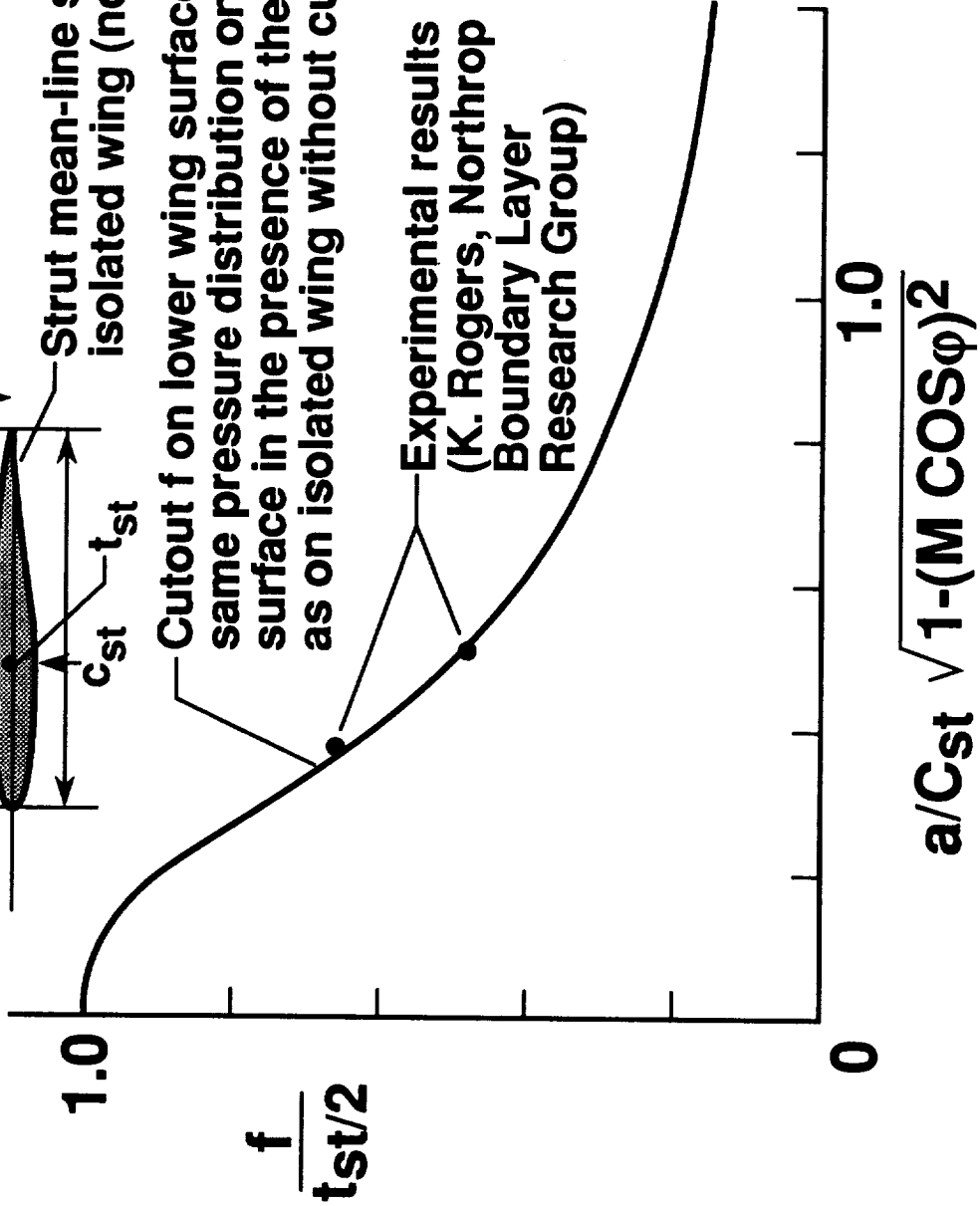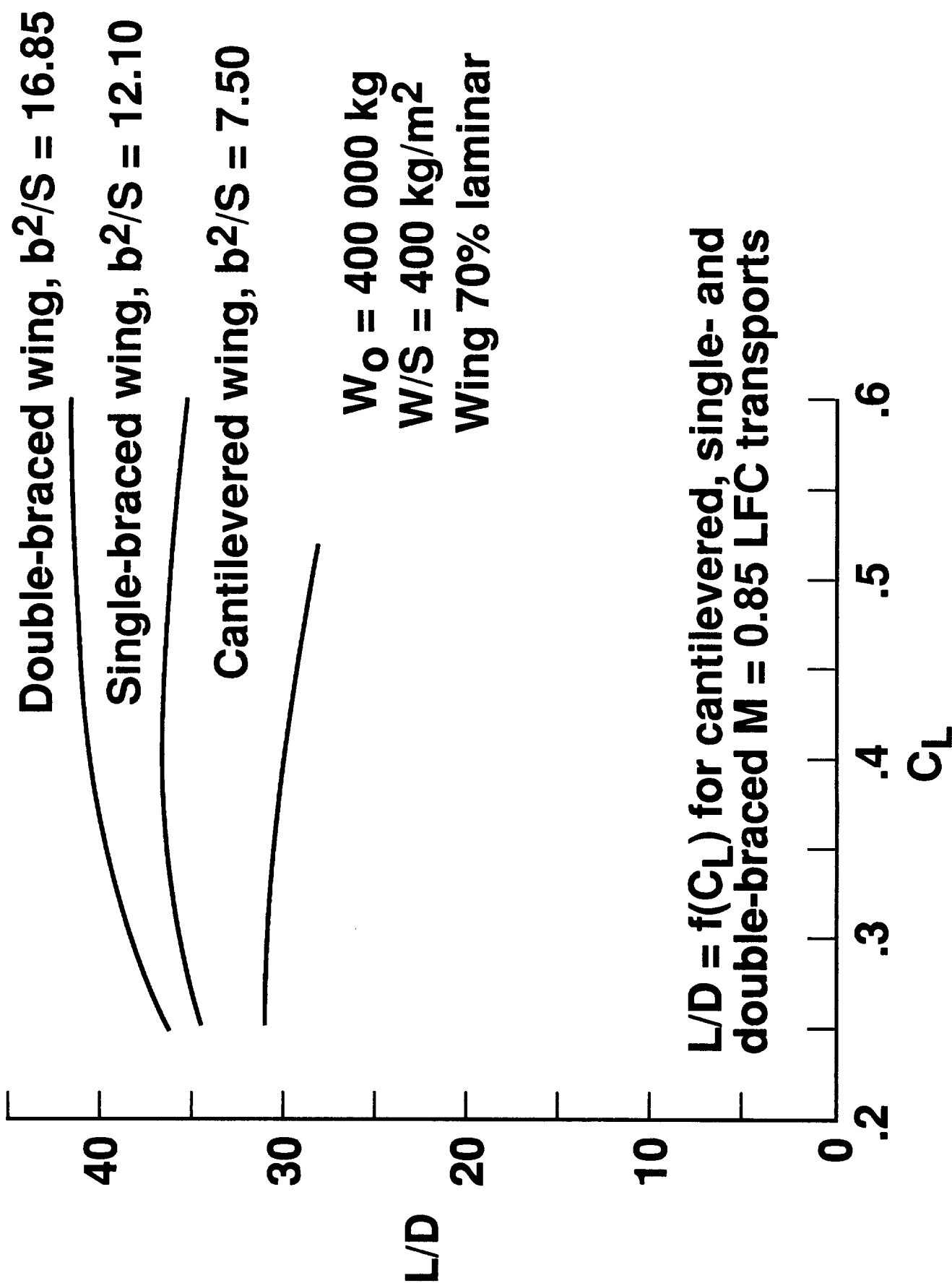
# AIRCRAFT RESPONSE DUE TO TURBULENCE (VERTICAL)

Lift = $C_L q S$

Gust lift = $\left( \dfrac{dU}{d\alpha} \cdot \Delta\alpha \right)$

$\qquad = \left( \dfrac{dU}{d\alpha} \cdot \dfrac{U}{V} \, K_g \right) \, q S$

U = vertical gust velocity, EAS

V = airplane forward velocity, EAS

$K_g$ = gust alleviation factor

# AIRPLANE GUST RESPONSE (ACCELERATION)

$$ = f \left( \dfrac{\dfrac{dU}{d\alpha} \quad U \, V \, K_g}{W/S} \right) $$

VG5-1

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# FAR 23.333 GUST SHAPE

The shape of the gust per § 23.333 is:

$$U = \frac{U_{de}}{2}\left[1 - \cos\frac{2\pi S}{25\bar{c}}\right]$$

Where -

$s$ = Distance penetrated into gust (ft);
$\bar{c}$ = Mean geometric chord of wing (ft);
and $U_{de}$ = Derived gust velocity, ft/sec



VG5-2

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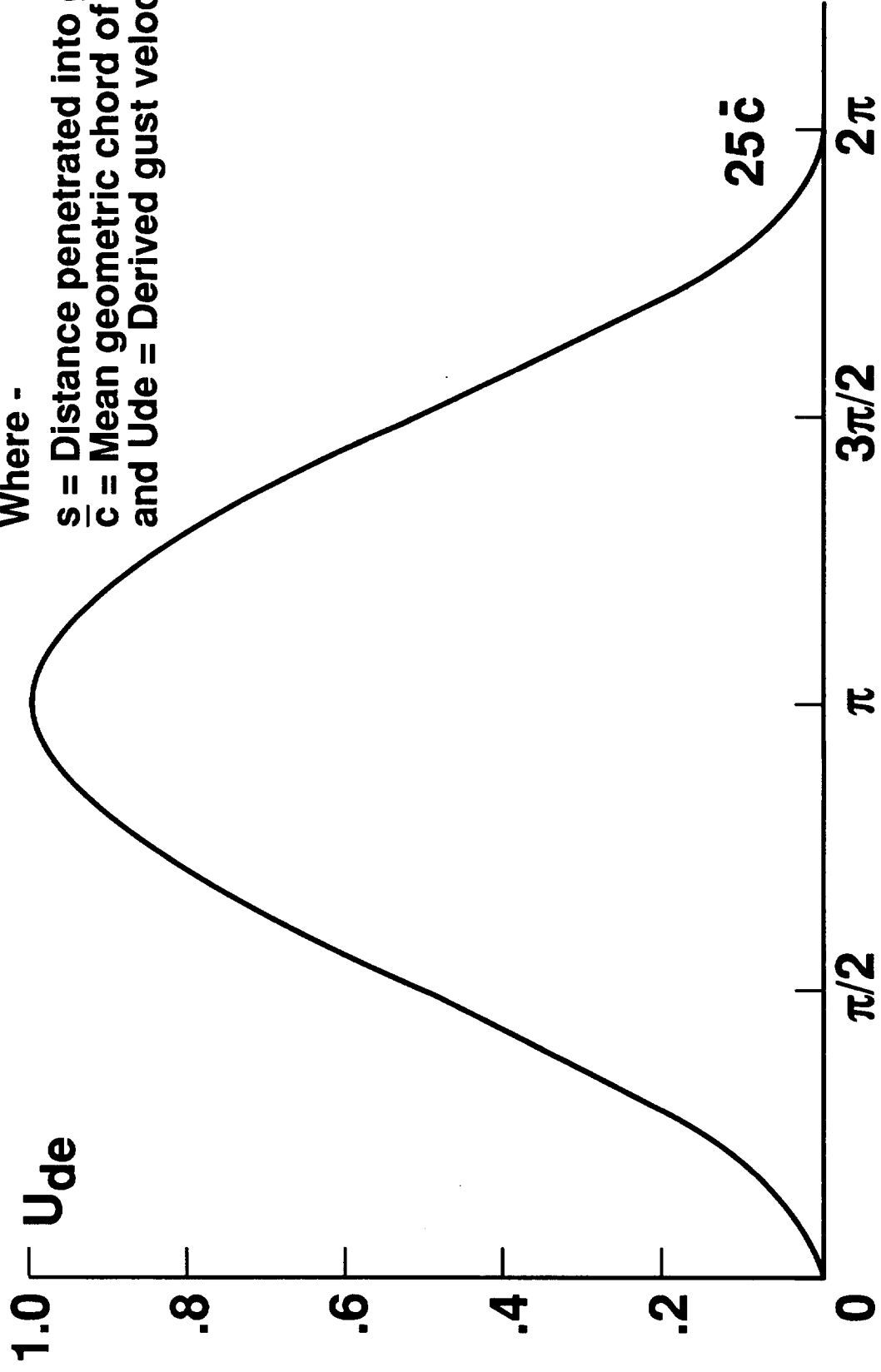
# CANARD AIRPLANE RESPONSE
# TO 1-COS GUST



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VG5-3
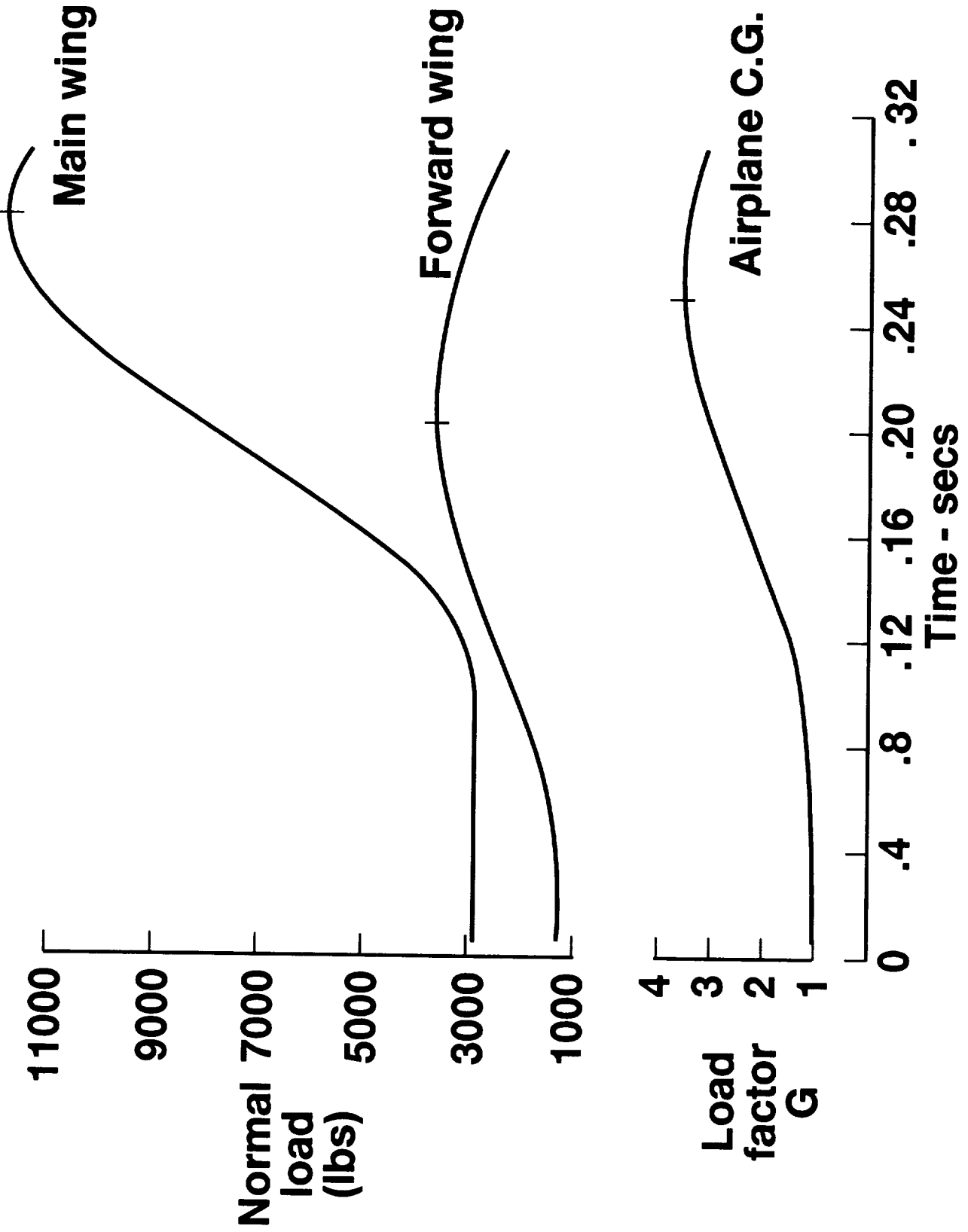
# EFFECTS OF AIRPORT PRODUCTIVITY ON AIRCRAFT CONFIGURATION

"Weather conditions and air traffic control adjustments are probably the outside factors that most influence the pilot's ability to conduct a smooth transition from the terminal descent and arrival phase of the flight into the approach and landing segment. Air traffic control adjustments include speed, maneuvering parameters (vectors for spacing), and descent rate changes."

" In addition to weather; one of the major variables affecting air traffic relates to the "hub and spoke" operation commonly used by most major air carriers today. During peak periods, traffic flow must be maximized and capacity increased at hub airports--"

REF: Bill Hendricks, Director, FAA Office of
    Accident Investigation

    FAA World article titled "Safe Landings",
    March 1993

VG5-4

BOEING 747-200 GUST ENCOUNTER EVENT 50100

W = 340900ko   M = .371   Alt = 1812 ft   VCAS = 239 kts   Flap 10 deg
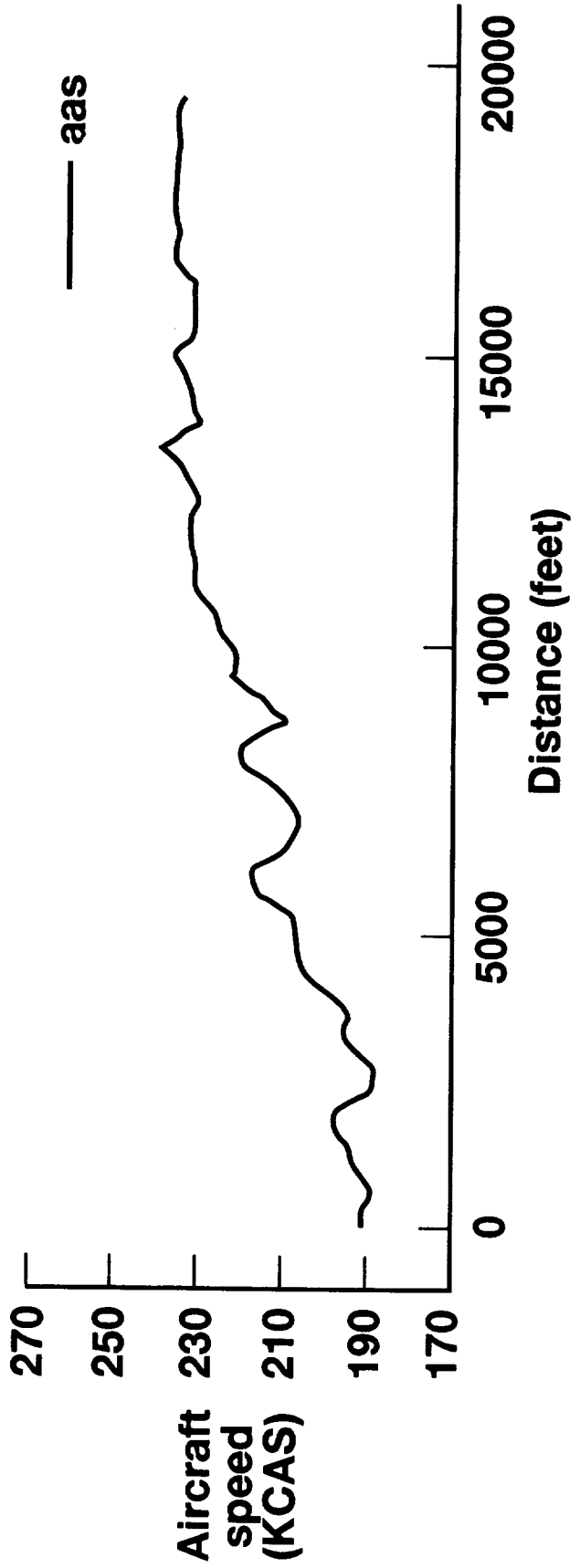
Ude

Gust velocity (ft/sec)

aas

Aircraft speed (KCAS)

Distance (feet)

VG5-5

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# UPWARD GUSTS

NLR TR 8213IL    (NACA TN 4332 A/P)
- ○   - AC=PH-BUD
- □   "   - AC=PH-BUG
- ◇   "   - AC=PH-BUL
- ⬠   "   - AC=HB-IGA
- ◁   "   - AC=LN-KHA

ALT 30K-35K FT



Exceedances per N.Mi. vs Derived gust velocity, UDE (FPS)

VG5-6

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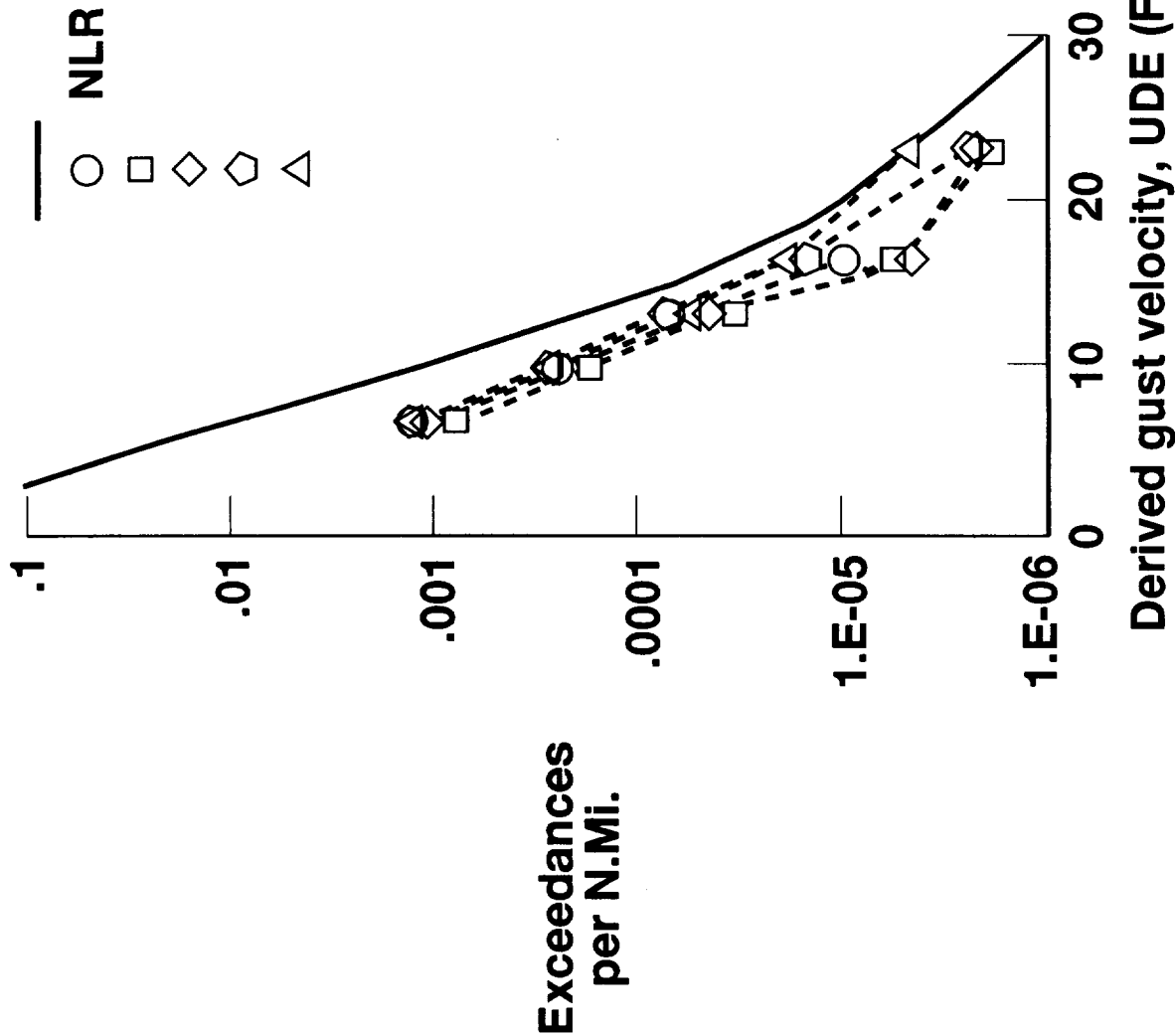
# UPWARD GUSTS

NLR TR 8213lL (NACA TN 4332 A/P)
○ — AC=PH-BUD
□ " — AC=PH-BUG
◇ " — AC=PH-BUL
⬠ " — AC=HB-IGA
◁ " — AC=LN-KHA

ALT 5K-10K FT

Exceedances per N.Mi.

Derived gust velocity, UDE (FPS)

VG5-7
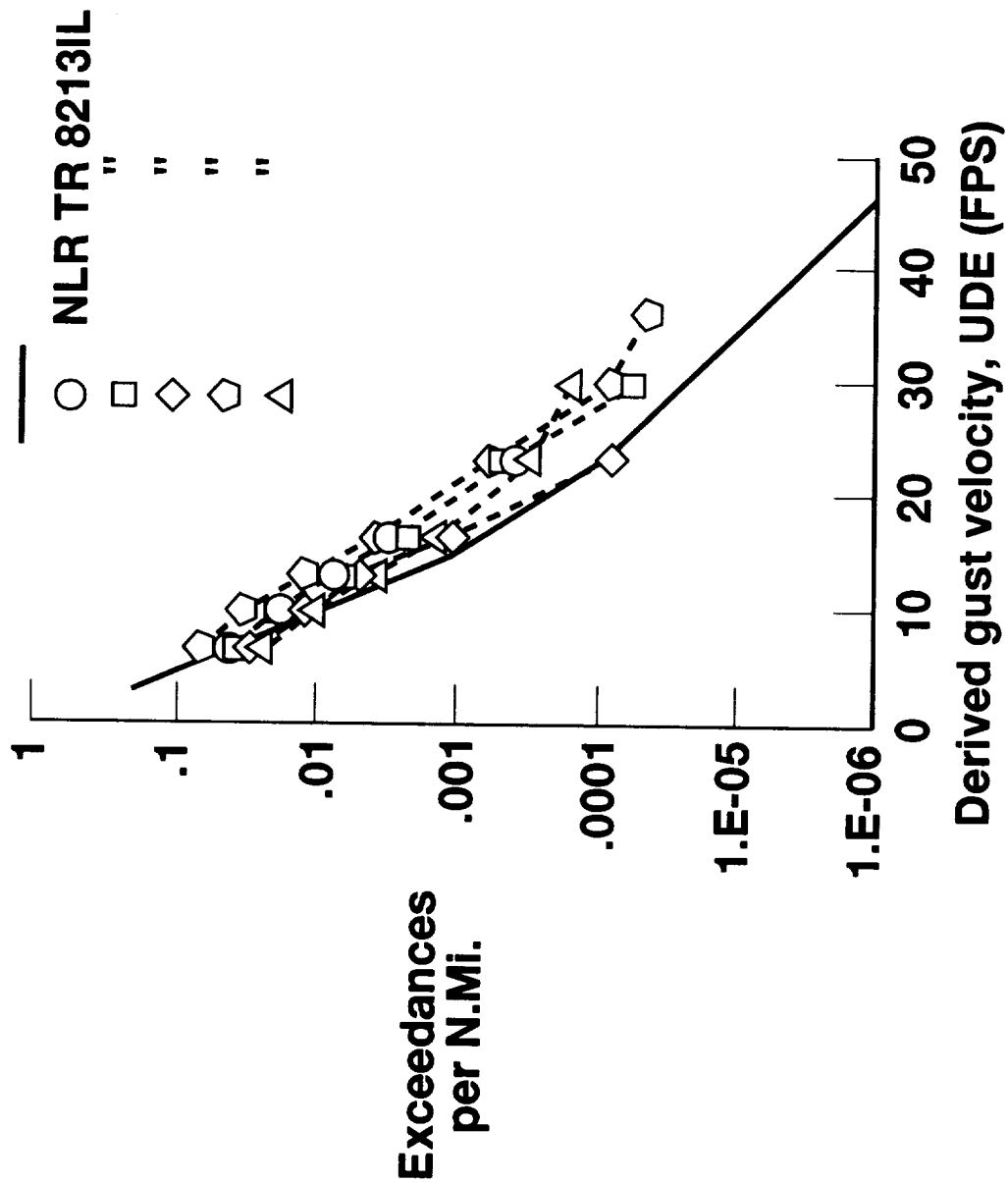
# MDCRS SYSTEM DIAGRAM
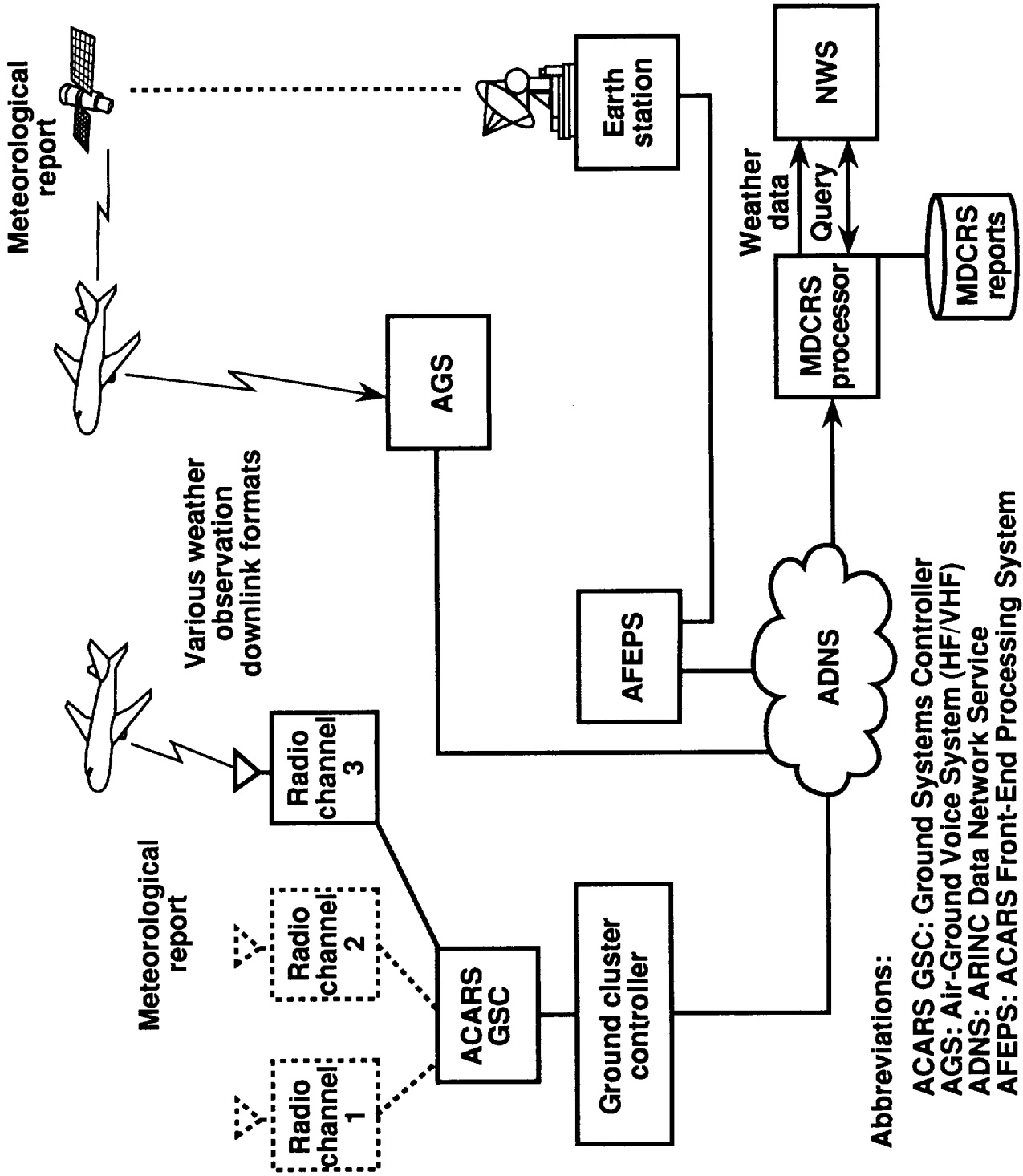


Abbreviations:

ACARS GSC: Ground Systems Controller
AGS: Air-Ground Voice System (HF/VHF)
ADNS: ARINC Data Network Service
AFEPS: ACARS Front-End Processing System

VG5-8

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## Session VI: Aircraft/Airport as a System

### by Christopher E. Glass

This chapter presents a overview of the aircraft/airport system session of the workshop. Included after this brief overview are copies of the overhead slides presented during the session. Additionally, a copy of Holmes' scheduled presentation is included for completeness. The session was split between discussions on private and general aviation aircraft, multidisciplinary design methodologies, and future transportation alternatives. These subjects may not seem to be interconnected to the aircraft/airport system; taken together however, these subjects provide a road map to a new aircraft/airport system for our country, a way to get there, and some alternatives for future transportation alternatives.

As a first step, we must look at where we are now. The present aircraft/airport system provides for the transportation needs of the flying public. During good weather conditions, one can expect an on time arrival at an airport, however, one can expect delays if the weather becomes bad. As an example, if a snowstorm affects the hub airports of the present system, delays of days can be encountered by the flying public as experienced during the spring snowstorm of 1993. The present system can and must be improved because the present system will not provide for the future needs of our country. Even a marginal improvement in the short term will ease the burden of facing hours of delay in huge aircraft traffic jams in the nation's sky.

What should the aircraft/airport system of the future look like? The presentations of Holmes, Crow, van't Riet, and Bushnell provide alternatives to the present system. Use of private aircraft with advanced electronics and better use of the smaller airports will relieve some congestion of our present system. The idea of a hybrid automobile/airplane presented by Crow could be made into a reality if the cost was within reach of the average citizen. The technology to build such a vehicle is now available and mass production would make the vehicle affordable. The

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California corridor study of van't Riet and his students is also intriguing because it provides a means of transporting vast numbers of people on the crowded west coast without using the present highway system. Also needed are similar studies for the southcentral, eastern, northeastern, and other densely populated areas of the country. Another alternative is the MAGLEV transportation system presented by Bushnell which will move people at greater speeds and lessen the future burden on the airport/aircraft system.

Future transportation alternatives like those presented and others must be identified and studied closely. Then well informed decisions as to the type and mix of the future transportation can be made. One method to aid in these decisions is multidisciplinary optimization. Multidisciplinary methodology is presently used to optimize product development as discussed by Coen and Tulinius. Newman, Sobieski, and Hou present multidisciplinary methodology as a tool which can be applied to combinative disciplines. Extending the methodology to the limit, one could use the multidisciplinary tool as a guide in decisions concerning parts of the future air transportation system. By identifying the functional dependence between configuration aerodynamics, enabling technologies, environmental concerns, economics, safety, passenger comfort, public opinion, etc., one can then use the calculus of the multidisciplinary methodology to optimize various future transportation system possibilities including the aircraft and airport as a system. The nation would then be in a position to take an aggressive posture in development of the technologies and industries needed to move us toward a better air transportation system. By evolving and acting on such an optimized future transportation vision, new economic opportunities for the United States in advanced transportation technologies would be created.

An example of using a multidisciplinary system approach to incorporate change into the present aircraft/airport system for the future is discussed below. Presently, to increase capacity or upgrade the air transportation system requires that either new aircraft be designed to fit within the constraints of existing airports or new airports be

designed to accommodate the present aircraft fleet. This restricts both the type of aircraft and type of airport to a system with rigid boundaries allowing for little change. Both the aircraft and airport treated in this manner are constrained by each other. However, the air transportation system need not be so constrained. The future transportation system may be based on a mixed fleet of aircraft using a mixed airport system in conjunction with ground transportation. Such a system needs to be optimized. A larger number of smaller aircraft including helicopters and tiltrotors could use existing general aviation airports for short distance flights. If the forecasts of the hybrid automobile-flying machine become a reality, there will be an increase of smaller aircraft. For longer flights, the fleet could consist of a mix of present turbojet aircraft, large seaplanes, and ultra-large aircraft. Large seaplanes require only a marine runway and are ideal for moving people along and between coastal regions of the of country. Use of ultra-large aircraft in the mixed fleet will require modification of a selected number of existing large airports. Ground linkage between small airports, seaplane ports, large airports, and urban centers within such a mixed air transportation system could be made by high speed rail, MAGLEV, or any other ground transportation system. The consumer of transportation would then have a number of options for their travel plans. A multidisciplinary approach to define such a mixed air and ground transportation system is possible. Optimization of such a system would increase capacity and upgrade our present air transportation system without being constrained by the present system.

**Presentations in the Appendix:**

"U. S. General Aviation: The Ingredients for a Renaissance, A Vision and Technology Strategy for U. S. Industry, NASA, FAA, and Universities" Bruce J. Holmes, NASA Langley Research Center.

"Advanced Navigation and Personal Aircraft" Steven C. Crow, The University of Arizona.

"How Far Can the Multidisciplinary Methodology be Taken?" Perry A. Newman, NASA Langley Research Center; Jaroslaw Sobieski, NASA Langley Research Center; and Gene J. Hou, Old Dominion University.

"Multidisciplinary Design Research at NASA Langley" Peter G. Coen, NASA Langley Research Center.

"Multidisciplinary Design Optimization is Key to Integrated Product Development Process" Jan Tulinius, Rockwell International.

"Future Transportation Alternatives" Robert van't Riet, California Polytechnical State University.

"MAGLEV" Dennis M. Bushnell, NASA Langley Research Center.

## U.S. GENERAL AVIATION: THE INGREDIENTS FOR A RENAISSANCE

A Vision and Technology Strategy
for
U.S. Industry
NASA
FAA
Universities

January, 1993
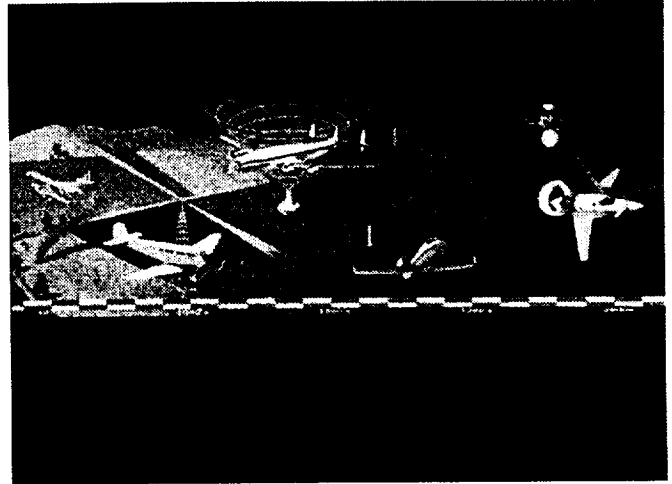


### Title

- In the Nation today, General Aviation
  - Is a **vital** component in the nation's air transportation system
  - Is **threatened** for survival
  - Has enormous **potential** for expansion in utility and use

- This potential for expansion is fueled by **new** satellite navigation and communication, small computers, flat panel displays, and **advanced** aerodynamics, materials and manufacturing methods, and propulsion technologies which create opportunities for new levels of environmental and economic acceptability.

- Expanded general aviation utility and use could have a large **impact** on the nation's jobs, commerce, industry, airspace capacity, trade balance, and quality of life.

### Panorama

- Nation's economic strength and quality of life depend on the utility, **capacity, safety, and efficiency** of transportation and communications systems.

- In the U.S., **Three waves of expansion** have occurred in transportation and communications. These three waves have fueled the nation's economic growth through the emigration of industries out of the cities, into the country.
  1. The first wave occurred earlier than aviation, with the development of canals, rural electrification, and railroads;
  2. The second wave occurred in the 1950's with the development of the Interstate Highways and Hub/Spoke air travel, as well as nation-wide telecommunications;
  3. We are in the beginnings of the third wave, with the implementation of Fiber-optics, satellite communications and navigation, and new air and ground transportation modes
  - On the **ground**, new high-speed and light rail will serve a few hub cities; we could see the introduction of Intelligent Vehicle/Highway Systems.
  - In the **air**, we will see a new generation of supersonic transport airplanes for transoceanic travel; very large (600 to 800 passenger) subsonic jet transports; fast commuter aircraft (perhaps including tilt-rotors); and, potentially, expanded general aviation to more completely serve the "off-airways" population in the nation.

I want to leave you today with a vision of how expanded general aviation transportation could **contribute** to the nation's future transportation infrastructure, **why now** is the time for action; and **how** we can make it happen



### General Aviation Shipment and Billings

- The opportunities facing us are exciting, but the threats are serious:
  - Active **pilots** down 15% in last 10 years
  - Active GA **fleet** contracting, down 10%/10yrs; 3% last year; 75% fly <100 hrs/yr
  - Public use **airports** down 15%/10yrs; 43% **FBOs** operate at loss
  - Aircraft production at 3% of 1978 peak; average **age** = 25 years; **technology** > 30 yrs.
  - **Jobs** down over 50% in last 10 years from 43,000 to 20,000 in general aviation
  - **Imports** today = exports of 1978
  - Public **misperceptions** of G.A.'s role in the air transportation system,
  - A broad range of inhibitors to **utility**;
  - The absence of a **national technology strategy** for general aviation.

- Before 1978, GA billings tracked the GNP/GDP. Decoupled in 1978; reasons?:
  - Product Liability
  - Tax code changes
  - GI Bill ended
  - Availability of cheap, used airplanes to satisfy the "enthusiast" market
  - Most important from a technology strategy standpoint, after 1978 we no longer invested in the development of technologies for utility. That is, the lower-end airplanes became out-of-date with the increasingly complex airspace system. In contrast, the higher-end airplanes did keep pace, and they are selling today.



### MARKET DEMAND

27 Air Traffic Hubs
(65% of Passengers)
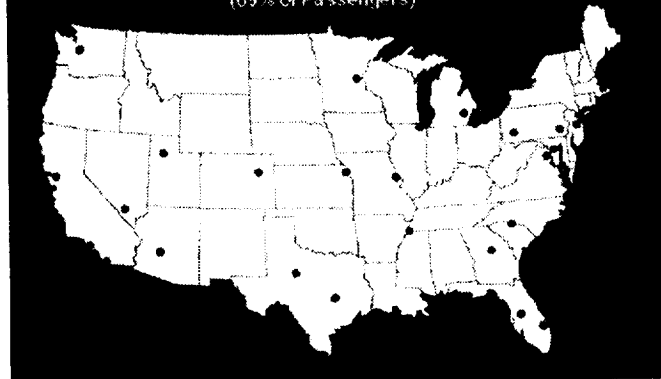
### Airport Infrastructure (Hubs)

- The Nation's 27 largest air traffic hubs serve about 65 percent of the total scheduled air carrier passengers.

- These long-haul route hubs are supported by the next level of service:
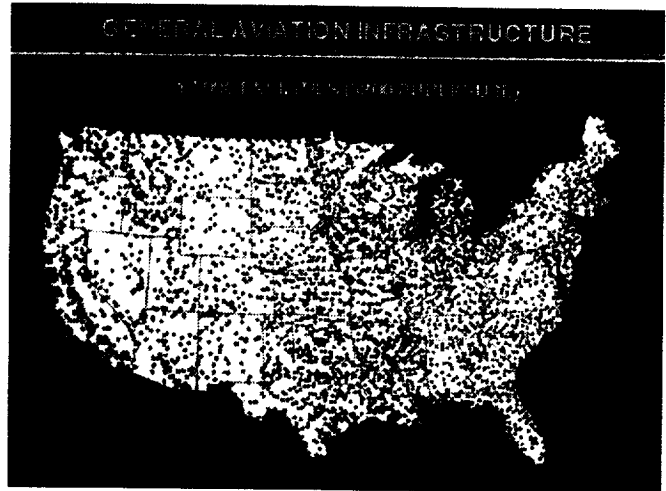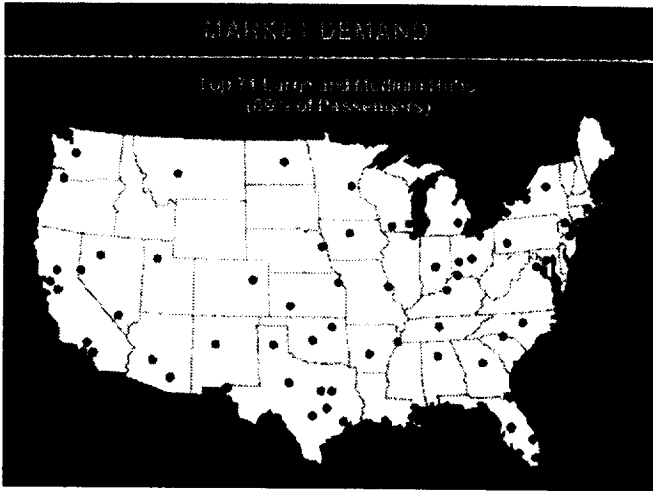
**Airport Infrastructure (Hubs + Spokes)**

- The top 71 largest and medium hubs serve almost 90% of the nation's total scheduled air carrier passengers.

- In total, the current hub-spoke system serves 483 cities with 582 airports. However, this hub-spoke system does not efficiently serve the nation's population which lives further than one-hour's drive from those 582 airports. This part of the nation's population is without scheduled (or even readily available, affordable, non-scheduled) air service, and is therefore out of the country's economic mainstream.

- These data beg the question: "How can the nation's air transportation infrastructure be expanded to provide air service to the rest of the population?" This presentation will suggest that the answer lies in general aviation.

- The good news is that we already have invested in the ground and air traffic management infrastructure needed to expand air transportation to the rest of the nation:
  - FAA Capital Investment Plan ($32B) for communications, navigation, surveillance
  - And the rest of the infrastructure consists of the nation's general aviation airport system:



**General Aviation Infrastructure**

- This is the general aviation component of the nation's air transportation infrastructure
  - Very under-utilized
  - Threatened
  - Need aircraft and airspace systems with higher utility to make full use of this national asset.

- The general aviation airport infrastructure consists of over 17,000 facilities, 13,000 airports, 5200 public-use airports.

- These airports provide many small and medium industries with transportation to their customers, rapid, on-demand, random-access transportation for parts delivery, aerial ambulance services, and organ donor flight support. It is because of the availability of air transportation that these airports help spread industry and commerce throughout the nation.

- Even small public-use airports contribute significant economic benefits. In Virginia, for example, the average public-use airport has only 23 aircraft based, and contributes 1.6 million per year in economic activity, most of which is spent locally.

- What you see here is the rest of the nation's air transportation infrastructure which we already own and which could be even more important, economically, in the future.
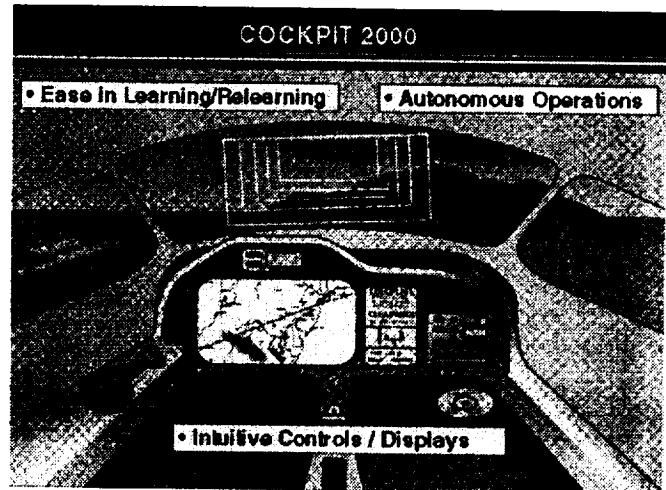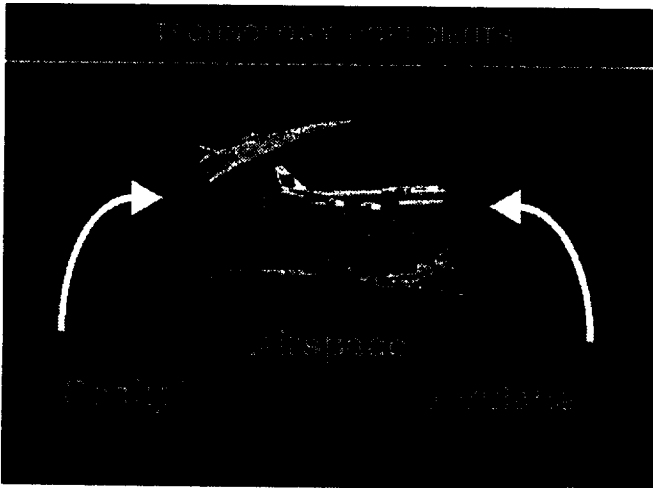


**Technology Ingredients**

- Let's look at the technology ingredients which can enable the development of a new generation of general aviation aircraft. Specifically, Cockpit/Airspace/Airplane Technologies have matured in 1980's and which will mature in the 1990's, enable the potential for an expansion in the utility, safety, and use of general aviation airplanes in the U.S. air transportation system



**Cockpit 2000**

The development of low cost, small computers and flat panel displays have created the opportunity to apply human-centered automation technologies which can enable the development of systems for controls, navigation, communication, and operations which are easier to learn and relearn, and systems which can provide for computer aided decision-making for simplified operations in future aircraft. These systems can also have embedded instruction capabilities; in fact, the cockpits in these future aircraft could have dual use as simulators on the ground for training purposes.

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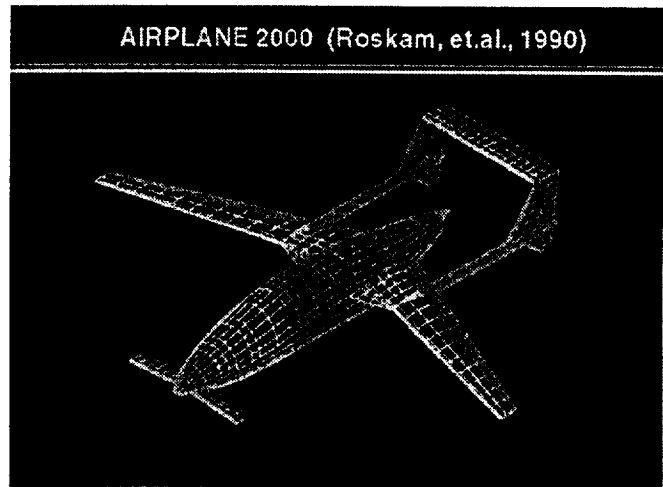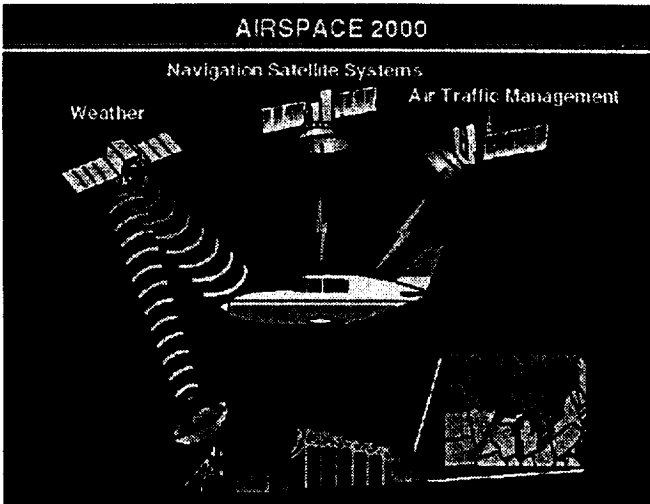
## AIRSPACE 2000



### Airspace 2000

- Within the past several years we have seen a **migration** of weather information centers out of the **flight service** weather bureau stations into briefing rooms at local airports. The next logical step in the migration is for weather information to be provided in the **cockpit**. In fact such a system was test flown in a Piper Malibu under a NASA SBIR research contract in the Summer of 1990, in Wisconsin. With today's communications and sensor capabilities, it is even possible have general aviation airplanes report meteorological data to other aircraft and ground stations, much the way the transport operators have started doing today.

- The development of GPS and other global navigation satellite systems is the most significant revolution since the **advent of radio navigation**. This technology will provide the **accuracy** to make every landing sight at least a Category I Precision Approach. The accuracy is only half the story, the **cost** is the other half. As the use of GPS navigators spreads throughout the world for both air and ground vehicles, economies of scale will drive costs down.

- The final part of the Airspace story is the future air traffic management system. The The FAA has been provided with $32 billion **Capital Investment Plan** to modernize the navigation, communication, surveillance, and control systems for our nation's next generation airspace system. This system has the potential to support the General Aviation Vision and strategy in this presentation.

## AIRPLANE 2000 (Roskam, et.al., 1990)



### Airplane 2000

- In order for the next generation of general aviation airplanes to be environmentally and economically acceptable, they need to take the fullest possible advantage of advancements in
  - acoustics,
  - materials and manufacturing methods,
  - aerodynamics,
  - and propulsion.

- As the world's aircraft companies have learned to squeeze every last drop of performance out of airplane designs, the competition has moved from performance to product development cycle times. This means that significant competitive advantage is gained by investing in the development of advanced computational design tools, improved testing techniques, and lower cost manufacturing technologies.

- These advancements need to be incorporated in order to "pay the way," so to speak, for the investment in the cockpit technologies which expand the utility and safety.
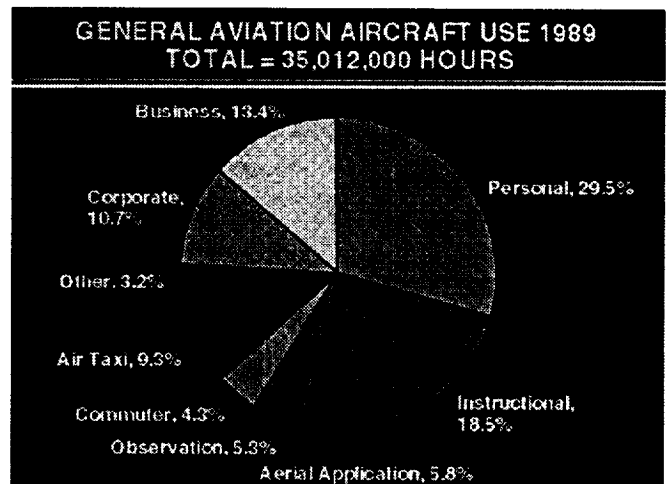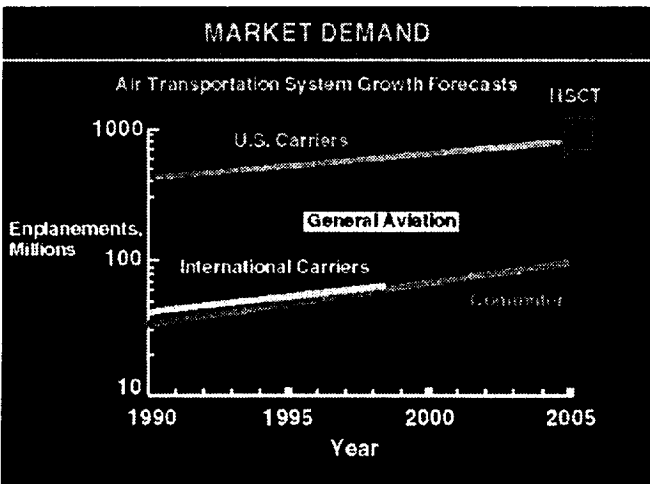
## MARKET DEMAND



### Market Demand

- General Aviation enplanements = 1/3 of U.S. Air Carriers, 3 times commuter & Int'l Carriers General Aviation **miles flown** (4.5578 billion) = Air Carrier (4.9478 billion miles)
  - In terms of enplanements, General Aviation is the **nation's largest airline!**
  - important to look at P-Ms for 150 to 700 mile trips: GA is 1/3 of those air trips, 4% of total air and ground
  - for shorter trips, <150 m., cars serve most of need
  - for longer trips, >700 m., long haul scheduled air carriers serve most of need
  - General Aviation could expand to fulfill more of the nation's need for the intermediate routes

- **What's wrong** with this picture is that the **growth rate** forecast for general aviation is only 0.3%, or one-tenth of the growth rate of a healthy GDP growth rate. In comparison, the other modes of air travel are forecast to grow at rates of 4 to 7 percent.

- From the perspective of **people served**, G.A. is a large part of the national air transportations system, is underutilitized, and can contribute in our efforts to improve airspace capacity and congestion.

## GENERAL AVIATION AIRCRAFT USE 1989 TOTAL = 35,012,000 HOURS



### General Aviation Aircraft Use

- G.A. flew 35M hours in 1989, twice the Air Carrier hours; 62% for cross-country

- 30% Personal Flying is the GA equivalent of tourist flying on the airlines (54% of Air Carrier flying is "personal"). Even the 30% personal use is important to the economic health of FBO's so that they will be able to serve the commercial users (47% of nation's FBO's lost money last year)

- By the measure of **value of usage**, technology development for expanded use of General Aviation would be a wise investment for the future U.S. Air Transportation System infrastructure

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**U.S. ANNUAL AIR TRAFFIC OPERATIONS 1987-1989 AVERAGE**
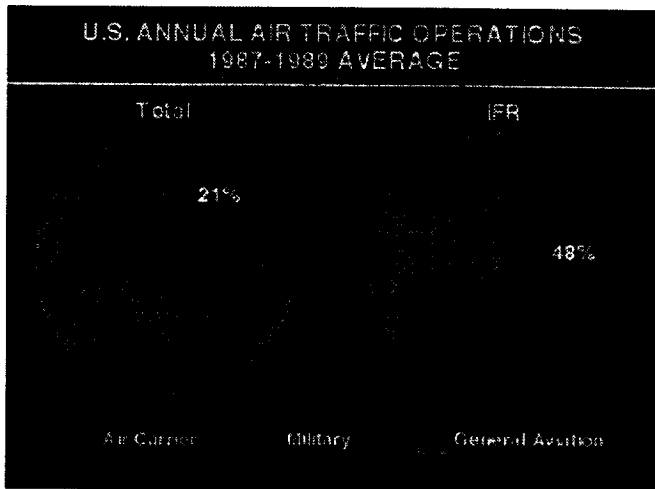
**U.S. Total Annual Air Traffic Operations, 1987-1989 Average**

* An operation is an arrival or a departure.

* Total U.S. operations comprised of 75% G.A. aircraft;
  G.A. departures are nearly 4 times the rate of Air Carriers

* There are important **differences** between the two kinds of pilots and operations.
  GA pilots tend to be part time, fly into **strange airports** more frequently than scheduled
  air carrier pilots, have less time to invest in **initial and recurrency training**, and have
  less capable **equipment** both in terms of aircraft and systems performance, and
  in cockpit flight systems.

* For maximum impact, research to improve the **operational
  capacity** of the national air transportation system should
  address the **cockpit and airspace** technologies specific to G.A.
  airplanes and pilots in addition to our current efforts for transport aircraft.



**GENERAL AVIATION FATAL ACCIDENTS 1982-1988**

**General Aviation Human Factors Accidents    (1982 - 1988)**

* Overwhelming proportion: Human Factors
  - Involving flight deck; ATC-flight deck interactions; aircraft
    maintenance; and airways maintenance

* The airframe/engine/systems play a decreasing role in accidents.

* Definition of "Human Factors" related accidents
  - Judgment
  - Man-machine interface
  - Need to include other than "Pilot-Error" in this category,
    Numerous casual factors include:
    - improper maintenance
    - improper installation
    - improper overhaul
    - improper part
    - improper assembly

* Technology offers to greatly alleviate many "Human Factors" accidents

* We need to expand General Aviation activities in the National Human Factors
  Research Program

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**GENERAL AVIATION FATAL ACCIDENTS 1982-1988**

**General Aviation Accidents (1982-1988, AOPA/ASF)**

* Enormous improvements over the past decades for G.A. accidents;
  **current fatalities/100 Khrs is 1/2 of 1975 rate;**
  **During past 4 years**, G.A. acft flown by salaried crews had fewer
  accidents/100Khrs than scheduled air carriers

* The message in these accident statistics is that newly maturing technologies can
  significantly impact nearly all of the kinds of accidents occurring today.

* The general aviation safety **goal** should be established by studying the reasons for the
  outstanding record for corporate aviation safety, understand the differences between the
  pilots, equipment, and operations, then apply the lessons to all of general aviation.

* Terminal operations accidents include taxi, takeoff, climb, descent, IFR
  and VFR approach, and landing. The casual factors in these accidents
  include stall/spin or other loss of control, attempted VFR into IFR
  conditions, improper operations, and mid-air collisions (which represent
  0.5% of all accidents).

* Cruise weather accidents are 4.7% of total, but 20.8% of fatal accidents. New technologies
  are particularly relevant to this kind of accident. If pilots can be aware on a near real time
  basis of their position, the relative location of weather and terrain, this kind of accident
  would greatly decrease. We have most of these technologies ready for integration today.
  The challenges are human factors engineering of the displays, and certification.



**FUEL EFFICIENCY COMPARISONS**

**Fuel Efficiency Comparisons**

* This figure illustrates the **strides** of the past two decades in airplane performance
  We have seen a doubling of the fuel efficiency at a given speed; conversely, we have
  seen a doubling of the speed at a given fuel efficiency.

* While these gains are impressive, even **further gains** are possible from advancements in:
  - Drag reduction aerodynamics, including laminar flow control
  - Lighter weight structures and materials
  - Improved engines with lower power-to-weight ratios and fuel burn

* As the world's airplane manufacturers continue to take advantage of these advancements,
  a new driver for competition is emerging: product **development cycle time**. The ability of
  U.S. manufacturers to compete in the future will increasingly depend on their ability to
  reduce the time required to design, test, and certify new aircraft and systems. Aeronautics
  research can contribute to reduced cycle times by improving the speed and accuracy of
  computational design tools, testing techniques, and certification processes.

## OBSTACLES TO UTILITY

### USER ACCEPTANCE

* Cost/Performance
* Time for learning/relearning
* Safety
* Comfort

---

### Obstacles to Utility

* The critical question is, "What obstacles inhibit the expanded use of General Aviation aircraft?" This is an important question because the solutions lie in the answers.

* Cost of ownership / operation / nearly all-weather systems performance
  - Product liability adds to the purchase price
  - Current production rates of 1500 aircraft do not command economy of scale
  - Tax laws, Airline competition, Reliability
  - Both technology and volume are required to bring costs down.

* Proficiency requirements
  - Learning and re-learning to fly airplanes requires expensive time/cost
  - Airplanes must be made easier to learn and re-learn how to fly

* General Aviation fleet safety is not yet competitive with automobiles
  - The goal for G.A. should be to achieve corporate levels of safety; it will be difficult to achieve, but technology offers significant help.

* Ride comfort
  - Gust response
  - Interior noise: without headphones;
  - Features: air-conditioning; audio systems; flight phones.

---

## OBSTACLES TO UTILITY

### USER ACCEPTANCE

* Cost/Performance
* Time for learning/relearning
* Safety
* Comfort

### COMMUNITY ACCEPTANCE

* Noise
* Safety
* Emissions
* Elitist Image

---

### Utilization Inhibitors. (Concluded)

* Airport noise concerns top the list. The threat of curtailed, curfewed, and and outright banning of aircraft operations at many of the world's airports is increasing.
  - Advanced acoustics technologies have improved our ability to to deal with these threats.

* Until safety improves for the entire General Aviation fleet, the community acceptance for this mode of travel will remain low.
  - The safety goals previously discussed can be sought after through the application of cockpit information and display technologies.

* Emissions are becoming an increasing concern as subsonic fleet sizes increase.
  - From a technology standpoint, we need to look at the application of advanced electronic engine controls and alternative engine cycles and fuels on future fleet emissions.

* The elitist image which many in the public have for General Aviation is a result of the fact that a relatively small part of the population makes direct use of this mode of travel. As an increasing part of the population comes to experience the benefits of General Aviation, either directly, or indirectly, this image should change.

---

## PROGRESS IN TECHNOLOGY

### Non - Aeronautical

* airbags
* anti-lock brakes (in 1.7 million 1992 cars)
* CD ROM
* cellular telephone
* cruise control
* electronic ignition
* electronic moving maps
* infrared remote controls
* interior noise control
* displays
* micro computers
* radial tires
* reliable powered subsystems
* smart "idiot" lights
* smart suspension system

---

### Progress in Technology

* Since the last applications of significant technical advancements in G.A., numerous technologies have become a part of everyday life in mass markets and presumably could contribute to the development of new airplanes.

* These non-aeronautical technologies have established the level of expectation of the marketplace for future airplanes which would be marketed to travelers beyond the historical "enthusiast" market.

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## PROGRESS IN TECHNOLOGY

### Aeronautical

* ACARS
* Active Noise Control
* Advanced Metallics
* CAD/CAM
* Computational Fluid Dynamics (CFD)
* Fault tolerance
* Fiber-optics
* Lightning Protected Composites
* Crash-worthiness
* Computational Structural Mechanics (CSM)
* Enhanced Visual Systems (EVS)
* GPS
* LORAN
* NLS/ILS
* Molded Phenolic Composite Engines

---

### Progress in Technology. (Concluded)

* During the past decade aeronautics technologies have advanced significantly.

* Many of these technologies have been incorporated into the modern fleet of business jet and turboprop aircraft built and selling in the U.S. today. However, these technologies have not been incorporated into the smaller aircraft which have less and less of the utility needed for safe, comfortable, economical operation in today's increasingly complex airspace system.

## FUTURE TECHNOLOGY DRIVERS



Advanced Airspace System

ATC
Datalink

1990    1995    2000
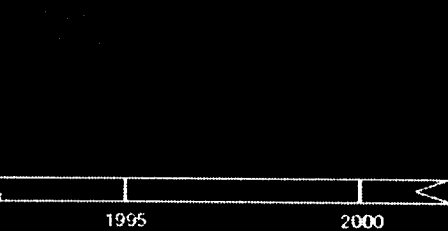
## FUTURE TECHNOLOGY DRIVERS



Advanced
Weather Measurements
and Forecasting

FBL/PBW

IVHS

1990    1995    2000

### Future Technology Drivers

- Direct broadcast satellites may be commercially operationally before 1994 to carry both voice and video information

- The first GPS precision approach is planned to be operational this summer for the Experimental Aircraft Association convention in Oshkosh, Wisconsin.

- Near real-time weather products in the cockpit could be available on a subscription basis by 1995.

- Advanced engine activities which are underway at NASA could result in a rotary engine flight evaluation in the 1995 time frame.

- The advent of satellite based cellular telephones could add a new dimension of creature comfort and convenience to all air transportation.

- The U.S. $32 billion investment in the FAA Advanced Airspace System has the potential to support the next generation general aviation transportation safety, utility, and expansion goals. ATC Datalink, as part of the communications system improvements, could be on line before 1998).

### Future Technology Drivers (cont'd)

- TerraFlops computing will increase speed 1000-fold and decrease cost of high-performance computing.

- Fly-by Light/Power-by-wire will come into maturity in the next decade

- Intelligent Vehicle/ Highway System may provide for crucial economies of scale for GPS components and flat panels when produced at the level of millions of units/year for automobiles.

- Advanced Weather Measurements
  - ASOS: (NWS, 537 units, 1992 - 1996)
  - AWOS: (FAA, 40 units, 1992 - 1993)
  - NEXRAD: (NWS, 113 sites, 1993 - 1996?)
  - TDWR   (FAA, 47 sites, 1993 - 1995)
  - Profilers (NWS: Block 1, mid U.S. today
    Block 2, 200-300 units nationwide about 2000 a.d.)
  - MAPS (NCAR/NWS, Aviation Gridded Forecast System, 1998)

## FINDINGS



## GENERAL AVIATION GOALS



- Environmentally, economically acceptable airplanes:
  - Acoustics
  - Propulsion
  - Materials and Manufacturing Methods
  - Aerodynamics

### Findings

- General Aviation's capability to serve the U.S. transportation needs is threatened, but GA can be revitalized with vastly greater safety, capacity, utility and efficiency to contribute fully to U.S. economic growth.

- Newly maturing technologies have laid the foundations for general aviation to expand, not only to meet U.S. needs, but to meet foreign market needs (especially third world) as well.

- As international aeronautical competition has squeezed nearly ever last mile-per-gallon out of technologies, the competitive playing field of the future will be dominated by who can move the fastest through product development cycles. This means that to be competitive, the U.S. must invest in the development of technologies affecting faster, more accurate computational design tools, advanced testing techniques, lower cost, faster manufacturing techniques, and more rapid certification processes.

- The primary task of the NASA Advisory Council, Aeronautics Advisory Committee, Task Force on General Aviation Transportation is to address the last point concerning a national technology strategy to define what technologies are needed to enable general aviation to contribute to the national airspace capacity issues and revitalize the U.S. general aviation industry through expanded use and volume of production.  While product liability is still critical, research planning must

### GA Goals

- The General Aviation Safety goals could be established by translating the lessons from the ultra-safe corporate operations, where feasible, to the General Aviation fleet.

- Electronic VFR: means minimize the IFR/VFR distinction
  - Wide field of view displays
  - Single, GPS-based universal approach procedures and systems
  - Near real-time weather in the cockpit

- Decision-Aided Flight Planning and Operations
  - increased autonomy, transparent to operator
  - Integrated weather, traffic information in the cockpit for preflight, enroute operations
  - GPS-based random access, point-to-point navigation

- Electronic Cockpit Libraries
  - Optical storage of enroute and terminal navigation information
  - Datalink for comm and clearance information
  - Electronically stored and displayed aircraft performance data

- Dual-Use Cockpits
  - Embedded Flight Training (recurrent and, ultimately, initial)
  - Intuitive (decoupled) flight controls and displays
  - Flight envelope protection systems
  - Self-teaching simulators and onboard flight systems

- Aircraft for expanded general aviation utility must meet community environmental expectations, and user expectations for utility and cost.

# Advanced Navigation and Personal Aviation

Steven C. Crow
Aerospace and Mechanical Engineering Department
The University of Arizona

Presented at the NASA Langley Research Center
Workshop on Air Transportation System Productivity
1 July 1993

## SMALLER, CHEAPER, BETTER IN CIVIL AERONAUTICS

| Current Paradigm | Alternative Paradigm |
|---|---|
| Hub and spoke routes | Network routes |
| Large platforms | Small platforms |
| Expert pilots | Automatic control |
| Rigid schedules | Flexible schedules |
| Human traffic management | Electronic traffic management |
| Service orientation | Consumer product orientation |

## INTELLIGENT AIRCRAFT/SKYWAY SYSTEM

**Suggestion**

NASA should undertake a major program on Intelligent Aircraft/Skyway Systems to complement the DOT program on Intelligent Vehicle/Highway Systems.

**Mission**

The program mission is to develop and demonstrate a new civil aviation system based on an electronically defined airspace of unprecedented safety and utility.

The program will integrate the traditional disciplines of aeronautics with the revolution in information technology and will facilitate the reinvestment of aerospace technology into civilian products.
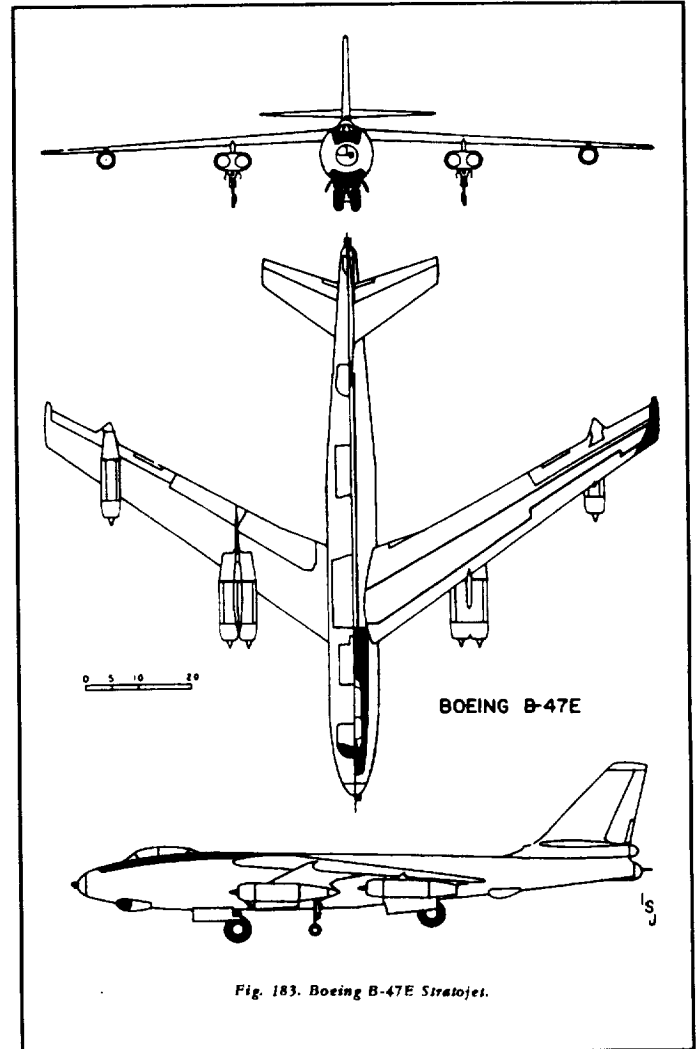


BOEING B-47E

*Fig. 183. Boeing B-47E Stratojet.*

### Economics 101 Takes Flight

Anyway, it's hard to imagine cutting-edge research helping the commercial aircraft industry. If you can tell a Boeing 727 from a Boeing 757 (most passengers neither know nor care) you will recognize that the new generation of commercial airplanes produced little or no enhancement of passenger welfare.

Even airlines gained little advantage. The new planes are more fuel efficient and require two pilots in the cockpit instead of three, but these lowered variable costs are trivial compared with the immense fixed costs of new planes with sticker prices double or triple the previous generation's.

## HUB AND SPOKE GEOMETRICS

**Tucson to Wichita via Euclid**

858 statute miles direct.

**American Airlines**

1,165 miles via Dallas at average speed of 169 direct mph.

**United Airlines**

1,052 miles via Denver at average speed of 158 direct mph.

**Hub and Spoke Averages**

Distance amplification of 1.29 and speed of 164 direct mph.



Lancair 320 DIMENSIONAL VIEWS
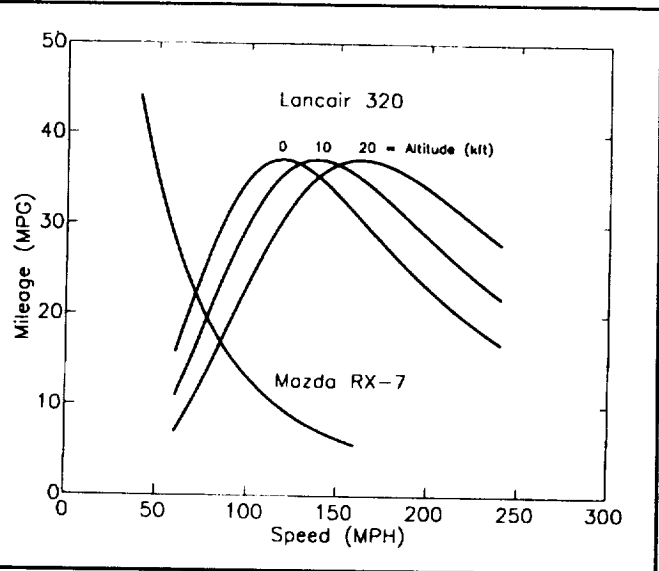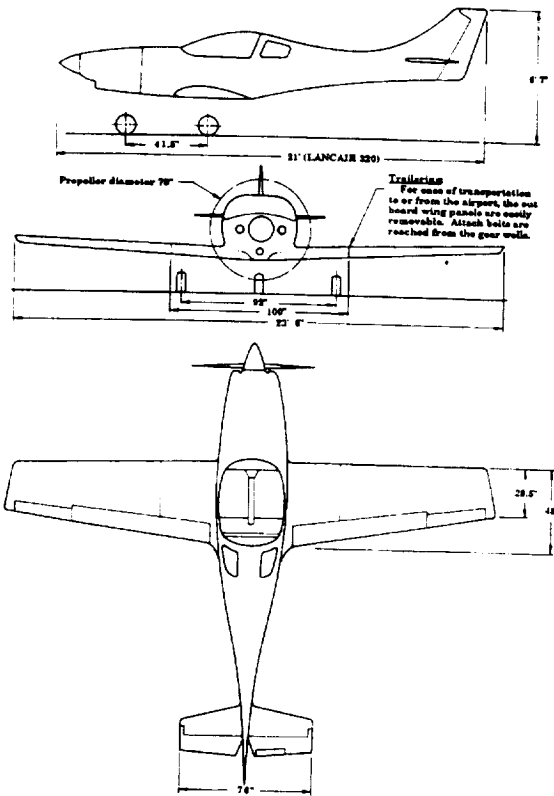


PERFORMANCE ADVANTAGES OF AN AIRPLANE OVER AN AUTOMOBILE

| Parameter | Mazda RX-7 | Lancair 320 | Airplane Advantage |
|---|---|---|---|
| $\rho$ (slug/ft$^3$) | 0.002378 | 0.001756 | 1.35 |
| c (lb/hr/hp) | 0.62 | 0.45 | 1.38 |
| $\eta$ | 0.90 | 0.85 | 0.94 |
| $S_d$ (ft$^2$) | 7.20 | 1.60 | 4.50 |
| Rolling friction | | | 1.18 |
| Net airplane advantage | | | 9.30 |

## Lancair 320 / Boeing 757-200

Seat Miles per Gallon vs Speed (MPH)

Lancair 320
0 10 20 = Altitude (kft)

Boeing 757-200
0 10 20 30 40

## F92 Racer / Boeing 757

Seat Miles per Gallon vs Speed (MPH)

F92 Racer
0 10 20 30 40 = Altitude (kft)

Boeing 757
0 10 20 30 40

## CAPITAL COSTS

**Lancair 320**

$150,000/2 seats = $75,000 per seat.

**Boeing 757**

$42,000,000/195 seats = $215,000 per seat amortized over 2,700 flight hours per year.

**Conclusion**

Small airplanes must be time shared or their prices reduced to automotive levels to compete on capital costs.

## GPS CONSTELLATION IN 1990

4.05

- 18 satellites, plus 3 active spares
- 6 orbit planes
- 12 hour period
- 20,000 km height
- (almost) full coverage
  (24 hours per day everywhere in the world)

© Canadian GPS Associates, May 1987

# GPS Signals

| | |
|---|---|
| L1 C/A Carrier | (1.58 GHz) |
| L1 P Carrier | (1.58 GHz) |
| L2 P Carrier | (1.23 GHz) |
| L1 P Code | (10.2 MHz) |
| L2 P Code | (10.2 MHz) |
| L1 C/A Code | (1.02 MHz) |



---

```
                    Satellite Control

          DP (m)       -8.36     1.72    8.88
          DV (m/sec)   -8.82     8.38    8.88

          DP (ft)      -1.17     5.64    8.88
          DV (mph)     -8.84     8.67    8.88

          Steering Wheel Angle    -2.92 degrees
          Steering Wheel Rate      8.88 deg/sec


 Tracking Filter for Pima      Base Sats    3  17  21   8
 18:51:14     12-13-1991       Vehicle Sats 3  17  21   8
```

Press any key to continue

---
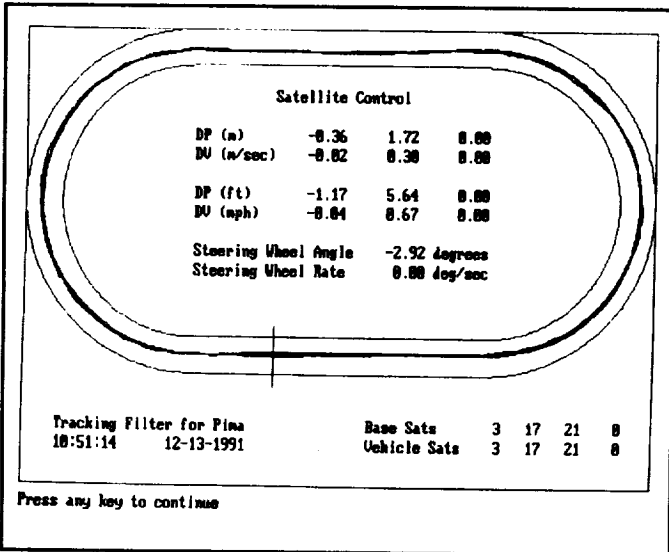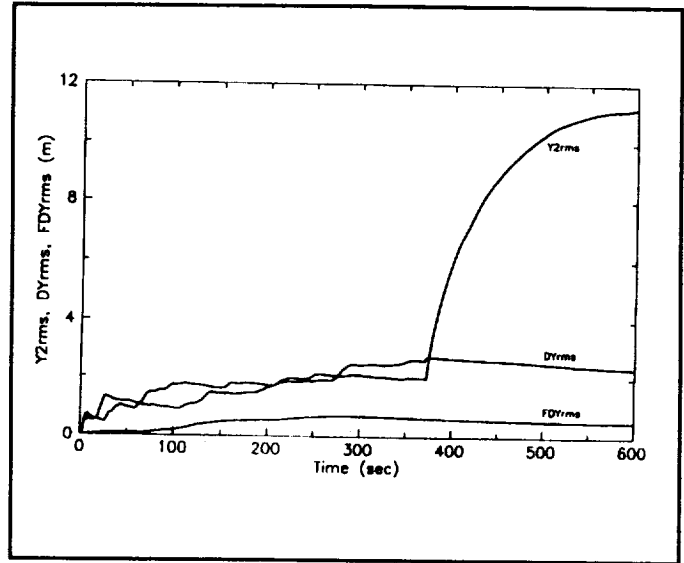
## HOW PRECISE IS GPS?

**GPS Code**

DOD guarantees 100 m (2drms) with Selective Availability (S/A).

**Differential GPS Code**

About 3 m (rms) vertical.

**Differential GPS Code with Carrier Phase Smoothing**

Maybe 1 m (rms) vertical.

**Double Difference Carrier with Real-Time Integer Ambiguity Resolution**

Potentially 2 mm (rms) vertical!

---

## SYSTEM ARCHITECTURE

**Global Positioning System**

Provides basis for navigation, precision guidance, and collision avoidance.

**Skyways**

Have legal structure of turnpike authorities to control liability.

Operate transformer stations.

Own and maintain sky modules.

**Starcars**

Passenger plus road module is a good automobile.

Passenger plus sky module is a good airplane.
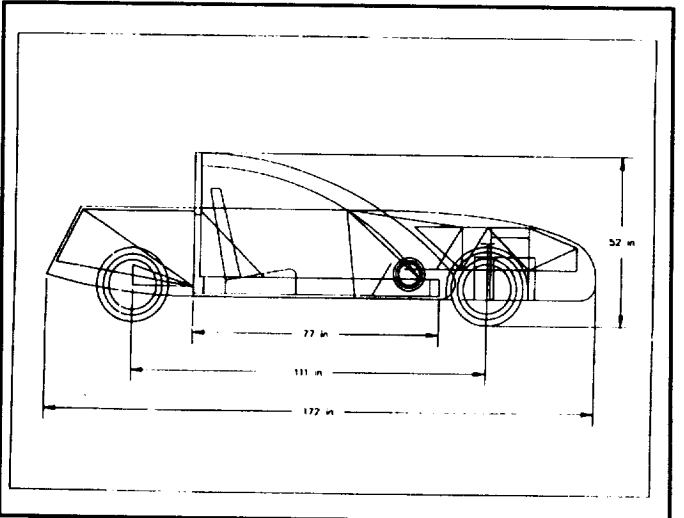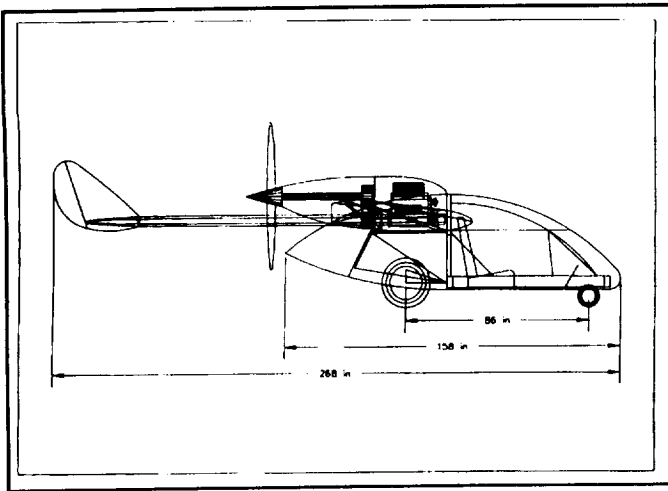
## ISSUES

**Policy**

Administrative status of the Global Positioning System.

Public acceptance of safe automated air travel.

**Information Technology**

Reliability of GPS guidance and control.

Architecture of skyway protocols and software.

**Vehicle Technology**

Application of automobile engines to aircraft.

Integration of "hard" metal and "soft" composite structures.

## CONCLUSIONS

The Global Positioning System can be the basis for automatic guidance and control of aircraft, including precision landings.

Collisions can be avoided through packet radio broadcasts of GPS positions and velocities.

Automatic control allows the use of small aircraft operating from the nation's 15,000 airports, compared with the 600 or so with current scheduled service.

Geometrical advantage of direct flight versus hub and spoke is typically 1.3.

Performance advantage of small aircraft versus B757 is 1.4-1.8.

Net operating advantage of direct flights with small aircraft is 1.9-2.3.

Capital cost advantage of small aircraft is 2.9 without benefit of mass production.

Production of small aircraft could be a signature industry of the 21st century.

# HOW FAR CAN MULTIDISCIPLINARY METHODOLOGY BE TAKEN ?

**Perry Newman & Jarek Sobieski**
**NASA Langley Research Center**

**Gene Hou**
**Old Dominion University**

**Workshop on**
**Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity**
**NASA Langley Research Center**
**June 29–July 1, 1993**
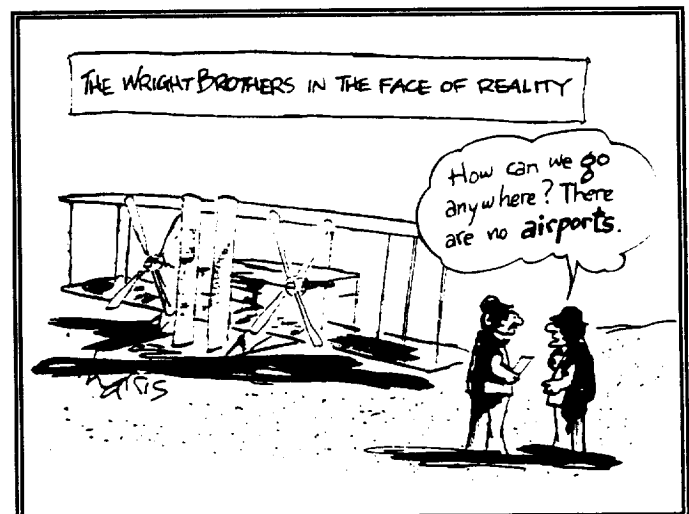
## WHAT IS MULTIDISCIPLINARY METHODOLOGY?

- Word Definitions
  - "Multidisciplinary"
    - (1) Consisting of or containing many disciplines
    - (2) Affecting many disciplines
  - "Methodology"
    - (1) Body of methods, procedures, postulates, working concepts, etc.
    - (2) Logic dealing with principles of procedure
    - (3) Science of methods or arrangement
- Common Perceptions or Misconceptions
  - Frequently local with few interactions
  - Disjoint or sequential in time
  - Only global systems
- Multidisciplinary Reality
  - Subconscious or reflex actions
  - Conscious or natural equilibrations
  - Formal mathematical procedures

---



**Common Perceptions?**

The Blind Men and The Elephant
By Saxe (1816-1887), Drawings by Abkulov

It was six men of Indostan to learning much inclined,
Who went to see the Elephant though all of them were blind,
That each by observation might satisfy his mind.

THE FIRST...
Is very like a WALL!

THE SECOND...
Is very like a SPEAR!

◄ Design team

◄ Multidisciplinary system

◄ Structures

◄ Armaments

---



THE THIRD...
Is very like a SNAKE!

THE FOURTH...
Is very like a TREE!

THE FIFTH...
Is very like a FAN!

THE SIXTH...
Is very like a ROPE!

And so these men of Indostan disputed loud and long,
Each in his own opinion exceeding stiff and strong,
Though each was partly in the right, and all were in the wrong!

◄ Low observables

◄ Operations

◄ Aero/Propulsion

◄ Controls

---

## WHAT IS MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO)?

- Word Definition
  - "MDO"--Methodology for design of complex (engineering) systems governed by mutually interacting (physical) phenomena and made up of distinct interacting subsystems

- Conceptual Components
  - Design-Oriented analyses
  - Approximation concepts
  - System mathematical modeling
  - Design space search algorithms
  - Optimization procedures
  - Human interfaces

---

## WHAT IS MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO)? (Continued)

- "Dimensions" of MDO
  - Scale or size of system
  - Multidisciplinary completeness of system
  - Depth or degree of analysis
  - Dynamic or time response scales

- Limitations to MDO

- Potential of MDO

---

**Multidisciplinary (Md) Design Phases**



Md Completeness

Aerodynamics ... Sets shape

Aerodynamics
Structures
Controls
Propulsion
Other

Structures

Propulsion-airframe integration

Aeroelasticity

Controls

Fabrication

Simplified incomplete analyses with estimates and assumptions for unavailable data.

Detailed work, in-depth analyses and experiments contained within one discipline or subsystem.

Requirements or Specs | Conceptual | Preliminary | Detailed | Final

Analysis Depth or Time

## MULTIDISCIPLINARY DECOMPOSITIONS

**Hierarchic**

A/F
W  F
B  R&S

AirFrame
Fuselage
Wing
Box
Ribs & Spars

**Non-Hierarchic**

A
S  C

Flexible wing:

Aerodyn.
Structure
Controls

**Hybrid**

A
S  C
B  R&S

Flexible wing with substructuring

---
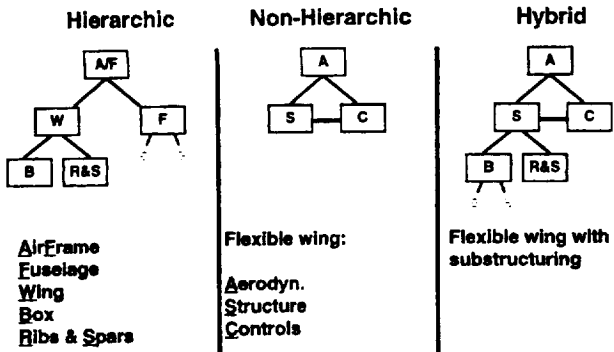
## MULTIDISCIPLINARY CONNECTIVITY

### HiSAIR Example

**Analysis**

ASE
AERO  DYN
GEOM
STRU  PERF
WTS
OUTPUT

**NxN Matrix**

GEOM
AERO
STRU
WTS
ASE
PERF
OUTPUT

---

## Multidisciplinary (Md) Design Phases



Md Completeness

Aerodynamics
Structures
Controls
Propulsion
Other

OR

HIERARCHIC

NON-HIERARCHIC

Analysis Depth or Time

Requirements or Specs   Conceptual   Preliminary   Detailed   Final

---
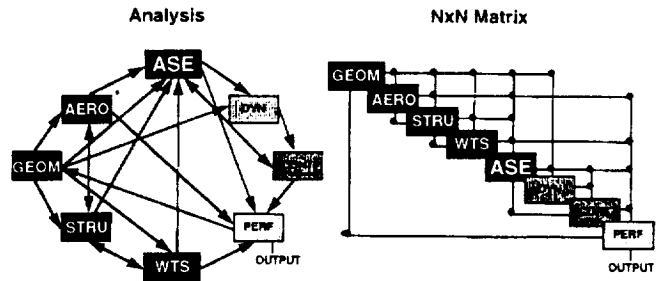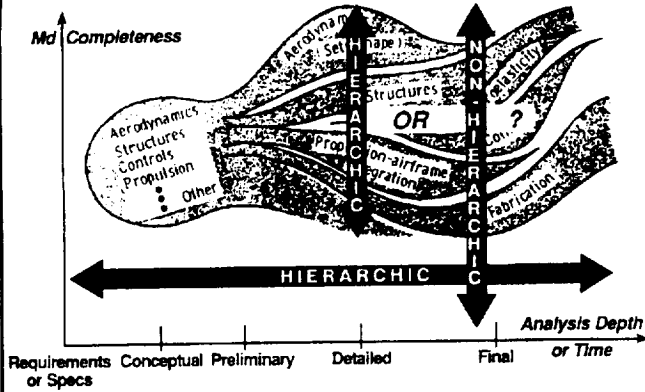
## GENERIC MDO EXAMPLE

**Two Design Variables Two Constraints**

**New Constraint Arises**

WING MINIMUM STRUCTURAL WEIGHT

P CONSTANT
INCREASING P
C1  C2
O1

ASPECT RATIO

P CONSTANT
INCREASING P
C1  C3  O2  C2
O3
O1

ASPECT RATIO

---

## GENERIC TIME RESPONSE

| | | |
|---|---|---|
| Proposal | T1 |
| Evaluation | T2 |
| Modification | T3 |
| Acceptance or Rejection | T5 |
| Implementation | T6 |
| Operation & Support | T7 |
| Revision | T8 |

T4

T9

---

## MDO FOR AIRCRAFT

Md Completeness

Integrated Controls   IC
Flight Deck
Acoustics   AC
Propulsion   PR
Performance   PF
Aerodynamics   AD
Structures
Weights   WE
Aeroelastics   AE
Controls   CO

Analysis Depth

Final
Detail
Preliminary
Conceptual
Requirements or Specifications

MDO FOR AIRCRAFT, PRODUCT/PROCESS



MDO FOR AIRCRAFT, PRODUCT/PROCESS, AVIATION SYSTEM



SYSTEM MDO

## LIMITATIONS TO MDO

- Physical System
  - Multidisciplinary understanding
  - Mathematical modeling
  - Computational feasibility
  - Time response

- Social & Political Issues
  - Non-rational elements
  - Existing regulations
  - Economic considerations
  - Institutional inertia
  - Diverse acceptance
  - Uncertain time scales

## POTENTIAL OF MDO

- Improved design process and product

- Enhanced communcation among subsystems

- Answered "WHAT IF?" questions

- Enabled by recently developed MDO tools

- Doable on emerging "Teraflop-rate" machines

- Extendable beyond "conventional design" into:
  - life cycle times
  - detail analysis depths
  - megasystem sizes
  - multidisciplinary completeness

# Multidisciplinary Design Research at NASA Langley

Peter G. Coen

Presented at the Potential Impacts of Advanced Aerodynamic Technology on Air Transportation System Productivity Workshop

June 29-July 1, 1993

---

*HISAIR*

## Presentation Outline

- Motivation and Background

- Research activities
  - Multidisciplinary analysis system
  - Data management
  - Optimization methods

- Conclusions

---

*HISAIR*

## BACKGROUND

- Multidisciplinary Research Advisory Committee (MRAC)
  - Set up airframe integration multidisciplinary structure
  - Use High Speed Civil Transport (HSCT) as vehicle focus

- HISAIR Goals
  - Establish multidisciplinary analysis process
    - Improve discipline interactions and level of fidelity
  - Develop multidisciplinary optimization methodology
  - Apply MDO to design with higher fidelity analysis

---

## DESIGN -- PROBLEM OF SCALE
### Communication Scaling Problem



TO 1950's — Pioneer Aeronautics–Central Designer

1960's EARLY 1970's — The Specialty Pie

LATE 1970's 1980's — The Pie With No Center
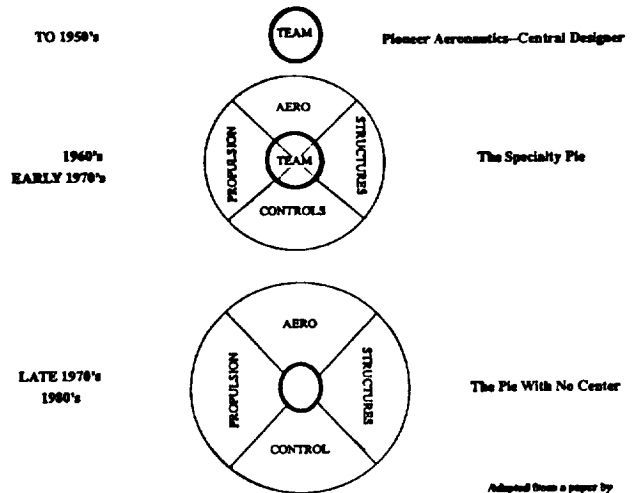
Adapted from a paper by
Dr. Bouchard, Lockheed Corp.

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*HISAIR*

## LaRC PARTICPATING DISCIPLINE ORGANIZATIONS



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*HISAIR*  *Process Chart*

ANALYSIS
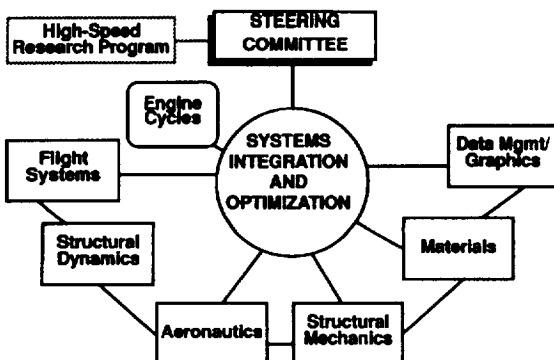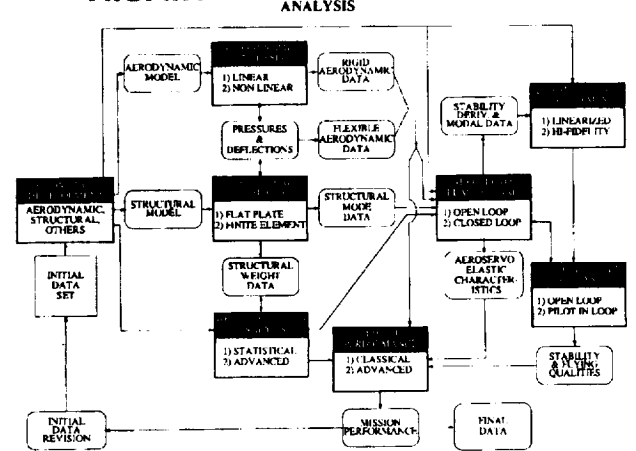
## Geometry Development

- **Established expertly staffed and well equipped laboratory environment (GEOLAB)**
  - Surface modeling
  - Grid generation
  - Flow visualization

- **Develop system to significantly reduce time required to generate detailed analysis models (SMART)**

- **Conduct geometry related research**
  - Surface parameterization in terms of design variables
  - Automatic grid generation

---

## Geometry Development System Improvement

*CURRENT PROCESS*



2 months +
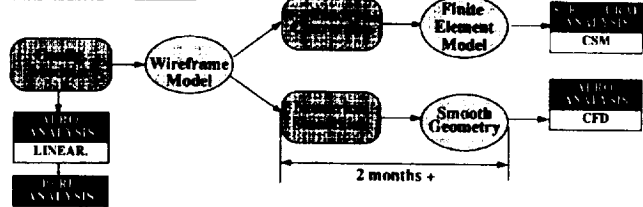
*SMART CENTERED PROCESS*



1 week

---
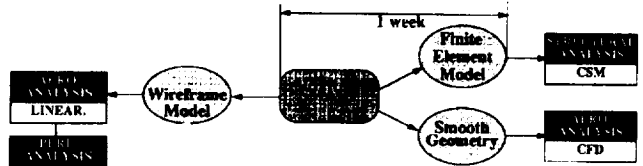
### Grid Perturbation Approaches



$(X_J, Y_J + \Delta Y_J)$

$(X_J, Y_J)$

$(X_1, Y_2 + \Delta Y_1)$

$(X_1, Y_1)$
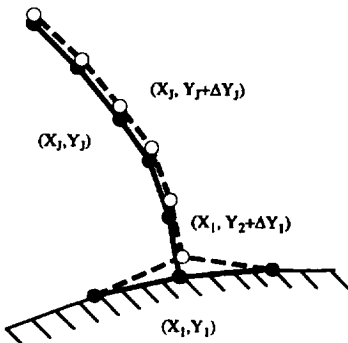
FULL FIELD:

$$\Delta Y_J = \Delta Y_1 \left(\frac{N-J}{N-1}\right)$$

TRANSLATED SHELL:

FOR $J < J_S$

$$\Delta Y_J = \Delta Y_1$$

FOR $J > J_S$

$$\Delta Y_J = \Delta Y_1 \left(\frac{N-J}{N-1}\right)$$

---

### Computational Approach for Flexible Wing Loads



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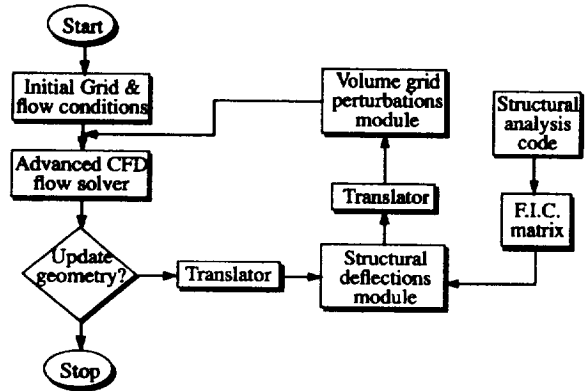
## Aerodynamics

- **Study most efficient use of different levels of analysis**

- **Study prediction of thermal loads with Navier-Stokes codes**

- **Interact with Structures discipline for development of flexible wing analysis technique**

- **Develop sensitivity derivative generation methods for higher order analysis methods**

---

## Structures

- **Interact with Aerodynamics discipline in development of techniques for mapping aerodynamic and thermal loads**
- **Improve techniques for structural optimization with finite element methods**
  - Section properties analysis
  - Tip displacement limits
  - Flutter constraints

## Aeroservoelasticity

- **Develop integrated system for analysis of aeroservoelastic characteristic of aircraft**
  - Flutter, divergence, control reversal
  - Damping
  - Flexible-to-rigid ratios for stability and control derivatives

- **Interact with Structures and Optimization for incorporation of flutter constraints in structural optimization studies**

---

## Aeroelastic Vehicle Analysis (AVA)



---
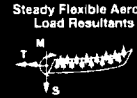
## RESULTS OF AEROELASTIC ANALYSIS OF MACH 2.4 HISAIR CONFIGURATION

### FLIGHT ENVELOPE CLEARANCE



- ● Flutter Instability
- ■ Static Longitudinal Instability

- —— Operational Envelope
- – – 1.2 Aeroelastic Envelope
- —— Altitude (1000 ft)
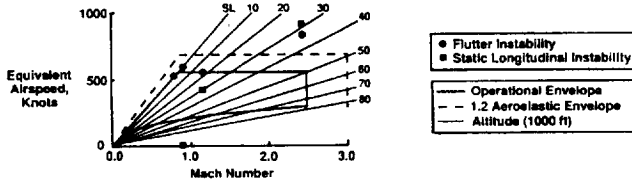
### CONTROL SURFACE REVERSAL



- –··– Leading Edge Inboard
- ····· Trailing Edge Inboard
- —— Leading Edge Outboard
- –·– Trailing Edge Outboard

---
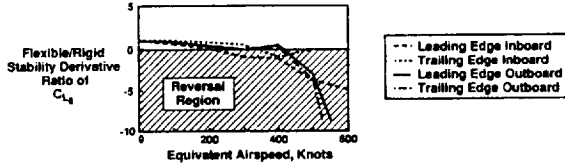
## Dynamics and Control

- **Identify sources and methods for development of required data**
  - Stability and control derivatives
  - Actuator and engine dynamics

- **Develop integrated control system analysis and design tool**
  - *Control Oriented Multidisciplinary Modeling, Analysis and Design*
  - "COMMAND"
  - Dynamics modeling
  - Vehicle performance and handling qualities analysis
  - Controller synthesis

- **Develop communication of results to other disciplines**

---

## Data Management

- **Development of data tracking and retrieval system**
  - Determine form and content of data models
    - Geometry
    - Aerodynamic force and moment coefficients
    - Stability and control derivatives
    - Flexible-to-rigid ratios
    - Vehicle performance
  - Develop user interface and database library
    - OSF/Motif
    - INFORMIX network based dbms

---

### HISAIR Process Chart

NxN MATRIX DIAGRAM

**HISAIR**

## Data Management System



LaRCNET Distributed Database

---

**HISAIR**

## Optimization Methods

- **Study application of sensitivity analysis and optimization to large multidisciplinary problem**
- **Use ongoing "Pathfinder" problem**
  - Structural optimization with fixed planform
  - Planform and camber optimization with empirical structural weight
  - Combined Aero-Structure-Performance optimization

---

**HISAIR** Process Chart

### CONFIGURATION OPTIMIZATION



---

## NUMERICAL RESULTS
## Wing Skin Thickness

INITIAL DESIGN

FINAL DESIGN

THICKNESS (IN)

0.25
0.20
0.15
0.10
0.05
0.00

h910419-08/jfb



---

**HISAIR**

## Concluding Remarks

- **Participation in multidisciplinary research is enhancing cooperation between disciplines at Langley**
- **New research topics are being pursued**
  - Geometry generation
  - Geometry parameterization
  - Coordinated use of different levels of analysis
  - Aerodynamics and structures interaction
  - Dynamic analysis and control system development
  - Data management
  - Optimization methods

## APPROACH TO DEVELOP QUALITY AFFORDABLE PRODUCTS
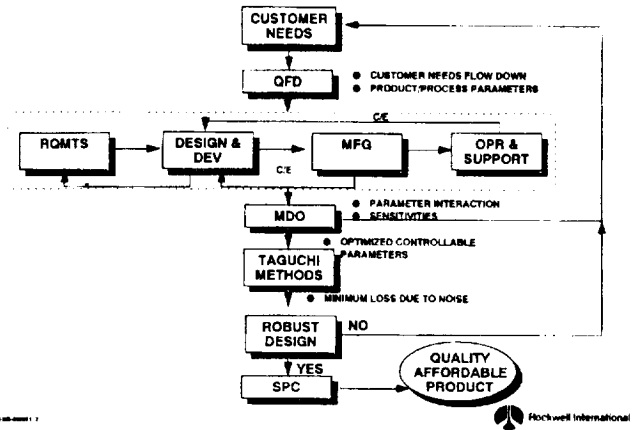


## QFD FLOWS CUSTOMER NEEDS DOWN TO PRODUCT /PROCESS PARAMETERS
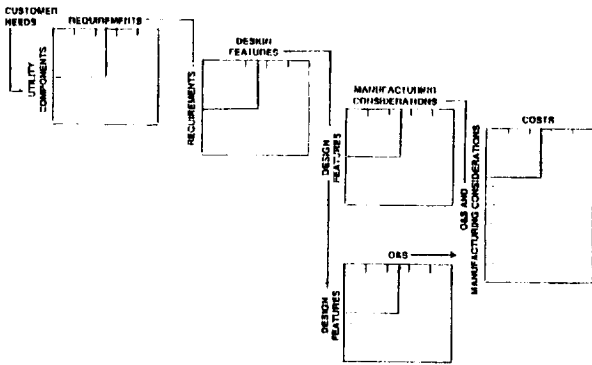


## FLOW DOWN FROM REQUIREMENTS TO DESIGN
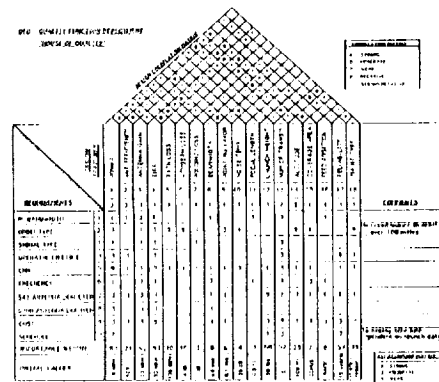


## FLOW DOWN FROM REQUIREMENTS TO DESIGN
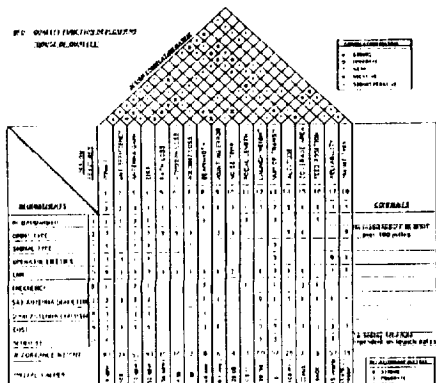


## CONCURRENT ENGINEERING STRONG INTERACTIONS
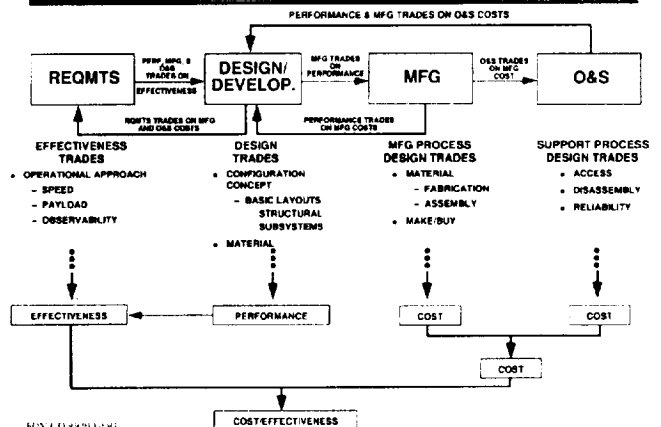
# Antenna Problem For Satellite Application

## VERY SMALL APERTURE TERMINAL (VSAT) SATELLITE SYSTEM CONCEPT
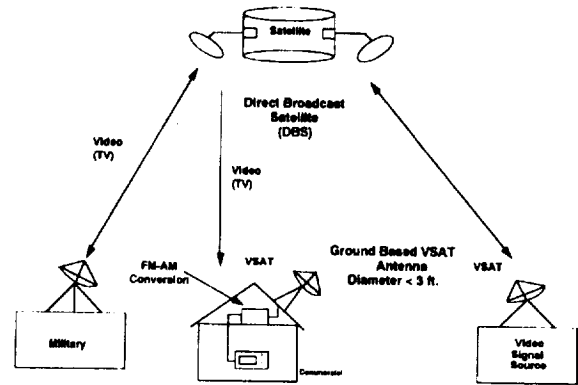
## CUSTOMER NEEDS/GOALS FOR SATELLITE ANTENNA SYSTEM

- Antenna to transmit and receive video signals (TV)
- Satellite in synchronous orbit - 22,300 miles above earth
- Operational lifetime of 20 years
- High transmitter/receiver CNR
- Assigned frequency (FCC) Ku-band 11.7 - 12.2 GHz Downlink
  14 - 14.5 GHz Uplink
- High RF Bandwidth
- Satellite Antenna ≤ 3 feet in diameter
- FM-AM conversion at the receiver
- VSAT ground antenna ≤ 1.5 feet in diameter
- Satellite antenna must be affordable
- Schedule - 18 months from design to operation in orbit

## LINK ANALYSIS PROVIDES THE INITIAL VALUES FOR THE MDO
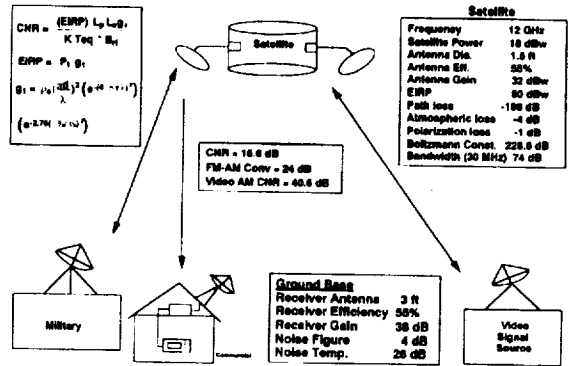
# Multidisciplinary Design Optimization (MDO)

## COMPLETE MDO PROCESS
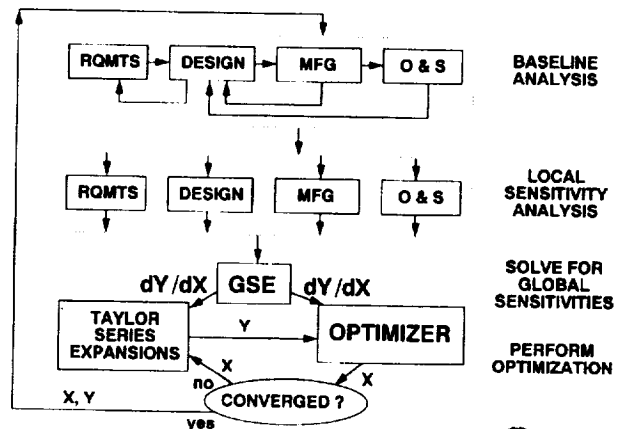
# SOLVE FOR GLOBAL SENSITIVITY DERIVATIVES

### GLOBAL SENSITIVITY MATRIX

(matrix diagram)

GLOBAL SENSITIVITIES

LOCAL SENSITIVITIES

# DESCRIPTION OF PARAMETERS

| RQMTS | DESIGN | MFG | O & S |
|---|---|---|---|
| **RF BANDWIDTH**<br>initial : 30 MHz or 74 dB<br>range : 10-30 MHz or 70-74 dB | **INPUT POWER**<br>initial : 18 dBw<br>range : 10-30 dBw | **FAB PROCESS**<br>process 1<br>mid $<br>medium tolerance | **LAUNCH TYPE**<br>1 - Titan with small shroud<br>low $<br>smallest max diameter |
| **FREQUENCY**<br>initial : 12 GHz<br>range : 1-30 GHz | **ANTENNA DIAMETER**<br>initial : 1.5 feet<br>range : 0.5 - 4 feet | process 2<br>high $<br>small tolerance | 2 - Titan with large shroud<br>mid $<br>medium max diameter |
| **RECEIVER ANTENNA DIA.**<br>initial : 3 feet<br>range : 1 - 3.1 feet | **ANTENNA EFFICIENCY**<br>initial : 55 %<br>range : 35 - 85 % | process 3<br>low $<br>large tolerance | 3 - Shuttle<br>high $<br>largest max diameter |
| | **ANTENNA MATERIAL**<br>material 1 : Gold-plated<br>material 2 : Copper based | | |

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# CASE 1

| fixed | optimized | fixed | fixed |
|---|---|---|---|
| RQMTS | DESIGN | MFG | O & S |
| **RF BANDWIDTH**<br>initial : 30 MHz or 74 dB | **INPUT POWER**<br>initial : 18 dBw<br>range : 10-30 dBw | **FAB PROCESS**<br>process 2<br>high $<br>small tolerance | **LAUNCH TYPE**<br>2 - Titan with large shroud<br>mid $<br>medium max diameter |
| **FREQUENCY**<br>initial : 12 GHz | **ANTENNA DIAMETER**<br>initial : 1.5 feet<br>range : 0.5 - 4 feet | | |
| **RECEIVER ANTENNA DIA.**<br>initial : 3 feet | **ANTENNA EFFICIENCY**<br>initial : 55 %<br>range : 35 - 85 % | | |
| | **ANTENNA MATERIAL**<br>material 1 : Gold-plated<br>material 2 : Copper based | | |

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# CASE 2

| fixed | optimized concurrently | | fixed |
|---|---|---|---|
| RQMTS | DESIGN | MFG | O & S |
| **RF BANDWIDTH**<br>initial : 30 MHz or 74 dB | **INPUT POWER**<br>initial : 18 dBw<br>range : 10-30 dBw | **FAB PROCESS**<br>process 2<br>high $<br>small tolerance | **LAUNCH TYPE**<br>2 - Titan with large shroud<br>mid $<br>medium max diameter |
| **FREQUENCY**<br>initial : 12 GHz | **ANTENNA DIAMETER**<br>initial : 1.5 feet<br>range : 0.5 - 4 feet | process 3<br>low $<br>large tolerance | |
| **RECEIVER ANTENNA DIA.**<br>initial : 3 feet | **ANTENNA EFFICIENCY**<br>initial : 55 %<br>range : 35 - 85 % | | |
| | **ANTENNA MATERIAL**<br>material 1 : Gold-plated<br>material 2 : Copper based | | |

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# CASE 3

| fixed | optimized concurrently | | |
|---|---|---|---|
| RQMTS | DESIGN | MFG | O & S |
| **RF BANDWIDTH**<br>initial : 30 MHz or 74 dB | **INPUT POWER**<br>initial : 18 dBw<br>range : 10-30 dBw | **FAB PROCESS**<br>process 1<br>mid $<br>medium tolerance | **LAUNCH TYPE**<br>1 - Titan with small shroud<br>low $<br>smallest max diameter |
| **FREQUENCY**<br>initial : 12 GHz | **ANTENNA DIAMETER**<br>initial : 1.5 feet<br>range : 0.5 - 4 feet | process 2<br>high $<br>small tolerance | 2 - Titan with large shroud<br>mid $<br>medium max diameter |
| **RECEIVER ANTENNA DIA.**<br>initial : 3 feet | **ANTENNA EFFICIENCY**<br>initial : 55 %<br>range : 35 - 85 % | process 3<br>low $<br>large tolerance | 3 - Shuttle<br>high $<br>largest max diameter |
| | **ANTENNA MATERIAL**<br>material 1 : Gold-plated<br>material 2 : Copper based | | |

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# CASE 4

| optimized concurrently | | | |
|---|---|---|---|
| RQMTS | DESIGN | MFG | O & S |
| **RF BANDWIDTH**<br>initial : 30 MHz or 74 dB<br>range : 10-30 MHz or 70-74 dB | **INPUT POWER**<br>initial : 18 dBw<br>range : 10-30 dBw | **FAB PROCESS**<br>process 1<br>mid $<br>medium tolerance | **LAUNCH TYPE**<br>1 - Titan with small shroud<br>low $<br>smallest max diameter |
| **FREQUENCY**<br>initial : 12 GHz<br>range : 1-30 GHz | **ANTENNA DIAMETER**<br>initial : 1.5 feet<br>range : 0.5 - 4 feet | process 2<br>high $<br>small tolerance | 2 - Titan with large shroud<br>mid $<br>medium max diameter |
| **RECEIVER ANTENNA DIA.**<br>initial : 3 feet<br>range : 1 - 3.1 feet | **ANTENNA EFFICIENCY**<br>initial : 55 %<br>range : 35 - 85 % | process 3<br>low $<br>large tolerance | 3 - Shuttle<br>high $<br>largest max diameter |
| | **ANTENNA MATERIAL**<br>material 1 : Gold-plated<br>material 2 : Copper based | | |

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## RESULTS COMPARISON



## FEATURES

- Uses QFD to identify key parameters, strong interactions, and decomposition of complex systems into subsystems
- Provides process to implement concurrent engineering
  - Decomposition allows each discipline to develop local sensitivities concurrently
  - Optimizes requirements, design parameters, manufacturing processes, and O&S processes concurrently
  - - Allows for integrated product development optimization with large number of strong interactions
- Global sensitivities are determined by solving a simple set of simultaneous equations
  - Provides insights into system drivers
  - Provides Taylor series expansions which represent total product development space with all strong interactions included
- Provides means to constrain product development optimization to obtain Taguchi derived robustness

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# Future Transportation Alternatives

- Bob van't Riet
  - California Polytechnic State University (Cal Poly)
  - San Luis Obispo
- Methods Applicable to the Identification of Future Transportation Alternatives

# Three Methods



1 Evolution

2 Revolution

3 Systems Approach

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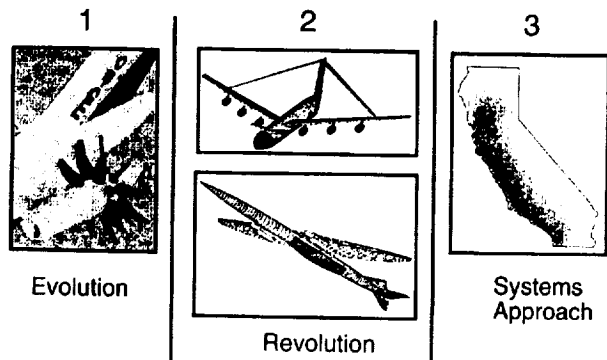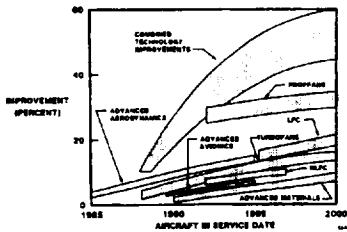
# Evolution



Fuel Efficiency Improvements
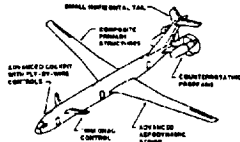


Advanced Transport

## Evolutionary Efficiency Trends
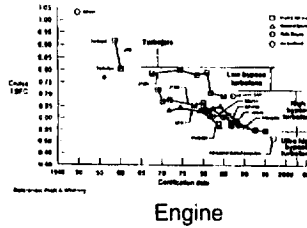


Engine
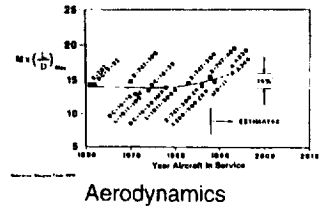


Aerodynamics

# Aircraft Fuel Efficiency Trend
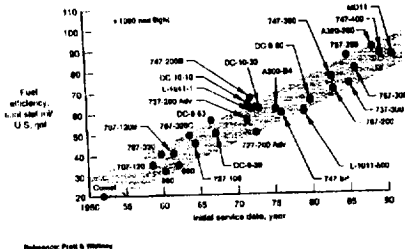
# Revolution
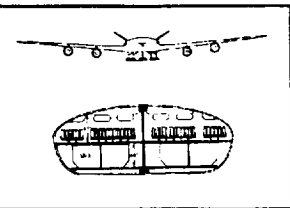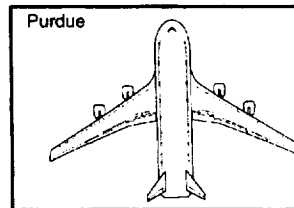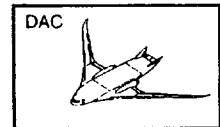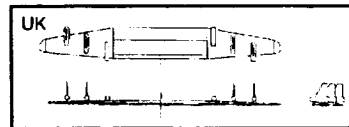
# An Example of a Systems Approach

## Cal Poly California Air Transportation Study

- 1997-1990
- NASA/USRA Funded
- Multidisciplinary Approach
  - Three Transportation Levels
    - Intra-City
    - High-Demand City Pairs
    - Continental and Intercontinental

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$C3$ -

# Consider

- Please Consider the Multidisciplinary Approach Not the Final Technical Solution

# Corridor Concept

- 21 Million Individuals
- Four Major Metropolitan Areas
  - Los Angeles basin
  - San Francisco Bay Area
  - Sacramento Area
  - San Diego Area

# Transportation Users

- Commuters
- Transient Travelers
- Miscellaneous Travelers
- Freight

# System Requirements

# System Integration

- Flexibility
- Congestion
- Environment
  - Resources
  - Alternate Fuels
  - Pollution
  - Noise
- Technical Risk
- Social Impact

# The System 1995-2005

- Time Phased
  - 1995
    - Efficient Ground Transportation
    - Quiet Short Takeoff and Landing Aircraft
  - 2005
    - Giant Semi Buoyant Helipsoids Aircraft
    - High Speed Automated Electric Rail Coaches

# The System 2010-2020

- 2010
  - Two New Airports Removed from Congested Areas
  - Magnetically Levitated Trains
- 2020
  - Personal Air Service Under Fully Automated Aircraft Control

# The Hardware

| 1995 | 2005 | 2020 |
|------|------|------|
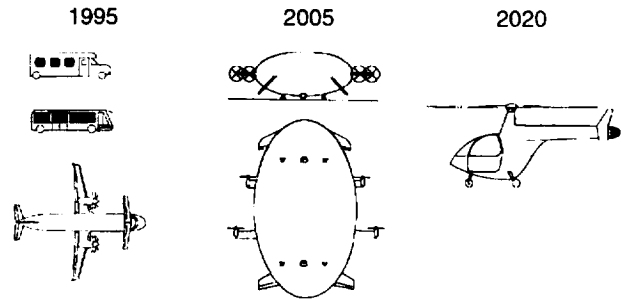
# The Commuter Trip
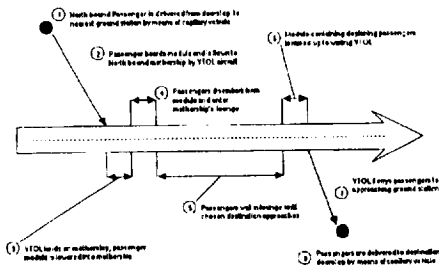
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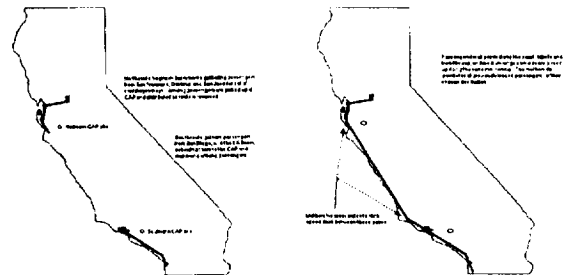
# California Air Transportation Study Results

- Multidisciplinary Systems Approach
- Board Based Requirements
- Board Based Solution

> Needs Updating and Technical Refinement. However, the Approach is Very Powerful.

# Conclusion

- Evolution, Revolution or a Systems Approach?
  - Evolution - Airframers and NASA
  - Revolution - NASA, Entrepreneurs and Universities
  - Systems Approach - Universities and NASA

## "Maglev"

- ~300 MPH Mag. Levit. Trains
- VISION
  - Elevated rails (guideways) on interstate right of ways
  - Alternative to short-haul A/C for < 0 (500ml)
- Program
  - Combined DOT,DOE, Corps of Engineers, NASA (Bushnell-Aero)
- Major issues
  - En efficiency vis-a-vis A/C ("flying" in dense ATM, high drag)

## *Magnetic Levitation Technology for Advanced Transit Systems*

SP-792
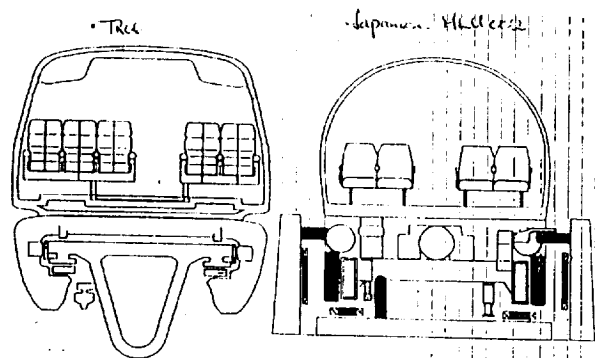


Future Transportation Technology
Conference and Exposition
Vancouver, BC, Canada
August 7-10, 1989

**SAE** The Engineering Society
For Advancing Mobility
Land Sea Air and Space

## Maglev "Players"

- Foster-Miller
- Boeing
- Grumman
- Bechtel/Draper Labs
- Magneplane/MIT Lincoln Labs

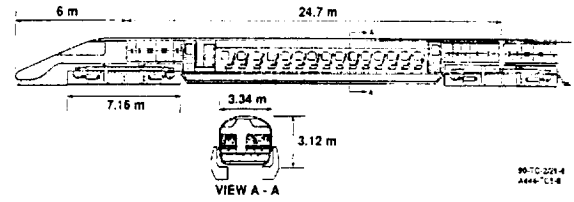  - All have many industrial "partners"
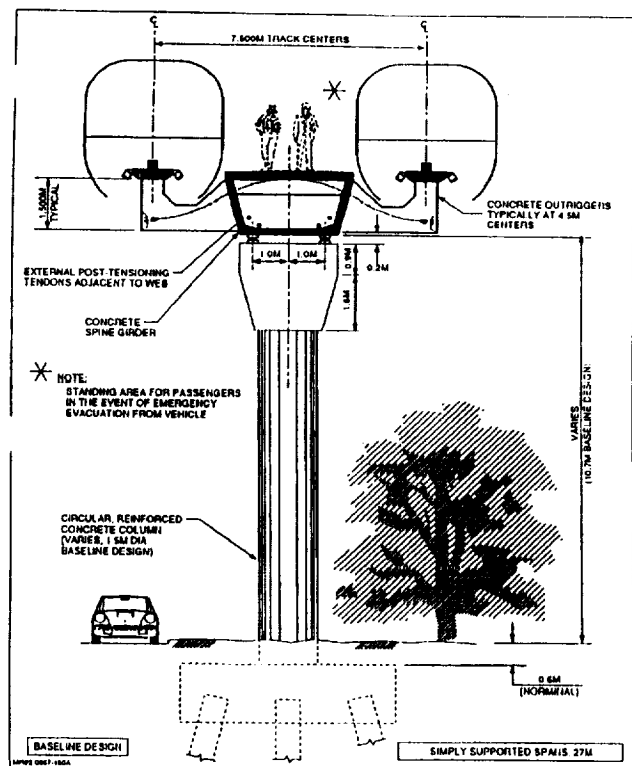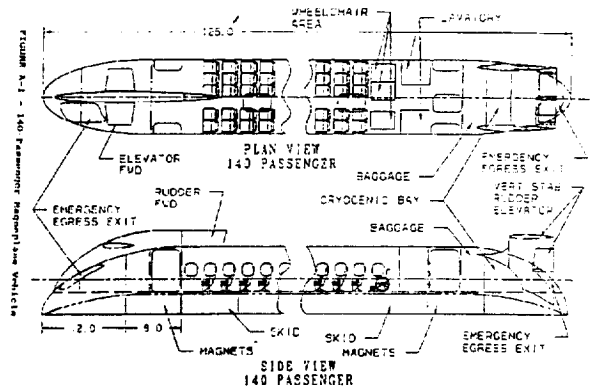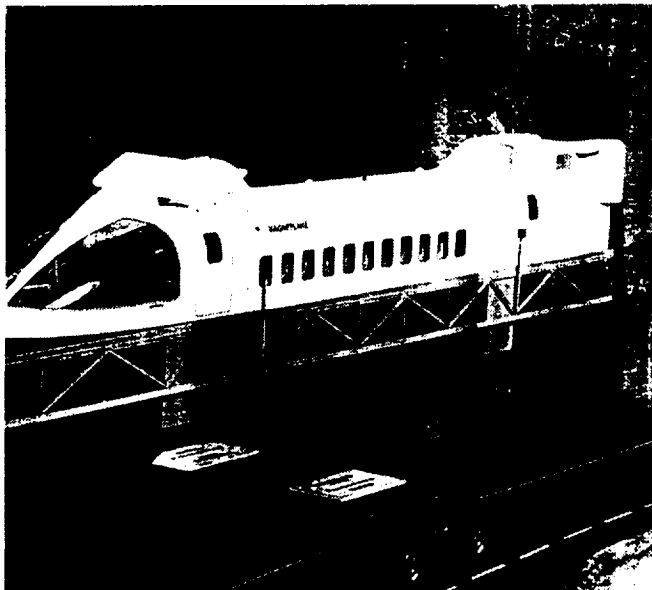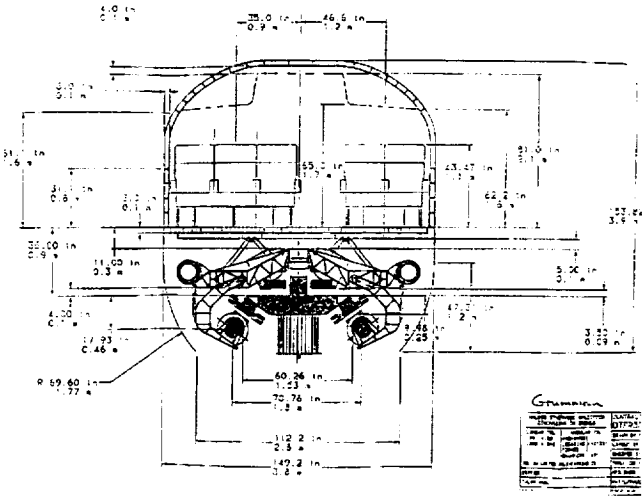


Fig. 3.2.2-10 Baseline Design Tangent Track

Foster-Miller Maglev
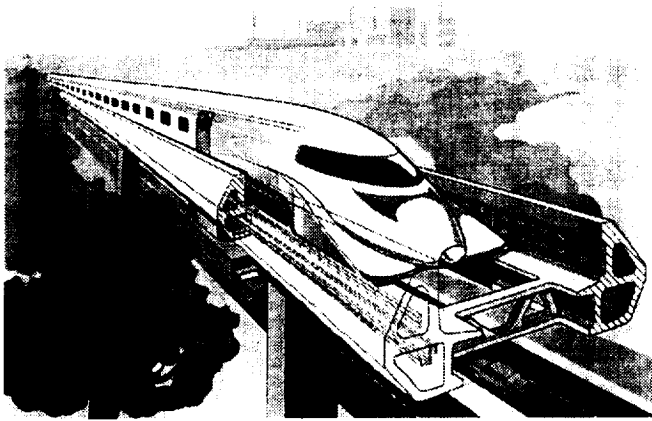
## OVERALL VEHICLE CONFIGURATION

6 m    24.7 m

7.16 m    3.34 m    3.12 m

VIEW A - A





FIGURE A-1 - 140 Passenger Magnaplane Vehicle

WHEELCHAIR AREA — LAVATORY

ELEVATOR FWD — PLAN VIEW 140 PASSENGER — BAGGAGE — EMERGENCY EGRESS EXIT

EMERGENCY EGRESS EXIT — RUDDER FWD — CRYOGENIC BAY — VERT STAB RUDDER ELEVATOR

BAGGAGE

MAGNETS — SKID    SKID — MAGNETS    EMERGENCY EGRESS EXIT

SIDE VIEW 140 PASSENGER

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## Maglev Aero Issues

- @ speed, aero drag/en. req. >> mag. drag/losses
- 3-D Noise/Base form drag red.
- Friction drag red. (external, guideway/channel)
- Drag-due-to-lift ($C_L \sim -.25$)
- "Protuberance drag" red. (mag. bogies, windows, gaps, leakage, roughness)
- Sidewinds/yaw, passing ("transonic")
- Tunnel drag red. (10x to 100x external drag)
  "State-of-the-art"
  - $C_{Dp} \sim .15$ ⎤ French/Jap. Hi Speed
  - $C_F \sim .004$ ⎦ trains, German maglev

## Sample Keys To Maglev Aero

- Determin. of phys. for 3-D "moving rail"/thin gap flow
- Flow "under & out of" skirt
  - rail interactions, 3-D bogy drag
  - effects on forebody/base press. drag
- Stability/control
- Red. of drag/en. req.

Some Possibilities
- Aero lift to reduce mag lift req.
- Body vorticity segmentation/control for red. of loads/control
- Elec. fan/Goldschmeid afterbody propul. adjunct

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