Cornell University
Graduate School of Business and Public Administration
Malott Hall, Ithaca, New York 14853

September 17, 1979

Mr. Garth Hull
Education Programs Office
NASA-Ames
Moffet Field, CA 94035

Dear Mr. Hull,

As I indicated in our phone conversation on Monday, 17Sep79, my purpose for visiting the NASA-Ames Research Facility on Friday, 21Sep79, is to be briefed on the following areas if possible:

1) Avionics, specifically the microwave landing system presently being researched for future implementation in helicopters (MLS/IFR);

2) Any informaton related to energy efficienty in military aircraft;

3) Any segment of NASA's Aircraft Energy Efficiency Program (ACEE) being conducted at NASA-Ames.

Although the above may not take a full day of visitation I would like to gain any information with which you could supply me in areas such as DARPA and/or the NASA/USAF/Rockwell International HiMat Program. I will arrive in San Francisco Thursday, 20Sep79, and intend to call you for the details on procedure for my visit the following day.

Sincerely,

Paul V. Sheridan

Paul V. Sheridan

FUTURE GENERATION ENERGY EFFICIENT AIRCRAFT

--AN INVESTIGATION AND OUTLOOK

Clifford C. Dickman
Paul V. Sheridan
May 1979

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EXECUTIVE SUMMARY

Similar to other energy end-use products, the modern passenger aircraft will continue to be affected by the diminishing supply of present energy forms, specifically aviation fuel. At present, the National Aeronautics and Space Administration (NASA) has focused their attention to this continuing problem through the Aircraft Energy Efficiency Program (ACEE). This report attempts to briefly highlight areas of research and development being conducted within this program that promise to yield significant savings in energy.

INTRODUCTION

Air travel has become an integral part of American way of life for both business and pleasure. Approximately 150 billion passenger miles will be flown this year in the United States, and this figure is increasing. The average life of existing fleets is presently in excess of 9 years and with increasing problems associated with fuel availability and rising costs, U. S. air carriers are interested in re-equipping their fleets with energy efficient aircraft.

Continued U. S. leadership in world commercial aircraft sales is crucial. Figure 1 shows a comparison of annual deliveries made by the U. S. and the rest of the world. After the slump in production of the early 1970's, the industry appears to be re-establishing its position in the world market.

Exports of commercial aircraft have contributed more than $13 billion dollars during the decade through 1976. Figure 2 shows that exporting one jumbo jet compensates the balance of trade of importing 9,000 small autos. The aerospace industry ranks second only to agriculture in terms of dollar exports.

Figures 3 and 4 show how rising fuel costs are rapidly driving up direct operating costs. Current domestic fuel prices are of the order of 60¢/gallon and international prices are about 10¢ more.

The European consortium, the main source of competition to the U. S. industry, offers several attractive aspects to prospective customers. Because of government involvement, liberal financing arrangements can be obtained and the A300B is a flying exhibition of an energy efficient aircraft.

Recognizing these facts, the U. S. government has allocated approximately $100 million in FY1978 to the research, technology and development of energy efficient aircraft.

The Aircraft Energy Efficiency Program (ACEE) has defined its objectives which are illustrated in Figure 5. The following report investigates the six major thrusts undertaken by NASA.

POTENTIAL TECHNOLOGIES FOR REDUCED FUEL CONSUMPTION

2.1: Engine Component Improvement

In a report presented to us (reference 1), it was indicated that this area of NASA's aeronautical research could yield as high as a five percent savings in fuel consumption. Although at face value this research may not appear to warrant as high a level of effort and expenditure, it must be realized that it is an activity almost totally prerequisite to the subsequent discussion of the advanced "energy efficient engine."

This research is hoped to result in higher temperature materials for use, most specifically, in the "hot section" or combustor component of the propulsion system. The metal matrix, wire-reinforced, superalloy composites in conjunction with the use of ceramics is expected to permit the combustor to operate at as high a temperature as 2500^{o}F. It is a generally known fact that the higher operating temperatures will result in substantial improvement of the thermodynamic cycle efficiencies.

Another strategy that is promising, in the area of engine component improvement, involves thermal barrier coating of engine blades and vanes. This technique was explained to result in as much as a 200°F improvement in present operating temperatures.

An area not generally focused on, in reference to reducing aviation fuel consumption, is the topic of improved engine mechanical durability. Obviously, durability will have an important effect on propulsion system performance, life, fuel efficiency and the overall cost of ownership. Progress in these areas will be effected by development of the necessary understanding and practical technologies targeted at the reduction of wear and the undesirable surface interactions encountered by gears, bearings and seals. Research concentrated to develop this technology, known as tribology, is absolutely essential for concurrent success to be achieved in "hot section" technology described briefly above. It will involve a deeper understanding of the physical and chemical interactions of the engine parts as well as the advanced lubricants and lubrication systems technically imperative to the "energy efficient engine."

2.2: Advanced "Energy Efficient Engine"

Although the responsibility of engine technology is vested in NASA's Lewis Research Center (flight propulsion laboratory) in Cleveland, Ohio, our visit at the Langley Research Center, as well as written materials received there, have facilitated a brief discussion of this area of ACEE. It was also indicated (reference 2) during our short visit to NASA central in Washington, D.C., that as high as a ten percent reduction in aviation fuel consumption could be readily achieved via the advanced "energy efficient engine" research.

It is essential that one realize the interconnected nature of aeronautical objectives. Performance, efficiency, economy, costs, productivity and many more areas of aeronautics are "directly linked to the capabilities and qualities of the propulsion system." Gas turbine combustor technology, briefly discussed in the Engine Component Improvement Section, and NASA's research projects in the area of turbine technology in general, will bring about improvements in, not only thermodynamic cycle efficiencies but also, expanded operating ranges. The implication of the latter is that of less en route stops for refueling and the obviously attractive consequence of increased air carrier operations efficiency.

Most of the efforts in the area of engine technology are carried out by the major U. S. commercial aircraft engine manufacturers while under contract to NASA. There are several areas of technological opportunity in the field of propulsion systems currently under study by these firms.

By and large the very nature of any technological design is one of compromise. The design compromises in aviation propulsion systems are those that permit operation of the aircraft in a wide range of conditions and environments. One particular technological opportunity, on the drawing boards, is known as the variable-cycle engine. It is analogous to the successful use of variable-wing geometry made by the "airfoil men," with the capability of providing large variations in the air flow with emphasis on thermodynamic cycle parameters via variable internal engine geometry. This technique permits more slack in the design compromises.with the use of low-noise variable coannular flow nozzles, flow control and mixing valves, variable flow fans and compressors; as well as the recycling of engine exhaust heat. Obviously this technology is growing more and more complex. Subsequently, if any form of efficiency is to result it will be due to concurrent development of electronic multivariable digital control systems. This area has not as yet established a significant R & T (research and technology) base but will ultimately replace the older conventional hydromechanical control systems. Exploratory studies in this field predict a "large future potential" for these systems which, as already mentioned, are essentially linked and resultantly required to "permit certain missions to be realized at all." Various written materials supplied by NASA indicate an optimistic thirty percent reduction in fuel use over today's most efficient engines via the variable-cycle engine and the related technologies.

Secondary gains of the variable-cycle engine will be in the form of broadened fuel specifications. This will effect wider fractions of petroleum crude to be used for aviation. It is estimated that the ten percent of high grade petroleum crude presently used in aviation would be doubled. "Broadened specifications will also reduce refinery energy losses by relaxing process requirements, further conserving basic energy supplies." This secondary gain will have increasingly significant effect and is a problem that must be tackled if the aviation industry is to grow or at least prosper.

2.3: Advanced Turboprops

Considerable effort is being applied to develop an advanced turboprop so that aircraft of the 1990's will be comfortable, quiet, fast and economical to operate (reference 3). The advanced turboprop program explores six areas: propeller aerodynamics and acoustics; propeller, nacelle and air frame interactions; propeller blades structural behavior; cabin acoustics; an advanced gear-box and pitch change mechanism and aircraft design.

The new turboprops are more efficient than existing high-bypass engines. Existing models have eight swept blades which have been aerodynamically and acoustically designed.

Some problems to be dealt with are that the tips of the blades are supersonic and the shock waves produce noise, and there may be some difficulty convincing the public that propellers are more efficient than jets after jets were considered superior for so long. Expected reduced fuel consumption is high at 15 - 20%.

2.4: Composite Structures

Composite materials are strong, lightweight combinations of various metals and plastics such as the boron or graphite epoxies. The term "composite" alludes to the technique of constructing what is called a "tape" by embedding the filaments of one material (typically of high tensile strength) into a sheet of another material. The latter sheet of material is called the "matrix." A composite material which is constructed with filaments of glass embedded in epoxy is a commonly known example; fiberglass. Of special interest to the ACEE program and commercial transport structures is the various graphite filaments and several different epoxies.

It was indicated (reference 4) that these materials could reduce aircraft weights by more than thirty percent, as compared to the aluminum structures presently being developed and tested by NASA. (various related research tasks are being contracted to commercial manufacturers). It was also noted that part of this endeavor would involve providing the three U. S. commercial transport manufacturers with the technology and confidence required to foster their commitment to composite structures production.

The business implications and problems associated with this technology would involve the know-how for, at least, predictable design changes and resultant low-cost fabrication. It will also be necessary to facilitate enough test and manufacturing experience to accurately predict durability for product warranties and costs for product pricing purposes--as well as the assured safety for certification by the FAA.

This area also involves assured maintainability before one can expect airline acceptance.

This problem is, in part, being tackled by NASA's ninety percent subsidy of composite versions of secondary control surface structures—development work which is being conducted by airline manufacturers. Implementation, at present, includes the rudder section of the McDonnell Douglas DC-10, the elevator of the Boeing-727 and the inboard ailerons of Lockheed's L-1011 (reference 5). The NASA flight service program has indicated that these components are being utilized with "good results."

The implementation of composite materials to the primary structures, which is defined as the load carrying structures, for example the wings, will depend, in large part, on the Douglas aircraft analysis. This work is specifically oriented at the material's ability to meet or exceed the various crashworthiness capabilities of the aluminum or metal structures. The "bottom line" will be determined by full-scale simulations which have not, as yet, been conducted.

Another important phase of this work will involve the way the aircraft is assembled. Conventional metallic structures are primarily joined with mechanical, relatively heavy fastening devices. The two emerging technologies of composites and superplastic forming is sighted to be combined with what is called diffusion bonding to substantially reduce both the weight and cost.

The weight savings of more than thirty percent, as a result of composite structures, is also predicted to reduce the "parts count" and raise the overall structural efficiency (reduced flutter, higher aspect-ratio wings without weight penalties, etc.) of the aircraft (reference 6). It is expected that the total effect of the composite structure implementations, as a result of the ACEE program, would allow a ten-to-fifteen percent reduction in fuel consumption to be realized.

2.5: Aerodynamic Improvements

Aerodynamics as the name implies is a branch of physics which deals with the movement of air. Broadly speaking it can be divided into three categories:

1. Low speed--incompressible flow
2. Transonic speed--compressible flow
3. Supersonic speed--compressible flow

Low speed aerodynamics deals with velocities less than one third the speed of sound, or about 250 mp.h. (mach number=.33) At these velocites, the effects of compressibility can be ignored. At velocities in excess of 250 m.p.h. compressibility effects become increasingly important and alter the incompressible results.

Transonic aerodynamics considers velocities close to the speed of sound or Mach 1 -- typically 0.85 mach number 1.15. Flows at these speeds have proven to be difficult to analyze analytically in the past. However the great advances in computer technology have enabled aerodynamicists to make significant strides with the development of better wings and propellers. It is interesting to note that most commercial transports of today and in the near future fly at transonic speeds.

For Mach numbers greater than one, that is supersonic flow, the presence of shock waves alters the flow significantly from that found in subsonic flows. The Concord and other SST's operate in this region.

Improved aerodynamic characteristics are essential in the improvement of energy consumption. Separated and turbulent flows around the aircraft are responsible for regions of high drag. Some of the recent discoveries and developments applied to commercial aircraft will have a significant impact on energy conservation in future generation aircraft.

2.5.1: Supercritical Wings

When an aircraft is in motion, the air travelling over the upper surface of the wing reaches a higher velocity than the free stream. Consequently as the aircraft accelerates, a point is reached (called the critical Mach number) when the velocity over the wing becomes sonic (the speed of sound). A shock wave forms as a result and with greater speeds a strong shock, such as is found on today's aircraft, can cause a flow separation and hence reduce performance and increase fuel consumption.

A significant breakthrough has been achieved with supercritical wing design (reference 7). Figure 6 shows a comparison between a supercritical and a conventional airfoil. Note that the former has a weaker shock and no flow separation. The drag reductions associated with the new airfoil will result in considerable energy savings.

2.5.2: Active Controls

Aerodynamic theory predicts that for minimum lift induced drag, the wing loading should be distributed elliptically across the span. This is not always attainable and conventional aircraft must be structurally capable of withstanding much higher loads with varying distributions produced by gusts and atmospheric turbulence. An Active Load Distribution Control System (ALDCS) has been developed by NASA. Sensors in the wing detect changes in the local loading. The information is analyzed by a microprocessor and an outboard aeleron is automatically moved in order to redistribute the load.

Figure 7 shows the differences in wing root being moment on a C5-A and a NASA model with the ALDCS operative and passive. With the ALDCS activated, considerable structural modifications can be made to reduce the aircraft weight. Projections for reduced fuel consumption range between 10 and 25% for the combination of improved aerodynamics and active controls.

2.6: Laminar Flow Control

At the leading edge of the wing of today's transports the airflow is smooth and layered--or laminar. At the speeds of flight now attainable, disturbances in air grow and ultimately produce a boundary of region of turbulent air close to the surfaces of an aircraft. Aerodynamicists have long known that, if some of the air can be maintained in a laminar--low-friction drag--state over the whole surface. This is what is meant by the term "Laminar Flow Control." One plan is to physically remove the boundary layer through the use of suction. Considerable design and development is necessary in order to achieve laminar flow control; however, the incentive is there because up to 40% fuel savings could be realized. Figure 8 shows a comparison between existing airfoils and a laminar flow control airfoil. The Air Force has already proved that LFC is technically feasible using its experimental X-21A aircraft (reference 5).

CONCLUSIONS

Figure 9 shows the potential of technologies for reduced fuel consumption. The combined potential is estimated to be approximately 50%. It should be noted that the sum of the savings is greater than the estimated combined potential. This is because any one saving reduces the residual savings.

viz.

$$\text{Total Savings} = (1 - R_1)(1 - R_2)(1 - R_3) \ldots$$

where R_1, R_2, R_3 etc. are the individual fuel reductions

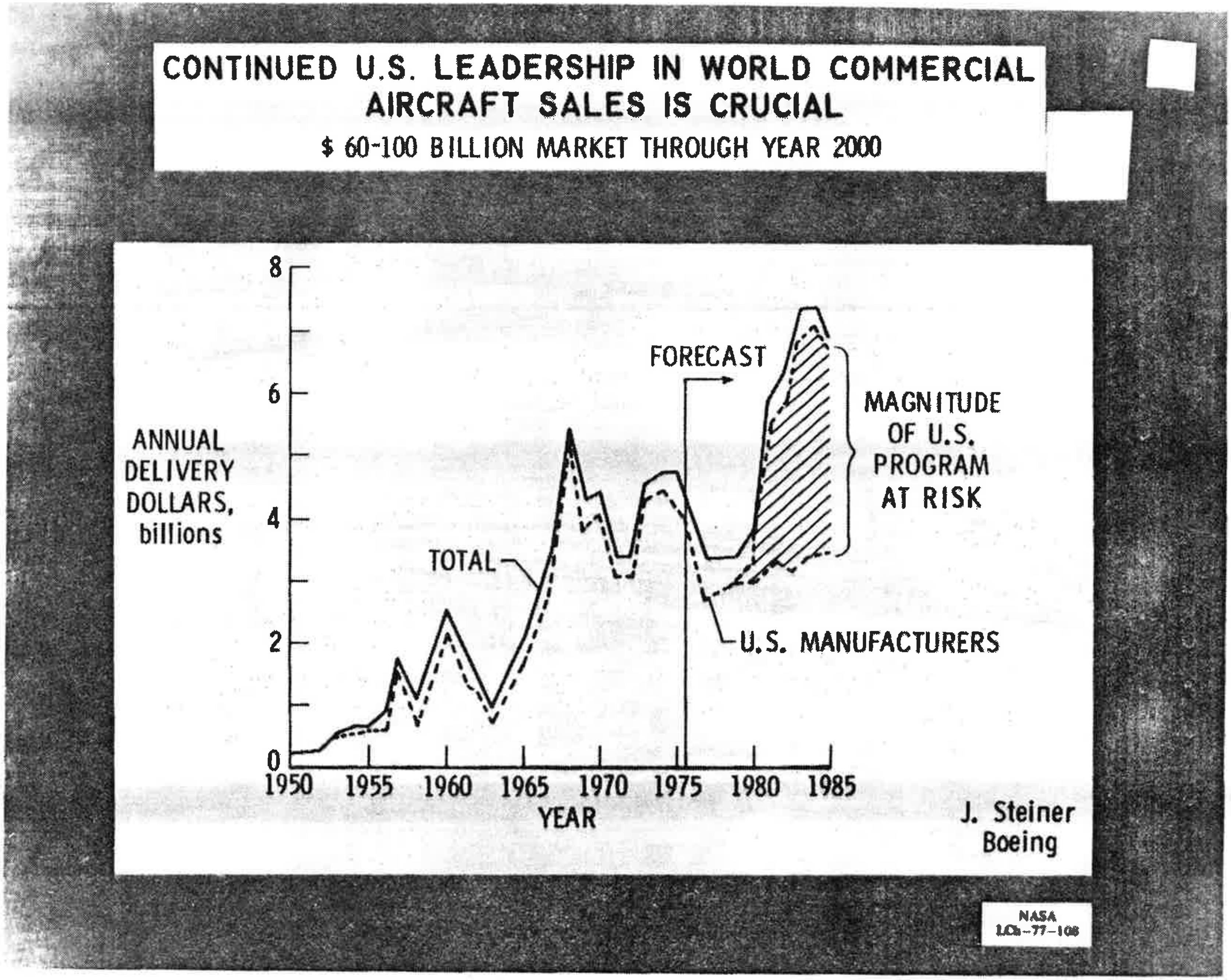
These projections will have a considerable impact on the energy efficiency of future generation commercial aircraft. It will make U. S. manufactured aircraft competitive with world competition, notably the European consortium, and will, of course, enable air carriers to operate a more economically efficient fleet.

ACKNOWLEDGEMENTS

The authors would like to extend their appreciation to Professor Robert C. Lind whose guidance and productive criticism helped focus our energies. We would also like to thank Dr. Roger Winblade, Dr. Guy Boswick, Dr. Robert Helton, Dr. Marion McKinney, and Dr. Robert Leonard of the National Aeronautics and Space Administration and their wonderful secretaries whose hospitality was tremendous!

APPENDIX I (FIGURES)

FIGURE 1



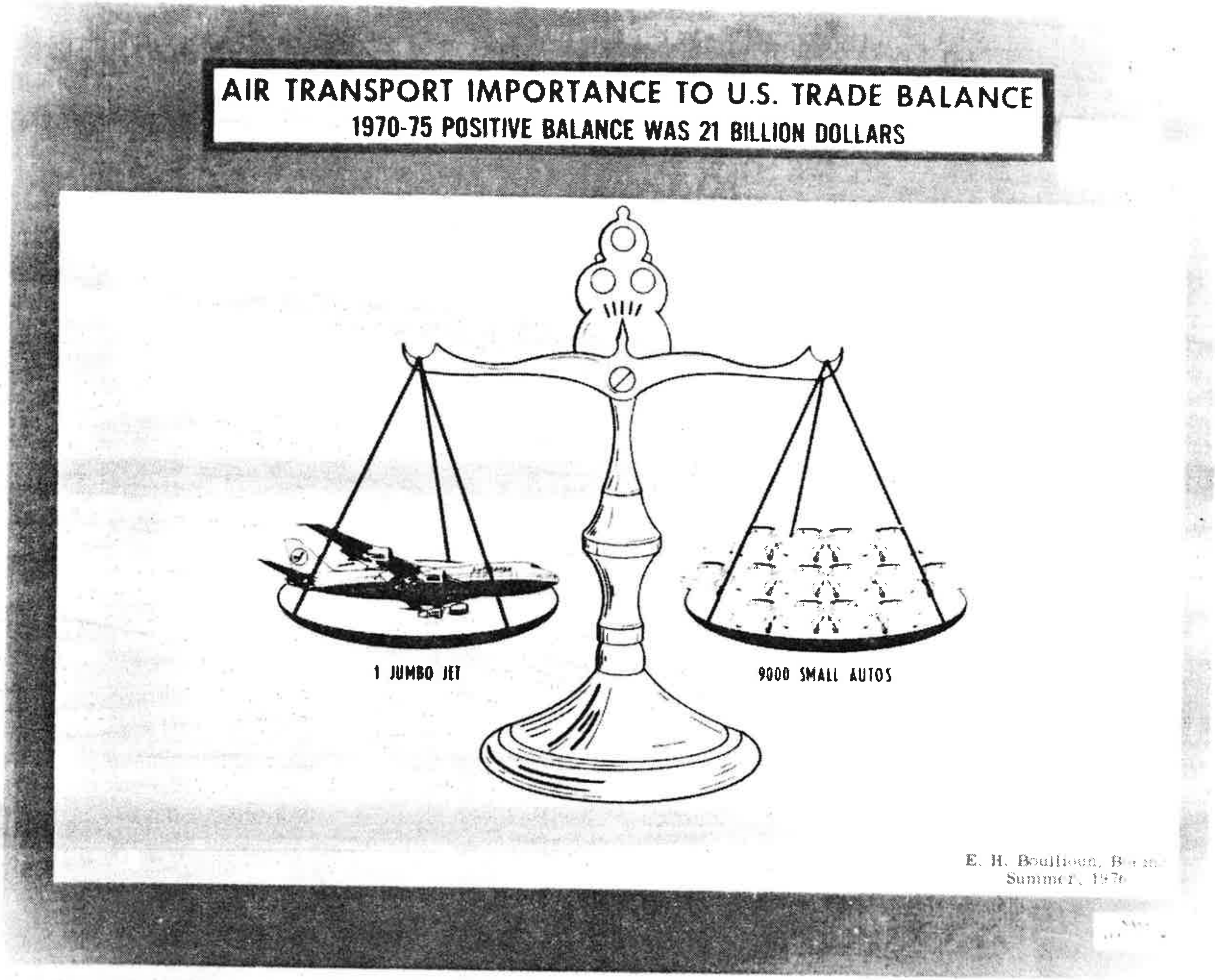
CONTINUED U.S. LEADERSHIP IN WORLD COMMERCIAL AIRCRAFT SALES IS CRUCIAL

$ 60-100 BILLION MARKET THROUGH YEAR 2000

J. Steiner
Boeing

NASA
LCS-77-108

FIGURE 2



AIR TRANSPORT IMPORTANCE TO U.S. TRADE BALANCE

1970-75 POSITIVE BALANCE WAS 21 BILLION DOLLARS

E. H. Boullioun, Boeing
Summer, 1976

FIGURE

CAB AVERAGE JET FUEL PRICES

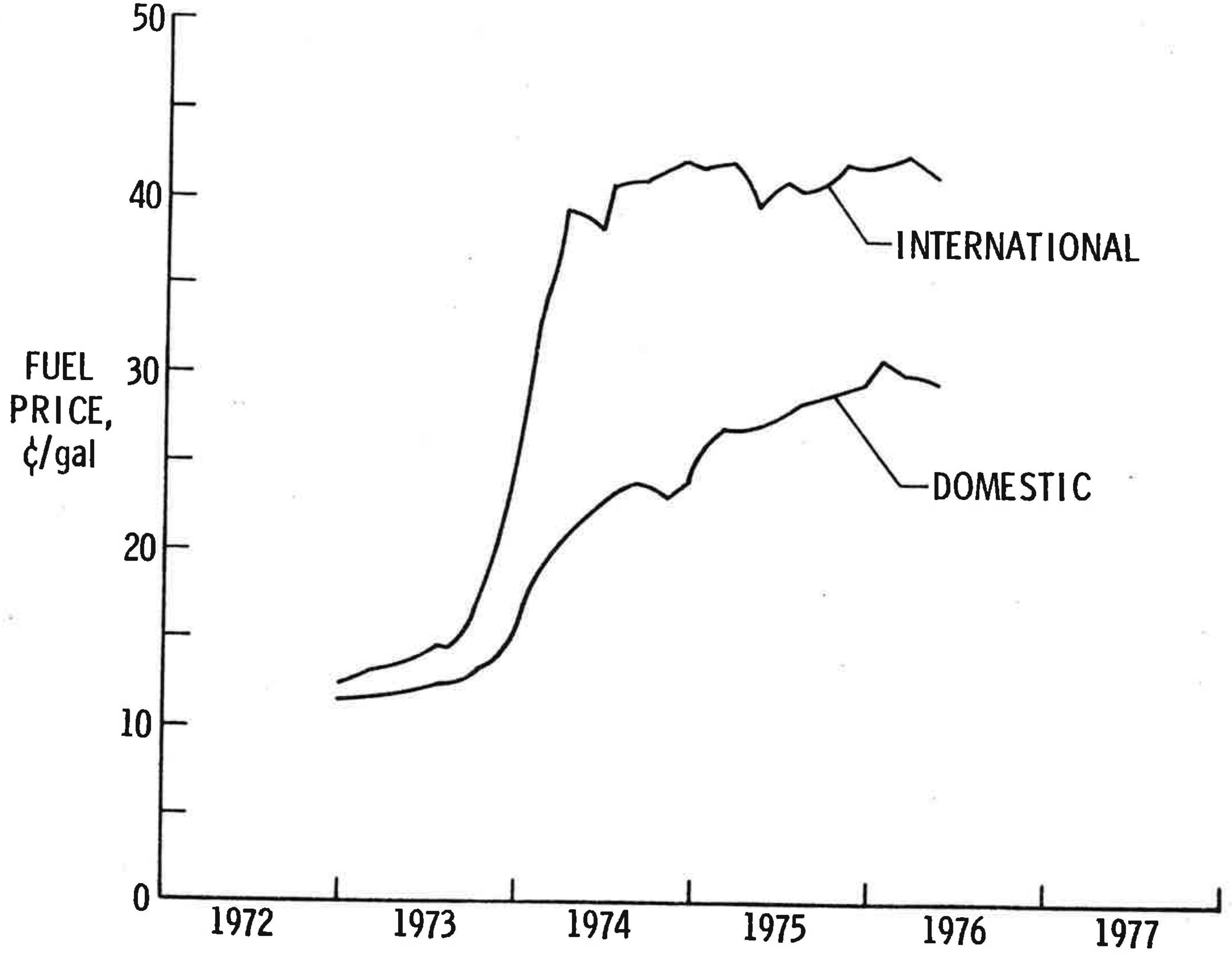


FIGURE 4

SIGNIFICANCE OF FUEL COSTS

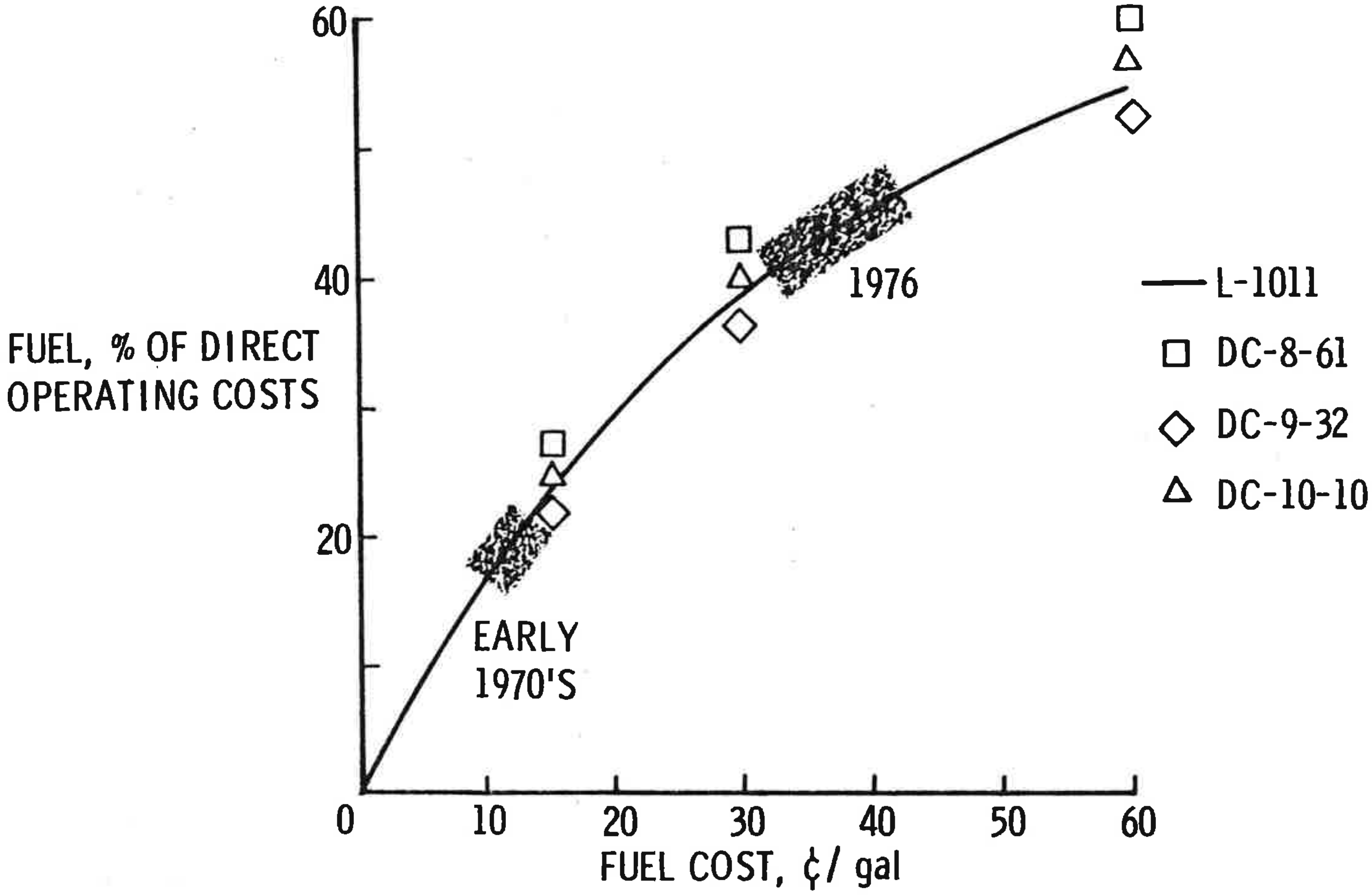


FIGURE 5

AIRCRAFT ENERGY EFFICIENCY PROGRAM

D4
4/79

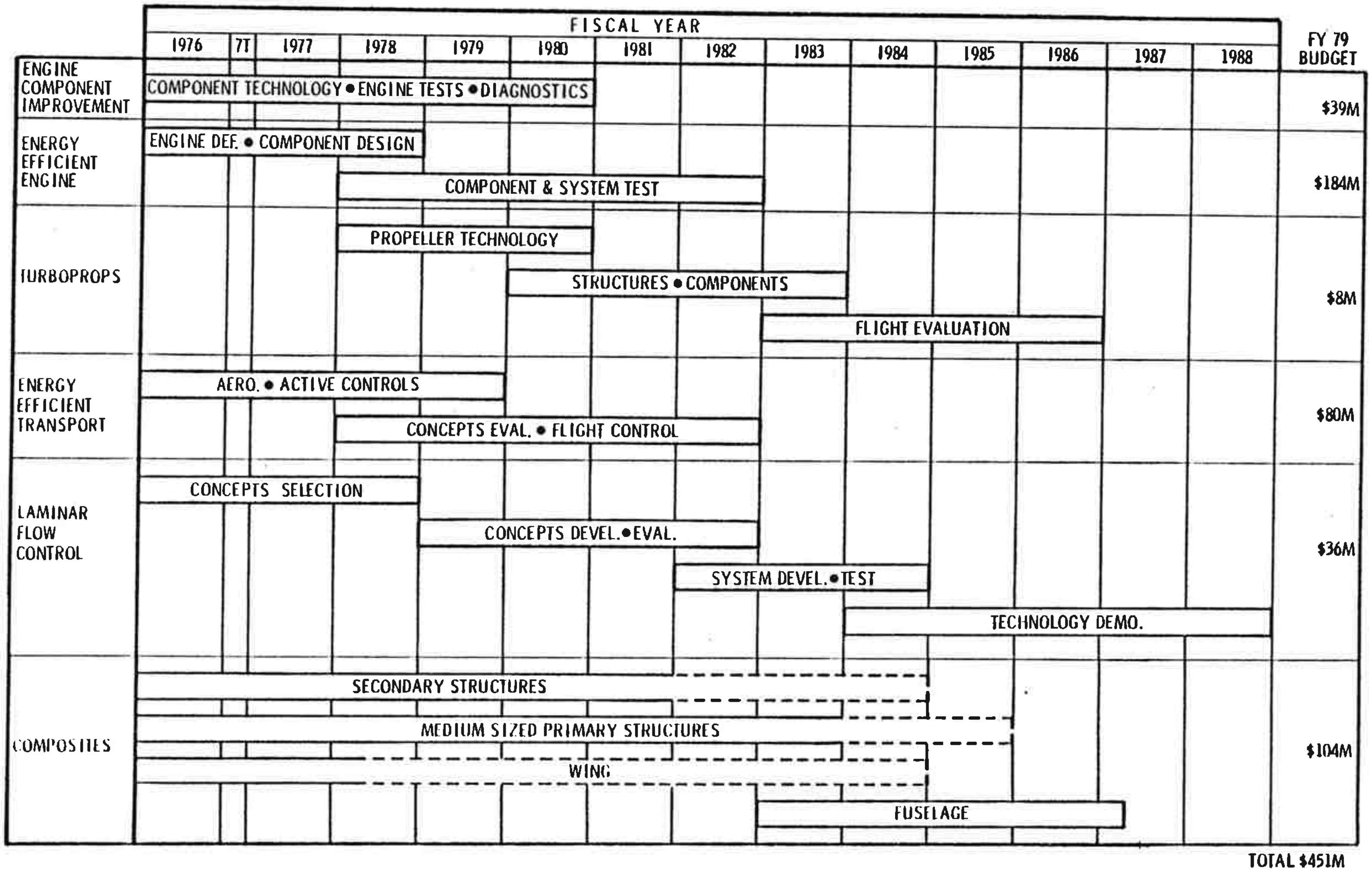
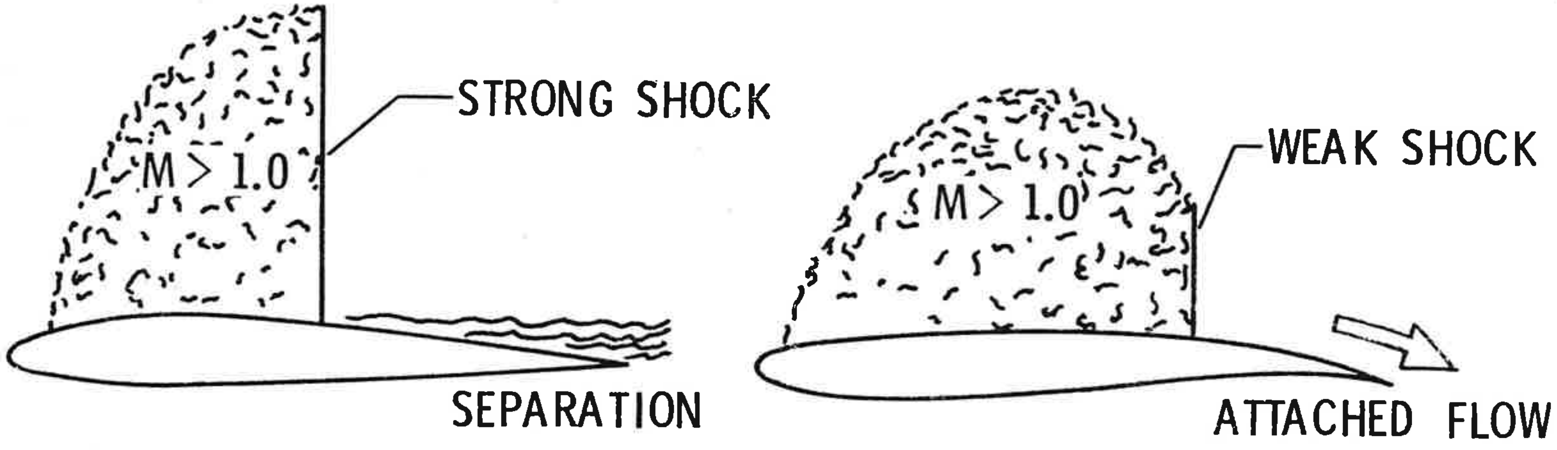


FIGURE 6

SUPERCRITICAL FLOW PHENOMENA



CONVENTIONAL AIRFOIL

SUPERCRITICAL AIRFOIL

FIGURE 7

EFFECT OF ACTIVE CONTROLS ON C-5A BENDING MOMENTS

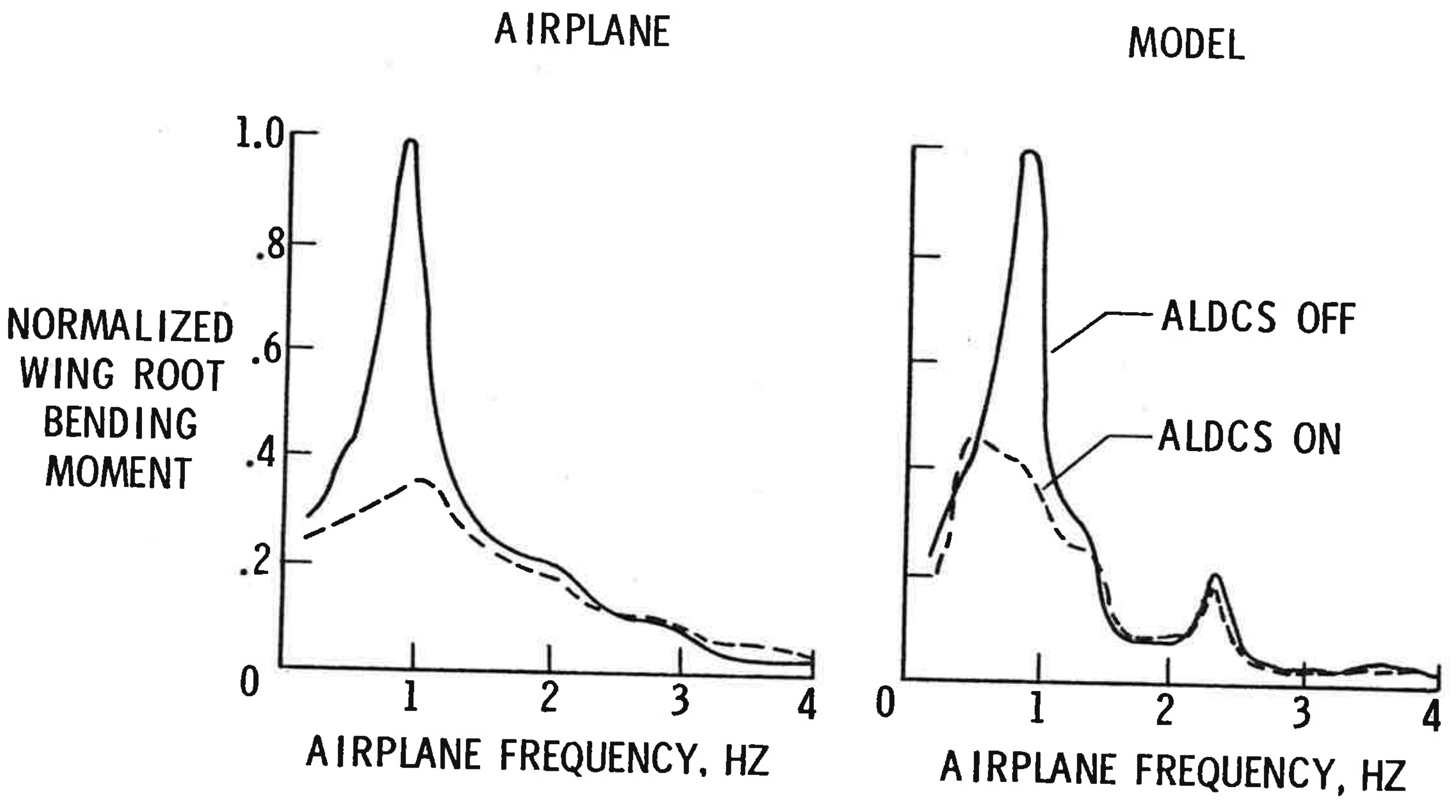
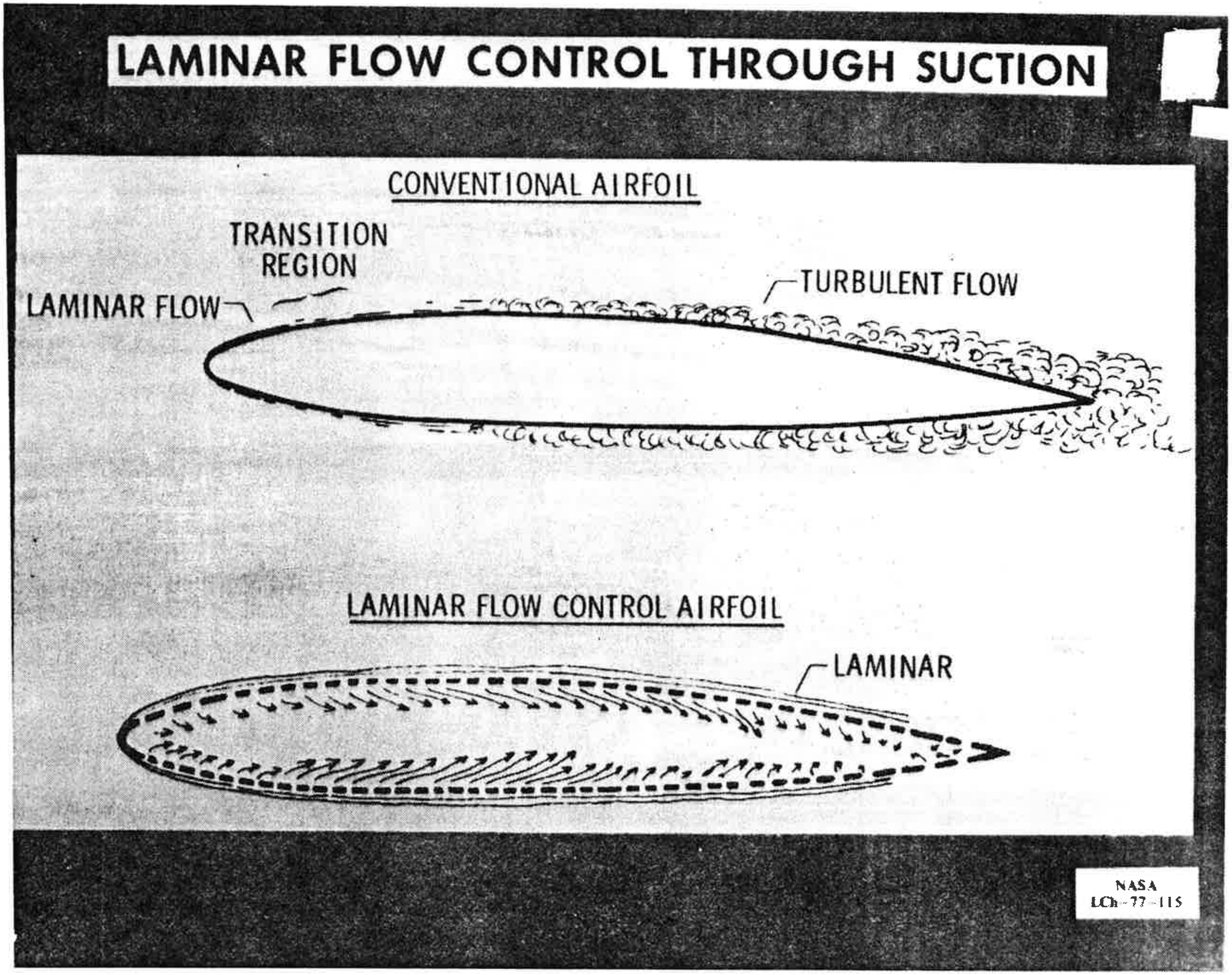


FIGURE 8



LAMINAR FLOW CONTROL THROUGH SUCTION

CONVENTIONAL AIRFOIL

LAMINAR FLOW CONTROL AIRFOIL

NASA
LCh-77-115

FIGURE 9

POTENTIAL OF TECHNOLOGIES FOR REDUCED FUEL CONSUMPTION

○ ENGINE COMPONENT IMPROVEMENT	5%
○ ADVANCED "ENERGY EFFICIENT ENGINE"	10%
○ ADVANCED TURBOPROPS	15-20%
○ COMPOSITE STRUCTURES	10-15%
○ AERODYNAMICS AND ACTIVE CONTROLS	10-20%
○ LAMINAR FLOW CONTROL	20-40%
○ COMBINED POTENTIAL	50%

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