NASA Contractor Report 159381

A FEASIBILITY STUDY FOR ADVANCED TECHNOLOGY INTEGRATION FOR GENERAL AVIATION

(NASA-CR-159381) A FEASIBILITY STUDY FOR
ADVANCED TECHNOLOGY INTEGRATION FOR GENERAL
AVIATION Final Report, 10 Apr. 1979 - 9
Apr. 1980 (Kansas Univ.) 533 p
HC A24/MF A01
CSCL 01B G3/01

N81-15974

Unclas
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NASA Contract NAS1-15770
November 1980

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton Virginia 23665

PREFACE

This volume constitutes the final report for NASA Contract NAS-1-15770. This contract was funded by NASA Langley Research Center for the period of 10 April 1979 through 9 April 1980, although the project actually began in January 1979.

This project was used to fulfill part of the requirements for the Master of Engineering (ME) and Doctor of Engineering (DE) degrees for three graduate students at the University of Kansas. Major Garey T. Matsuyama, a DE candidate on leave from the United States Air Force Academy, served as project director. Assisting him were Kevin Hawley and Paul Meredith, ME candidates, who both made significant contributions to the project.

The objective of the ME-DE program at the University of Kansas is to provide students with an educational experience which includes graduate level technical and management courses, practical engineering experience through an internship program in industry or government, and a significant engineering project which provides direct experience with management problems, interpersonal relations, communication, and challenging technical problems.

We are grateful to the NASA Langley Research Center for supporting this project which not only provided the unique experiences required for the success of this educational program but also contributed to advancing the level of aeronautical technology.

David L. Kohlman
Principal Investigator
Professor of Aerospace Engineering

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LIST OF SYMBOLS

Symbol	Definition	Dimensions SI (British)
A or AR	wing aspect ratio	------
Ae	effective aspect ratio (A)(e)	------
b or b_w	wing span	m (ft)
b_f/b	flap span to wing span ratio	------
BFL	balanced field length	m (ft)
b_{ij}	relative benefit of technology i in category j	------
BSFC	brake specific fuel consumption	kg/kW/hr (lb/hp/hr)
c	wing chord	m (ft)
c_d	2D drag coefficient	------
C_D	3D drag coefficient	------
C_{D_o}	zero lift drag coefficient	------
c_f/c	flap chord to wing chord ratio	------
c_ℓ	2D lift coefficient	------
C_{ℓ_β}	variation of rolling moment coefficient due to sideslip angle	rad^{-1} (deg^{-1})
C_L	3D lift coefficient	------
CL_i	confidence level of survey participant i	------
$c_{m_{c/4}}$	section pitching moment coefficient about the quarter chord	------
c_{m_o}	section pitching moment coefficient at zero angle of attack	------

C_{m_α}	variation of pitching moment coefficient with angle of attack	rad^{-1} (deg^{-1})
C_{n_r}	variation of yawing moment coefficient with yaw rate	rad^{-1} (deg^{-1})
CR	compression ratio	------
dC_m/dC_L	change in pitching moment coefficient with respect to lift coefficient	------
Dn	propeller diameter x rotation speed	m/s (ft/sec)
e	Airplane efficiency factor	------
f/a or F/A	fuel to air ratio	------
FM_i	figure of merit of technology i	------
h	altitude	m (ft)
L/D	lift-to-drag ratio	------
M	Mach number	------
n	number of survey participants	------
P/W	power to weight ratio (usually P_{max}/W_{gross})	kW/N (hp/lb)
$\bar{q}$	dynamic pressure	N/m^2 (lb/ft^2)
R	range	km (nm)
$\bar{R}_j$	mean rating of category j	------
$\bar{R}_{c_j}$	corrected mean rating of category j	------
Re	Reynold's number	------
RF	range factor	kg/km/l (lb/nm/gal)
R_{ij}	rating given by participant i to category j	------

S	wing area	m^2 (ft^2)
sfc or SFC	specific fuel consumption	kg/kW/hr (lb/hp/hr)
t/c	airfoil section thickness-to-chord ratio	------
T_{ijk}	voting indicator of participant i in category j for rating k	------
TNC_i	number of participants who changed their rating of category i between two successive survey rounds	------
TPC_i	total percent change in the number of participancs changing their ratings of category i between two successive survey rounds	------
TSFC	thrust specific fuel consumption	N/kg/hr (lbf/lbm/hr)
V	velocity	m/s (ft/sec)
V_{jk}	number of votes in category j for rating k	------
w_j	weighting of category j	------
W	weight	kg (lb)
W_E/W_G	empty to gross weight ratio	------
W/S	wing loading	N/m^2 (lb/ft^2)

<u>Greek Symbols</u>:

α	angle of attack	rad (deg)
β	sideslip angle	rad (deg)
Δ	increment (used as a prefix)	------
δ_e	elevator deflection	rad (deg)
η_p	propeller efficiency	------

$\eta_p P/W$	effective power loading (usually that required at a specific flight condition, as opposed to the maximum)	kW/N (hp/lb)
μ	runway friction coefficient	------
ρ	air density	kg/m^3 $(slug/ft^3)$

LIST OF ACRONYMS

Acronym	Definition
ACARS	Automatic Communication and Reporting System
ACEE	Aircraft Energy Efficiency program
ADCOM	Advanced Technology Commuter, Conventional Configuration
ADCOMCN	Advanced Technology Commuter, Canard Configuration
ADF	Automatic Direction Finder
ADI	Attitude Direction Indicator
AFCS	Automatic Flight Control System
AGL	Above Ground Level
AHRS	Attitude Heading Reference System
ALT	Altitude
ARA	Advanced Research Airplane (Princeton)
ARAD or ARA-D	Advanced propeller sections developed by Aircraft Research Association, Ltd. (ARA) and funded by Dowty Rotol, Ltd.
ARINC	Aeronautical Radio, Inc.
ASEE	American Society for Engineering Education
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATLIT	Advanced Technology Light Twin research airplane (modified Piper Seneca) tested by NASA Langley, Piper, and the University of Kansas, Flight Research Laboratory.

A/C	Aircraft
BDC	Bottom Dead Center
BFL	Balanced Field Length
BHP	Brake Horsepower
BMDP	Biomedical Computer Programs
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CADCAM	Computer Aided Design/Computer Aided Manufacturing
CAMI	Civil Aeromedical Institute (FAA-Oklahoma City)
CAS	Collision Avoidance System
CCV	Control Configured Vehicle
CEP	Circular Error Probability
CHT	Cylinder Head Temperature
CL	Confidence Level
COMBL	Current technology Commuter Baseline configuration
CONUS	Continental United States
CPM	Critical Path Method
CR	Compression Ratio
CRT	Cathode Ray Tube
CT	Candidate Technology
CVCC	Compound Vortex Controlled Combustion system (Honda stratified charge system)
DAAS	Demonstrator Advanced Avionics System
DABS	Discrete Address Beacon System
DARE	Digital Avionics Research system (NASA-Langley)
DDBS	Digital Data Broadcast System

DLC	Direct Lift Control
DME	Distance Measuring Equipment
DOC	Direct Operating Cost
DOT	Department of Transportation
EET	Energy Efficient Transport (element of the ACEE program)
EGT	Exhaust Gas Temperature
EHSI	Electronic Horizontal Situation Indicator
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
ESHP	Equivalent Shaft Horsepower
ET	Evaluation Technique
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBL	Fly-by-Light
FBW	Fly-by-Wire
FCT	Final Candidate Technologies
FM	Figure of Merit
FOD	Foreign Object Damage
GA or G.A.	General Aviation
GAMA	General Aviation Manufacturer's Association
GAP	General Aviation Propeller program
GASP	General Aviation Synthesis Program
GATE	General Aviation Turbine Engine
GA(W)	General Aviation Whitcomb airfoil series

GPS	Global Positioning System
HCRLB	High Compression Ratio/Lean Burn reciprocating engine
HMD	Head-Mounted Display
HSI	Horizontal Situation Indicator
HUD	Heads-Up Display
IDCC	Integrated Data Control Center
IDRF	Impact Dynamics Research Facility (NASA-Langley)
IEEE	Institute of Electrical and Electronics Engineers
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INS	Inertial Navigation System
IPS	Intermittent Positive Control
ISA	International Civil Aeronautical Organization (ICAO) Standard Atmosphere
LaRC	Langley Research Center (NASA)
LC	Liquid Crystal
LCC	Life Cycle Cost
LED	Light Emitting Diode
LFC	Laminar Flow Control
LS	Low-Speed airfoil series (NASA)
MLS	Microwave Landing System
MSL	Mean Sea Level
MSOMLA	Modified Seat-Occupant Model for Light Aircraft
MTBF	Mean Time Between Failures
NACA	National Advisory Committee for Aeronautics

NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis computer code
NAVSTAR	Navigation System using Time And Ranging
Nicad	Nickel/Cadmium battery
NLF	Natural Laminar Flow
NLFC	Natural Laminar Flow Control
NTIS	National Technical Information Service
OEM	Original Equipment Manufacturer
OSU	Ohio State University
PCAAS	Preliminary Candidate Advanced Avionics System
PCT	Preliminary Candidate Technology
PERT	Program Evaluation and Review Technique
PLOE	Pessimistic-Likely-Optimistic-Expected (scenarios to examine the Evaluation Technique)
POL	Problem-Oriented Language computer codes
PROCO	Programmed Combustion (Ford stratified charge system)
QCGAT	Quiet, Clean, General Aviation Turbofan
QVLM	Quasi-Vortex Lattice Method
RC	Rotary Combustion
RF	Range Factor
Redhawk	Langley Research Center/University of Kansas, Flight Research Laboratory research airplane (modified Cessna Cardinal)
RSR	Rapid Solidification Rate
R/C	Radio Controlled
R & D	Research and Development

SAS	Stability Augmentation System
SCAN	Problem-oriented language computer code developed at the University of Illinois.
SCAN (NASA)	NASA Selected Current Aerospace Notices. Index published twice each month.
SCAS	Stability and Control Augmentation System
SFC or sfc	Specific Fuel Consumption
SHP or shp	Shaft Horsepower
SIU	Southern Illinois University
SSSA	Separate Surface Stability Augmentation system
STAR (NASA)	NASA Scientific and Technical Aerospace Reports. Index published twice each month.
STAT	Small Transport Aircraft Technology
STC	Supplemental Type Certificate
STI	Systems Technology, Inc.
TBO	Time Between Overhaul
TCCS	Texaco Controlled Combustion System (Texaco stratified charge system)
TCHLST	Computer program written at the University of Kansas, Flight Research Center which incorporates the Evaluation Technique.
TDC	Top Dead Center
TIT	Turbine Inlet Temperature
TSFC	Thrust Specific Fuel Consumption
TSO	Technical Standard Order
UG3RD	Upgraded 3rd Generation Air Traffic Control system
VFR	Visual Flight Rules
VHF	Very High Frequency
VLF	Very Low Frequency

VLM	Vortex Lattice Method
VOR	Very High Frequency Omni-Directional Range
VORTAC	VOR and Tactical Air Navigation System
V/STOL	Vertical/Short Takeoff and Landing

CHAPTER 1

SUMMARY

A study directed toward the identification and evaluation of applicable advanced technologies for general aviation was performed. An extensive data base was generated through visits to 31 general aviation manufacturers and 3 NASA research centers as well as through an exhaustive literature search. An evaluation technique was developed which allowed candidate technologies to be ranked according to potential benefit. Finally, design studies were performed for a 6-passenger personal/business airplane and a 19-passenger commuter airplane. The General Aviation Synthesis Program (GASP) was utilized during the design studies for propulsion system and vehicle sizing as well as mission performance analysis.

In assembling the data base, extensive notes which were acquired from the visits were edited and are included in the report as an appendix. 56 of the 137 technologies initially identified were evaluated and are discussed separately in the report.

The results of the technology evaluation indicated that propulsion, aerodynamic, and composite technologies are extremely attractive to general aviation. When these technologies were incorporated into the design synthesis of the two airplanes, higher wing loadings and smaller airplanes resulted. Fuel savings of 50% for the 6-passenger airplane and 40% for the commuter were realized.

CHAPTER 2

INTRODUCTION

General aviation represents 96% of the civilian pilot force flying 99% of the civil aircraft and 84% of the total flight hours in the United States. During 1979 alone, factory billings for aircraft shipments amounted to $2.2 billion. However, propeller technology is largely of World War II vintage, reciprocating propulsion systems are cooled by excessively rich mixtures during climb, autopilot functions are fed back to the pilot as distracting control movements, and construction is typified by conventional aluminum sheet-stringer structure with protruding rivet heads in a large number of current aircraft.

This apparent conflict, where the fleet size is large and heavily utilized, the industry is enjoying record sales, while the equipment appears outmoded, points to some unique characteristics of the general aviation environment. Specifically, (1) the users (particularly single-engine and commuter users) are much more sensitive to purchase price than their heavy-jet, commercial airline counterparts, (2) manufacturers are reluctant to incur increased production costs through product improvement for an apparently already satisfied market, and (3) the capital intensive nature of the industry may easily spell financial disaster for the manufacturer who misjudges the product improvement expectations of the user.

However, the fuel price and availability problems which began in 1973, together with strong public reaction to noise and emissions pollution, have resulted in the acceleration in development of several new and promising technologies.

2.1 BACKGROUND

The recent development of many different technologies with potential application to the general aviation fleet of aircraft has reached a point where radically improved airplanes can now be foreseen. However, to realize these improvements applicable technologies must be identified and actively pursued in an orderly and timely manner. Also, synergistic effects resulting from the integration of appropriate technologies require identification in order to better define research.

To illustrate this latter point, consider the development of an advanced natural laminar flow airfoil. Thorough evaluation of this technology would appear to dictate eventual full scale tunnel tests and flight tests. However, since surface roughness can impose severe penalties on the performance of this airfoil, a composite or bonded wing may be called for in order to eliminate the problem of rivet lines and butted skin joints. Here, a decision to pursue natural laminar airfoils through conventional manufacturing techniques may lead to an erroneous evaluation, while a decision to investigate a composite wing may be delayed if its potential benefit is seen only as an improvement in empty weight (when a conventional airfoil is utilized).

The key issues facing both research institutions (NASA Research Centers) and a capital intensive industry when confronted with the question of which technologies to pursue appear to lie in how to identify those technologies which offer great potential for improving safety, performance, and cost as well as how to identify those with questionable benefits. An attendant result of such an evaluation appears to be the identification of those technologies with noteworthy (as opposed to highly significant) benefits which might be attained for a rather low level of development effort.

Significant pioneering work done in this area of technology evaluation was recently completed by Bergey (Ref. 18). The present research represents an effort to continue with this type of work on a much broader scale and in much greater depth.

2.2 PURPOSE

In light of the above discussion, the purpose of this research is threefold:

(1) Identify candidate technologies which appear to offer improvements in safety, fuel efficiency, performance, and utility of general aviation airplanes.

(2) Quantify the magnitude of these improvements.

(3) Investigate the synergistic effects of advanced technology integration on general aviation airplanes.

2.3 SCOPE

Recognizing the different requirements of different types of airplanes within general aviation, this research effort was directed to an investigation of the impact of new technologies on a small airplane with a 6-passenger cabin (including pilots) and a larger airplane with at least a 12-passenger cabin (excluding pilots). Performance guidelines for these two airplanes were very broad. General guidelines adopted for this study included high maximum lift-to-drag ratios on the order of 18, cruise speeds on the order of 250 knots, and landing speeds below 60 knots.

Those tasks which were specified as a part of this study included the following:

(1) Representative manufacturers within the general aviation industry and certain NASA Research Centers were visited in order to integrate the views of government agencies and industry concerning new technologies.

(2) Promising new technologies were identified, and their impacts on two different airplanes were evaluated.

(3) Trade studies for the two specified airplanes configured conventionally with aft tails and also as canards were performed (although the canard studies met with difficulties).

(4) The General Aviation Synthesis Program (GASP) was utilized in the evaluation of those technologies which affect vehicle weight and performance.

2.4 APPROACH

The approach utilized to accomplish the required tasks leading to successful attainment of the goal of this research may be broadly categorized as follows:

(1) Identify and develop a data base.
    (a) Conduct a literature search.
    (b) Acquire, review, and tabulate pertinent documents.
    (c) Visit manufacturers and NASA research centers.
(2) Identify, develop, and test an evaluation technique.
(3) Identify and evaluate technologies.
(4) GASP
    (a) Gain familiarity with the program.
    (b) Modify as required to evaluate technologies.
    (c) Benchmark against current technologies.
    (d) Use to size configurations.
(5) Design and evaluate two advanced technology airplanes.

2.5 REPORT FORMAT

Each of the four major tasks listed previously in Section 2.3 is discussed in a separate chapter within this report, and an associated appendix is included where supporting documentation for three chapters is provided. Here Appendix A is provided for Chapter 3 (visits), Appendix B is provided for Chapter 4 (techno-evaluation), and Appendix C is provided for Chapter 5 (designs). GASP modifications are discussed in Chapter 6.

Finally, Chapter 7 summarizes the results of the research effort and Chapter 8 closes with conclusions and recommendations.

CHAPTER 3

VISITS TO MANUFACTURERS AND RESEARCH FACILITIES

3.1 INTRODUCTION

Visits to manufacturers and NASA research facilities formed one of three major thrusts of the present research. The purpose of this particular effort was to interview representative industry and research facilities with the goal of developing the information base and contacts required to support the project. The 34 facilities which were visited provided a wealth of information and, as a spinoff, directed attention to many other sources of pertinent information.

This chapter presents an overview of the planning, initiation, proceedings, and results of the visitation phase. Appendix A is included as a supplement, where notes assembled by the research team during each visit have been compiled, edited, and are presented in abbreviated form.

3.2 MANUFACTURERS, RESEARCH FACILITIES, AND MEETINGS

The work statement for this research effort listed 28 manufacturers and research facilities to be visited. As the project progressed, the list was modified to accomodate changes in order to provide the required data base for the ensuing technology evaluation. In order to support the final visitation list without exceeding budget constraints, different modes of transportation were utilized. Figure 3.1 illustrates the scope of the visitation phase by presenting the geographical location of the facilities involved in this research project.

3.2.1 Manufacturing Facilities

Table 3.1 provides a listing of those manufacturers visited.

3.2.2 Changes to the Manufacturer Visitation Schedule

These changes represent the addition of five facilities to those already planned for. The following is a summary of the changes and the rationale for including them.

(1) Bellanca Aircraft Engineering. This firm was responsible for the development of the Bellanca Skyrocket, a high performance single engine aircraft. The inclusion of this firm was believed to be important because of their achievements in low drag airframes and composite construction techniques.

(2) Hartzell, Hamilton Standard, and McCauley. An examination of the initial list of facilities detected deficiencies in the propulsion area. While engine manufacturers were included, representatives of the propeller manufacturers were not. These three companies were added to the facility list to broaden the propulsion technology base.

(3) Curtiss-Wright. This facility was added because of their work with rotary combustion engines.

3.2.3 Professional Meetings

These meetings proved valuable to the research efforts of the project and provided significant insight to technology

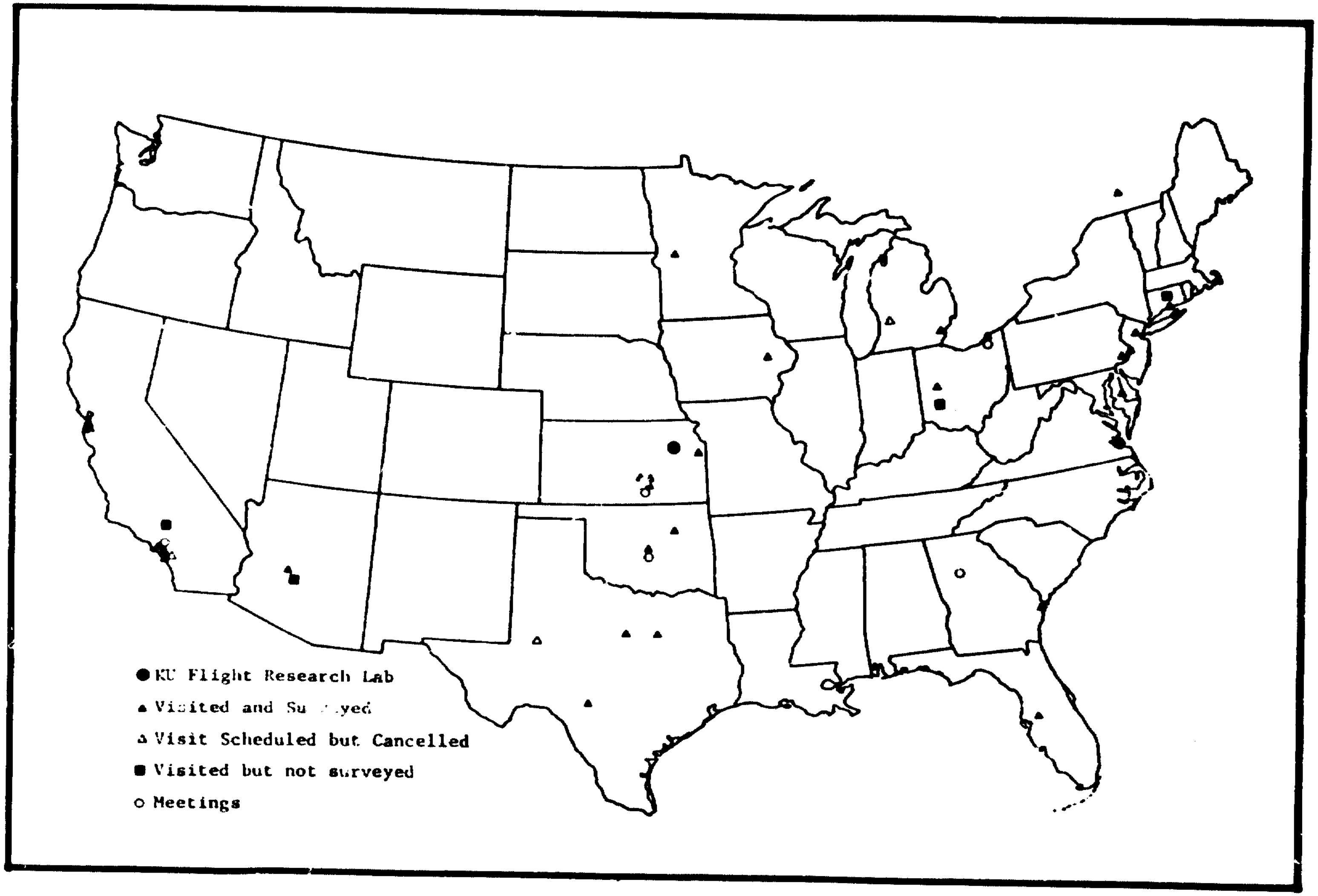


Fig. 3.1. Locations of Facilities and Meetings

Table 3.1. General Aviation Manufacturing Facilities Visited

Type Facility	Company	Location
Airframe	Beech Aircraft Corporation	Wichita, Kansas
	Bellanca Aircraft Corporation	Alexandria, Minnesota
	Bellanca Aircraft Engineering, Inc.	Middletown, Delaware
	Cessna Aircraft Corporation	
	Pawnee Division	Wichita, Kansas
	Wallace Division	Wichita, Kansas
	Gates Learjet Corporation	Wichita, Kansas
	Gulfstream American Corporation	Savannah, Georgia
	Mooney Aircraft Corporation	Kerrville, Texas
	Piper Aircraft Corporation	Lakeland, Florida
	Rockwell International	
	General Aviation Division	Bethany, Oklahoma
	Rutan Aircraft Factory	Mojave, California
Avionics and Autopilots	Brittain Industries, Inc.	Tulsa, Oklahoma
	Cessna Aircraft Corporation	
	Aircraft Radio & Control Division (ARC)	Boonton, New Jersey

Table 3.1. General Aviation Manufacturing Facilities Visited (Continued)

Avionics and Autopilots (cont)	Edo Aire/Mitchell	Mineral Wells, Texas
	King Radio Corporation	Olathe, Kansas
	Narco Avionics	Fort Washington, Pennsylvania
	Rockwell International	
	Avionics and Missile Group (Collins Avionics)	Cedar Rapids, Iowa
	Sperry Flight Systems	
	Avionics Division	Phoenix, Arizona
Systems	Bell Helicopter Textron	Fort Worth, Texas
	Bertea Corporation (Division, Parker Hannifin Corp)	Irvine, California
	Garrett AiResearch Industrial Division	Los Angeles, California
	Systems Technology Inc. (STI)	Hawthorne, California
Propulsion	Avco Lycoming Stratford Division	Stratford, Connecticut
	Cessna Aircraft Corporation	
	McCauley Accessory Division	Dayton, Ohio
	Curtiss-Wright Corporation	Wood-Ridge, New Jersey
	Garrett AiResearch Manufacturing Co.	Phoenix, Arizona
	Hartzell Propeller Inc.	Piqua, Ohio

Table 3.1. General Aviation Manufacturing Facilities Visited (Concluded)

Propulsion (cont)	Teledyne Continental Motors	
	Aircraft Products Division	Mobile, Alabama
	United Technologies Corporation	
	Hamilton Standard Division	Windsor Locks, Connecticut
	Pratt and Whitney of Canada	Montreal, Canada
	Williams Research Corporation	Walled Lake, Michigan

implementation, current state-of-the-art, and advanced technology development efforts. An attendant benefit was the acquisition of reference material. The presentations provided exposure to many subject areas of interest and the acquired papers provided documented support for the opinions expressed by the speakers. The NBAA meeting differed significantly from the others in that it provided product information as well as an exposure to the marketing strategies of manufacturers. Table 3.2 provides a list of the meetings attended.

3.2.4 Research Facilities

Three NASA research facilities were visited as shown in Table 3.3. These centers provided the necessary technical background for emerging technologies which would otherwise be

Table 3.2. Professional Meetings

Meeting	Organization	Month (1979)	Location
1st Central Oklahoma AIAA Mini Symposium	American Institute of Aeronautics and Astronautics	Feb	Norman, Oklahoma
Business Aircraft Meeting	Society of Automotive Engineers	Apr	Wichita, Kansas
Display Systems Engineering Short Course	University of California at Los Angeles	Jun	Los Angeles, California
AIAA Systems and Technology Meeting	American Institute of Aeronautics and Astronautics	Aug	New York, New York
NBAA National Convention	National Business Aircraft Association	Aug	Atlanta, Georgia
General Aviation Propulsion Conference	Lewis Research Center (NASA)	Nov	Cleveland, Ohio

unavailable (unpublished). Also, they willingly discussed both strengths and weaknesses of candidate technologies within their fields of expertise.

Table 3.3. NASA Research Centers

Center	Date	Location
Ames Research Center	June, 1979	Moffett Field, Calif.
Langley Research Center	August, 1979	Hampton, Virginia
Lewis Research Center	June, 1979	Cleveland, Ohio

3.2.5 Facility Contacts

Successful implementation and completion of the visitation phase relied heavily upon the contacts established with the facilities. Table 3.4 lists the final contacts at each facility.

3.3 MEETINGS

All meetings within the visitation phase proved quite fruitful. In every case, the reception of the project staff by the facility representatives was exceptional, and an open and candid atmosphere prevailed throughout all discussions. Areas of mutual interest regarding current work on advanced technologies as well as the impressions and attitudes of the general aviation industry were discussed. To cover each of these meetings individually is impractical in this text. Therefore, an abbreviated compilation of notes generated by the project staff at each of the facilities visited is included as Appendix A.

The following discussion is intended to serve as an introduction to that appendix. As such, it provides a brief description of the subject areas discussed during the meetings. Manufacturer visits are first discussed, followed by NASA visits.

3.3.1 Discussions With Manufacturing Facilities

3.3.1.1 Airframe. The airframe manufacturers are, in every sense, the generalists of the industry. Their final product, an operational airplane, must include products representing many technologies and disciplines. Thus, these manufacturers must have an awareness of all aspects of the industry.

Table 3.4. Facility Contacts

Facility	Contact
Ames Research Center	Seth Anderson Research Assistant Intra-Agency Programs
Avco Lycoming	Walt Schraeder Director of Advanced Technology Engines
Beech Aircraft Corporation	Bill Wise Vice President Advanced Technology
Bell Helicopter Textron	Hugh Upton Group Engineer Research Electronics
Bellanca Aircraft Corporation	Andrew Vano Chief Engineer
Bellanca Aircraft Engineering, Inc.	August Bellanca President & Chief Engineer
Bertea Corporation	John C. Hall Group Vice President
Brittain Industries, Inc.	Charles Walters President
Cessna Aircraft Corporation	
ARC Division	Virgil Davis Chief Engineer
McCauley Accessory Division	W.B. Voisard Chief Engineer
Pawnee Division	Harvey Nay Chief Engineer
Wallace Division	Emmett Kraus Supervisor of Advanced Design
Curtiss-Wright Corporation	Bill Silvestri RC Engine Program Manager

Table 3.4. Facility Contacts (Continued)

Facility	Contact
Edo Aire/Mitchell	John Nixon Chief Engineer
Garrett AiResearch	
Industrial Division	Dick Barcus Project Engineer Aircraft Systems & Control
Manufacturing Company	M.C. Steele Director of Engineering
Gates Learjet Corporation	Richard Etherington Director of Technical Engineering
Gulfstream American Corporation	Bob Stewart Assistant to the Vice President of Engineering
Hartzell Propeller Inc.	Ben Harlamert Vice President, Engineering & Chief Engineer
King Radio Corporation	Dan Rodgers Group Leader Special Programs
Langley Research Center	Bruce Holmes Aerospace Technologist Flight Mechanics Division
Lewis Research Center	William Strack Supervisory Aerospace Engineer Propulsion Section
Mooney Aircraft Corporation	Fen Taylor Chief of Aerodynamics and Performance
Narco Avionics	Norman Messinger Manager Advanced Development

Table 3.4. Facility Contacts (Concluded)

Facility	Contact
Piper Aircraft Corporation	Grahame Gates Director Advanced Engineering
Rockwell International	
Collins Avionics	G.L. Benning Vice President of Advanced Technology and Engineering
General Aviation Division	Larry McHughes Director, Engineering
Rutan Aircraft Factory	Bert Rutan
Sperry Flight Systems	W.T. Robertson Manager, Engineering
Systems Technology Inc.	Irving L. Ashkenas Vice President
Teledyne Continental Motors	L. Waters Vice President Aeronautical Engineering
United Technologies Corp.	
Hamilton Standard Division	D.F. Phillips Head of Technical Planning
Pratt & Whitney of Canada	Sid Monaghan Chief, Research and Development Support
Williams Research Corporation	Edward J. Lays Senior Applications Engineer

Key areas included in the discussions were:

(1) Propulsion and powerplants. New generation engines, engine controls, propellers, and their integration into an airframe.

(2) Structures. Composites, metal-metal bonding.

(3) Systems. Flight control systems, micro-computer based systems, and avionics.

(4) Aerodynamics. New generation NASA airfoil sections, and computational aerodynamics.

(5) Configuration. The advantages and disadvantages of canards and tandem wings.

3.3.1.2 Propulsion. Much developmental work is occuring within this industry, and many promising concepts are emerging. The "new generation" of general aviation powerplants and propellers was a prime topic throughout the industrial and research community.

Topics discussed with the propulsion representatives were:

(1) General Aviation Turbine Engine - GATE.

(2) General Aviation Propeller Study - GAP.

(3) Advanced propellers - configuration aspects, advanced airfoil sections, composite materials.

(4) Propulsion integration - airframe-powerplant integration.

(5) High speed propellers - propfan.

(6) Positive displacement engines - diesel, rotary combustion engine, advanced reciprocating engine concepts.

(7) Powerplant control - integrated controls, microprocessor-based controls.

3.3.1.3 Avionics. Advanced technology prevails within this manufacturing group due to the competitive nature of this particular market. Survivability demands continued research and development in new technology areas, resulting in a level of sophistication that often surpasses military and commercial markets.

Areas covered during the discussions included:

(1) Digital technology - analog versus digital avionics.

(2) Integration - multi-function avionics packages and standardization, multiplexing.

(3) Displays - electronic displays and instrumentation.

(4) Flight controls - digital and electronic flight control systems.

3.3.1.4 Systems. Systems manufacturers offer areas of technology transfer to general aviation. For the most part, their main contributions lie in areas other than general aviation. Broad foundations in other fields allow "spinoff" technologies to filter in under circumstances and costs that are acceptable to the community of manufacturers and users.

The areas discussed included:

(1) Flight control actuators - advanced hydraulics applied to general aviation.

(2) Turbocharging - advancements for general aviation.

(3) Displays - Heads up and head mounted displays.

(4) Fiber optics - signal transmission, airframe structural monitoring.

(5) Flight control systems - microprocessor based systems, fluidics.

It should be noted that comments by industry representatives were not limited solely to the topics listed. Due to the nature of the interviews, the personal interests of the participants, and the degree of integration required for production of general aviation hardware, much overlap between subject areas existed. Appendix A should be consulted for further information.

3.3.2 NASA Research Centers

Appendix A also includes the summarized notes from the visits to the Ames, Langley, and Lewis Research Centers.

3.3.2.1 Ames Research Center Topics.

(1) Avionics
  (a) Preliminary Candidate Advanced Avionics Systems (PCAAS).
  (b) Demonstrator for Advanced Avionics Systems (DAAS).
(2) Stall/spin aerodynamic tailoring.
(3) Cooling drag.
(4) Small Transport Aircraft Technology (STAT).
(5) Aerodynamics.

3.3.2.2 Langley Research Center Topics.

(1) Crash dynamics - seats, restraints, structures, fire prevention.
(2) Composites - types, testing, characteristics.
(3) Aerodynamics
  (a) 3-dimensional
  (b) 2-dimensional
    - natural laminar flow sections
    - low speed sections

        - high speed sections

(4) Avionics and controls - pilot-ATC interface, fluidics, pilot workload.

(5) Stall/spin research.

3.3.2.3 Lewis Research Center Topics.

(1) GATE

(2) Positive displacement engines

    (a) Advanced reciprocating engines.

    (b) Alternative engine systems

        - Diesel engines
        - Rotary combustion engines

(3) Propeller Technology - turboprop, prop fan, variable pitch fan, turbofan, GAP program.

3.4 RESULTS OF THE FACILITY VISITS

The visitation phase of the project proved to be quite successful. A strong data base was developed through the interviews as well as from those sources of information identified during the interviews. Also, the insight and opinions of the various representatives provided indications of the practicality and/or feasibility for advanced technology development.

3.4.1 Technology and the Industry

To general aviation, like other industries, a technology is of no use unless:

(1) it satisfies a need,

(2) the developer can afford it,

(3) it is profitable to the user, and

(4) it is introduced at the right time.

The most important factor affecting technology implementation is user acceptance. Manufacturers cannot afford to pursue a technology merely to improve a product unless the user requires it. A market for the technology must exist, and the associated developmental costs must be acceptable to the manufacturer.

3.4.2 Technology and Cost

Three major cost constraints exist for the general aviation manufacturer when incorporating new technologies. In general, these may be grouped into the broad categories of developmental costs, certification costs, and product liability costs.

3.4.2.1 Developmental Costs. Developmental costs can be extreme, particularly in high technology areas. Many companies cannot absorb these and must rely instead on developments within NASA research centers or industries external to general aviation. Often, the production base or technology requirements of the automotive industry or the spinoffs realized from other technologies serve to reduce general aviation developmental costs. For example, the cost of the 8,000 aircraft turbochargers produced annually benefits significantly from the 1 million units demanded by the automotive and trucking industry.

3.4.2.2 Certification Costs. While the project was concerned primarily with an assessment of advanced technologies, the feasibility of promising technologies being integrated into future airplanes appeared to be jeopardized as much by certification costs as by technological risks. Some manufacturers, for example, pointed out that these costs can amount to 10 to 100 times the cost of developing the technology itself.

Since this difficulty presented serious implications for the research at hand, an effort was made to solicit the opinions of manufacturers regarding certification procedures. This was done in order to evaluate manufacturer perceptions of the process and is not intended to be an evaluation of the process itself. In every case discussed, members of the present research team noted that sufficient information to allow an unbiased evaluation of the problems identified was lacking. However, the following points appear to merit further discussion and consequently are incorporated into this report.

(1) Interpretations of the same regulation by different FAA regional offices may sometimes result in markedly different certification requirements for the same technology in different regions.

(2) Delays resulting from "excessive red tape" are expensive to manufacturers. One frustrated manufacturer produced documentation which indicated that an application filed more than 6 months earlier had yet to generate a response.

(3) Personnel qualifications were addressed by one manufacturer.

In this particular case, the manufacturer was irritated because an inexperienced individual with a civil engineering background was given the responsibility for establishing compliance with propulsion/airframe certification requirements.

(4) **New technologies are often evaluated by old or outdated techniques. In one case, an attempt to utilize a finite element computer code (NASTRAN) to validate structural integrity computations was perceived by the manufacturer** to be hampered by a lack of familiarity with the code on the part of the certifying officials.

The significant and common denominator which appeared whenever a manufacturer chose to identify "difficulties with certification" was that the issue was usually an emotional one. Better communications between manufacturers and FAA regional offices such that both parties recognize the difficulties faced by the other appears to be a fundamental requirement if the issues are to be resolved. The inescapable fact is that manufacturers pay a heavy premium in order to certify a new technology.

3.4.2.3 Product Liability Costs. These costs are also high. One airframe manufacturer pointed out that 15% of a single engine airplane's price represented product liability costs. Another general aviation manufacturer pointed to insurance premiums of $3 million per year to illustrate these costs.

Nuisance suits seem to prevail within this industry, and several examples were pointed out by some of the manufacturers.

Whether justified or not, such suits represent a very real cost to the manufacturer.

The disturbing aspect of high product liability costs is that they point to a history of large court settlements. This would appear to deter the incorporation of new technologies and, instead, promote an atmosphere of conservatism within the industry.

Two facets of product liability deserve mention. In one case, manufacturers may avoid new technologies for fear that the incorporation of improvements to systems may be interpreted to mean that deficiencies exist in previous models of the same system. This otherwise unnecessary exposure to suits can be a very real deterrent to the incorporation of new technologies.

The second point to be made is that the incorporation of a new technology always has attendant risks. Here, the experience gained with a mature system will no longer assist the manufacturer in avoiding the many unforeseen problems associated with new technologies. Product liability takes on added significance under these conditions.

3.5 RECOMMENDATIONS FOR NASA

The following suggestions and recommendations are the result of observations made during the visits to manufacturers and research facilities.

3.5.1 Communications

Better communications need to be maintained between NASA and the industry with regard to forthcoming research topics and the results of completed research projects. For example, several companies indicated that they were not aware of the final results of the Redhawk and ATLIT programs. While this points to a disturbing lack of awareness of technical publications on the part of industry, NASA will promote its image immensely if industry officials are advised of the availability of these reports. Interestingly, NASA publications designed to fulfill this task (SCAN's, STAR's, Tech Briefs, etc) apparently are not reaching the industry or are not being used by them.

3.5.2 Basic Research and Product Development

Industry encourages NASA involvement with basic research and discourages any efforts aimed toward product development. Since industry involvement with basic research is small (less than 5% of the total engineering budget for one of the industry's leaders), this research team emphasizes that NASA should continue its efforts in basic research. High risk technologies such as those associated with propulsion, and sophisticated aerodynamic analytical tools such as those associated with natural laminar flow airfoils and numerical optimization techniques deserve special attention. Avionics manufacturers, on the other hand, appear wary of any NASA efforts which may be perceived to lead to standardization similar to those embodied in ARINC specifications.

3.5.3 Research Contracts

NASA should not fund programs which diminish a competitive advantage which may already be enjoyed by a manufacturer through its own research efforts. In those cases where the problem is more perceived than real, NASA should clearly and publicly define the limits of the research contract being awarded.

CHAPTER 4

TECHNOLOGY EVALUATION

The goal of this phase of the study was to establish a rank ordering of technologies according to their benefits to general aviation airplanes. This involved three major tasks: (1) selecting the method of evaluation, (2) identifying the candidate technologies, and (3) evaluating the candidate technologies.

4.1 METHOD OF TECHNOLOGY EVALUATION

In selecting the evaluation method, the following criteria were applied to the available techniques in an effort to determine the technique best suited to the requirements of the present research effort.

(1) The method must allow the evaluation of specific technologies.

(2) The method must allow dissimilar technologies to be evaluated in a consistent manner.

(3) The method must be within the means (cost and time) of the project.

(4) The method must be as objective as possible subject to the three previous criteria.

Many of the techniques used in technological forecasting did not fulfill the requirements of this research effort. For example, regression and trend analyses assume one has suitable data to construct extrapolations. Such data does not exist for many of the technologies considered in this study because they have had only limited use in general aviation airplanes. A direct technology evaluation using the Delphi Method (Ref. 125) was rejected as beyond the means of the project due to the large number of technologies to be investigated. The evaluation method finally adopted is based on a technology figure of merit concept and has already met with some success (Ref. 18). This method, here termed "evaluation technique," is a simple linear compensatory model and is discussed below.

4.1.1 Evaluation Technique

In the evaluation technique (ET), candidate technologies (CT) are evaluated relative to current technologies by assessing their impacts on a group of categories. The categories model the major factors involved in the operation of an airplane and are assigned weightings (w) according to their relative importance. The impact of a CT in a given category is quantified by a relative benefit (b), where $b > 0$ indicates that the CT offers an improvement in the category (relative to current technology) and $b < 0$ indicates that the CT causes a degradation in the category (relative to current technology). Summing the products of the relative benefits and category weightings yields a figure of merit (FM) for the CT which is a measure of how much improvement the candidate technology offers in the overall operation of the airplane. The figure of merit is defined by Equation 4.1 while Fig. 4.1 illustrates the general concept of the evaluation technique.

$$FM_i = \sum_{j=1}^{n} b_{ij} w_j \tag{4.1}$$

where : n is the number of categories,

b_{ij} is the relative benefit of technology i in category j,

w_j is the weighting of category j, and

FM_i is the figure of merit of technology i.

Referring to Fig. 4.1, one notes that the adoption of this type of technology evaluation method is not without difficulties. First, the categories must be selected, and second, their weightings must be determined. So, while the ET inherently satisfied the first three criteria, the fourth criteria, that of objectivity, demanded that special attention be given to the category selection and weighting.

4.1.2 Category Selection

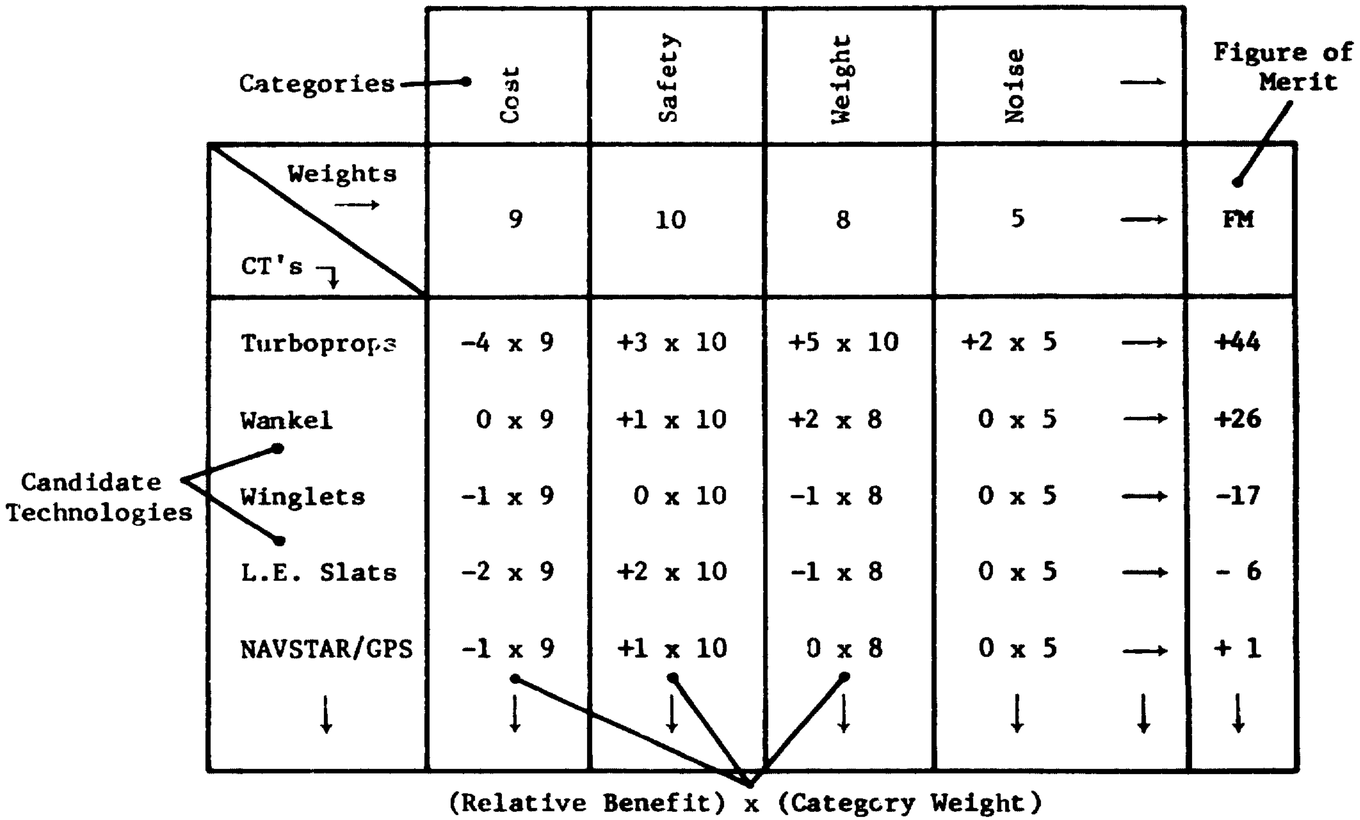
The first step in defining the category group was the establishment of the following selection criteria:

(1) The group of categories must be broad enough to model the major factors involved in the operation of an airplane.

(2) There should be a minimum of overlap between individual categories.

(3) The number of categories should be as small as possible while satisfying the first two criteria.

Various selection schemes were studied, and it soon became obvious that all of them involved generating a consensus from a set of opinions. The Delphi Method, although too involved for the overall technology evaluation, seemed well suited to the category selection problem and was therefore used. The survey group for the cateogry selection consisted of the project staff and the



Weights → / CT's ↓	Cost	Safety	Weight	Noise	→	Figure of Merit
	9	10	8	5	→	FM
Turboprops	-4 x 9	+3 x 10	+5 x 10	+2 x 5	→	+44
Wankel	0 x 9	+1 x 10	+2 x 8	0 x 5	→	+26
Winglets	-1 x 9	0 x 10	-1 x 8	0 x 5	→	-17
L.E. Slats	-2 x 9	+2 x 10	-1 x 8	0 x 5	→	- 6
NAVSTAR/GPS	-1 x 9	+1 x 10	0 x 8	0 x 5	→	+ 1
↓	↓	↓	↓	↓	↓	↓

Figure 4.1. Illustration of the Evaluation Technique

the faculty members of the Department of Aerospace Engineering at the University of Kansas.

The category selection surveys involved the following procedures:

(1) Obtain a category list, confidence level, and comments from each of the participants. The confidence level is a measure of a participant's confidence in his response.

(2) Analyze the group response and generate an "average" category list.

(3) Feed back the average category list along with participant comments.

(4) Repeat (2) through (3) until a viable "average" category list is obtained.

The Delphi Method worked quite well although the analysis of the group response was complicated by the fact that the survey dealt with symbols (in the form of category names) instead of numbers. The survey converged to an acceptable category list (17 categories) in four survey rounds. The final category list is given in Table 4.1.

Referring to Table 4.1, one notes that some categories appear to overlap. Examples are the categories of Fuel Efficiency, Reliability, and Direct Operating Cost. The problem is minimized when one considers that Fuel Efficiency is concerned with fuel availability as well as with fuel costs. Likewise, Reliability is concerned with operational readiness as well as maintenance costs.

With these factors in mind, the category list was considered acceptable. Further discussion of the category selection survey may be found in Appendix B.1.

Table 4.1. Technology Evaluation Categories

Category	Definition
Ceiling	Altitude at which the maximum rate of climb is 0.51 m/s (service ceiling).
Crashworthiness	The characteristics of an airplane which determine the level of occupant protection in the event of a crash.
Cruise Speed	Maximum continuous cruise speed.
Direct Operating Cost	All costs directly attributable to flying and keeping an airplane operational. All scheduled and unscheduled maintenance costs and fuel costs are included.
Emissions	Pollutants produced during the operation of an airplane; does not include noise.
Empty Weight	Airplane weight without fuel, crew, and payload.
Exterior Noise	Noise perceived at ground level due to the operation of an airplane.
Fuel Efficiency	Airplane cruise efficiency measured in air-miles per pound-fuel.
Interior Noise	Noise perceived by the occupants of an airplane.

Table 4.1. Technology Evaluation Categories (concluded)

Category	Definition
Pilot Workload	The amount of time, concentration, and effort a pilot must devote to the safe operation of an airplane. This includes the effects of airplane handling qualities.
Purchase Price	The price paid for a new airplane by the user, including avionics and equipment costs.
Range	The distance an airplane can fly without refueling, allowing for appropriate fuel reserves.
Reliability	A measure of the probability of failure of an airplane component or system.
Ride Qualities	A measure of the effects of aircraft motion on the smoothness and comfort of the ride experienced by the occupants.
Safety	A measure of an airplane's inherent characteristics which reduce the probability of an accident.
Static Comfort	A measure of an airplane's inherent comfort. This includes roominess, seat comfort, ventilation, decor, ease of entry, etc.
Takeoff/Landing Performance	This parameter includes takeoff and landing speeds, field length requirements, and rates of climb and descent.

4.1.3 Category Weightings

Having completed the category selection survey, the Delphi Method was again used in the determination of the category weights. This survey, termed the "category rating survey", was conducted on a much larger scale than the category selection survey with 42 participants representing general aviation manufacturers and user groups, university faculty, NASA centers, and project staff. A list of the participants is given in Table 4.2.

Upon reviewing the 17 categories to be weighted, it was noted that in general, different types of airplanes would have different sets of category weights because of differing operational priorities. Because the statement of work (for this study) specified that two types of airplanes were to be investigated, two sets of category weightings were generated. In the rest of the text, the two airplanes are referred to as Airplane A, which is a six passenger (including pilots) airplane for business and/or personal transportation, and Airplane B, which is a 19 passenger (excluding pilots) commuter airliner.

The category rating survey was conducted as outlined below:

(1) Participants gave each category (for each airplane) a rating (R) constrained by $0 \leq R \leq 10$ with a minimum scale increment of .5. $R = 10$ was assigned to the category considered most important and the other categories were rated in a relative manner with $R = 0$ meaning the category is of no importance relative to the most important one. Duplications in ratings were allowed because two or more categories could be of equal

Table 4.2. Category Rating Survey Participants

Aircraft Owners and Pilots Association
AVCO Lycoming
Beech Aircraft Corporation
Bell Helicopter Textron
Bellanca Aircraft Corporation
Bellanca Aircraft Engineering, Inc.
Brittain Industries, Inc.
Cessna Aircraft Company - Aircraft Radio and Control Division
Cessna Aircraft Company - Pawnee Division
Cessna Aircraft Company - Wallace Division
Commuter Airlines Association of America
Curtiss-Wright Corporation
Edo-Aire Mitchell Division
Garrett-AiResearch - Industrial Division
Gates Learjet Corporation
Gulfstream American Corporation
Hartzell Propeller, Inc.
King Radio Corporation
Mooney Aircraft Corporation
Narco Avionics Division
NASA Ames Research Center
NASA Langley Research Center
NASA Lewis Research Center
National Business Aircraft Association

Table 4.2. Category Rating Survey Participants (concluded)

Parker Hannifin Corporation - Control System Division (formerly Bertea Corporation)
Piper Aircraft Corporation
Pratt & Whitney Aircraft of Canada, Ltd.
Rockwell International - Collins Division
Rockwell International - General Aviation Division
Sperry Flight Systems - Avionics Division
Systems Technology Incorporated
Teledyne Continental
Williams Research Corporation
University of Kansas, Aerospace Engineering Faculty*
Project Staff*

* These groups each contributed more than one participant

importance. Participants also rated their degree of confidence in their response with a confidence level (CL) constrained by $0 \leq CL \leq 1$ for each airplane. Comments on the category ratings were encouraged.

(2) Feedback to the participants consisted of information regarding the mean category ratings, the category rating distributions (in the form of histograms), and participant comments for each of the airplanes.

(3) The survey continued until the participant response reached a predetermined level of stability (less than 15% change in participant voting).

The category rating survey required three rounds to achieve satisfactory convergence. The category weightings used in the evaluation technique are simply the mean category ratings from the final survey rounds.

Table 4.3 presents the final category weightings for Airplanes A and B and Table 4.4 shows the category rankings in order of importance. Details of the category rating survey may be found in Appendix B.2.

4.2 CANDIDATE TECHNOLOGY IDENTIFICATION

This section deals with the selection of the technologies to be analyzed with the evaluation technique and discusses the data base used. Since a large list of advanced technologies is easily created, several constraints were placed on the selection process. An early list, defined as "Preliminary Candidate Technologies," and a final list, defined as "final Candidate Technologies," are both discussed here.

4.2.1 Data Base

In selecting candidate technologies, one must first collect information regarding technologies in general. The project relied on three major sources of information as detailed below.

4.2.1.1 Literature Search. A computerized literature search was conducted using the Lockheed DIALOG system. In preparing for the computer search, a manual search was made of the NASA STAR index to identify key words, technology areas, and sample titles. This

Table 4.3. Evaluation Technique Category Weightings

Category	Weightings	
	Airplane A[*]	Airplane B[**]
Ceiling	5.429	5.447
Crashworthiness	6.816	7.333
Cruise Speed	7.922	7.480
Direct Operating Cost	7.906	9.451
Emissions	1.606	2.156
Empty Weight	4.340	5.657
Exterior Noise	4.287	5.413
Fuel Efficiency	8.157	8.606
Interior Noise	7.037	7.452
Pilot Workload	7.349	6.998
Purchase Price	8.515	7.761
Range	7.290	7.181
Reliability	8.854	9.547
Ride Qualities	6.110	7.238
Safety	9.422	9.544
Static Comfort	6.244	6.797
Takeoff/Landing Performence	6.874	7.407

[*] Airplane A - 6 Passenger Business/Personal Airplane

[**] Airplane B - 19 Passenger Commuter Airliner

Table 4.4. Evaluation Technique Category Rankings

Rank Order	Categories	
	Airplane A*	Airplane B**
1	Safety	Reliability
2	Reliability	Safety
3	Purchase Price	Direct Operating Cost
4	Fuel Efficiency	Fuel Efficiency
5	Cruise Speed	Purchase Price
6	Direct Operating Cost	Cruise Speed
7	Pilot Workload	Interior Noise
8	Range	Takeoff/Landing Performance
9	Interior Noise	Crashworthiness
10	Takeoff/Landing Performance	Ride Qualities
11	Crashworthiness	Range
12	Static Comfort	Pilot Workload
13	Ride Qualities	Static Comfort
14	Ceiling	Empty Weight
15	Empty Weight	Ceiling
16	Exterior Noise	Exterior Noise
17	Emissions	Emissions

*Airplane A - 6 Passenger Business/Personal Airplane

**Airplane B - 19 Passenger Commuter Airliner resulted in six primary search topics (a-f) to which three specific topics (g-i) were later added.

(a) Aircraft Design

(b) Aircraft Propulsion

(c) Aircraft Structures

(d) Flight Controls

(e) Navigational Aids

(f) Avionics

(g) Canard Configurations

(h) NAVSTAR/GPS

(i) GASP (General Aviation Synthesis Program)

Table 4.5 presents the initial results of the computer search in terms of the number of abstracts printed for each search topic; note that some topics were combined to eliminate duplications. The 1655 abstracts were reviewed individually to identify pertinent articles. This resulted in 107 articles which were obtained from NTIS. The specific search procedures used for each topic may be found in Appendix B.3.

4.2.1.2 Visits and Meetings. Quite a few articles were found through recommendations of various people and from the references given in other articles. Also, aviation related magazines and journals were helpful in finding information.

The bibliography lists the most important books, articles, and papers obtained while the discussions of Chapter 3 and Appendix A summarize the information gained from the visits and meetings.

Table 4.5. Computerized Literature Search Results

Topic	Abstracts Printed
(a) Aircraft Design	133
(b) Aircraft Propulsion	206
(c) Aircraft Structures	275
(d) Flight Controls	780
(e) Navigational Aids	780
(f) Avionics	780
(g) Canard Configurations	22
(h) NAVSTAR/GPS	89
(i) GASP	0

4.2.2 Preliminary Candidate Technologies

The preliminary candidate technologies (PCT) were the result of the first formal attempt to identify technologies felt to have some application to General Aviation airplanes. Selecting the PCT proved more difficult than expected for several reasons, not the least of which was how to define a "technology." To select technologies in a consistent manner, three criteria were formulated.

(1) Operational results of a technology are not themselves technologies: Examples: "stall/spin prevention" and "increased TBO (time between overhaul)" are the results of the application of various technologies.

(2) Design variables (parameters) are not technologies. Examples: "high wing loading," "high aspect ratio."

(3) Non-specific "wish list" technologies are to be avoided. Examples: "low-cost sensors," "low-cost weather radar."

These criteria were followed as closely as possible but marginal technologies were given the benefit of the doubt to insure that all applicable technologies were considered. The PCT selection process resulted in 137 technologies which are given in Table 4.6, grouped according to technology area.

Table 4.6. Preliminary Candidate Technologies

I. AERODYNAMICS (11)

- Winglets
- Variable geometry winglets
- Spoilers
- Fowler flaps
- Low drag surface coatings
- Leading edge devices
- Advanced low and medium speed airfoils (turbulent)
- Supercritical airfoils
- Advanced natural laminar flow airfoils
- Improved stall/spin through aerodynamic tailoring
- Active laminar flow control

II. AIRCRAFT SYSTEMS (12)

- Microwave anti-icing
- Sonic/pulsating anti-icing

Table 4.6. Preliminary Candidate Technologies (continued)

II. AIRCRAFT SYSTEMS (concluded)

- Lithium hydroxide/hydrogen peroxide batteries
- Air cycle environmental systems
- Improved lead-acid batteries
- AC electrical systems
- Passive anti-icing through icephobic coatings
- Variable cycle environmental systems
- Accurate fuel monitoring and management
- High speed brushless alternator
- Single unit starter-generator
- Air bearings

III. COMPUTATIONAL METHODS (4)

- Computational aerodynamics
- Computational structural design/analysis
- Aeroacoustic modeling/analysis
- CADCAM

IV. CRASHWORTHINESS (7)

- Load limiting seats
- Improved restraints
- Foam filled fuel tanks
- Burst/tear resistant fuel tanks
- Energy absorbing floor
- Anti-misting fuel treatment
- Frangible fuel fittings

Table 4.6. Preliminary Candidate Technologies (continued)

V. FLIGHT CONTROL SYSTEMS (21)

- Fly-by-wire
- Fly-by-light
- Active gust alleviation
- Active ride smoothing
- Active flutter supression
- Active controls for relaxed inherent stability (CCV)
- Integrated low-cost wing leveler
- Integrated yaw damper
- Separate surface technology
- Winglets for lateral-directional control
- Direct side-force control
- Direct lift control
- Single level thrust/drag control
- Force-stick controllers
- Digital automatic flight controls
- Fluidic automatic flight controls
- Stick shaker/pusher for stall prevention
- Stabilizer/elevator spoilers for stall prevention
- Pneumatic actuators
- Hydraulic actuators
- Electro-mechanical actuators

VI. INFORMATION SYSTEMS (28)

- Flush antennas
- Digital data links

Table 4.6. Preliminary Candidate Technologies (continued)

VI. INFORMATION SYSTEMS (continued)

- Single function CRT displays
- Time-shared CRT displays
- HUD
- Micro HUD
- Warning annuciators
- Total panel-mounted avionics
- Active outside imaging
- Fluidic shed-vortex airspeed sensor
- Airplane health/diagnostic systems
- Fluidic rate sensors
- Multiplexing
- ARINC-type broadcast hierarchy
- Integrated avionics and displays
- Piezo-resistive pressure transducers
- Fiber optics for data transmission
- Liquid crystal displays
- Flat CRT displays
- Touch sensitive CRT
- Weather radar
- Alternate weather detection
- Radar altimeter
- Onboard computing capability
- 3-axis magnetometer acceleration sensor

Table 4.6. Preliminary Candidate Technologies (continued)

VI. INFORMATION SYSTEMS (concluded)

- Improved stall warning
- Laser gyros

VII. MATERIALS/PROCESSES (12)

- Metal/metal bonding
- Fiberglass composites
- Kevlar composites
- Graphite composites
- Honeycomb core composite skin panels
- Single crystal metal
- Powdered metal
- Isothermal forging
- Diffusion bonding
- Friction welding
- Corrosion resistant coatings
- Matched-die fiber reinforced plastic (FRP)

VIII. NAVIGATION CONCEPTS (11)

- VOR/DME RNAV
- Scanning VOR/DME RNAV
- Omega
- Differential Omega
- VLF NAVCOM
- Loran C
- NAVSTAR/GPS

Table 4.6. Preliminary Candidate Technologies (continued)

VIII. NAVIGATION CONCEPTS (concluded)

- Inertial navigation
- Doppler navigation
- MLS
- Inertial smoothing

IX. NOISE (6)

- Noise absorbing materials
- Improved mufflers
- Variable engine/prop gearing
- Quiet propeller technology
- Low level pressurization
- Ducted propulsors

X. PROPULSION (25)

- Advanced diesel engine
- Advanced rotary combustion engine
- Advanced reciprocating engine
- GATE engine
- Auto engine conversions
- QCGAT engine
- Liquid cooling
- Stratified charge
- Improved turbocharging
- Variable timing
- Electronic ignition

Table 4.6. Preliminary Candidate Technologies (concluded)

X. PROPULSION (concluded)

- Automatic mixture control
- Lean burn combustion
- Density compensating fuel injection
- Total microprocessor engine control
- Variable bypass turbofan
- Variable pitch fan
- Efficient propeller technology
- Prop fan
- Cooled turbine blades
- Ceramic turbines
- Composite propellers
- Torsionally (aeroelastically) tailored propeller blades
- Single lever throttle/mixture control

4.2.3 Final Candidate Technologies

As a group, the 137 PCT of Table 4.7 were not equally suited to the evaluation technique. First, the PCT exhibit different technology levels. In the propulsion area for example, complete advanced technology engines are compared against component technologies. One cannot really compare the two although both may be important. Second, the PCT exhibit different technology orders, meaning that while most technologies are first order (i.e., on the airplane) some are second order (i.e., not on the airplane).

Examples are "advanced natural laminar flow airfoils" (first order) and "computational aerodynamics" (second order). The first requires the second. Hence, the two technologies are not really comparable. In addition to these fundamental problems, four other constraints are noted: (1) the ET category weightings are valid only for six passenger and commuter airplanes, (2) the project scope requires 1990 technology implementation, (3) technologies for which data are lacking cannot be evaluated objectively, and (4) some of the technologies are already gaining acceptance in general aviation.

These factors gave rise to a second set of criteria which were used to select the final candidate technologies (FCT).

(1) Try to reduce the differences in technology levels.

(2) Delete second order technologies.

(3) Delete technologies not applicable to the six passenger or commuter airplanes.

(4) Delete technologies which will not be ready for implementation by 1990.

(5) Delete technologies for which sufficient data are lacking.

(6) Delete technologies already gaining acceptance in general aviation.

Application of the above criteria resulted in 56 final candidate technologies which are presented in Table 4.7 and are subsequently discussed in Section 4.4. Appendix B.3 contains a complete discussion of the candidate technology selection process.

Table 4.7. Final Candidate Technologies

I. AERODYNAMICS (9)

- Winglets
- Spoilers
- Fowler flaps
- Low drag surface coatings
- Active laminar flow control
- Leading edge devices
- Advanced low/medium speed airfoils
- Improved stall/spin through aerodynamic tailoring

II. AIRCRAFT SYSTEMS (2)

- Anti-icing surface coatings
- AC electrical systems

III. CRASHWORTHINESS (4)

- Load limiting seats
- Energy absorbing floor
- Improved restraints
- Burst/tear resistant fuel tanks

IV. FLIGHT CONTROL SYSTEMS (14)

- Fly-by-wire
- Fly-by-light
- Active gust alleviation
- Active ride smoothing
- Active flutter suppression

Table 4.7. Final Candidate Technologies (continued)

IV. FLIGHT CONTROL SYSTEMS (concluded)

- Active controls for relaxed inherent stability (CCV)
- Integrated yaw damper
- Integrated low-cost wing leveler
- Separate surface technology (SSSA)
- Direct side-force control
- Direct lift control
- Single lever thrust/drag control
- Fluidic automatic flight control system
- Active stall prevention

V. INFORMATION SYSTEMS (8)

- Digital data links
- CRT displays
- HUD
- Micro HUD
- Systems status display
- Integrated avionics and displays
- Fiber optics for data transmission
- Laser gyros

VI. NAVIGATION CONCEPTS (6)

- NAVSTAR/GPS
- Inertial navigation
- Doppler navigation

Table 4.7. Final Candidate Technologies (concluded)

VI. <u>NAVIGATION CONCEPTS (concluded)</u>

- Microwave Landing System (MLS)
- Loran C
- Omega

VII. <u>NOISE (3)</u>

- Quiet, efficient propeller technology
- Low-level pressurization
- Ducted propulsors

VIII. <u>PROPULSION (7)</u>

- GATE engine
- Stratified charge rotary combustion engine
- HCRLB reciprocating engine
- Stratified charge reciprocating engine
- Advanced diesel engine
- Liquid cooling
- Improved turbocharging

IX. <u>STRUCTURAL MATERIALS (3)</u>

- Fiberglass composites
- Kevlar composites
- Graphite composites

4.3 APPLICATION OF THE EVALUATION TECHNIQUE

The application of the ET involved three main tasks: the mechanization of the ET, the determination of the relative benefits, and the analysis of the ET-generated figures of merit. The reader may find Figure 4.1 useful in the following discussion.

Mechanization of the Evaluation Technique

Because of the sheer number of calculations required to evaluate 56 technologies in 17 categories for two airplane types, a FORTRAN computer program known as TCHLST was written to compute the figures of merit. Since the considerations of paramount interest to any user (input, output, and efficiency) are particularly significant for the case at hand, input and output were simplified by employing a problem oriented language (POL) known as SCAN, while efficiency was maintained by using arrays, array pointers, and packed arrays. While SCAN is available from the University of Illinois for several mainframes, its limited use together with other peculiarities built into TCHLST which are system-dependent (word size and system software) have resulted in a decision not to include the program listing with this report. The program capabilities, however, are briefly discussed here in order to support the resulting data.

Input data, if not managed properly, can quickly invalidate results. Hence SCAN was employed to allow data inputs in the form:

```
AIRPLANE A
AERODYNAMICS
'WINGLETS' .5 0 0 .5 0 -2 0 .5 0 0 -1 .5 0 0 0 0 0
'SPOILERS'-.5 0 2  1 0  1 0  1 0.5 0  1 0 2 0 0 0
```

and incorporate commands such as

```
PRINT  INPUT
PRINT  TABULAR  CATEGORIES
OMIT  CRASHWORTHINESS
PRINT  BARCHART  ALL
RESET  OMIT
RESET  PRINT, etc.
```

in order to (1) allow easy data entry, (2) allow accurate input verification, (3) allow quick, accurate data analysis, and (4) provide for sensitivity analyses under different category weightings. Efficiency was maintained by array management where, for example, different addresses were packed into the left and right half of a word size (36 bits). Hence, although not portable, the program was very efficient, with costs on the order of $3 to compute, sort, format, and output original data as well as perturbed data (which could be demanded in real time).

4.3.2 Determination of Relative Benefits

In assigning relative benefits, three factors were found to be of great importance. They are the relative benefit scale, the technology baseline, and the technology application and integration.

4.3.2.1 Relative Benefit Scale. The scale of relative benefits ($-b_{max} \leq b_{ij} \leq b_{max}$) must be broad enough to allow adequate differentiation between technology impacts but narrow enough that guessing is avoided. This is a strong function of the amount of information available for a given technology so in general, an optimum scale for one technology will not be optimum for another technology. A workable compromise was found to be $-3 \leq b_{ij} \leq 3$ where increments of ± 1 are normally used but, if justified, increments of ± .5 are allowed.

4.3.2.2 Technology Baselines. A technology baseline must be established before any relative benefits are obtained because by definition, a relative benefit compares a candidate technology to a current technology baseline. Since different classes of airplanes utilize different technologies, separate technology baselines were established for the six passenger and commuter airplanes. These baselines are presented in Table 4.8.

4.3.2.3 Technology Application and Integration. In evaluating a given technology, a decision must be made as to how the technology will be used and to what extent other airplane parameters will change. For example, spoilers do not offer much (if any) advantage over ailerons unless the freed trailing edge is used for additional flap span. Even then, one must decide if

Table 4.8. Technology Baselines

Airplane A*	Airplane B**
• Reciprocating engine	• Turboprop
• Aluminum structure	• Aluminum structure
• Limited flush riveting and/or bonding	• Extensive flush riveting and/or bonding
• Conventional avionics with VOR/DME RNAV but no autopilot	• Conventional avionics with autopilot but no RNAV
• Plain or single-slotted flaps	• Single-slotted Fowler flaps
• Conventional controls and control surfaces	• Conventional controls and control surfaces
• No anti-icing	• Anti-icing in the form of hot air or boots

*Airplane A - 6 Passenger Business/Personal Airplane

**Airplane B - 19 Passenger Commuter Airplane

takeoff and landing performance will be improved with a fixed wing loading, or if an improvement in cruise efficiency will be sought by increasing wing loading. Similar technology application and integration effects are exhibited by many technologies, especially in the areas of composite structures and advanced propulsion. After reviewing the performance characteristics of current six passenger and commuter airplanes, it was decided that technologies offering either cruise or takeoff and landing performance improvements would be used to benefit cruise since the current airplanes seemed to have adequate takeoff and landing performance.

4.3.3 Sensitivity to Relative Benefits

Uncertainty in generating relative benefits is unavoidable and therefore must be accounted for. Using the guidelines of Section 4.3.2, three sets of relative benefits were generated for each technology and are termed "pessimistic," "likely," and "optimistic" (PLO) relative benefits. Their use and definition are analogous to the pessimistic, most likely, and optimistic time estimates frequently used in CPM and PERT analyses. Likewise, a Beta distribution is assumed such that an "expected" relative benefit is obtained as given by Equation 4.2 (Ref. 219).

$$b_E = \frac{b_P + 4b_L + b_O}{6} \tag{4.2}$$

To avoid unnecessary computations, only the PLO relative benefits are found and the expected figures of merit (FM_E) are obtained directly from the PLO figures of merit. It is easy to show that the expected figure of merit is given by Equation 4.3.

$$FM_E = \frac{FM_P + 4FM_L + FM_O}{6} \tag{4.3}$$

The PLO relative benefits were generated by an iterative process. First, information on each of the technologies was obtained from the project data base: Second, the PLO relative benefits for each technology were estimated. Finally, the PLO relative benefits were reviewed and updated as required. The PLO relative benefits are preliminary in that they are used only to test the evaluation procedure.

Figure 4.2 presents a sample of the pessimistic, likely, optimistic, and expected (PLOE) figures of merit where the expected figures of merit were computed with equation 4.3. (Complete results may be found in Appendix B.4.) This figure illustrates the characteristics of consistency and uncertainty which are discussed below.

4.3.3.1 Consistency of Relative Benefits. To obtain a meaningful ranking of the technologies, each must be evaluated in a similar manner with the same level of objectivity. Doing so results in a consistent set of likely relative benefits. While it is impossible to insure absolute consistency, the PLOE figures of merit provide information which allows one to check for reasonable consistency. This is done by comparing the likely and expected figures of merit for each technology. If a technology exhibits a large difference in these figures of merit, it implies that the likely relative benefit was itself either optimistic ($FM_L > FM_E$) or pessimistic ($FM_L < FM_E$) and needs to be refined. The data of Figure 4.5 is typical and shows that the preliminary likely relative benefits

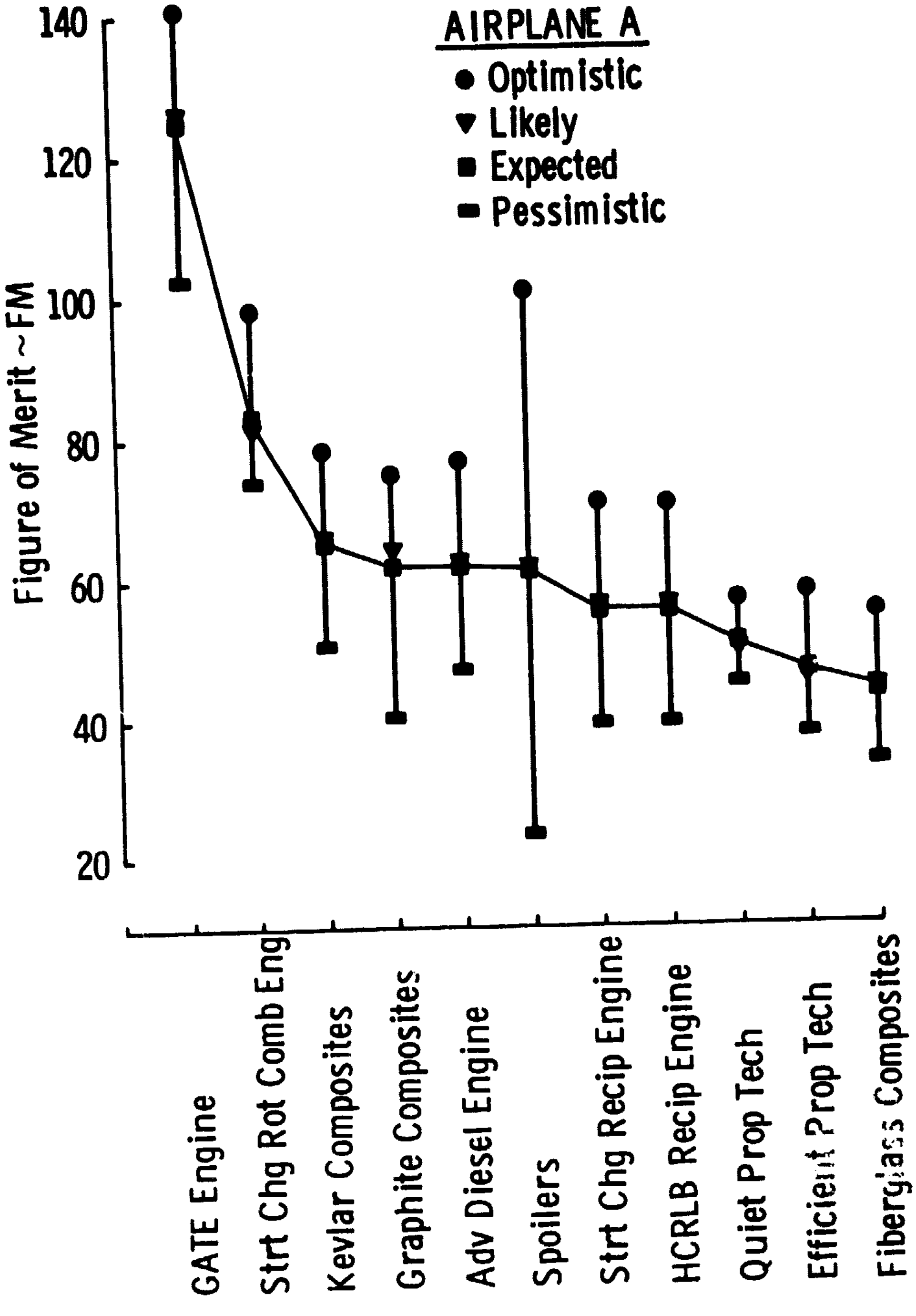


Figure 4.2. Sample of the Pessimistic, Likely, Optimistic, and Expected Figure of Merit

are quite consistent in that the likely and expected figures of merit are nearly identical for most technologies. The small inconsistencies exhibited by a few technologies were kept in mind when the final relative benefits were determined.

4.3.3.2 Uncertainty of Relative Benefits. It was hoped that the PLOE approach, in addition to providing a check on consistency, would give a measure of the uncertainty involved in the evaluation of each technology.

For example, examining Fig. 4.2 one might conclude that the degree of uncertainty in the evaluation of a technology is directly related to the difference in its optimistic and pessimistic figures of merit. This has not proved to be a legitimate assumption because technologies which impact nearly all of the categories exhibit large changes in figure of merit for small changes in the relative benefits which results in an exaggerated perception of uncertainty.

The initial testing of the evaluation technique (PLOE studies) proved that the procedures established for evaluating the technologies worked well and resulted in consistent analyses. The following sections address the final evaluation of the candidate technologies in detail.

4.4 OBSERVATIONS ON THE UTILIZATION OF THE EVALUATION TECHNIQUE

This section briefly discusses some of the more salient points involving the use and interpretation of the evaluation technique. Specific items addressed include:

(1) the effect of qualitative values of different raters in assigning relative benefits to technologies,

(2) the stability of figures of merit under different conditions,

(3) the orthogonality of categories,

(4) the effect of varying the weighting for Empty Weight, and

(5) the significance of figure of merit scores.

4.4.1 Qualitative Values of Raters

As the evaluation technique was applied, it became evident that different raters had a different range of figures of merit resulting from different relative benefits applied to each of the technologies. However, an examination of the several results indicated remarkable consistency between the relative rankings of technologies. It was therefore decided to use one rater and emphasize the refinement of relative benefits generated by the rater rather than to standardize the results of several raters at the expense of exhaustive refinement.

4.4.2 Stability of Figures of Merit

After several data sets were analyzed, it became evident that the figures of merit:

(1) exhibited consistency in ranking technologies as was predicted by the PLOE studies discussed previously in Section 4.3.3.

(2) could change significantly if its anticipated application and integration changed (Section 4.3.2.3) regardless of whether

this change resulted from a technology breakthrough or a more innovative (less conservative) application.

In light of (2) above, every effort has been made to define the baseline and the perceived application of each technology as shown in Section 4.5.

4.4.3 Orthogonality of Categories

The orthogonality of categories and their weightings as developed by Surveys 1 and 2 and discussed in Sections 4.1.2 and 4.1.3 was investigated by performing a factor analysis of the relative benefit matrix (56 x 17) for both Airplanes A and B. The Biomedical Computer Programs (BMDP) statistical computer package as described in Reference 218 and available on-line at the University of Kansas was used to generate the factor data.

The intent of this study was to determine the possibility of grouping the 17 categories into a smaller, orthogonal set of components. If this could be done (and it was strongly suspected that such would be the case), then the possibility of reducing the number of categories into a smaller and more manageable set needed to be investigated (see Section 4.1.2).

BMDP results for both Airplane A and Airplane B indicated that six factors would explain a significant amount of the variance in both relative benefit data sets (74% for Airplane A and 76% for Airplane B). Furthermore, the first three factors explained 50% and 51% of the data variance for Airplane A and B respectively. These three factors included 11 of the 17 categories for both airplanes where ten of the 11 categories were common to both. The six factors are shown in Table 4.9.

An examination of this table, however, quickly identifies extreme difficulties in implementing an evaluation technique consisting of only six orthogonal components. Specifically, the loss of differentiation between vehicle performance measurements would defeat the purpose of the technology evaluation. For example, benefits in cruise speed could not be differentiated from those accorded to empty weight. Likewise, improvements in noise control could not be differentiated from takeoff and landing performance. Although purchase price is grouped with DOC and reliability for Airplane B, it is statistically tied to static comfort and crashworthiness for Airplane A. Yet, purchase price received a score other than zero in 51 of 56 technologies for Airplane A and 44 of 51 technologies for Airplane B.

Armed with this information, it was decided that the 17 categories developed by Survey 1 provided a better measurement of a technology's impact than the six factors resulting from the factor analysis.

4.4.4 Effect of Empty Weight

A concern expressed early in the development of the evaluation technique dealt with the quantification of category weightings through the Delphi Method. Since a major benefit of the method is to allow respondents to preserve their views without coercion from others, a decision to halt further rounds of the surveys is often

Table 4.9. Six Factors for Airplanes A and B

Factor	Airplane A Categories	Factor	Airplane B Categories
1	Range Cruise Speed Ceiling Fuel Efficiency Empty Weight	1	Fuel Efficiency Ceiling Cruise Speed Range Empty Weight
2	Exterior Noise Interior Noise Takeoff/Landing Performance	2	Exterior Noise Interior Noise Takeoff/Landing Performance
3	Reliability DOC Emissions	3	DOC Reliability Purchase Price
4	Static Comfort Crashworthiness Purchase Price	4	Safety Pilot Workload
5	Safety Pilot Workload	5	Crashworthiness Static Comfort
14	Ride Quality	6	Emissions Ride Quality

made based on the stability of responses. This implies that the use of an average rating may be misleading if a large dispersion of responses is noted. (Note that "stability" is implied by a large number of unchanged responses from one round to the next, and does not imply that ratings have converged about a mean.) Such was the case for the Empty Weight category for Airplane B. As shown in the histograms in Appendix B.2., these ratings ranged almost uniformly from 0 to 9.5. Hence, results reflecting Empty Weights of 0, 5.657, and 9.5 (low, mean, hi) for Airplane B are included in Appendix B.5.

4.4.5 Significance of Figure of Merit Scores

Before proceeding to the actual results of the evaluation technique, one should be aware of the following aspects of the figures of merit:

(1) Values near zero imply no significant improvement in effect on the user. For example, an improvement in range may be offset by high cost or maintenance.

(2) Positive numbers reflect net benefits to the user while negative numbers reflect net penalites to the user.

(3) Macroscopic figures of merit (FM) are fairly stable, where $FM_i = 50$ signals greater benefit from technology i than $FM_j = 30$ does for technology j. However, $FM_i = 50$ is difficult to differentiate from say, $FM_k = 45$. A major exception to this rule is noted in (4) below.

(4) Those technologies impacting many categories have higher figures of merit than those which affect only a few. Hence, the four technologies listed under the crashworthiness group have scores which do not truly measure their benefit to the user. This is due to the fact that although they all received maximum scores (+3) for Crashworthiness, they did not impact DOC, Safety, Reliability, etc. (Also, Crashworthiness received relatively low scores as shown in Tables 4.3 and 4.4.)

(5) The figures of merit reflect relative benefits as opposed to benefit/risk. Hence, although the propulsion group reflects particularly high benefits to the user, the extremely high risk of development to the manufacturer is not accounted for.

C - 2

4.5 EVALUATION TECHNIQUE RESULTS

This section discusses the final figures of merit obtained when Equation 4.1 was applied to the 56 final candidate technologies (FCT) identified in Table 4.7. The 17 category weights used here are those shown in Table 4.3 and are average weights. Technology groupings were established for convenience and have no bearing on the relative benefits or the figures of merit.

Each technology group is first discussed in general terms followed by a tabular ranking of those technologies which were considered to be in the particular group. A brief discussion of each technology then follows.

4.5.1 Overall Technology Ranking

Tables 4.10 and 4.11 show overall rankings for the 56 and 51 technologies considered for Airplanes A and B respectively. Both lists are identical except for five propulsion technologies which were not considered appropriate for Airplane B.

4.5.2 Aerodynamics

Nine technologies were evaluated and are shown in Table 4.12. As shown in Table 4.10, the first three technologies under Airplane A were among the top seven of 56 technologies. Winglets, when considered for a new wing, offer little benefit to the user of either airplane. Spoilers (implying full-span Fowler Flaps) appear rather attractive for Airplane B as shown in Table 4.11.

Table 4.10. Overall Technology Ranking For Airplane A

```
                                             AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                              CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD      FIG OF
                         CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF       MERIT
      CATEGORY WEIGHTS   5.43 6.82 7.92 7.91 1.61 4.34 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87

GATE ENGINE               2.0 0.   1.0  1.0  1.0  3.0  0.   2.0  1.0  1.0 -3.0  1.0  1.0  1.0  1.0  0.   1.0       85.017
STRT CNG ROT COMB ENGINE  1.0 0.   1.0  2.0  2.0  1.0  0.5  2.0  1.0  1.0 -2.0  1.0  1.0  1.0  1.0  0.   0.        84.205
NAT LAM FLOW AIRFOILS     1.0 0.   2.0  2.0  0.   1.0  0.   1.0  0.   0.  -0.5  2.0 -1.0  0.   0.   0.   1.0       57.924
SPOILERS                 -0.5 0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.5  0.   1.0  0.   2.0  0.   0.   0.        56.717
FIBERGLASS COMPOSITES     2.0 0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.        55.375
KEVLAR COMPOSITES         2.0 0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.        51.200
FOWLER FLAPS             -0.5 0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0  0.   2.0  0.   0.   0.        48.785
GRAPHITE COMPOSITES       2.0 0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.        42.685
INTEG LOW-COST WG LVLER   0.  0.   0.   0.   0.  -0.5  0.   0.   0.   3.0 -0.5  0.  -0.5  0.   3.0  0.   0.        39.458
2 STR ADV DIESEL ENGINE   0.  0.   0.   2.0  0.   0.   0.5  3.0  0.5  0.  -2.0  1.0  0.   0.   0.   0.   0.        36.205
DIGITAL DATA LINKS        0.  0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.        33.283
INTEG AVIONICS AND DSPYS  0.  0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   2.0  0.   0.        31.767
IMPROVED TURBOCHARGING    1.0 0.   1.0  0.5  0.   0.   0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   1.0       31.110
LOW/MEDM SPEED AIRFOILS   0.  0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0       29.096
LEADING EDGE DEVICES      1.0 0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -1.0  0.5  0.   1.0  0.   0.   1.0       25.536
SYS STATUS DISPLAYS       0.  0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.        25.027
IMPR STLL/SPN--AERO TLRG  0.  0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   3.0  0.   0.        24.008
QUIET EFFICIENT PROPS     0.  0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.        23.901
SEPARATE SFC TECHNOLOGY   0.  0.   0.  -0.5  0.  -0.5  0.   0.   0.   3.0 -2.0  0.  -0.5  3.0  1.0  0.   0.        22.219
LOAD LIMITING SEATS       0.  3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.        17.326
IMPROVED RESTRAINTS       0.  3.0  0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.        16.191
ENERGY ABSORBING FLOOR    0.  3.0  0.   0.   0.  -0.5  0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.        16.020
ACTIVE STALL PREVENTION   0.  0.   0.   0.   0.  -0.5  0.   0.   0.   0.  -1.0  0.  -0.5  0.   3.0  0.   0.        13.154
LIQUID COOLING            0.  0.   0.   2.0  0.  -1.0  1.0  1.0  1.0  0.   0.   0.  -1.0  0.  -1.0  0.   0.        12.677
```

Table 4.10. Overall Technology Ranking For Airplane A (concluded)

STRAT CHG RECIP ENGINE	0.	0.	0.	1.0	2.0	-0.5	0.	1.0	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	12.235
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-2.0	0.	1.0	0.	0.5	0.	0.	11.233
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	11.206
HCRLD RECIP ENGINE	0.	0.	0.	0.5	2.0	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	13.631
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.5	0.	0.	1.0	0.	0.	0.	-1.0	0.	0.	0.	1.0	0.	0.	9.147
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.236
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	7.593
ICEPHOBIC SFC COATINGS	-0.5	0.	0.	-0.5	0.	-1.0	0.	0.	0.	0.	-1.0	-0.5	0.	0.	3.0	0.	0.	5.098
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	-2.0	0.	0.	0.	2.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	1.0	3.843
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	2.539
MICRO HUD	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	1.535
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	-0.030
DUCTED PROPULSORS	-0.5	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	2.0	-1.708
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-2.671
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-2.884
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	-0.5	0.	-0.5	0.	0.	-1.0	-0.5	1.0	0.	0.	0.	0.	-12.269
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.5	0.	0.	-1.0	0.	0.	0.	0.	0.	-0.5	-13.997
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-14.098
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0	0.	0.	-14.098
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-15.933
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.141
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-22.525
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-0.5	0.	0.	-23.776
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-25.545
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-0.5	0.	0.	-26.033
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-36.517
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-38.383
ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-42.305
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-52.938

Table 4.11. Overall Technology Ranking For Airplane B

```
                                                AIRPLANE B

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                              CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD      FIG OF
                         CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  QLTY QLTY SFTY CMFT PERF       MERIT
       CATEGORY WEIGHTS 5.45 7.33 7.48 9.45 2.16 5.66 5.41 8.61 7.45 7.00 7.76 7.18 9.55 7.24 9.56 6.71 7.41


FIBERGLASS COMPOSITES     2.0  0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.      57.962
KEVLAR COMPOSITES         2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.      55.858
GRAPHITE COMPOSITES       2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.      48.097
INTEG AVIONICS AND DSPYS  0.   0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -1.0  0.   0.   0.   2.0  0.   0.      41.772
SPOILERS                  0.   0.   1.0  1.0  0.   0.5  0.   0.5  0.   0.5  0.   0.5  0.   1.0  0.   0.   0.      38.390
DIGITAL DATA LINKS        0.   0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.      34.106
ICEPHOBIC SFC COATINGS    1.0  0.   0.   0.   0.   1.0  0.   0.5  0.   0.   1.0  0.   0.5  0.   0.5  0.   0.      32.716
GATE ENGINE               0.   0.   0.   1.0  0.   0.   0.   1.0  0.   0.   0.   2.0  0.   0.   0.   0.   0.      32.419
LOW/MEDM SPEED AIRFOILS   0.   0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0     31.226
QUIET EFFICIENT PROPS     0.   0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.      29.116
LEADING EDGE DEVICES      1.0  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -0.5  0.5  0.   0.5  0.   0.   1.0     28.952
NAT LAM FLOW AIRFOILS     0.5  0.   1.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0 -2.0  0.   0.   0.   1.0     25.531
SYS STATUS DISPLAYS       0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.      25.323
SEPARATE SFC TECHNOLOGY   0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  0.   0.   0.   1.0  1.0  0.   0.      23.786
FOWLER FLAPS              0.   0.   0.5  0.5  0.   0.   0.   0.5  0.   0.   0.   0.5  0.   1.0  0.   0.   0.      23.597
STRT CHG ROT COMB ENGINE  0.   0.   0.   1.0  1.0 -1.0  0.   0.   0.   0.   1.0  1.0  0.   0.   0.   0.   0.      20.893
CRT DISPLAYS              0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   1.0  0.   0.5  0.   0.      20.556
MICROWAVE LANDING SYSTEM  0.   0.   0.   1.0  0.   0.   1.0  0.   0.   0.  -0.5  0.   0.   0.   1.0  0.   0.      20.527
LOAD LIMITING SEATS       0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.      18.646
DUCTED PROPULSORS        -0.5  0.  -1.0 -0.5  0.  -1.0  3.0 -0.5  3.0  0.  -1.0 -1.0  0.   0.   0.5  0.   2.0     18.350
IMPROVED RESTRAINTS       0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.      18.118
```

Table 4.11. Overall Technology Ranking For Airplane B (concluded)

AC ELECTRICAL SYSTEMS	0.5	0.	0.	0.	0.	0.5	0.	0.	0.	0.	1.0	0.5	0.	0.	0.	0.	0.	16.904
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	16.097
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	15.290
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	0.	0.	15.207
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	12.120
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.781
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	8.581
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	7.761
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	5.952
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	4.529
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.0	0.	-0.5	3.0	0.	0.	0.	3.691
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.289
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	-0.5	1.0	0.	0.	0.	0.	-1.070
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-3.312
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-3.733
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.068
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-13.689
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	-0.5	-15.138
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.852
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-23.283
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-26.398
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-1.0	0.	0.	-29.632
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-29.905
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-31.377
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
ACT GUST ALLEVIATION	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	1.0	0.	0.	0.	-35.043
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-37.556
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-39.802
ACTIVE LAMINAR FLOW CTL	2.0	0.	0.	-3.0	0.	0.	0.	1.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	1.0	-45.189
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-57.013

Table 4.12 Aerodynamics

Technology (9)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Natural Laminar Flow Airfoils	58	25
Spoilers	57	38
Fowler Flaps	48	24
Low/Medium Speed Airfoils	29	31
Leading Edge Devices	24	29
Improved Stall/Spin -- Aerodynamic Tailoring	24	15
Active Laminar Flow Control	4	-46
Winglets	- 3	- 4
Low Drag Surface Coatings	-14	-15

*Total number of technologies/lowest FM/highest FM

4.5.2.1 Winglets. The advantages of winglets are not yet clear. Although they promise to reduce induced drag while increasing wing bending moments when applied as a modification to existing aircraft, there is little data to suggest that they would offer improvements to aerodynamic efficiency that could not be gained through increased aspect ratio and wing twist. Difficulties involving flutter and large sideslip angles require further study. Reference 156 describes theoretical improvements in range of 6% to 8% over a similar wing without winglets. Although this article cites large stabilizing moments in yaw at sideslip angles of 6° to 8°, the addition of winglets also resulted in a weakly divergent dutch roll mode.

The baseline against which this technology was evaluated for both Airplane A and Airplane B was a high-aspect-ratio, twisted wing. Small benefits in cruise performance were offset by weight penalties to compensate for substantial increases in root bending moments.

4.5.2.2 Spoilers. Spoilers alone offer only small advantages to general aviation aircraft by eliminating adverse yaw. However, they offer the promise of major improvements in performance by freeing the entire wing trailing edge for high lift devices (full span flaps). As mentioned previously in Section 4.3.2, this additional maximum lift capability can be used to either improve takeoff and landing performance or, at the other extreme, improve cruise performance by increasing wing loading (W/S). Since increased wing loading offers substantial benefits in fuel efficiency and ride qualities with only a small penalty (if any) in cruise ceiling, this technology is evaluated from the standpoint of increased W/S. It should be noted that since typical single engine aircraft operate at $W/S \simeq 730$ to $1220\ N/m^2$ while commuters operate at $W/S \simeq 2390$ to $2870\ N/m^2$, Airplane A will reflect larger impacts from this technology (W/S for heavy transports are typically on the order of 4790 to $6700\ N/m^2$).

Although cruise performance promises to reflect substantial gains, the incorporation of spoilers does have attendant risks.

Nonlinear control response, sluggishness, control reversal (due to flow reattachment), increase of authority with full span flaps deployed, and loss of control authority at negative angles of attack are but a few which are identified in the literature. Laundry, however, has expressed the view that the limited use of spoilers is attributable not so much to the lack of spoiler handbook data, but rather to the vast amount of aileron handbook data available (Ref. 121).

Still unavailable is a verified thin-airfoil method for predicting 2D characteristics of a wing-spoiler-slotted-flap configuration. However, Parkinson has reported on research using a numerical thick airfoil method utilizing a 2-source model to predict c_ℓ and c_{m_o} vs. α for an airfoil with a spoiler and slotted flap (Ref. 159).

Furthermore, Reference 111 reports favorably on flight test results of spoiler characteristics on a modified Cessna 177 Cardinal (Redhawk program) and Reference 110 does likewise for spoilers on a modified PA34-200 Piper Seneca (ATLIT program). Reference 183 provides an overview of the state of the art of general aviation spoilers in 1974.

4.5.2.3 Fowler Flaps. Fowler flaps offer significant improvements in maximum lift coefficient ($C_{L_{max}}$) when compared to the plain, split, or single slotted flaps which are typical of the single engine general aviation (GA) fleet. However, their real benefits are more fully exploited when used as full span flaps in conjunction with spoilers. Although this idea is not new (References 80, 122, 224), difficulties associated with integrating the spoilers have delayed the widespread use of this concept.

Paulson (Ref. 161) reports an increase in $C_{L_{max}}$ of 96% when Fowler flaps were fully deflected on a wind tunnel model wing. In a comparison between plain, slotted, and Fowler flaps, where the plain and slotted flaps had flap spans approximately 50% of the wing semi-span while the Fowler flaps had flap spans approximately 75% of the wing semi-span, Paulson (Ref. 162) reports a $C_{L_{max}}$ for the Fowler flap approximately 48% greater than the plain or slotted flap. Under the conditions of this latter investigation, the Fowler-flapped configuration could either land at a speed 18% lower than its counterpart or reduce its wing area by 33%. Wentz (Ref. 224) reports a $C_{L_{max}} = 3$ for a one-quarter scale ATLIT wing equipped with full span Fowler flaps.

For the evaluation at hand, Airplane A is presumed to have plain or single slotted half span flaps and Airplane B is presumed to be equipped with half span Fowler flaps. The anticipated effects of full span Fowler flaps is reflected in the evaluation. Hence, this technology is considered to be intergrated with spoilers.

4.5.2.4 Low Drag Surface Coatings. This technology is described in Reference 22, where an investigation was conducted by the Boeing Commerical Airplane Company of nine liquid coatings and 60 film/adhesive systems. This investigation is part of the Energy Efficient Transport (EET) element of the Aircraft Energy Efficiency (ACEE) program and was performed under contract to NASA-Langley Research Center. Three liquid coatings and four film/adhesives are currently undergoing further testing and evaluation.

Motivation for this research was supplied by the 1973 fuel crisis, and preliminary research by NASA of a T-33 wing reflected a 12% reduction in drag when skin joints, hinge lines, etc. were covered with a smooth thin film. Boeing's research indicates, however, that only a 1.6% reduction in drag coefficient (C_D) can be expected due to the existance of unsealed gaps for high lift devices and control surfaces. Still, this 1.6% reduction translates to a fuel savings of 128,690 ℓ (34,000 gals) per Boeing 727 per year.

Analysis of the data reveals that although almost all of the drag associated with roughness is eliminated from wing and tails, only 25% of the drag associated with gaps was eliminated. Hence, application of a low drag surface coating to a wing with protruding rivets makes little sense. From a mission profile consideration, Airplane A could benefit more from this technology than Airplane B because its mission is cruise dominated whereas Airplane B's is characterized by more time in climbs and approaches where drag-due-to-lift is usually more significant than profile drag.

However, even if one considers an advanced airplane characterized by flush rivets, bonded surfaces, or composite construction, the propulsion system will invariably include a propeller, and system efficiencies will dictate lower cruise speeds closer to

L/D_{max} than for a turbojet or turbofan counterpart. Realizable savings due to small reductions in profile drag are probably more than offset by penalties in weight, initial cost, and DOC for both Airplane A and B.

4.5.2.5 Active Laminar Flow Control. This technology is receiving renewed interest in light of soaring fuel costs. As Shevell points out in Reference 191, nothing else has the potential of reducing drag to as great an extent. An example in his article, based on an aircraft operating at Reynolds numbers of 20 to 70 x 10^6 with 200 passengers and a range of 5500 nautical miles, illustrates his point. If this vehicle operated with 75% of its wing and tail surfaces effectively laminarized, drag would be reduced by 30% and L/D would increase by 30%. For a similar type of vehicle ($M=.8$, 200 passengers, JT9D engines), Maddalon points out that laminar flow control (LFC) energy requirements decrease as AR increases above 7 (Ref. 129). For this type of air carrier operation, DOC decreased despite a 17% penalty in maintenance costs and a 3% penalty in purchase price.

Although LFC offers a far greater potential for parasitic drag reduction than low drag surface coatings, it still promises significant penalties for Airplane A and Airplane B. As with all systems which reduce parasitic drag, the benefits realized by a propeller-powered airplane may be expected to be less than for a jet or fan powered vehicle. Also, fuel costs represent a significantly smaller percentage of DOC for Airplane A, and the mission profile of Airplane B does not allow it to take full advantage of the system. The low altitude environment of Airplane B and the associated higher susceptibility to insects, dust, and other debris suggest higher maintenance costs for Airplane B than for a high-altitude cruise vehicle.

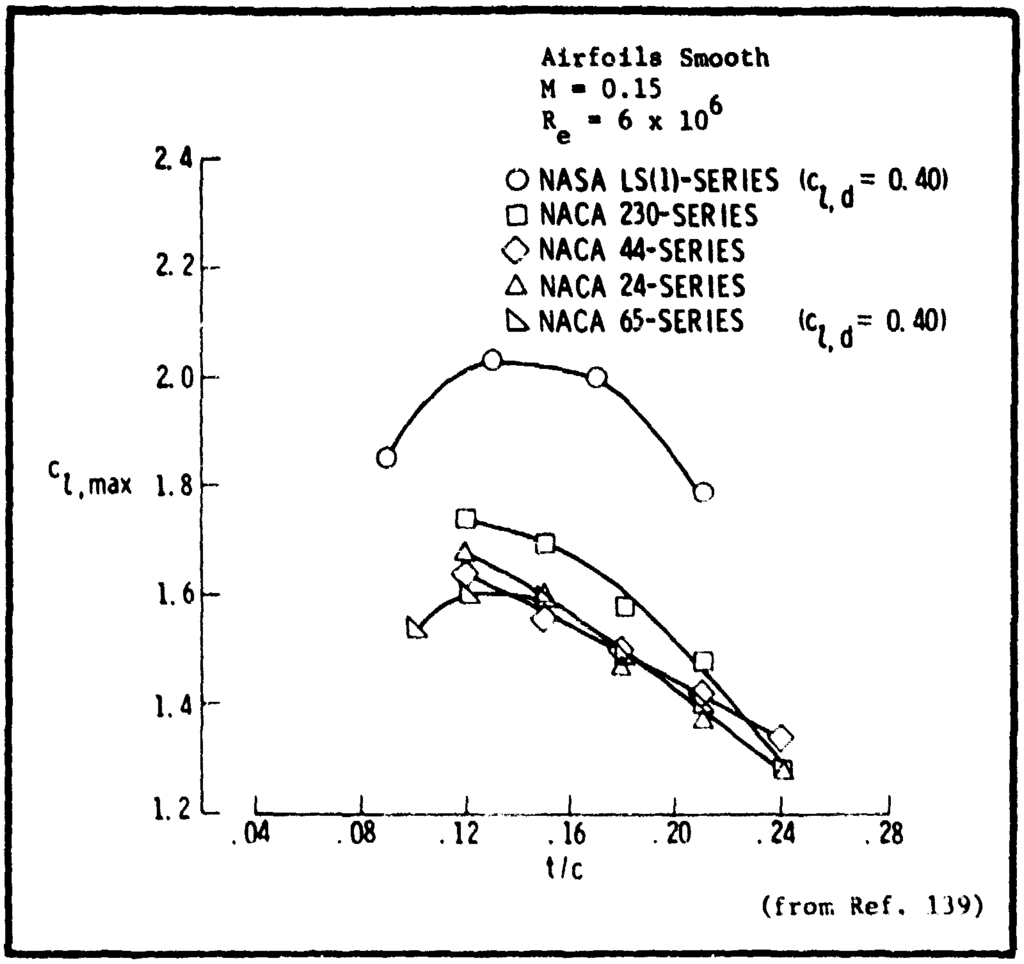
It should be reiterated at this point that one factor which this evaluation process significantly does not measure is risk. For the case at hand, an airplane optimized for LFC operation from the beginning of the design process will have markedly different characteristics than a non-LFC counterpart. Degradation of the LFC system promises significant (although yet unquantified) penalites in performance and operating costs.

4.5.2.6 Leading Edge Devices. These devices, which are found on almost every contemporary commercial jet liner, are only rarely found in GA aircraft. Fixed devices offer the same low performance advantages as retractable Krueger flaps or slats. However, cruise performance is degraded in exchange for the simplicity of a fixed system. Reference 111 presents some flight test results of a Krueger system installed on the Redhawk. Although they displayed excellent characteristics ($\Delta C_{L_{max}}$ = .59 for the Krueger flaps with Fowler flaps deployed 40°), it was suggested that such a system was probably too heavy and too complex for a light GA single engine aircraft.

In exchange for the increase in $C_{L_{max}}$, W/S could be increased even further to improve cruise performance. However, these benefits would be offset by a probable degradation in ceiling.

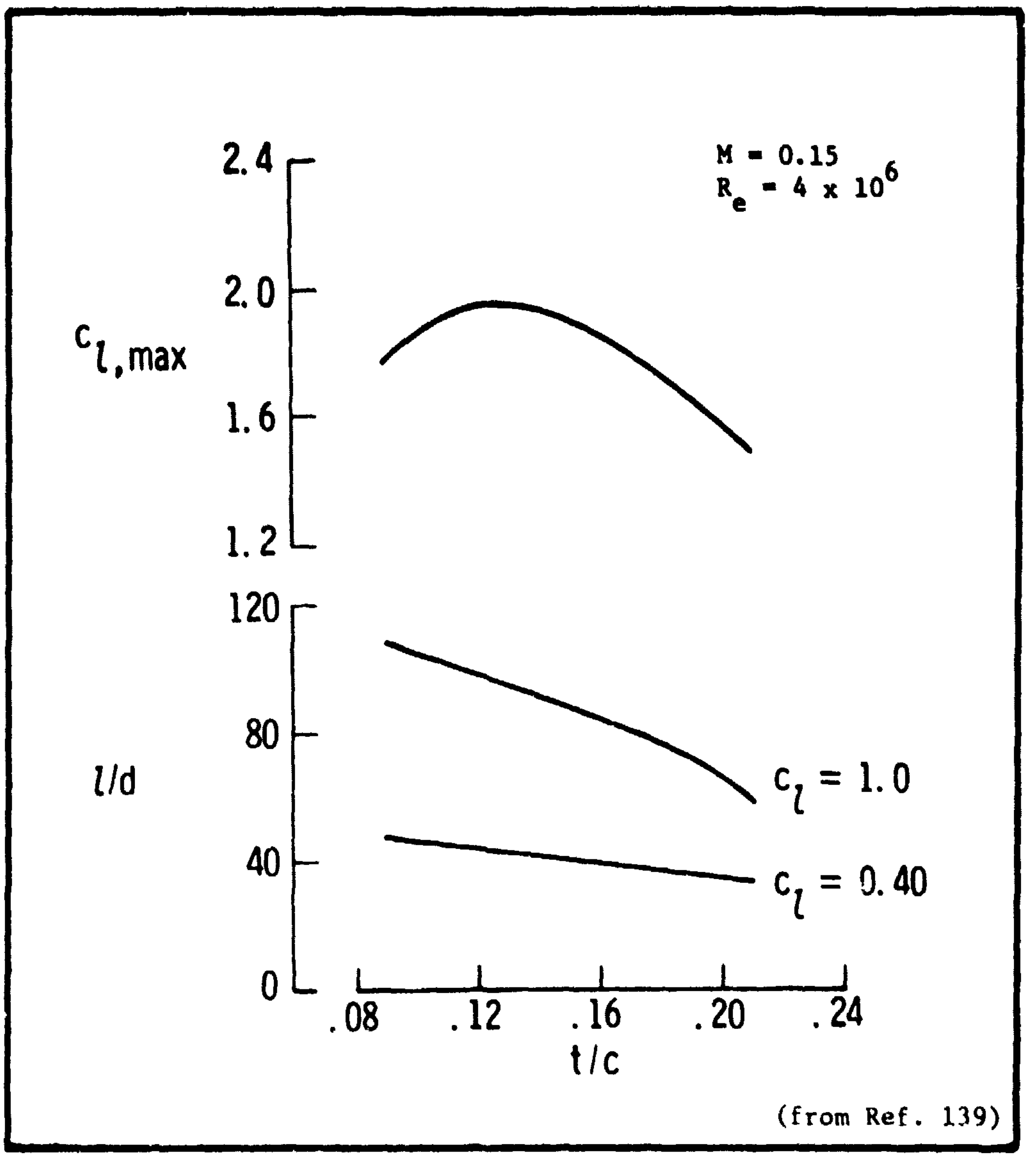
An interesting application of a retractable leading edge device would be in their use on the outboard section of the aft wing of a canard configured vehicle. Such an application could offset the effects of increased upwash from the canard during low speed high angle-of-attack operations.

4.5.2.7 Advanced Low and Medium Speed Airfoils. These airfoils are characterized by turbulent flow conditions and were initially designed as low speed airfoils to provide low cruise drag, high climb lift-to-drag ratios, high maximum lift, and well behaved stall characteristics. Results of these efforts are documented by McGhee, Beasley and Whitcomb in Reference 139 and are shown in Figures 4.3 and 4.4, where the LS(1) series encompasses both the GA(W)-1 and GA(W)-2. As shown, these low speed airfoils have better $c_{\ell_{max}}$ than more conventional NACA sections and $t/c \approx .13$ produced the highest $c_{\ell_{max}}$. Reference 139 also describes work done to reduce pitching moments of a 17% thick airfoil as well as increase the lift-to-drag ratio of a 21% thick airfoil. These low speed airfoils all have a design c_ℓ of 0.4. Two medium speed airfoils are described where $c_\ell = .3$, $R_e = 14 \times 10^6$, and $M = .72$ and .68. The design family of airfoils is shown in Figure 4.5. These airfoils, however, are characterized by higher pitching moments and higher drag than, for example, 6-series airfoils. Accordingly, an effort by Hicks and Schairer to increase the maximum lift coefficient of 63_2-215 airfoil is described in Reference 84. Figure 4.6 shows the modification and Figure 4.7 shows one of several figures depicting typical results. This may be compared to Figure 4.8 from Reference 139 which shows low and medium speed airfoil data.



(from Ref. 139)

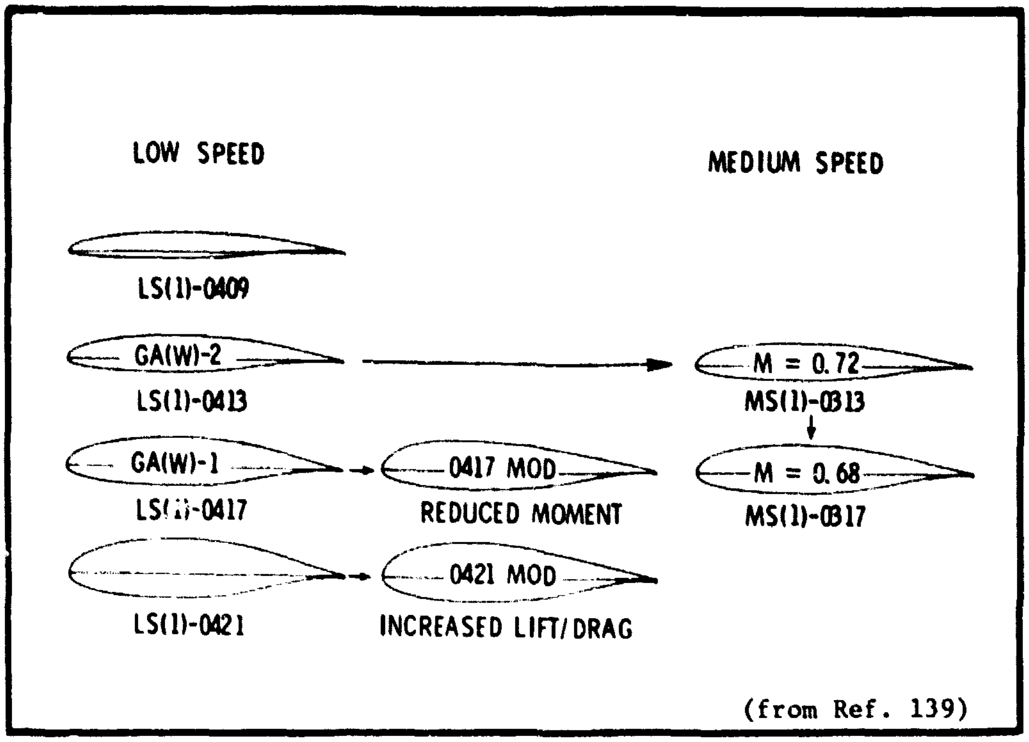
Fig. 4.3. $c_{\ell_{max}}$ vs t/c of NASA Low-Speed and NACA Airfoils.



(from Ref. 139)

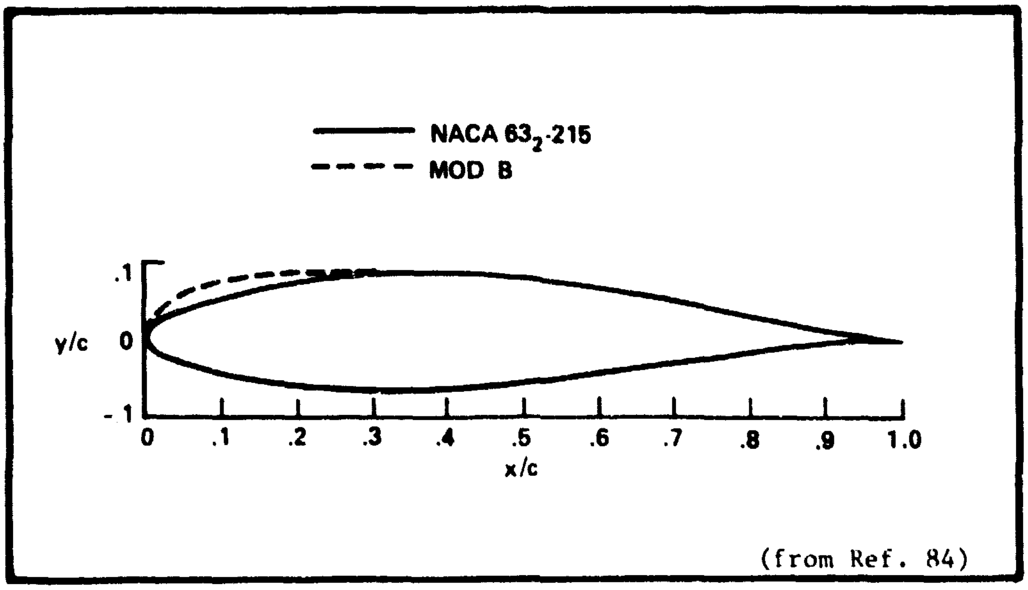
Fig. 4.4. Effect of t/c on $c_{\ell_{max}}$ and ℓ/d for NASA Low-Speed Airfoils.

One difficulty which is posed for the thinner airfoils (t/c ≃ .13) is that these airfoils do not lend themselves to easy configuration integration in GA aircraft. Thicker airfoils (t/c ≃ .17) offer more wing volume for fuel and control linkages. Also, they suffer a smaller weight penalty in construction.



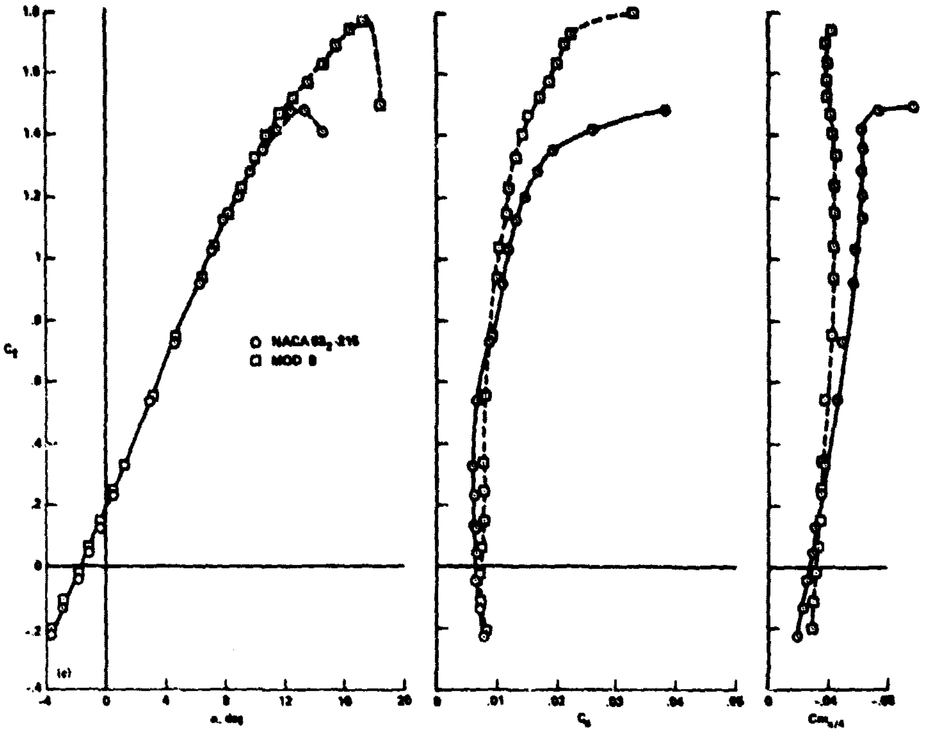
(from Ref. 139)

Fig. 4.5. Design Family of NASA Low-Speed Airfoils.



(from Ref. 84)

Fig. 4.6. Modification to NACA 63_2-215 Airfoil.



$M = 0.2 \quad R_e = 2.5 \times 10^6$

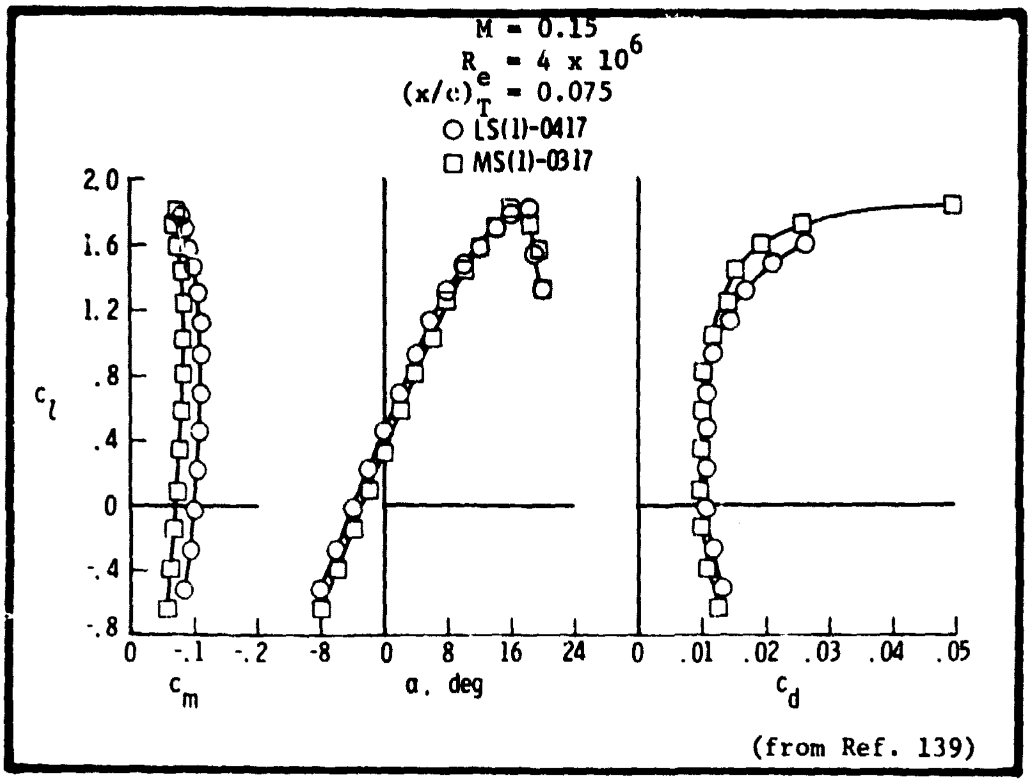
(from Ref. 84)

Fig. 4.7. Experimental Results of a Modification to an NACA 63_2-215 Airfoil.

Difficulties with implementation of the LS(1) series into a configuration are suggested by the highly aft-loaded airfoil pressure distribution and suggest that a moderate amount of tailoring may be required at the wing-body junction to preclude premature flow separation of both the wing and fuselage in this region.

For the technology evaluation, it was assumed that neither Airplane A or B employed low or medium speed airfoils. Airplane B

should suffer a smaller penalty in parasitic drag since its mission profile is more dominated by climbs and approaches where drag-due-to-lift is more dominant than in cruise.



(from Ref. 139)

Fig. 4.8. Experimental Results of Low and Medium Speed Airfoils.

4.5.2.8 <u>Advanced Natural Laminar Flow Airfoils</u>. Present efforts to develop a natural laminar airfoil are aimed at achieving a $c_{\ell_{max}}$ at least as great as that associated with the GA(W)-2 while maintaining pitching moment coefficients lower than those of the same airfoil. Preliminary work suggests sectional reductions in drag by as much as 25% at design c_ℓ. Improvements in performance are offset by a requirement to maintain a smooth surface, and relatively severe penalties in drag appear with the introduction of roughness. This suggests that flush riveting, bonding, or composite materials may be required to eliminate protruding rivet heads. Also, the user may expect to be confronted with a requirement to maintain a relatively insect-free surface.

This technology proved fairly difficult to evaluate. Airplane A could benefit rather significantly from this technology, but purchase cost penalties could outweigh benefits if a baseline of present manufacturing processes is upgraded to total flush riveting. For purposes of this evaluation, it will be assumed that this technology will be integrated with a composite wing since the latter offers reduced manufacturing costs. In the absence of an insect-free surface technology, Airplane B will encounter DOC expenses and reliability penalties associated with its more severe operating environment.

4.5.2.9 Improved Stall/Spin Characteristics Through Aerodynamic Tailoring. Solutions to stall/spin accidents range from better pilot stall recognition training to better designed vehicles. This evaluation addresses only the latter solution (in a rather restricted sense.

Anderson notes that solutions to the design problem appear to lie in (1) providing good handling qualities up to and beyond maximum lift, (2) making the aircraft spin resistant, and (3) providing stable static and dynamic stability characteristics with good control about the pitch, roll, and yaw axes (Ref. 4). Three approaches which appear feasible are:

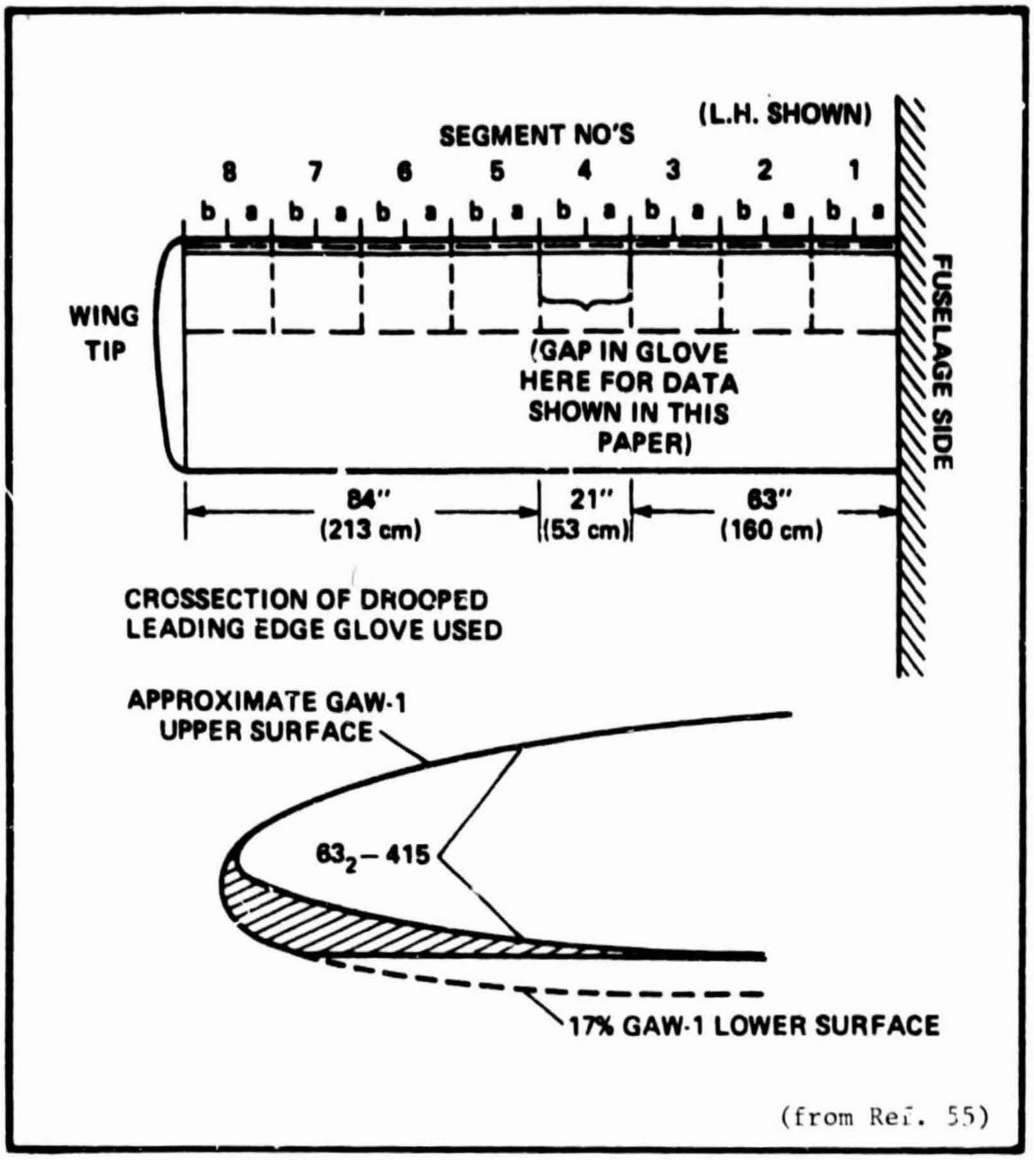
(1) Control stall progression on the wing to provide greater post-stall roll damping and natural buffet stall warning.

(2) Limit longitudinal control power to prevent complete wing stall.

(3) Minimize adverse cross coupling by automatic (SAS) means.

Item 2 is addressed by attempts to reduce the relative horizontal tail power through (1) tailoring, (2) active controls (Ref. 29) or (3) employing a canard configuration (Ref. 185). Item 3 has already been successfully demonstrated by the military. Certainly, separate surface technology as discussed elsewhere in this paper should be investigated. Artificial stall warning devices appear to provide significant contributions, and Ellis notes that a large portion of stall, mush, and spin accidents occur in airplanes which are not equipped with these systems (Ref. 49). Stick shakers appear to be the most effective warning device. Aural warnings also provide a certain margin of safety, but visual-only angle-of-attack indicators appear ineffective.

Having discussed certain problems and solutions which appear in the literature, emphasis is now focused on methods of controlling stall progression through aerodynamic tailoring. Feistal, Anderson, and Kroeger have reported on promising results based on a leading edge discontinuity as illustrated in Figure 4.9 (Ref. 85). Figure 4.10 depicts an essentially flat-topped lift curve out to

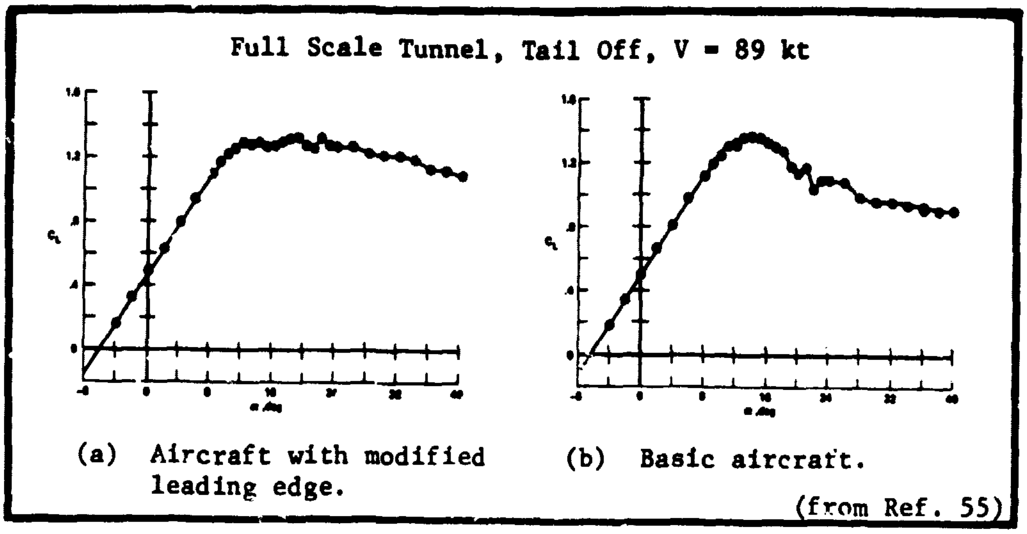


(from Ref. 55)

Fig. 4.9. Leading Edge Modification for Stall/Spin Alleviation

an angle-of-attach of 32°. Significantly, rolling moment excursions as well as yawing moments were acceptable throughout the range of angle-of-attacks tested. Hicks and Henne have reported on a numerical optimization technique where a low speed wing (GA(W)-2 section) could theoretically be modified to move the initial stall to the wing root without affecting either span loading or induced drag characteristics (Ref. 83).

For this study, only the technologies representing efforts to control separation are evaluated. Both Airplane A and B achieve substantial benefits in safety at little cost.



Full Scale Tunnel, Tail Off, V = 89 kt

(a) Aircraft with modified leading edge.

(b) Basic aircraft.

(from Ref. 55)

Fig. 4.10. Flat-Topped Lift Curve from Leading Edge Modification for Stall/Spin Alleviation.

4.5.3 Aircraft Systems

Only two systems as shown in Table 4.12 were evaluated. Surprisingly, Icephobic Surface Coatings did not fare as exceptionally well as one might expect. Here, minor penalties in weight (which affected ceiling and range to a lesser extent) and cost almost totally negated the +3 relative benefit awarded for safety. Airplane B appears to benefit substantially when pneumatic boots or hot air systems are replaced.

Table 4.13. Aircraft Systems

Technology (2)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Icephobic Surface Coatings	5	33
AC Electrical Systems	0	17

*Total number of technologies/lowest FM/highest FM

4.5.3.1 Icephobic Surface Coatings. Very little was found in the literature on icephobic surface coatings. Although Reference 18 mentions olefin plastics on helicopter blades, no mention is made of the success or failure of this research. Certainly, the rewards obtainable from a surface coating of this type demand further research. When one consideres that vertical and horizontal tails, wheel pants, struts, etc., could all be protected from ice accumulation in addition to the more conventional and limited GA application to wing leading edges only, the potential benefits of such a system become staggering. It is suspected that in-house, unpublished research has already been performed by interested agencies. However, no information relating to efforts or results surfaced in the data gathering trips performed as part of this research.

For this technology evaluation, the baseline for Airplane A is not considered to be equipped with an anti-icing system, while the baseline for Airplane B is presumed to be equipped with a pneumatic system consisting of either boots or ducted hot air.

Airplane A is penalized for weight and cost but receives a higher benefit in safety. On the other hand, Airplane B receives an improvement in reliability, cost, and weight with only small improvements in safety.

4.5.3.2 AC Electrical Systems. Major research activity in shifting from DC to AC electrical systems was not detected either in the literature or during data gathering trips. However, at least one manufacturer cited a potential for large weight savings in their aircraft product line.

For the present, neither Aircraft A's nor Aircraft B's technology baseline is expected to benefit to any great extent. Airplane A is characterized by limited weight penalties associated with wiring, while Aircraft B is known to favor panel-mounted vs remote-mounted avionics due to cost considerations (Ref. 167). Although newer commuters are usually equipped with autopilots and flight director systems, it is suspected that the majority of operational commuters are still hand flown on conventional round dial instruments with cross pointers. Hence, the potential weight savings are not as great as for a current business jet.

4.5.4 Crashworthiness

Four technologies as shown in Table 4.14 were investigated. These technologies are considered to be extremely attractive. As explained earlier, their figures of merit are relatively low because they affect only a few categories and specifically do not influence DOC, Safety, or Reliability. Also, as shown in Table 4.3 and 4.4, the category weighting for Crashworthiness was 6.816 (#11 of 17) for Airplane A and 7.333 (#9 of 17) for Airplane B.

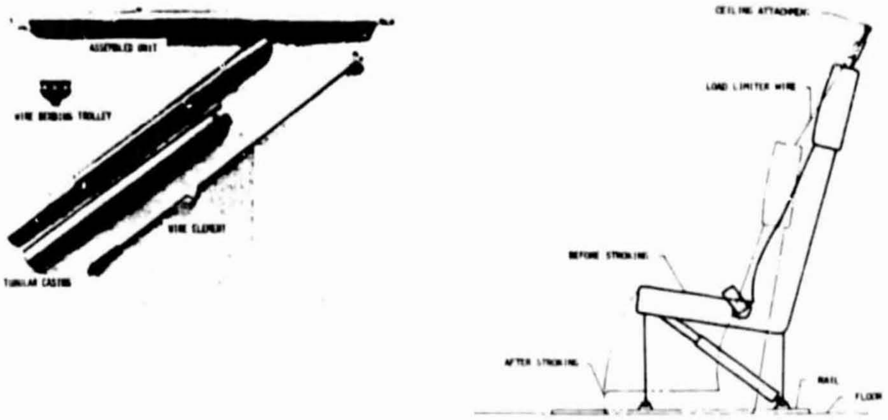
Table 4.14. Crashworthiness

Technology (4)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Load Limiting Seats	17	19
Energy Absorbing Floor	14	15
Improved Restraints	14	15
Burst/Tear Resistant Tanks	8	9

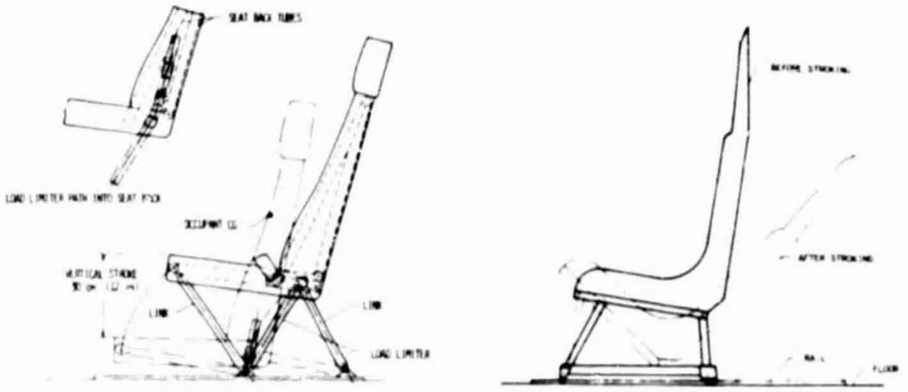
*Total number of technologies/lowest FM/highest FM

4.5.4.1 Load Limiting Seats. Efforts to improve occupant survivability in the event of a crash are becoming more refined with the correlations of test data obtained from the NASA Impact Dynamics Research Facility (IDRF) and the FAA Civil Aeromedical Institute (CAMI) with analytical data from a modified computer algorithm known as MSOMLA (for Modified Seat-Occupant Model for Light Aircraft). Fasanella and Alfaro-Bou note good agreement between CAMI sled data and full scale results from the IDRF. MSOMLA (which uses a spring-damper model as opposed to the finite element model in SOMLA) also showed good agreement (Ref. 53).

Having noted that there is much which can be done towards improving survivability through improved seat design, three different types of improved seats as shown in Figures 4.11 (b), (c), and (d) are being investigated. The wire bending load limiter is shown in Figure 4.11 (a).



(a) Wire bending load limiter (b) Ceiling suspended seat



(b) Floor mounted seat (d) Rocker action seat

Fig. 4.11. Load Limiting Seat Concepts.

During stroking, the wire loop is translated along the wire under a constant force of 4.4 kN (1000 lbf). Tests as of April 1979 indicate that the ceiling mounted seat reduced longitudunal pelvic accelerations by 40% during a 15 m/s (50 fps) sled pulse and vertical accelerations by 50% during a 13 m/s (42 fps) sled pulse (Ref. 53). This seat, which has a 9.1 kg mass, suffers from added installation weight and a possible loss of stroking distance resulting from cabin deformation at impact. From an applications/integration viewpoint, it appears that the floor mounted seat (10 kg or 23 lbm) may offer more promise. However, preliminary test results indicated a requirement for further development work for the floor mounted and rocker action seats. Thomson and Goetz (Ref. 210) note in a similar report that the human tolerance of 25 g's can be met with a 30 cm (12 in) stroke dissipated over 0.1 sec. Such a system places an upper bound of 12.2 m/s (40 fps) on the seats.

Since the typical general aviation seat of 11 kg (25 lb) dissipates energy through seat deformation and leg buckling, load limiting seats offer great potential for improving vehicle crashworthiness and occupant survivability.

4.5.4.2 Energy Absorbing Floor. Several schemes which offer promise in application are described in Reference 210 and depicted in Figure 4.12. Assuming a 15 cm (6 in) available stroke (through floor deformation), Thomson and Goetz point to an upper limit of 8.2 m/s (27 fps) which can be dissipated by the floor structure through controlled collapse. Despite information obtained from airframe manufacturers which indicates that this type of occupant protection is already being introduced in a few product lines, widespread incorporation is not yet noted. Tests and data correlation with analytical models indicate that three computer codes (KRASH, ACTION and DYCAST) demonstrate good quantitative results in predicting dynamic vehicle response to impact loadings (Ref. 79). The continued development of these tools promises to give further insight to floor and cabin deformation. Fasanella and Alfaro-Bou report, for example, that IDRF data showed a GA aircraft cabin during a 27 m/s (89 fps) impact deforming and become 21 cm (8.3 in) wider and 23 cm (9 in) lower. The apparent upheaval of the center floor section was actually the result of the cabin side walls forcing the floor down at the wall junction. Incorporation of the energy absorbing floor into future GA aircraft takes on added significance in view of such recent test data.

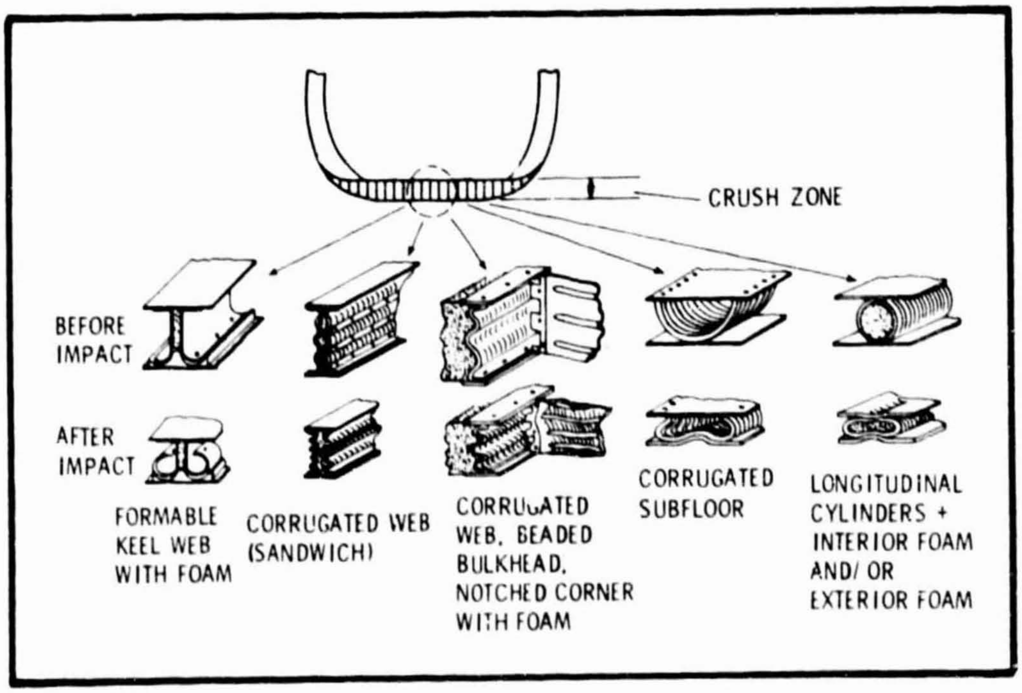
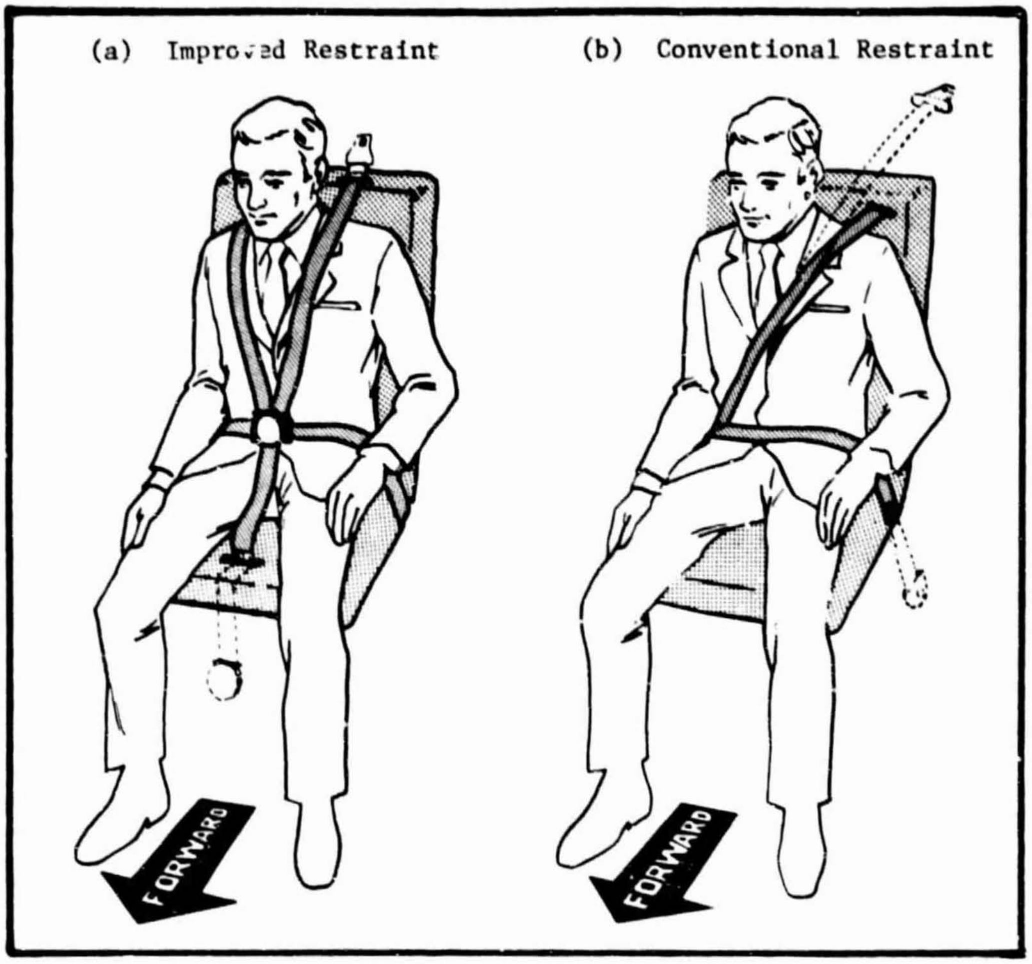


Fig. 4.12. Energy Absorbing Floor Concepts.

Both Airplane A and B will gain significantly in crashworthiness from this technology at an undetermined cost in weight. (Note that all of the five concepts depicted in Figure 4.12 incorporate an energy-dissipating foam.)

4.5.4.3 Improved Restraints. When an analysis of business aircraft accident investigations showed that the use of shoulder belts reflected a marked increase in survival, the researchers concluded that this use is considered to be the single most important means of improving occupant crash impact protection (Ref. 194). This report also noted that restraints attached to the seat provided little protection when the seat failed and separated from the floor. Further research by others indicates that a single shoulder strap allows the occupant to roll out of the restraint in some accidents. Hence, a restraining system consisting of two shoulder straps, two lap belts, and crotch strap, all connected at a single point centered on the lap belts appears to offer major improvements in crashworthiness. (Fig. 4.13(a) depicts such a system.) Such a system would incorporate locking inertia reels in the shoulder harness and thereby afford the passenger more freedom of movement during normal operations than a diagonal single shoulder strap would. Tests to date indicate that a tensile force of .54 kN (122 lb) may be encountered in the harness system during a 27 m/sec (89 fps) impact. Hence, metal-to-metal buckles are preferred to metal-to-fabric cam systems.

This technology promises significant benefits to both Airplane A and B. Anticipated penalties lie in increased costs.



(a) Improved Restraint (b) Conventional Restraint

Fig. 4.13. Five Point Improved Restraint vs Conventional Restraint

4.5.4.4 Burst/Tear Resistant Fuel Tanks. Efforts to develop a crash/tear resistant fuel tank were encouraged by the success of Army helicopter programs. However, the tanks developed under the Army programs are too heavy and expensive for general aviation aircraft (Bergey notes in Ref. 18 that a 130 liter helicopter tank may cost on the order of $10,000). In an attempt to simplify the system, ballistic protection was eliminated as a criterion, and 1-, 2-, and 3 ply tanks with frangible fittings were manufactured and tested in a full size airframe which was accelerated using a catapult. Reference 48 notes that the lightest tank which performed satisfactorily with no leakage after a 29 m/s (96 fps) impact was one manufactured by Uniroyal Corporation from a single ply with a fabric weight of 43.23 gram/m^2. None of the 2- and 3-ply tanks failed, but two other (lighter) 1-ply tanks and the original tank did. Figure 4.14 shows the installed tank, and Figures 4.15 and 4.16 show the crash site and test where the test vehicle impacted an earthen hill equipped with sunken steel tubes and rock piles. Figure 4.17 shows the external damage done to the wing where the single ply tank did not fail. (Note that a system to shear the fuel line from the tank was incorporated, and the frangible fittings did not leak.)

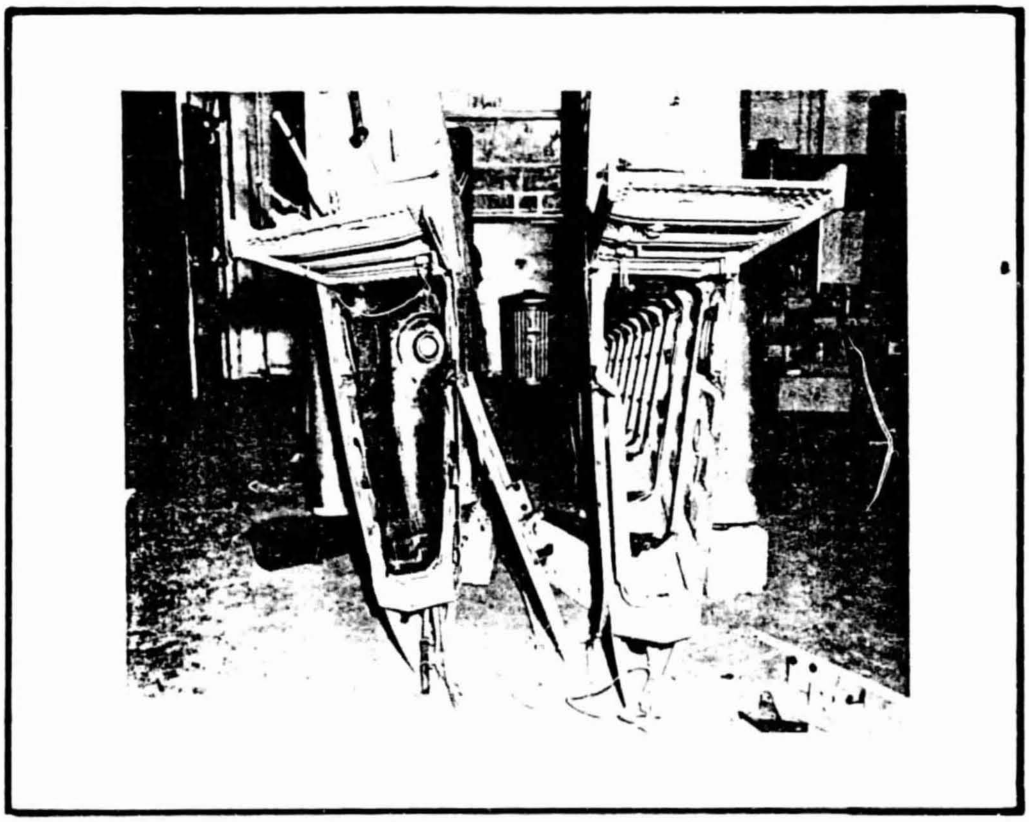


Fig. 4.14. Modified Fuel Tank Installed in Wing.

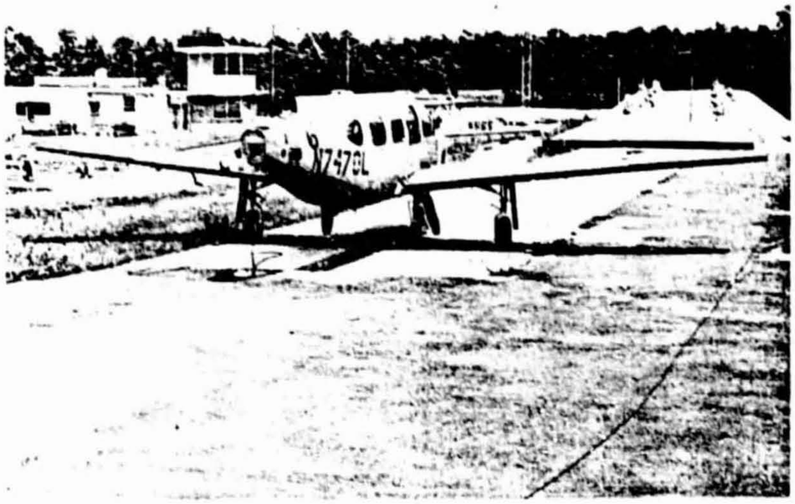


Fig. 4.15. Airframe on Catapult with Earthen Hill, Steel Tubes, and Rockpiles Visible.

Since annual GA accidents over the ten year period between 1966 and 1976 numbered from 4,200 to 6,100 with post crash fires reported in approximately 350 of the accidents annually, the potential for improved safety for GA aircraft offered by these tanks is significant.

Weight and cost appear to pose disadvantages for both Airplane A and B. The 1-ply test tank weighed 9.4 kg (21 lb) including the fittings while the original tank weighed 4.4 kg (9.6 lb). In spite of a volume penalty of 5.3 liters (1.4 gals) per tank, production tanks may be expected to have a volume difference of less than 3.8 liters (1 gal) from conventional bladder tanks. These weight and volume penalites are expected to be greater when compared to a wet wing concept. However, a wet wing may be expected to suffer from post crash impact failures at least as often as conventional bladder tanks.

Fig. 4.16. Typical Impact of Airframe Following Catapult Acceleration.

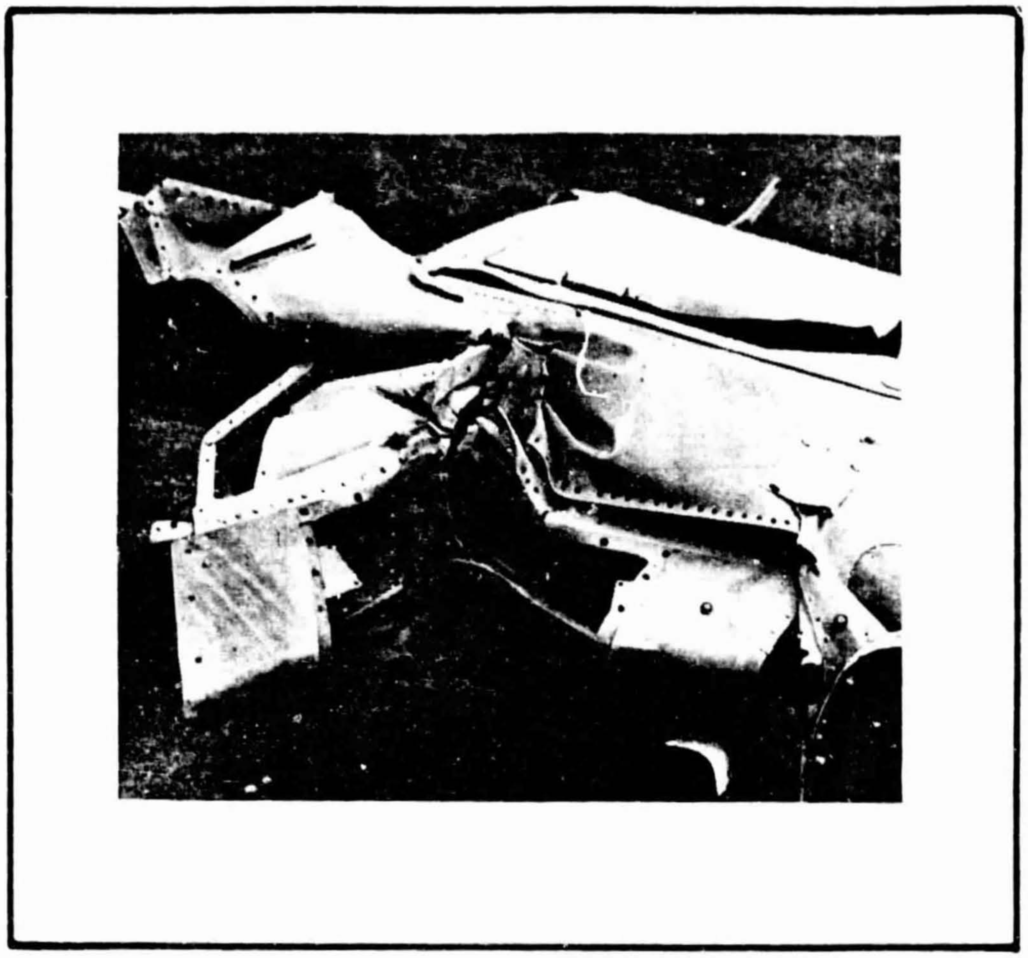


Fig. 4.17. Wing Damage Where a 1-Ply Tank Did Not Leak.

4.5.5 Flight Control Systems

Fourteen technologies as shown in Table 4.15 were evaluated for Airplanes A and B. Here, the integrated, low-cost wing leveler appears attractive for Airplane A (see Table 4.10) but does not appear so for Airplane B. The major difference for the ratings lies in the fact that Airplane A is not equipped with an autopilot while B is. When a similar scenario is offered for Separate Surface Technology, Airplane A's benefits to Pilot Workload and Ride Quality offset the initial cost and DOC penalties. Airplane B, on the other hand, suffers no penalty in costs (autopilot replacement) and smaller benefits in Pilot Workload and Ride Quality.

Table 4.15. Flight Control Systems

Technology (14)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Integrated Low Cost Wing Leveler	39	8
Separate Surface Technology	22	24
Active Stall Prevention	13	16
Direct Lift Control	11	12
Integrated Yaw Damper	3	6
Act Ctls for Relaxed Stability	-0	5
Single Lever Thrust/Drag Control	-3	-3
Fluidic Automatic Flight Controls	-12	-1
Active Ride Smoothing	-14	4
Direct Side Force Control	-14	-11
Active Flutter Suppression	-38	-38
Active Gust Alleviation	-42	-35
Fly-by Wire	-47	-33
Fly-by-Light	-47	-30

*Total number of technologies/lowest FM/highest FM

Active controls, fly-by-wire, and fly-by-light are extremely unattractive due to cost, where the flight environment considered for Airplane A and B (low cruise speed) does not take full advantage of the benefits available to aircraft with high cruise speeds.

4.5.5.1 Fly-By-Wire. This technology is considered to be fairly well developed but very costly. Papers presented at an AGARD Conference in 1974 (Ref. 25 and 57) noted then that the methods of designing a fly-by-wire (FBW) system were well understood but that safety considerations alone (without regard for certification requirements) cause the systems to be very complex and expensive. The economic justification for such a system is very much dependent on the aircraft mission. Hence it is difficult to visualize their incorporation into the GA fleet within the next ten years, especially when one considers the availability and cost of maintenance for such systems. Some points regarding such a system deserve mention, however. For example, the integration of FBW is considered mandatory if and when active flight controls prove economically justifiable. Such flight controls include those designed for relaxed longitudinal static stability, gust alleviation, and flutter suppression. All of these technologies promise weight savings and improved operational efficiencies which lower direct operating costs (DOC) for commercial air transport. An intriguing research program which is currently being pursued by the NASA/Langley Research Center together with Princeton University involves Langley's Digital Avionics Research system (DARE), and Princeton's Avionics

Research Aircraft (ARA). The ARA is a fully instrumented, five-degree-of-freedom, FBW, low-wing, single engine GA aircraft. This vehicle, which has already been used to investigate flying qualities, human factors, and control, will be used with DARE to expand on the above investigations as well as those dealing with advanced digital control concepts (Ref. 45).

4.5.5.2 Fly-By-Light. This technology complements the capabilities and possible active controls applications of a FBW system because of the following characteristics attributable to fiber optics:

(1) Quicker data transmission than possible with wires.

(2) Large bandwidth capability offers the potential for replacing several wires with one fiber.

(3) Fibers are non-inductive and non-conductive.

(4) Provides better signal isolation than wires by decreasing "crosstalk."

(5) Does not present either electrical or fire hazards.

However, fly-by-light (FBL) systems represent a somewhat significant cost penalty over FBW systems. As such, their integration into the general aviation fleet appears even more remote than FBW systems. At the same time, it should be noted that Bell Helicopter has logged several hundred flight test hours on their Model 206 equipped with a fiber optic yaw SCAS which includes an optical encoder, fiber optic link, and an optical receiver and decoder. Bell also employed five complete fiber optic systems in the control of the swashplate of an iron bird configuration

demonstrator. In this configuration, failure of three systems still allowed control authority over the main rotor.

4.5.5.3 **Active Gust Alleviation.** **This technology could offer potentially large performance benefits resulting from reduced structural weight for those high speed aircraft which operate out of short fields on the order of 610 m (2000 ft). These aircraft will require relatively low wing loadings on the order of 1.9 kN/m^2 (40 lb/ft^2), and structural weight penalties may be incurred when decreased field length capabilities are sought.** Active gust alleviation holds promise for configurations subjected to gust load factors on the order of five or above. When integrated to reduce structural weight (and strength), however, the system becomes safety-of-flight critical and requires costly redundancies and certification testing. A unique passive system for single engine GA aircraft is described in Reference 173 where auxiliary aerodynamic surfaces were attached to a Cessna 172 to sense angle-of-attack and drive the flap system through a direct linkage. Although this system successfully attenuated gusts up to 3 m/s (10 fps) in the frequency range between that of the phugoid and short-period mode, it did so at the expense of reducing C_{m_α}. Consequently, further studies where a linkage to all of the controls can be investigated appear warranted. An important point to be made here is that gust alleviation becomes attractive when significant structural weight savings can be realized. Since these savings usually represent the elimination of penalties incurred through strength requirements which are dictated by adverse gust loads in cruise, any system or technology which increases $C_{L_{max}}$ of a wing (and thereby allows for higher W/S) will probably be more cost effective for the low-speed GA fleet. Active gust alleviation is not expected to offer quantifiable benefits to either Airplane A or B due to the relatively low cruise speeds (low gust factors) of these vehicles.

4.5.5.4 Active Ride Smoothing. This technology is differentiated from that of active gust alleviation in the sense that this system does not provide for reduced structural weights. As such it is not safety-of-flight critical.

Primary benefits result from improved handling qualities and ride comfort. Reference 34 suggests that additional cost penalties for a commercial transport would be approximately 2% to 5% of total testing and certification expenses of a new vehicle with an integrated system. Retrofit of the system would incur higher cost penalties. Feasibility studies using a deHavilland DH6 have been performed and indicate that total system weight should not exceed 2% of the aircraft's gross weight while total power requirements would not exceed 0.3% of total engine power. However, an effective ride smoothing system will require relatively large direct lift and side force surfaces located near the aircraft center-of-gravity (Ref. 34). No major reliability or maintenance problems are forseen.

For the present evaluation, both Aircraft A and B will incur cost penalties in exchange for improvements in ride and handling qualities.

4.5.5.5 Active Flutter Control. This technology's attractiveness is dependent largely on the amount of weight which could be saved at the expense of torsional stiffness. When short haul airplanes with their attendant low W/S and high AR are considered, advocates of active control point to wing structural weight savings on the order of 40% attributable directly to gust alleviation systems. This weight savings, however, may reduce torsional stiffness and flutter speed, and mandate active flutter control systems.

GA aircraft, on the other hand, already operate at low W/S and relatively low cruise speeds. As AR is increased, more attention will have to be focused on problems associated with aeroelastic phenomena such as flutter. Active flutter control is attractive when otherwise realizable structural weight savings result in an unacceptable degradation of torsional stiffness.

For the present evaluation, both Airplane A and B are presumed to possess sufficient torsional stiffness to negate a requirement for flutter suppression. As with active gust alleviation, this system is safety-of-flight critical since its anticipated use would be to reduce structural weights by reducing aerodynamic loads. It must be realized that the evaluation ratings will change considerably if an unanticipated increase in torsional stiffness is required as a result of increases in aspect ratio.

4.5.5.6 Active Controls for Relaxed Inherent Stability. This concept holds promise for reduced DOC through reduced fuel consumption. Like all active control systems, however, it poses very high penalites in terms of front end (purchase) costs. Unlike gust alleviation and flutter suppression, where aerodynamic efficiencies result from decreased structural weights, this technology offers a direct payoff by allowing for reduced drag resulting from relaxed (natural) stability constraints. This is achieved by sizing the tail to meet control constraints instead of stability constraints and usually results in smaller tails with decreased (parasitic) downloads when the main (forward) wing is moved forward. Results from studies of medium and heavy commercial transports were very promising. Reference 107 showed that in the case where takeoff gross weight was kept constant, either payload was increased by 15% or range was increased by 20%. Reference 144 noted that in the case where the mission (payload and range) was kept constant, relaxed static stability could yield a 10% reduction in gross weight and a 5% increase in cruise L/D. Reference 118 notes that a study involving the NASA Jetstar airplane, where active gust alleviation and relaxed static stability were investigated, showed tail surface areas reduced by 40% and fuel consumption reduced by 21%. This latter example should be interpreted with caution, however, since the effect of the gust alleviation system was to allow for a substantial decrease in wing sweep with an increase in AR form 5.3 to 9, which in itself offered a significant improvement in L/D.

4.5.5.7 Integrated Yaw Damper. Yaw dampers typically are employed on high altitude, high speed airplanes, although they also may be applied effectively for yaw damping at low speeds in general aviation aircraft. Typically, they may be employed whenever a poorly damped dutch roll mode attributable to low values of the yaw damping derivative C_{n_r} are encountered. The integration of this type of system is difficult with present autopilots, however, because yaw damper functions are typically fed back to the GA pilot through the controls as annoying distractions, usually during the approach-to-landing phase. This may lead pilots to turn the system off at a time when they need it the most. Hence, a system integrated through separate surface technology where the pilot receives no feedback and system failures do not result in critical situations appears attractive. Yaw dampers will allow aircraft vertical control surfaces (rudders) to be optimally sized for particular flight conditions while retaining superior handling qualities over the aircraft's entire flight envelope.

4.5.5.8 *Integrated Low Cost Wing Leveler*. Bergey notes that an automatic and low cost wing leveler that does not depend on auxiliary power would be extremely valuable to the GA community (Ref. 18). While investigating inflight airframe failures for the period 1966-1975, Stapleford (Ref. 197) notes that a lack of spiral stability is probably a key factor in determining the frequency of loss of control. Two flight test programs (one by the FAA using a Beech Debonair A-33 and one by NASA using a Mooney M20) clearly demonstrated the serious problems encountered by a non-instrument-rated pilot who ventures into IFR conditions. Stapleford goes on to note that the absence of any airframe failures by the Mooney M20 during the ten years investigated and encompassing over six million flight hours points clearly to the benefits of a wing leveler. (The M20 was equipped with a wing leveler as standard equipment.) The attractiveness of a wing leveler, then, is predicated on enhancing spiral stability and reducing the potential for airframe failures resulting from recovery procedures (or lack of them) from unusual attitudes. Under more favorable flight conditions, a wing leveler still offers significant benefits in reduced pilot workload.

At present, there is a low cost (≈ $100) fluidic system available to the GA community. Also, a separate surface system retrofitted to a Cessna 172 has been satisfactorily demonstrated (Ref. 176). For the evaluation at hand, data on forecast autopilot use appears to indicate that half the aircraft in Airplane A's category will have autopilots, and almost all new commuters (Airplane B) will be so equipped. Hence, it will be arbitrarily assumed that Airplane A does not have a basic autopilot and that Airplane B does.

4.5.5.9 Separate Surface Technology. This technology has particular significance to the GA community due to the nature of controls (reversible) incorporated by most single engine and commuter airplanes. In such systems, autopilot functions are mechanized by tying a servomotor into the primary surface cable controls. Hence, all autopilot functions are fed back to the pilot and, with the system off, stability augmentation capabilities which may be incorporated into the autopilot are lost. Separate surface technology, on the other hand, can provide continuous wing leveler and yaw damper functions with appropriate wash out circuits incorporated so as not to interfere with pilot control, and hence remain totally transparent to the pilot. An autopilot function could also be incorporated which, too, would be transparent. Such a system (SSSA) has been flight tested in a Cessna 172 in a wing leveler mode and a Beech M99 in a three axis autopilot attitude command mode with excellent results. Costs of such a system are expected to be similar to present autopilots, with improved safety. Hard-over failures result in the pilot flying the aircraft in an out-of-trim condition with no requirement to override an autopilot servomotor since one is not tied to the primary cable system. References 175, 176, 181, and 182 provide more details on SSSA, and Reference 20 notes that the development of samarian cobalt motors makes SSSA appear even more attractive. It should be noted that SSSA has recently been incorporated into the GA fleet in the form of a yaw damper on the Mitsubishi Diamond I. As with the wing leveler evaluation, Airplane A is considered to not have an autopilot while Airplane B does.

4.5.5.10 Direct Side Force Control. The primary application of this type of system would be to augment active ride smoothing systems. Lapins and Jacobson (Ref. 119) noted that side force controllers are more effective than rudders alone in alleviating the effects of turbulence through active ride smoothing systems.

This same requirement was noted by Conner and Thompson in Reference 85. When used for ride smoothing, such a system will not be considered safety-of-flight critical. Still, heavy cost penalties are expected for both Airplane A and B, although Airplane B should benefit considerably through greater passenger satisfaction in what promises to be a more turbulent flight environment.

4.5.5.11 Direct Lift Control. Several applications of direct lift control (DLC) are envisioned, and all are mechanized through spoilers. In the more sophisticated systems, DLC will be required for ride smoothing in order to offset vertical loads. In some large commercial aircraft, DLC may be required for adequate flight path control as W/S is increased. When such a system was employed in the Redhawk (modified Cessna 172), more precise, easier, and apparently safer approaches resulted since flight path angles could be controlled without changing aircraft attitude. Likewise, landing ground roll can be reduced substantially in those cases where the approach path is constrained by obstacles. This would allow descents beyond the obstacle without a requirement to lower the aircraft nose and increase airspeed. Also, when the spoilers are maintained in a partially deployed configuration, a more conventional approach may be flown at higher airspeeds without incurring a landing performance penalty. This latter application promises improved safety since a greater airspeed stall margin can be maintained.

4.5.5.12 Single Lever Thrust/Drag Control. The use of spoilers to control flight path angle during approach to landing is known to improve the landing performance of most pilots. When such a system is mechanized through the throttle, pilot workload is reduced both during the approach and during any required go-arounds. Improvements in reduced pilot workload were noted even in the case where the throttle lever retains its individual function but has the DLC spoiler control mounted on it as a thumb wheel (as was done on the Redhawk).

It should be mentioned that single lever thrust control alone offers promising advantages in reduced workload. Teledyne Continental Motors has incorporated a governor into a single lever control which effectively combines the functions of throttle, mixture, and RPM. This system, although not yet in production, has undergone over three years of development and is presumed ready for production. In its present configuration, the throttle is used to set RPM, and the governor mechanization acts to control manifold pressure and fuel flow.

4.5.5.13 Fluidic Automatic Flight Control Systems. The fluidic three axis system designed for NASA by Honeywell and subsequently flight tested in an Aero Commander 680 FP showed excellent reliability and functioned very similarly to conventional autopilot systems (Ref. 222). Altitude hold, however, was degraded above 1,830 m and power recovery of the fluidic servo amplifiers was only 40%. Yet, systems such as these demonstrate a clear capability for further developemnt. The continuing decrease in the cost of microprocessor logic, however, has done much to offset the initial advantages of lower cost and high reliability attributed to fluidic systems. On the other hand, developments in low-cost fluidic sensors such as the low speed airspeed indicator, the vortex rate sensor, and fluidic stall sensor, offer significant benefits at reduced cost. One of the most advantageous systems to result from efforts in fluidics was a wing leveler which incorporated a laminar flow proportional fluid amplifier with a very high signal-to-noise ratio that was developed by NASA Langley personnel.

4.5.5.14 Active Stall Prevention. This technology offers great potential for reducing stall/spin accidents. Work by Chevalier where a spoiler is added to the lower surface of the horizontal tail to prevent the attainment of the stall angle-of-attack (Ref. 29) appears encouraging. Since it appears that a significant number of stall-related accidents occur in airplanes which are not euqipped with artificial stall warning systems (Ref. 49), the need for an effective stall warning/prevention device appears well justified. Several warning concepts (stick shaker, audible horn, visual angle of attack indicator) are technologically mature. Of these, the stick shaker appears to be the most effective. The possibility of incorporating a stick pusher also appears attractive.

One detraction to active prevention systems lies in their accurate operation. Although the incorporation of active prevention in light GA single engine aircraft appears warranted, the question of degraded control authority below the stall angle-of-attack

detracts from the otherwise undisputed utility of such a system. Cost appears to be another possible detraction. In order to achieve widespread acceptance, such a system must either be mandated or offered at very low cost.

3.5.6 Information Systems.

Eight technologies were evaluated under this grouping and are shown in Table 4.16. As illustrated, Digital Data Links, Integrated Avionics and Displays, and Systems Status Displays are all fairly attractive technologies. The Micro HUD, although presently reflecting no benefit to the user, deserves mention here. This system, discussed further in Section 4.5.6.5, promises to provide all HUD functions without either a CRT or the associated optical system. Presently, its main penalty lies in cost. Widespread use of such a system could drive costs down significantly and make this technology extremely attractive.

4.5.6.1 Digital Data Links. This concept entails the communcation of data (which is presently rendered verbally) between the airplane and various agencies in a digitized format much as present data links are used for encoding altimeters. Three types of systems are addressed in this section. The Digital Data Broadcast System (DDBS) is intended to provide RNAV systems with information required to satisfactorily navigate both preplanned direct routes and "whatever charted routes which are retained as an integral part of the ultimate area navigation environment" (Ref 97). Data would be broadcast in repeating data streams for specified station or route coverage and would be accessed by tuning in the appropriate VORTAC frequency. It should be noted that this system would marry RNAV to the existing VORTAC route structure instead of providing the more flexible option of inputting geographic coordinates. The present status of this system is unknown, and the last time it appeared in the literature used in the present research was in 1976 (Ref. 97).

Table 4.16. Information Systems

Technology (8)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Digital Data Links	33	38
Integrated Avionics and Displays	32	42
Systems Status Displays	25	25
CRT Displays	11	21
Micro HUD	2	2
Laser Gyros	-16	-14
Heads Up Displays	-23	-24
Fiber Optics (Data Trns)	-26	-23

*Total number of technologies/lowest FM/highest FM

The second system to be discussed here is the Discrete Address Beacon System (DABS), which formed a significant aspect of the upgraded third generation ATC system (UG3RD) as discussed by the DOT Air Traffic Control Advisory Committee in December 1969.

This system has continuously appeared in the literature and receives further attention in a report prepared as part of the 1979 Summer Faculty Fellowship Program in Engineering Systems Design (Ref. 148). As discussed in that reference, DABS will accommodate the following information between the aircraft and its ATC environment:

(1) Clearances.

(2) Runway surface winds to include wind shear and wake vortex information.

(3) Weather information.

(4) Minimum safe altitude warning.

(5) Confirmation of assigned altitude.

(6) Automated Terminal Information Service (ATIS).

(7) Runway Visual Range (RVR).

(8) Holding instructions.

(9) Approach and departure clearance.

(10) Conflict alert and resolution instructions.

(11) Instructions as to proper heading, speed, altitude, and the time to execute the ATC instructions.

The third system to be discussed is the Automatic Communication and Reporting System (ACARS), which is used in conjunction with existing VHF radio equipment and allows for both voice as well as digitized information communication to enhance air-ground operational control communications. Although this type of system has been available for ten years, it has not been implemented as rapidly as hoped due primarily to its $5,000 price tag (Ref. 148).

It appears significant at this time to point out that studies of future ATC environments point to a congested environment as a very real possibility, and this suggests that the pilot could well become saturated with communications functions alone. At a NASA-sponsored Avionics and Controls Research and Technology Workship (Ref. 147), the team discussing "General Aviation and Short Haul" recommended that a principal focus for research is suggested to:

(1) Minimize or eliminate the requirement for communication (talk) to as great an extent as possible.

(2) Allow IFR flights of the future to be performed as easily as VFR flights are today.

In view of this observation/recommendation, DABS appears to offer the most significant benefits of the three systems discussed. It should be noted that DABS is crucial to the Intermittent Positive Control (IPC) conception for Collision Aviodance Systems (CAS). A basic DABS unit may be expected to cost about the same amount as present transponders ($750) or $2000 with an IPC display (Ref. 97).

For the present evaluation, both airplanes are presumed to already be equipped with encoding altimeters but are penalized for the IPC display. Substantial benefits in improved pilot workload and safety are realized.

4.5.6.2 Cathode Ray Tube (CRT) Displays. CRT displays may be evaluated against mechanical, conventional instruments, or against other electronic displays. For purposes of this evaluation, they will be evaluated against the former because other electronic systems are not envisioned to be competitive from a cost standpoint.

Still, some discussion appears warranted for various electronic display methods. The following data of 1975 vintage is condensed from Reference 196 and shown here as Table 4.17.

Table 4.17. 1975 Characteristics of Some Electronic Displays

System	$/Character	Volts/Panel
CRT	< 1	10,000-25,000
Plasma Panel	< 3	100
LED	< 4	
LC		< 6

The display application also needs to be addressed and is summarized in Table 4.18 in terms of their 1979 status.

The versatile capabilities and low cost of the CRT tend to more than offset its disadvantage of relative size and high voltage, although the latter can pose a safety problem. A flat panel CRT, developed by Northrop for the Army and whose rights were subsequently sold to Texas Instruments, greatly reduces the problem of size but was found to be prohibitively expensive due to high manufacturing costs (Ref. 219). Present CRT's rely on a $130 million annual market in computer terminals (which is doubling every three years) to offer very low costs. Indeed, one source

(Tannas, Ref. 219), suggests OEM costs of $9.00 for black and white units and $36.00 for color in very large quantities. When present CRT capabilities are used as a baseline, the relative performance of other electronic displays in six major problem areas may be briefly tabulated as in Table 4.19.

Table 4.18. Electronic Display Technology Perspective

Display Application	Available	In R & D
Discretes, Meters, & Legends	Electromechanical Galvanometers Incandescent Light Emitting Diode	Liquid Crystal
Alphanumeric	Cathode Ray Tube Electromechanical Incandescent Light Emitting Diode Liquid Crystal Plasma	Chemoluminescent Electrochromic Electroluminescent Electrophoretic Ferroelectric
Vectorgraphic	Cathode Ray Tube Plasma Panel	Electroluminescent Light Emitting Diode Liquid Crystal
Video	Cathode Ray Tube	Electroluminiscent Ferroelectric Laser Liquid Crystal Plasma Panel

(data from Reference 219)

Armed with this background information, CRT's are evaluated now against their mechanical conventional counterparts. These systems offer reduced pilot workload in that scanning tasks can be

Table 4.19. Six Major Display Problem Areas & Their Impact on New Technologies

(X designates problem with respect to current CRT)

	Light Emitting Diodes	Plasma Discharge	Flat CRT	Electro-luminescence	Liquid Crystal	Electro-phoretics	Electro-chromics
Luminous Efficiency	X	X					
Matrix Addressing					X	X	X
Duty Cycle		X			X	X	X
Uniformity/ Gray Scale	X	X				X	X
Full Color	X	X		X		X	X
Cost (including Electronics)	X	X	X	X	X	X	X

(data from Reference 219)

reduced from a 22 cm (9 in) radius about the artificial horizon to 6.4 cm (2.54 in). This, of course, implies an integrated avionics package capable of providing continuous systems monitoring and, inherently, warning-by-exception. Since the CRT's eliminate mechanical flags, etc. (as many as five or more in an integrated attitude director) reliability will be increased. (One avionics manufacturer indicated that possible sticking needles and flags on a production ADI were corrected through the incorporation of servomotors to drive the flags.) For those airplanes using remote mounted avionics, substantial weight savings can result by reducing the number of signal paths.

Both Airplane A and B should receive significant benefits in reduced pilot workload and safety. (Recall that a display device is essential to DABS/IPC implementation.)

4.5.6.3 Heads Up Displays (HUD). HUD systems offer the potential for reducing pilot workload during approaches to landing under both VFR and IFR conditions. Currently, they display information such as course guidance, airspeed, angle-of-attack, altitude, etc., via a CRT through a lens system/combining screen which collimates the display on the aircraft windscreen. Thus the pilot may devote his attention to external cues from his landing environment and still receive flight data without having to redirect (and re-focus) his attention to within the cockpit. Associated with this capability, however, is the problem of cost. HUD systems are envisioned to cost on the order of $25 to $45 thousand for GA applications while they may cost several $100 thousand in military applications. Other data which tends to detract from HUD implementation are the observations that:

(1) At the NASA-sponsored General Aviation Avionics Workshop, no general agreement could be reached on the question of whether HUD studies for GA should be pursued (Ref. 196).

(2) A USAF study concerning the use of HUD's as a primary instrument reference in the A-7D, F-15, and F-111D in 1976 resulted in mixed responses from 123 pilots on the question of using HUD's during approach to landing. Although a significant majority of A-7D and F-15 pilots said the HUD enhanced IFR operations, only a small percentage preferred its use during approaches. Most F-111D pilots preferred not to use the HUD for normal operations where weapons delivery was not involved (Ref. 15). The major complaint of the USAF pilots was that erroneous information could be displayed without warning.

For both Airplane A and B, improvements in pilot workload and safety were offset by penalties in maintenance cost, empty weight, reliability, and purchase price.

4.5.6.4. Micro HUD. A micro HUD, developed by Bell Helicopter Textron, offers HUD capability at an anticiapted 50% of the cost of regular HUD's. Although this cost penalty is still significant for GA, the system merits discussion due to its unique implementation. The system uses a micro-processor to drive a fiber optic symbol generator which presently has the capability to generate a large range of dynamic symbols and numbers. (When the signal generator was viewed during July 1979, the microprocessor was not fully implemented and consequently only a limited set of symbols were generated. This generator is illustrated in Figure 4.18.) The most unique aspect of the system however, lies in the absence of the large and heavy optical system required of conventional HUD's. This system uses a pair of eyeglasses with a minute mirror centered in the eyepiece as shown in Figure 4.19. Signals are transmitted to the glasses via a fiber optic bundle and collimated to display images as shown in Figure 4.20. Two similar systems are currently being tested by the Army.

The benefits of this system over conventional HUD's lie in the elimination of (1) the high voltage and higher power requirements of a CRT, and (2) the elimination of costly and heavy associated optical equipment.

Although the same benefits for the HUD were credited here, severe cost penalties were also awarded on the basis of an estimated $20,000 price tag, which could not be supported by either Airplane A or B.

4.5.6.5. Systems Status Displays. Comprehensive engine health monitoring is significantly absent in present GA aircraft and, consequently, pilots are confronted with having to derive this information from existing displays (when sufficient raw data is available). The current DAAS system promises to rectify this situation by sensing:

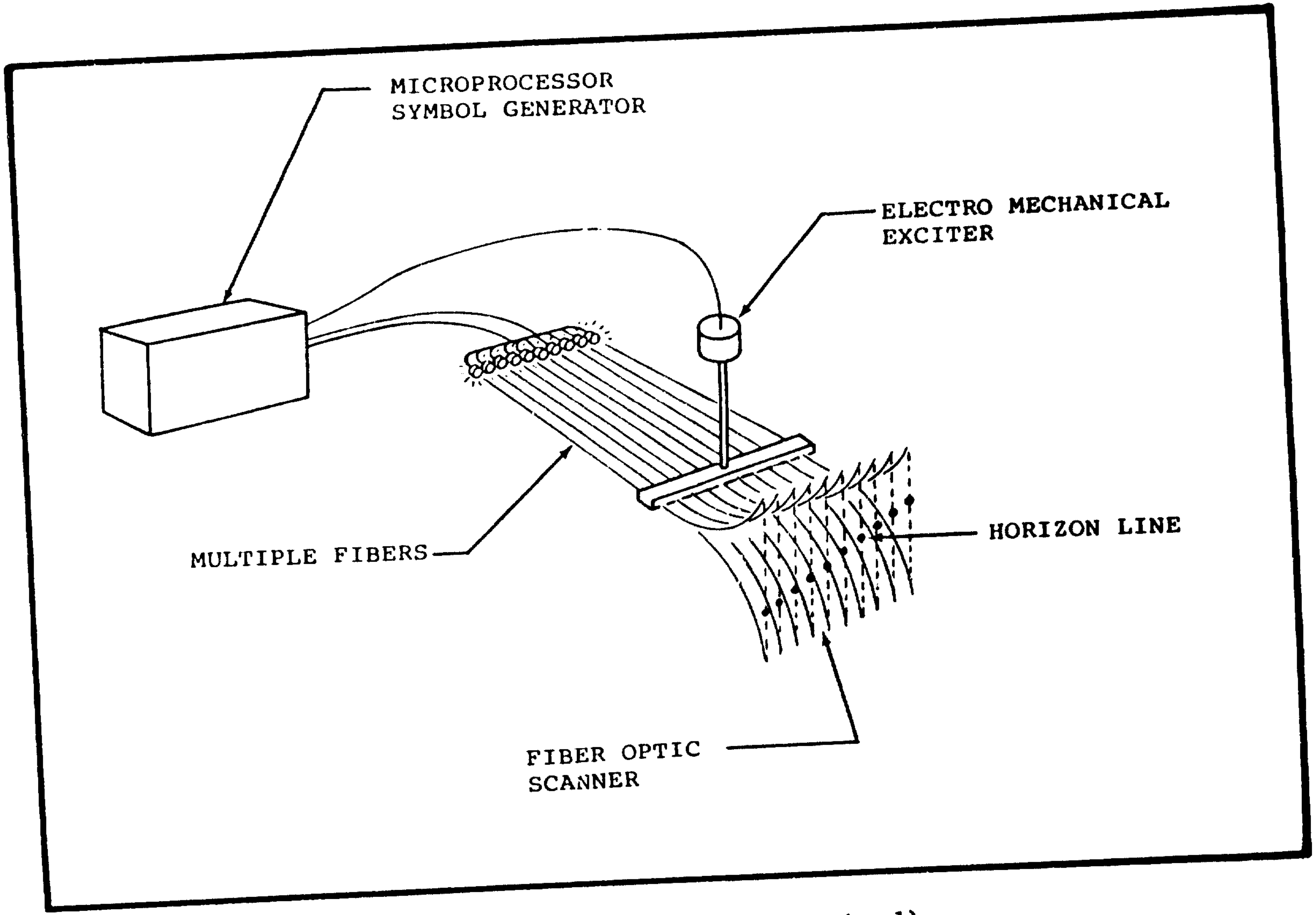


Fig. 4.18. Preliminary Fiber Optic Symbol Generator (Operational)

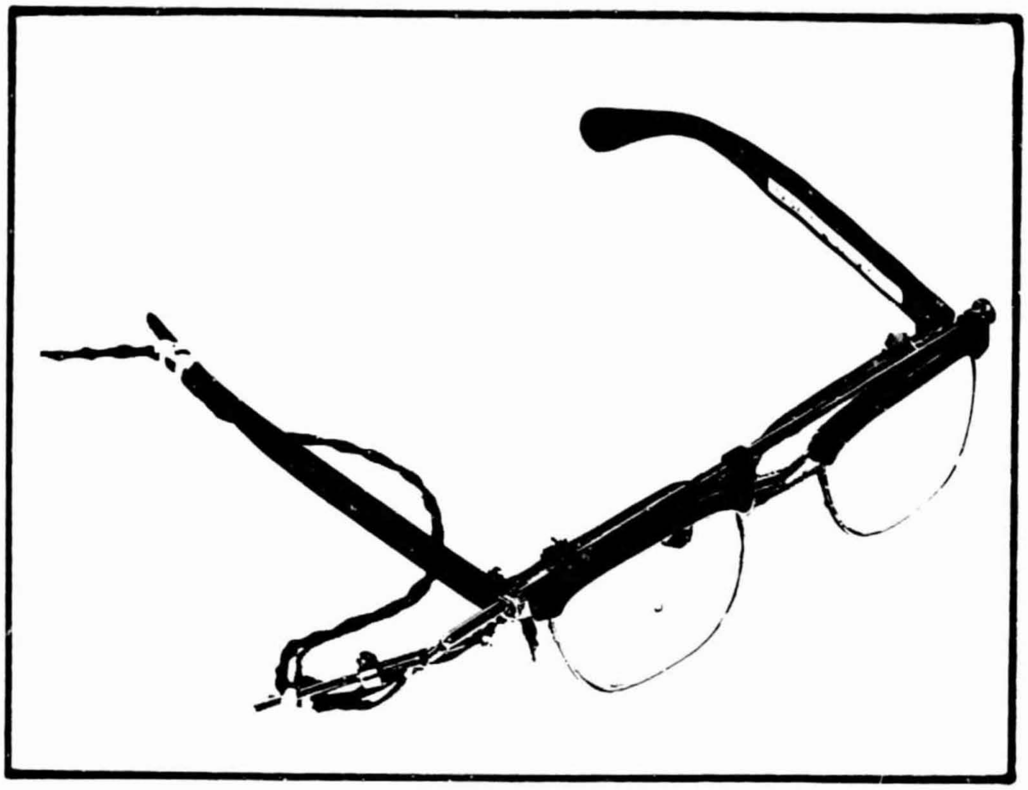


Fig. 4.19. Micro HUD with Fiber Optic Link and Mirror.

(1) Manifold pressure

(2) Engine RPM

(3) Fuel Flow

(4) Fuel Quantity

(5) Oil Temperature

(6) Oil Pressure

(7) Cylinder head temperature for each cylinder

(8) Exhaust gas temperature for each cylinder

(9) Exhaust gas oxygen for each cylinder

(10) Cowl flap position

(11) Auxiliary fuel pumps

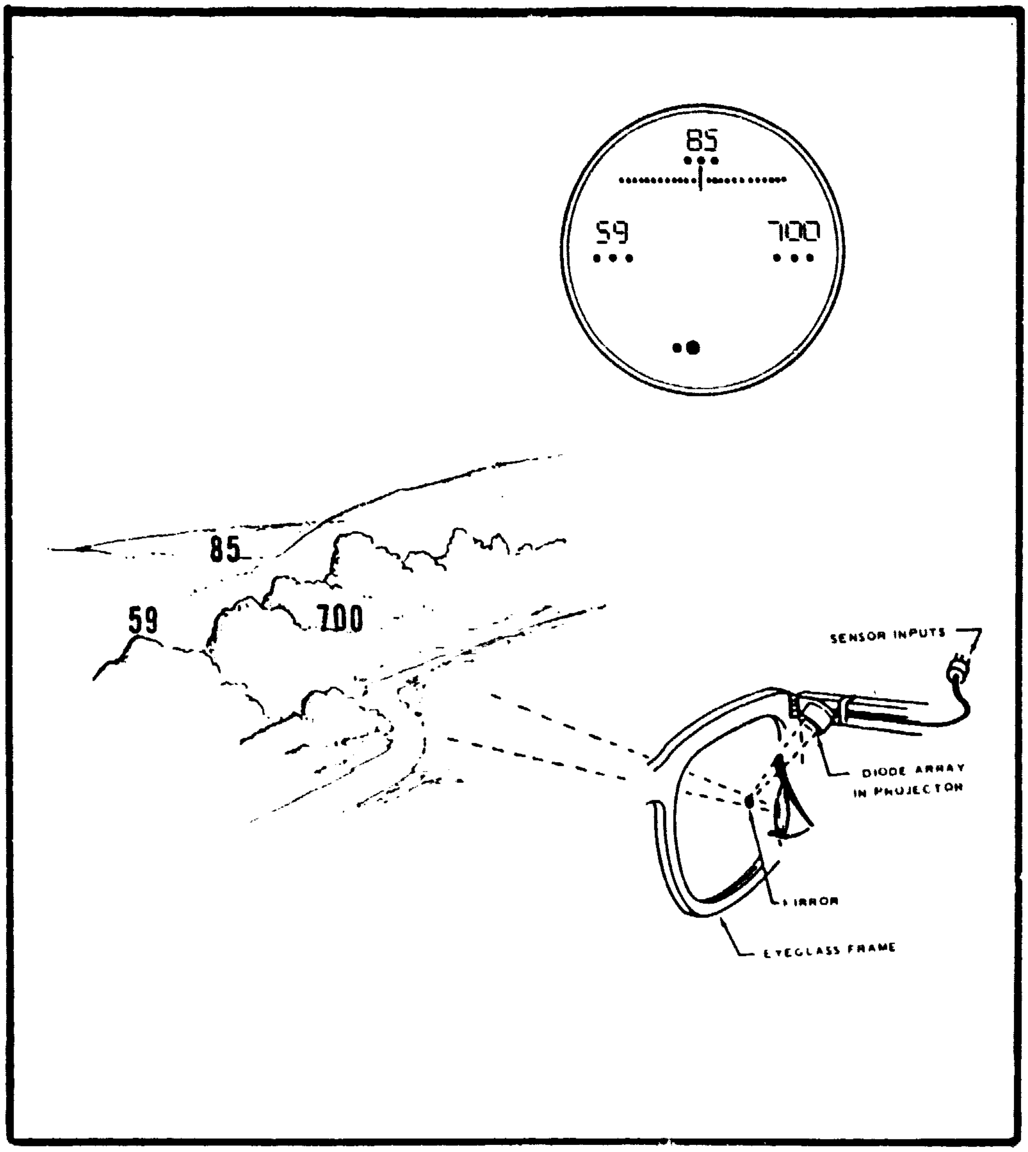


Fig. 4.20. Micro HUD Image Display.

plus numerous other aircraft system parameters. This system will alert the pilot to any critical out-of-tolerance condition and advise corrective action in some cases. It also presents commands to the pilot for setting the mixture lever (Ref. 39). Such enhanced capabilities do much to relieve the pilot from scanning and provides warning signals on an exception basis. The incorporation of an annunciator of some sort appears warranted for such a system, and it is noted that Princeton's Avionics Research Airplane (ARA) is so equipped. Reference 31 points to integrated multifunction displays as having the highest priority of ten equipment disciplines for NASA funding/study. This report (done in 1974) identifies a desired or expected purchase price of such displays at $500-$1500 for a single engine airplane and $3000-$7000 for a turboprop system.

When sufficiently integrated, system status displays promise more advanced warning of possible engine failures, more information to assist in selecting optimal power settings, and reduced pilot workload. Engine TBO's may have the opportunity for being improved through better engine management on the part of the pilot. These benefits appear to apply equally to both Airplane A and B.

4.5.6.6 Integrated Avionics and Displays. This concept has received considerable interest and publicity over the past decade, due largely to the anticipated effects of increased air traffic congestion and the attendant increased pilot workload associated with a more restrictive flight environment, particularly under single-pilot IFR operations. NASA efforts to identify and develop an orderly investigation involving industry, educational institutions, and other agencies, are reflected in the Langley-sponsored Avionics and Controls Research and Technology Workshop (Ref. 147) and the 1979 Summer Faculty Fellowship Program in Engineering Systems Design which was co-sponsored by ASEE (Ref. 148).

Ames efforts have been centered on the Advanced Avionics Systems studies which recently resulted in a Honeywell/King Radio contract in August 1978 to design and build a Demonstration Advanced Avionics System (DAAS) which will eventually be flight tested in a twin engine aircraft. Highlights of this program include several studies and a workshop as follows:

(1) An ATC environment forecast (Ref. 97).

(2) An electronics technology forecast.

(3) A GA advanced avionics workshop (Ref. 196).

(4) Preliminary Candidate Advanced Avionics Systems (PCAAS) study contracts to Southern Illinois University (Ref. 133) and Systems Technology Incorporated (Ref. 208).

(5) In-house efforts at Ames investigated, among other things, different low-cost options to solve navigation algorithms and to define a low-cost option to gyro sensors.

Interesting results to number five above involve the incorporation of a phase-locked-loop to enhance VOR scanning capabilities and the incorporation of magnetometers to solve the attitude sensing problem. Preliminary results comparing INS data with derived data using magnetometers is presented in Figure 4.21.

Under the present contract, the Honeywell/King DAAS effort will incorporate the following functions (Ref. 39):

(1) Automated guidance and navigation using VOR/DME navigational facilities.

(2) Flight planning.

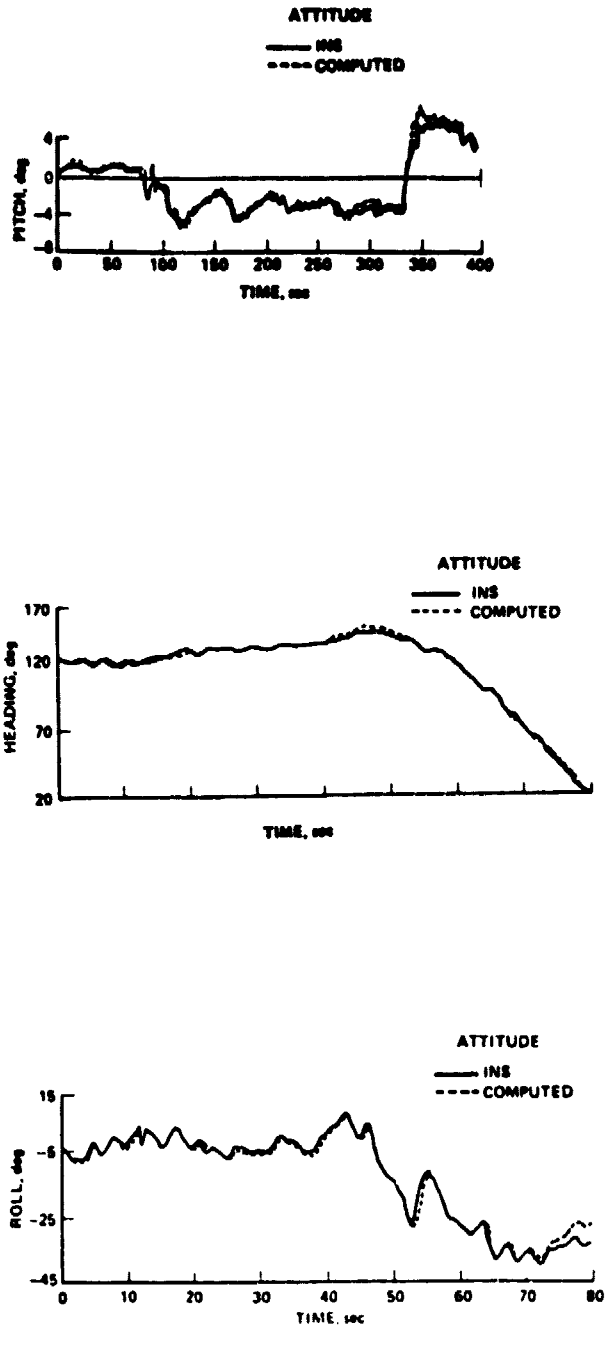


Fig. 4.21. Comparison of Pitch, Heading, and Roll Computations.

(3) **Weight and balance and performance calculations.**

(4) **Monitoring and warning.**

(5) **Storage of normal and emergency checklists and operational limitations.**

Pilot interface with this system is through a touch panel which in turn provides inputs to the Integrated Data Control Center (IDCC). The system is organized around an IEEE 488 bus and includes five microprocessors. Conventional pilot displays are incorporated with the exception of two CRT's. One serves as an IDCC interface with the pilot and the other serves as an Electronic Horizontal Situation Indicator (EHSI) with an electronic map capability. Unfortunately, no cost forecasts for this system were readily available. The STI study (which was dependent on the availibility of a $6000 OMEGA system) penalized an unsophisticated avionics user $4900 for a $13,275 total avionics package and a sophisticated user $13,300 for a $62,645 system. The SIU study, on the other hand, forecast a cost of $23,850 for a full IFR system in a Cessna 402 and $9962 for a single engine new installation. (The STI PCAAS system used cockpit display formats similar to DAAS but with seven microprocessors, and the SIU system replaced all conventional instruments with plasma panel displays.)

It should be mentioned that the GA avionics community is not in total agreement with the single bus architecture, and at least two manufacturers which were visited expressed concern over possible single point failures which would render the entire system either inoperative or unacceptably degraded. On the other hand, the concept of an integrated avionics system with or without the bus structure offers certain advantages which would otherwise be delayed. For example, the powerplant health monitoring capability of DAAS is seen as a major advance over present systems. Here, the advantage of DAAS is that it allows for more types of information to be displayed to the pilot through the IDCC, where present configurations do not allow for either the required panel display space or separate display costs to be efficiently absorbed.

A forseeable spin-off from a system which incorporates microprocessor logic systems lies in the further introduction of these systems into GA aircraft. Certainly, one of the most beneficial applications of such logic systems lies in the electronic control of propulsion fuel systems to allow for more efficient operation. For example, advanced positive displacement engines will almost invariably require a high-pressure fuel injection system where the fuel is injected directly to each cylinder. Such a system will benefit substantially from an electronic control which senses induction air density and modulates as well as times the fuel flow. (This is to be contrasted to low-pressure continuous-flow systems in operation today.) Since the possibility of failure of such an electronic fuel injection system may be unacceptably high, the system could be mechanically driven and only modulated by an electronic logic circuit in order to achieve the highest efficiencies. The fact that DAAS already incorporates a propulsion monitoring function (no control) could lead to a reduction of in-flight engine failures by providing advance warning or indication of impending failure.

4.5.6.7 Fiber Optics for Data Transmission. Fiber optics have the capability to:

(1) Transmit data faster than by wires.

(2) Replace several wires with one fiber since fibers have a larger bandwidth capability.

(3) Function without the inductive or conductive properties of wires.

(4) Retain better signal isolation between fibers than possible between wires.

(5) Function without introducing electrical and/or fire hazards. (Ref. 158.)

However, no appreciable weight savings or benefits may be anticipated for retrofit systems, especially where data transmission rates are lower than one megabyte/sec.

Hence, fiber optic data transmission systems are not envisioned to offer advantages significant enough to justify their cost in the GA fleet.

4.5.6.8 Laser Gyros. These systems, developed by Honeywell, contain no moving parts and sense accelerations by measuring fringe shifts between two laser beams. Reliability is expected to be very high, but costs are expected to be equally high. Hence, their incorporation into the GA fleet is not envisioned at this time.

4.5.7 Navigation Concepts

Six technologies as shown in Table 4.20 were evaluated in this technology group. Microwave Landing Systems appear more attractive to Airplane B than A due to a larger number of IFR terminal operations. Of the three area navigation concepts investigated, none appeared to provide significant benefits. This was due largely to the fact that both airplanes were presumed to already have full IFR capability, and Airplane A was also equipped with an existing RNAV system. The two velocity information sources (Doppler and Inertial systems) were both extremely unattractive to Airplanes A and B.

Table 4.20. Navigation Concepts

Technology (6)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Microwave Landing Systems	9	21
NAVSTAR/GPS	8	8
Loran C	-24	-30
Omega	-26	-32
Doppler Navigation	-37	-40
Inertial Navigation	-53	-57

*Total number of technologies/lowest FM/highest FM

4.5.7.1 **NAVSTAR/GPS.** **This system is a global, satellite-based navigation system being pursued by the U.S. Air Force. Six of the originally-planned 24 satellites are already in orbit (Ref. 148), but Reference 8 indicates that the total number has been reduced to 18, with a planned operational date of 1987 to 1990. This system is extremely attractive to civil aviation because it provides a (forecast) reasonably priced navigation system capable of**

(1) Extreme accuracies in x, y, z and t reference frames.

(2) Area navigation.

(3) Global coverage down to ground level.

(4) Collision avoidance.

When one considers that a general aviation GPS system is expected to possibly cost as little as $2800 (Ref. 1 and 102) to $3600 (Ref. 148) while an RNAV system comprised of 1 VOR, 1 DME and 1 RNAV computer will cost $3700 (Ref. 148) while still being dependent on an ability to receive an acceptable VOR/DME signal, the attractiveness of GPS becomes clearly evident. It should be noted that the VOR/DME/RNAV system described above still cannot provide altitude information, and velocity information is highly dependent upon accurate VOR/DME position fixes which must be differentiated.

Three levels of system accuracy are provided, where the first two are protected by the military. The third, envisioned to remain unprotected for civil aviation use, was recently found to be "too accurate" and consequently will probably be degraded to offer 200 meter (660 ft) accuracies with a 50% confidence level (Ref. 8). In order to realize how accurate GPS is, one should note that tests performed at 6 km (20,000 ft) by a C-141 using either one or both of two satellites which were then in orbit reflected errors on the order of 4 m (13 ft) in x, y, and z (Ref. 1).

It is significant that a GPS-equipped aircraft will never be threatened by a signal-saturated environment because airborne equipment is totally passive, i.e. no signals are transmitted from the aircraft as is the case with DME. When a digital data link is added (Time-Division-Multiple-Access Link) together with a ground-based GPS transmitter, accuracies sufficient for terminal area guidance results, together with a collision avoidance capability.

In view of the above, benefits are expected for both Airplane A and B in terms of safety. Since the baselines for both airplanes include IFR avionics, only minor cost penalties are expected. It should be noted here that the forecast data on costs is considered fairly optimistic and did not appear to be supported by manufacturers. Hence, a penalty of -1 was assessed. If, on the other hand, costs do attain forecast levels, then a +1 might be warranted. In such a case, the figures of merit for both airplanes would be on the order of +24.

4.5.7.2 Inertial Navigation Systems (INS). Inertial navigation provides the attractiveness of a self-contained navigational system. Also, it provides a capability of computing reasonably accurate velocities which normally could not be obtained by other means without enhancement, e.g., ILS signals are too noisy to be differentiated with any confidence (Ref. 155). When INS is used with radio ranging and a Kalman filter, an Aided INS results, which has applicability to short haul transports by providing 4-D or two-segment approach guidance (Ref. 193). However, INS purchase prices are on the order of $100,000 in larger commercial aricraft and are not expected to fall below $30,000 for the GA market (Ref. 97). The Aided INS system is an exception since it is predicated on low cost gyros. Annual maintenance costs are also exorbitant. In a study of relative avionics costs to the user, one investigator penalized INS $9000/year while choosing not to assess such costs against other systems (Ref. 195).

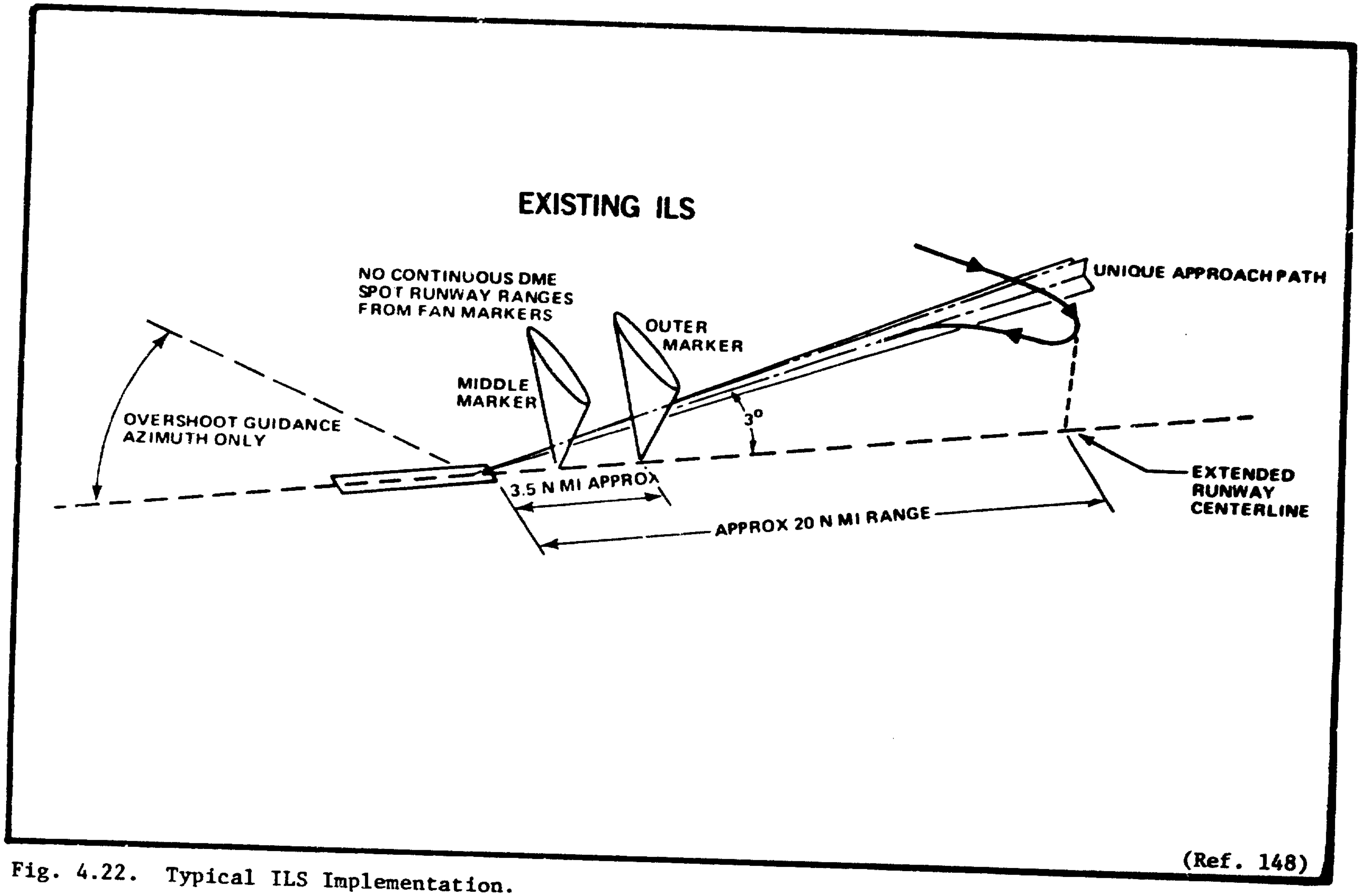
Based on the above, both Airplane A and B will suffer severe penalties with only negligible gains in their operating environment. GPS, for example, can provide global coverage with velocity capabilities for a fraction of the cost.

4.5.7.3 Doppler Navigation. This navigation mode, like INS, is self contained and therefore not dependent on ground based systems. When used in conjunction with current navigation aids such as VOR/DME, it offers the potential for 4-D navigation in the terminal area. Like INS, however, it is an expensive alternative to an augmented GPS terminal environment. In the enroute phase of flight, the differentiation of DME signals when proceeding to/from a DME station or the integration of RNAV capabilities with DME and, say, three VOR stations should provide a satisfactory velocity computation in either the airway or area navigation environment. Certainly, GPS should provide satisfactory velocities in its conventional (unaugmented) mode during enroute flight.

Doppler navigation systems are therefore expected to assess high cost penalites to users where the same capabilities are expected to be available at much lower costs.

4.5.7.4 Microwave Landing Systems (MLS). MLS offers an attractive alternative to conventional Instrument Landing Systems (ILS) due to an ability to handle several aircraft flying at different airspeeds in the approach phase. This capability offers promise even today to the GA aircraft operating in high-density, mixed-traffic, terminal environments. Figure 4.22 shows a conventional ILS profile and Figure 4.23 shows an MLS profile where the advantages of such a system are more obvious. If one visualizes a GA aircraft operating at 40% to 60% the approach speed of larger commercial jets and trying to execute an approach to the same runway as his jet counterparts are, the advantages of the MLS system becomes evident. Certainly, significant savings in fuel expended in the terminal area may be expected, particularly by commuter operations whose flight profiles dictate that larger amounts of their total flight time between refuelings is spent in the approach to landing phase.

Although Madden and Desai (Ref. 130) noted in 1973 that it was possible to track a curved approach path using MLS and DME to accuracies within the resolution of ATC radar, Hoffman and Hollister (Ref. 97) noted in 1976 that pilots expressed a reluctance to:



(Ref. 148)

Fig. 4.22. Typical ILS Implementation.

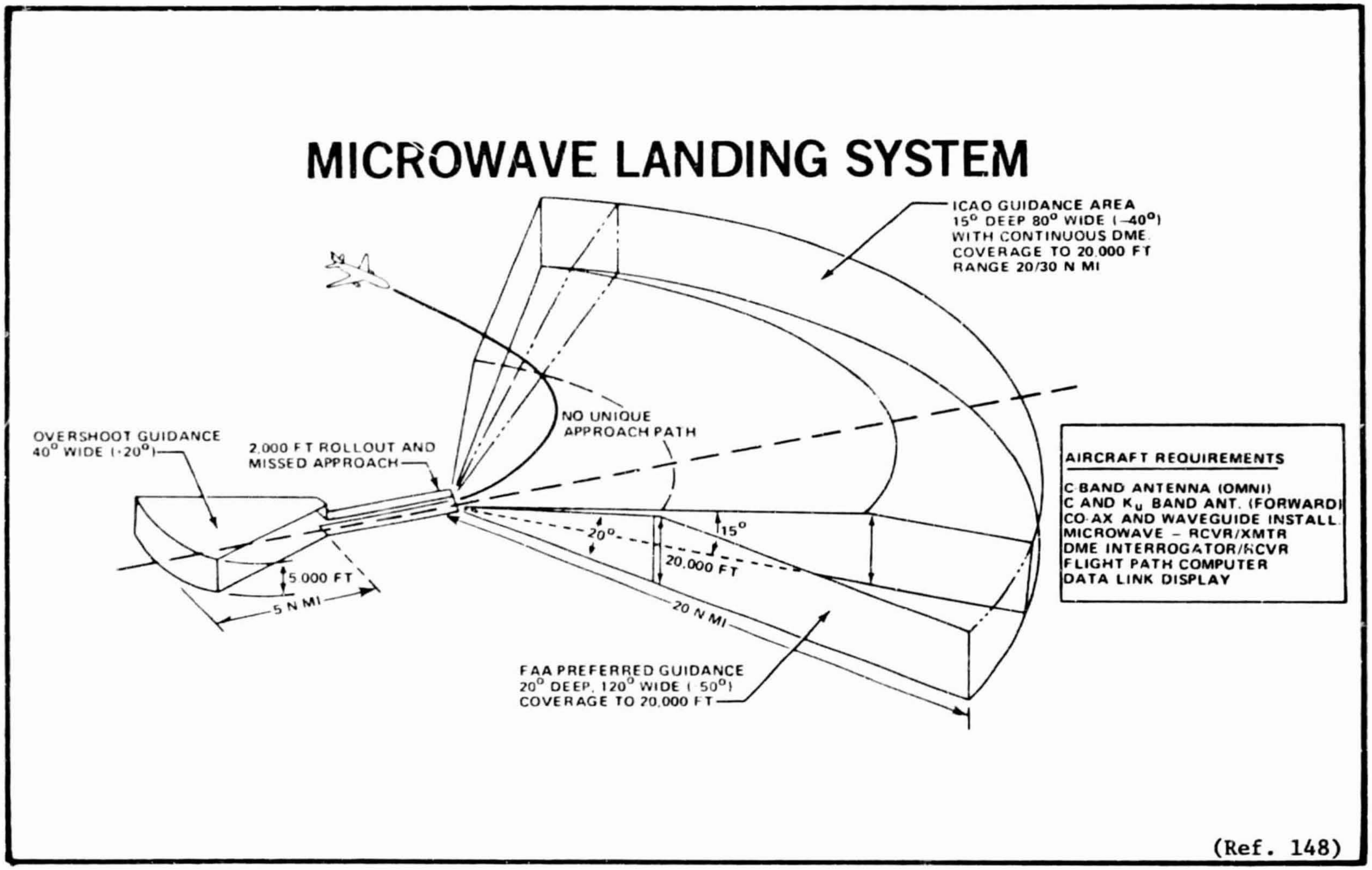


Fig. 4.23. Typical MLS Implementation.

(1) fly steep approaches which do not level off to the more conventional 3° prior to the final flare, and

(2) fly curved approaches beyond the point where the 3° glide slope is intercepted.

A reasonable plan appears to be one where the curved and steeper flight paths are used to within 150 m (500 ft) AGL and a transition is made to a conventional glide slope.

Current ILS systems are characterized by reliability, safety, and efficient service. Probably, its only drawbacks are limited available channels (40, although only 20 are used currently) and performance degradation resulting from terrain irregularities and heavy snow. (Terrain effects stem from the fact that ILS glide slope signals require radiated energy to be reflected from the ground plane.) MLS incorporates a microprocessor as well as a digital data link and costs are forecast to be on the order of $2000 for GA and $34000 for the commercial jet carrier by the year 2000.

MLS on the other hand, offers five times the channel availability and is not affected by terrain features. Also, a spin-off from the versatility of the MLS is that noise abatement procedures can be more easily integrated than under present ILS systems.

Hence, MLS offers improvements in efficient terminal operations and possible noise benefits for some penalty in cost to both Airplane A and Airplane B.

4.5.7.5 **LORAN C. LORAN C is a low-frequency, long-range, all-weather radio navigation system with absolute accuracies on the order of 0.5 km (1600 ft). This accuracy may be improved by a factor of 2 or 3 by implementing more sophisticated user equipment. Use of LORAN is predicated on having velocity information, and this implies either differentiating the LORAN C time difference measurements (TD) or implementing an INS. LORAN provides area navigation capabilities down to ground level, but at present does not have full coverage of the Continental United** States (CONUS). GA user costs for a receiver (without INS) are expected to be as low as $3000 (Ref. 195), while military systems may cost $20,000 (Ref. 148). The receiver unit weighs approximately 11 kg.

LORAN C is being considered as a possible GA navigation aid primarily because it is being considered as a replacement for the present VOR/DME network which is characterized by extremely high operations and maintenance costs. The LORAN C ground-based system costs are expected to be an order of magnitude smaller than the present VOR/DME network.

As presently conceived, Airplane A and B will both suffer cost penalties if LORAN C is implemented. LORAN C does not provide precision terminal guidance, although ILS systems do. In evaluating this technology, the system is considered without an INS. Hence, the cost penalty is not as severe but is traded for deficiencies in reliability and safety.

As this report was being finalized, new information regarding a joint test effort between DOT, NASA and the State of Vermont surfaced. The interested reader is referred to Aviation Week and Space Technology, March 24, 1980, pgs. 51-58.

4.5.7.6 OMEGA. Like LORAN C, OMEGA is a low-frequency, long-range, all weather navigation system. Unlike LORAN, however, it does have complete CONUS coverage. Its greatest deficiency is that of accuracy, and CEP's on the order of 4 km (13,000 ft) are reported in Reference 1. When an accurate INS is integrated with the system, errors on the order of 2 km (6500 ft) are quoted. Consequently, no terminal guidance is provided. Cost for an inexpensive OMEGA system is forecast to be on the order of $3000 (Ref. 195) without the INS. However, it should be noted that 1977 receiver costs were on the order of $20,000 to $59,000 (Ref. 208).

Like LORAN C, this system's attractiveness lies in operational and maintenance costs of ground facilities which may be two orders of magnitude below that of the current VOR/DME network. This is better understood when one considers that only eight stations are used to provide complete global coverage.

For the present evaluation where neither Airplane A nor Airplane B is used over water, OMEGA (without INS) offers penalties in cost and safety.

4.5.8 Noise

The three technologies investigated here are shown in Table 4.21. Quiet, Efficient Propeller technology appears fairly attractive to both Airplane A and B, due primarily to a promise for reduced interior noise. Ducted Propulsors appear attractive to Airplane B due to the maximum scores (+3) awarded for interior and exterior noise and this vehicle's unique flight profile.

Table 4.21. Noise

Technology (3)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Quiet Efficient Propellers	24	29
Ducted Propulsors	- 2	18
Low Level Pressurization	-17	-18

*Total number of technologies/lowest FM/highest FM

4.5.8.1 Quiet Efficient Propeller Technology. The fact that current propellers already operate at efficiencies on the order of 87% may lead one to doubt the existence of significant payoffs in this particular field of endeavor. A review of the literature, however, quickly identifies shortcomings: most of the propellers in use today are based on WW II technology, with appropriate refinements resulting from "cut and try" processes applied to a basic design. More recently, however, the requirements for reduced fuel consumption and noise pollution have led to renewed interest in propeller technology.

NASA efforts to aid in the development of improved propellers are focused in the General Aviation Propeller (GAP) Technology program, with a goal toward reducing fuel use by 8% to 9%, lowering noise by 5 to 10 db, and improving safety. This ambitious program involves propeller and airframe manufacturers, consultants, and several universities.

Essentially, the major problem associated with propellers lies in the fact that they have been traditionally designed for performance, with little regard for noise. As one attempts to reduce noise, penalties in performance and/or weight usually materialize. However, since the propeller produces approximately 85% of powerplant noise, the attenuation of this noise will do much to improve community relations and ride comfort.

A major hurdle in reducing noise lies in its accurate prediction. Succi (Ref. 205) recently reported on the accurate prediction of the sound field using the Ffowcs-Williams Hawkins equation modified for computational simplicity. Having achieved this, he then reported on different means of reducing flyover noise:

(1) Reducing propeller radius by 20% resulted in an 8 dbA reduction with a 4 1/2% loss in efficiency.

(2) Altering the radial load concentration from 80% to 60% by

(a) re-twisting resulted in a 4.2 dbA reduction with a 3.9% loss in efficiency.

(b) changing planform resulted in a 4.8 dbA reduction and a 1% loss in efficiency.

Two additional methods are also discussed (increasing the number of blades and the blade sweep) but results were not quantified as above.

Other developments which promise to increase fuel efficiencies lie in airfoil development. The ARA-D, reported in Reference 38, appears particularly promising for turboprop application. Briefly, this particular airfoil retains its takeoff performance instead of showing the typical reductions in thrust which accompany reductions in activity factor. When one considers that higher cruise efficiencies are obtainable at lower activity factors (and what has traditionally implied lower takeoff performance), the ARA-D looks very attractive.

Increasing the number of blades has been recognized as an effective means of reducing noise. However, this presents a weight penalty which is compounded possibly by increased strength requirements resulting from increased vibration. In this light, the Kevlar composite propeller developed and certified by Hartzell is extremely attractive. This propeller has a 50% blade weight reduction with a 100% increase in strength. Unfortunately, its price was increased by a factor of 2.5. As composites are better understood and manufacturing processes refined, significant weight and price reductions appear inevitable.

In light of the above discussion, both Airplane A and B should receive significant benefits in noise and weight reductions as well as safety, with a modest penalty in cost.

4.5.8.2 Low Level Pressurization. This technology was envisioned as employing a low Δp on the order of 14 kN/m^2 (2 psi) for the sole purpose of attenuating noise. However, the addition of such a system will still require that a pressurization system be added at a distinct cost and weight penalty. Also, it was quickly noted that although this Δp could reduce an ambient altitude of 4.87 km (16,000 ft) to a cabin altitude of 3.05 km (10,000 ft), it would also exert an outward force of 9.61 KN on a 0.762 x 0.914 m door (2160 lbf on a 2.5 x 3 ft door). Hence, even "low level pressurization" will impose significant loads on the aircraft structure, implying further (structural) weight penalties in addition to those of the system.

Both airplanes may be expected to be heavily penalized for a reduction in interior noise.

4.5.8.3 Ducted Propulsors. Ducted propulsors are investigated here as a possible means for reducing noise. Associated with much improved interior and exterior noise characteristics are improved takeoff and landing performance characteristics. However, cruise performance is degraded and significant weight penalties may be incurred. Hence, ducted propulsors offer Airplane B greater benefits in takeoff and landing performance due to its mission profile.

An interesting proposal toward attenuating noise is the Q-Fan as reported in Reference 230. However, this system is not considered compatible with the low speed characteristics of Airplane A and B.

4.5.9 Propulsion

Five propulsion systems and two related technologies were considered for Airplane A, while only two propulsion systems were examined for Airplane B. As shown in Table 4.22, the GATE Engine had the highest figure of merit for Airplane A, and the Stratified Charge Rotary Combustion Engine was second. As shown in Table 4.10, the third technology for Airplane A had a figure of merit of 58. The ratings for both engines considered for Airplane B are encouraging since the baseline for this vehicle already included a turboprop.

In view of the particularly high figures of merit attained by this technology group, it appears appropriate to reiterate the fact that the present evaluation technique provides a measure of potential benefit to the user as opposed to a benefit/risk evaluation.

4.5.9.1 GATE Engine. The General Aviation Turbine Engine studies which were begun in 1977 involved Detroit Diesel Allison, Garrett AiResearch, Teledyne CAE, and Williams Research, while management of the program was provided by the NASA Lewis Research Facility. This study was devoted to investigating opportunities for advanced

Table 4.22. Propulsion

Technology (8)	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/85*
GATE Engine	85	32
Stratified Charge Rotary Combustion Engine	84	21
Advanced Diesel Engine	36	
Improved Turbocharging	31	
Liquid Cooling	13	
Stratified Charge Reciprocating Engine	12	
HCRLB Reciprocating Engine	11	

*Total number of technologies/lowest FM/highest FM

technologies in small turbine engines below the 750 kw size class, and one key issue involved the question of how to make the turbine engine cost-competitive with reciprocating engines. The results of the study were extremely encouraging and have been reported in the literature (Ref. 12, 65, 123, 204). Briefly summarized, turbine engines in general traditionally suffer from penalties in purchase price and fuel consumption and consequently have not penetrated the cost-conscious GA market. Their dominance in larger aircraft can be attributed in large part to their attractive features which include lower weight, apparently better safety, improved ride comfort, and improved aircraft performance expressed in terms of higher ceilings and cruise speeds. In addition, the JP4 which they utilize has an approximate 10% advantage in energy content and a 10% price advantage when compared with avgas (Ref. 204). Interestingly, three of the four study participants forecast competitive purchase prices which were the result of lower component manufacturing costs and increased sales volume. The fourth participant elected to increase sophistication and efficiencies to the extent that purchase price was raised but operating costs were much lower.

Two major advantages of turbines which may not be readily apparent lie in its three-to-one weight advantage and potential for attaining greater cruising speeds. In a cruise dominated mission this results in a markedly smaller airplane for the same payload and range as a reciprocating-powered counterpart due to the cascading effect that lower engine weight and cleaner installations have on vehicle size. As an illustration, consider that the lighter engine allows for a smaller and lighter vehicle, which allows for less drag. This allows for a reduction in required fuel volume which results in an even smaller airplane, which requires even less fuel.

For the present evaluation, Airplane A was considered to be powered by a conventional reciprocating engine. A maximum purchase price penalty (-3) was assessed primarily because the market forecast used in the GATE studies appeared somewhat optimistic. Airplane B, on the other hand, was given a purchase price advantage due to an anticipated significant reduction in manufacturing cost. Recall that this airplane's baseline was presumed to already be powered by a turboprop. Hence, performance improvements in speed and ceiling were not allowed although improvements in BSFC and purchase price were credited.

4.5.9.2 Stratified Charge Rotary Combustion Engine. Research in this particular field shows promising results. The rotary combustion engine, possesses several inherent features which make it extremely attractive for application as an aircraft powerplant. For example, it is simple, lightweight, and compact. Since power generation is not based on reciprocating pistons it is smoother. Liquid cooling allows for quieter operation, safer cabin heat and a probable reduction in cooling drag (since present air cooled installations are typically somewhat inefficient with unnecessary drag penalties). The absence of valves and cams also promises quieter operation and improved maintenance. Whereas homogeneous charge fuel efficiencies were less than competitive some years ago, (BSF ≃ .328 kg/kW/hr or .54 lb/hp/hr), stratified charge BSFC's of .262 kg/kW/hr (.43 lb/hr/hr) have recently been achieved and compare very favorably with present reciprocating engines. Projections for the future are for BSFC's on the order of .231 kg/kW/hr (.38 lb/hp/hr).

A significant feature of this system lies in its multi-fuel capacity. One engine presently operational at Curtiss-Wright burns JP4, diesel fuel, alcohol, or avgas. As such, it is extremely attractive in that transitions from avgas to JP4 with changes in market trends which may be forced through fuel shortages will have minimal effects on this powerplant. The key to this versatility lies in the air motion within the combustion chamber which apparently is conducive to stratified charge operation.

However, certain drawbacks to this system may be deduced from present and forecast levels of the state-of-the-art. Specifically, high pressure, timed fuel injection and timed ignition systems are expected to be required. These represent fairly high cost technologies. Also, although the induction manifold is smaller than for reciprocating counterparts (leading to lower turbocharging requirements), an improved turbocharging capability will probably be required. This alone can represent significant increases in cost, particularly if the production base is not supported by automotive engine requirements.

For this evaluation, Airplane A is presumed to be powered by a conventional reciprocating engine and Airplane B by a current technology turboprop.

4.5.9.3 High Comprssion Ratio Lean Burn Engine (HCRLB). Increasing compression ratio and leaning the fuel mixture are the most effective ways of improving fuel economy. When this process is applied to improve the performance of a current technology, homogeneous charge reciprocating engine, the type of engine identified by the acronym HCRLB results. High compression ratio offers increases in thermal efficiency of both air standard cycles as well as fuel-air cycles. However, when applied to a homogeneous charge engine, an upper limit is established by fuel octane number. (Present engines operate at CR's on the order of 8.5:1 and have BSFC's on the order of .255 to .268 kg/kW/hr (.42-.44 lb/hp/hr)). When improved fuel injection (timed, moderate pressure) and improved cylinder cooling techniques are applied, leaner fuel/air mixtures may be obtained. Reference 169 points to BSFC improvements on the order of 4% to 5% when leaner operation incorporating improved fuel injection and cooling methods are applied to a TCM IO-520 engine. However, costs to the user are expected to be prohibitively high as recertification costs are recouped. The reader is referred to References 169 and 170, both by Rezy, Stukes, Tucker, and Meyers, for excellent discussions and analytical results of very current concepts regarding the emissions and fuel consumption of reciprocating engines.

Only Airplane A was considered in the present evaluation, where B was considered to be powered by a turboprop.

4.5.9.4 Stratified Charge Reciprocating Engine. Much of the discussion material presented in this section resulted from information received from Teledyne Continental Motors and is unpublished. Their assistance is deeply appreciated and acknowledged. Interpretations of the general information acquired, on the other hand, are solely those of the present research team.

Reciprocating engine stratified charge systems are not new. Three concepts presently being pursued by industry are (1) the Honda Compound Vortex Controlled Combustion (CVCC) system, (2) the Texaco Controlled Combustion System (TCCS), and (3) The

Ford Programmed Combustion System (PROCO). These three systems operate under different combustion processes and are briefly described below.

Stratified Charge systems differ from homogeneous charge (current) systems in that the fuel/air mixture of the former is not homogeneous within the combustion chamber. Instead, a rich zone is maintained at the point of ignition, and the flame front then progresses into a lean region which would not normally be expected to sustain combustion alone. The overall effect is a leaner combustion process which yields lower emissions and better fuel efficiency. Two methods of charge stratification are currently visualized. In one case, stratification is achieved physically by injecting the rich mixture into a prechamber where it is ignited. The second method relies on obtaining an air flow pattern within the cylinder itself to maintain stratification and hence is called an open chamber system. The CVCC is based on a prechamber system while the PROCO and TCCS employ open chamber methods.

At present, prechamber technology appears to have progressed to the point where a GA powerplant could be put into production with a certain degree of confidence. Such a system, when compared to open chamber systems, appears to have less efficient output which would result in a heavier engine for a given power level. Also, the chamber itself will probably require additional cooling, and this may present a problem in an air-cooled configuration. On the other hand, the lean fuel-air ratio can probably be extended, and NO_x will be greatly reduced while HC and CO may be expected to increase.

The PROCO and TCCS, both open chamber systems, differ primarily in fuel injection time. PROCO uses early injection near BDC, while TCCS uses late injection near TDC. PROCO, as a result, offers the possibility of better air utilization but has no multi-fuel capability. TCCS, while retaining a multi-fuel capability, can suffer from a smoke problem due to incomplete air utilization. Both systems operate at very high compression ratios with TCCS at 12:1 and PROCO at 11:1.

Of the above systems, TCCS appears to be more attractive for GA application due to its multi-fuel capability. Also, due to its late injection feature, turbocharging and compression ratios are limited by structural considerations rather than combustion considerations. When tested in a jeep, TCCS showed BSFC reductions on the order of 35% under part load operation. At the anticipated higher power loadings, differences between homogeneous and stratified charge operations indicate a 25% improvement with a turbocharged TCCS displaying BSFC's on the order of .25 kg/kW/hr (.41 lb/hp/hr) at BMEP's of 552 to 689 kN/m^2 (80 to 100 psi). Turbocharging the TCCS is expected to increase output without reducing fuel economy or multi-fuel capability. If air throttling is employed, its application will probably be used to improve emissions control at low power settings.

With respect to present GA engines, TCCS will require a high pressure, timed fuel injection system and a variable timing ignition system. Less effective air utilization points to heavier engines while complexity points to increased costs. Improvements to the reciprocating engine, then, tend to detract from its presently undisputed cost advantage, while its advantage in fuel efficiency appears to be eroding. On the other hand, one cannot ignore the fact that this powerplant has established itself in the GA market, and it is difficult to visualize other engine types replacing it in the next decade.

4.5.9.5 Advanced Diesel Engine. The diesel engine appears attractive for GA application due to its low-cost fuel (20% advantage) and its low BSFC's. Its fuel characteristics alone (where it is not octane/detonation limited) allow for higher compression ratios and higher efficiencies.

At present, Teledyne Continental Motors, General Products Division, is investigating advanced two-stroke diesel engine concepts which are being applied to a six cylinder, radial, 300 kW (400 hp) engine and a four cylinder, radial, 150 kW (200 hp) engine. The 300 kW engine is considered to involve higher risk than the 200 kW engine, and includes those associated with (1) ceramic components, (2) operation in an unfinned cylinder environment (no cooling air), (3) high speed turbo starter/alternator, and (4) catalytic combustors. Impressive performance characteristics of this engine include takeoff BSFC's on the order of .225 kg/kW/hr

(.37 lb/hp/hr) and cruise BSFC's of .195 kg/kW/hr (.32 lb/hp/hr). Since this engine already enjoys a fuel price advantage, fuel costs alone could experience a 40% reduction over present day GA propulsion systems. Other attributes of this system include what has occasionally been called "uncooled operation." However, although the cylinders are unfinned, the injector pumps and aftercooler require cooling, and it is evident that cooling air of some sort must be provided for. This requirement is nevertheless anticipated to allow for lower cooling drag losses than presently experienced by the GA fleet of air-cooled engines. Weight advantages of the system could not be ascertained. Although the dry engine weight of the 300 kW engine is listed as 207 kg (457 lb) vs 262 kg (578 lb) for a comparable GTSIO-520-H, the diesel engine is known to require oil cooling, and this suggests that installed weight advantages may fail to materialize if the oil system weight is high. The purchase price disadvantage has been estimated to be on the order of 20%.

Airplane A should receive advantages in DOC due to fuel efficiencies but is penalized for purchase price. No data for emissions characteristics was found, but the quieter operation attributed to the absence of valves was considered to be only a small advantage.

4.5.9.6 Liquid Cooling. This technology is considered mature but due to risks involved with single point failures such as those associated with leaks, thermostat failures, and pump failures, has disappeared from the GA reciprocating engine powered fleet. Still, the advantages attributed to its incorporation are significant enough that its possible re-implementation is investigated here. Only a few of the more salient characteristics associated with its advantages and disadvantages are listed here.

Advantages:

(1) More uniform cylinder temperatures can be maintained, thereby relieving thermal stresses and improving TBO.

(2) Engines can be manufactured with closer clearances by reducing the effect of thermal stresses, particularly those associated with idle power rapid letdowns. This could aid in TBO improvement.

(3) More freedom is gained in engine/airframe configuration integration.

(4) Engines can be more compact due to the absence of fin spacing requirements.

(5) Critical cooling requirements such as required for exhaust valves can be more easily met.

(6) Fuel consumption during climbs should improve on the order of 10% due to the elimination of the requirement for cooling through rich operation.

(7) Cooling drag associated with inefficient methods often encountered in air-cooled installations can be significantly reduced. (This drag can be significant as reported in References 36 and 142.)

(8) Quieter operation may be expected due to the water jacket provided about the engine.

(9) Cabin heat can be provided much more safely through a liquid heat exchanger than through present methods. The latter suffers from the distinct possibility of introducing exhaust fumes into the cockpit should the exhaust pipe heat exchanger fail.

Disadvantages:

(1) Single point failures resulting from a loss of coolant, thermostat failures in the closed position, or pump failures, are serious.

(2) Warm up times will be extended. In cold weather, this could result in severe engine wear, with the distinct possibility of condensed products of combustion contributing to cylinder corrosion.

(3) Deterioration of system efficiency through scaling suggests problems with system maintenance.

(4) A vapor pocket in the coolant system can result in localized interruptions in cooling.

(5) Engine maintenance costs may be expected to increase due to an increase in manhours required to remove or disassemble the engine. Air cooled systems offer the possibility of removing single cylinders from the engine.

(6) Although dry weights may be expected to be on the order of air cooled systems, installed (wet) weights will be greater.

For the present evaluation, both reliability and safety were penalized by -1, thereby reflecting some optimism in the ability of technological improvements to offset Disadvantage No. 1. If this assumption should prove to be invalid, the severe penalty which would result will make liquid cooling extremely unattractive.

4.5.9.7 Improved Turbocharging. Improved turbocharging promises to improve fuel efficiency and increase climb and cruise speed. By increasing the critical altitude and aircraft ceiling, significant improvements on the order of 10% to 15% can be expected in range.

However, procurement costs can be expected to be significantly higher if the improvements in turbocharging are dictated for the GA fleet alone. Today, for example, procurement costs are kept low due to a very high production base provided by the automotive and truck engine markets. A major manufacturer, for example, cites a production base on the order of one million units/year, with only 8,000 units being used by the GA fleet. The specific technology which promises to have the greatest impact on improved turbocharger performance appears to be that of air bearings.

It seems safe to predict that improved turbochargers will not find their way into the GA fleet until automotive requirements dictate their production. However, efforts toward improving fuel efficiencies (including the possibility of production of the PROCO or TCCS engines) may dictate their improvement. Accordingly, only a modest penalty in cost is assessed for this technology.

4.5.10 Structural Materials

Three technologies were considered and, as shown in Table 4.23, appear extremely attractive. Here, all three were evaluated on the basis of anticipated maturity in certification procedures and small purchase price penalties. Hence, in view of presently increasing manpower costs which would be significantly offset by composite manufacturing processes, the user was forecast to suffer no significant purchase price penalties. The advantages of composites which lie in cleaner aerodynamic shapes and weight reductions, allow for improvements in ceiling, cruise speed, fuel efficiency, and range.

Table 4.23 Structural Materials

Technology 3	Figures of Merit for	
	Airplane A 56/-53/85*	Airplane B 51/-57/58*
Fiberglass Composites	55	58
Kevlar Composites	51	56
Graphite Composites	43	48

*Total number of technologies/lowest FM/highest FM

4.5.10.1 Fiberglass Composites. These composites are attractive because they promise significant weight reductions at lower cost and risk than those associated with Kevlar or graphite, although the latter two show greater tensile strength. Advantages noted also include the promise of reduced production cost, improved drag characteristics, low corrosion, and greater strength than aluminum. In one corrosion test, epoxy-fiberglass was noted to not corrode when in contact with anodized, primed, or painted aluminum surfaces. In fact, its inert and durable characteristics allow it to be used as one of several isolators for graphite, which reacts very strongly as a cathode to almost every metal. In one test, epoxy fiberglass was exposed to a 5% salt spray for 5000 hours and showed only superficial corrosion (Ref. 126). In another, a helicopter blade fabricated by Bell Helicopters was cracked and then run for an additional 900 hours without further failure (Ref. 120).

Its use in primary aircraft structures has seen only limited application in Rutan's canard configured vehicles, the Windecker Eagle, and the Bellanca Skyrocket, but this is seen to be largely the result of the over-designing required to certify a new production process, where weight advantages are quickly nullified.

4.5.10.2 Kevlar Composites. These aramid fibers have greater tensile strength than either fiberglass or graphite and are inherently inert. Current costs are on the order of $33 per kg as a woven cloth vs graphite, which costs on the order of $110 per kg in cloth form.

Hartzell's certified composite propeller is made from Kevlar. This blade is 50% lighter and twice as strong as its conventional counterpart but costs 2.5 times as much. As certification procedures are refined to allow the full potential of composites to be exploited, both cost and weight should be considerably reduced.

4.5.10.3 **Graphite Composites**. Most of the literature on composites published recently appears to deal with graphite. This composite has the strength and stiffness of steel, but only 60% of the density. Although it does not possess the tensile strength of Kevlar, its compressive strength is greater, and offers the potential for a 30% weight reduction in certain components. Although essentially inert when isolated, it acts as a strong cathode when in contact with aluminum and must be isolated through the use of other materials such as fiberglass. It is by far the most expensive of the three composites investigated, although costs have dropped from $550-$1200 per kilogram in 1968 to $55-$110 per kilogram currently. Here, the lower figure is for single fiber filaments while the upper figure represents the cost for its woven cloth form. As in many of the other technologies, its cost is expected to drop substantially if the auto industry forms a production base for its use.

As its characteristics become better understood, its intrusion into the GA market appears inevitable. At present, it is expected to be used extensively in the Lear Fan.

4.6 OTHER PROMISING TECHNOLOGIES

As one might suspect, certain promising technologies were omitted from the present evaluation due primarily to application considerations for airplane type as discussed previously in Section 4.2.3. In other words, a technology applicable to the jet fleet but not applicable to the single engine, light twin, or commuter airplane fleet could not be evaluated utilizing the present technique since the category weights were developed for specific mission profiles.

Two technologies receiving considerable attention in the current literature and which were not considered to be a part of the present research are the Prop Fan and the Quiet, Clean General Aviation Turbofan (QCGAT). Both of these technologies appear very promising for long-haul high speed cruise, and are discussed here.

4.6.1 Prop Fan

The now familiar 8-bladed propeller which has appeared in several periodicals offers extreme promise for the present turbofan-powered commercial fleet. It was not evaluated as part of Airplane A- or Airplane B-related technologies due to the fact that it is presently being developed for Mach numbers on the order of 0.8.

Presently, both an 8-bladed and a 10-bladed version have been investigated with extremely promising results. Fuel efficiency improvements on the order of 22% are forecast, with DOC improvements of 7% over comparable turbofans possible with improvements in design for maintainability (Ref. 46). The fuel figure is particularly impressive when one realizes that a 1% improvement provides an annual savings of 100 million gallons of aircraft fuel (Ref. 46) for the present civil fleet.

The major disadvantage of the prop fan is noise, and extensive studies are being performed to rectify this difficulty. When one

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considers that military long endurance aircraft can realize 35% fuel savings and reduce gross weight by 25%, the additional weight penalty for noise treatment appears to be a small price. However, exterior noise still would not be resolved. (Note that noise cancelling techniques already employed through blade sweep have decreased sound pressure levels on the order of 6 db.) The interested reader is directed to References 46, 100, 101, and 141 for further information regarding prop fans.

4.6.2 Quiet, Clean, General Aviation Turbofan (QCGAT)

AVCO Lycoming and Garrett AiResearch have both performed research in this area for NASA Lewis with promising results. As was the case for the prop fan, this technology was not evaluated as part of the present study due to the lack of applicability of turbofans to either Airplane A or B. In the research performed, Garrett chose to synthesize a stretched Lear 35 with a range of 3300 km (1780 nm) at an altitude of 12,200 m (40,000 ft) and M = 0.8 for its modified TPE 731-3. AVCO, on the other hand, had Beech synthesize an aircraft for its modified LTS 101 which resulted in a vehicle capable of 2780 km (1500 nm) at an altitude of 10,000 m (33,000 ft) and M = 0.6. It is emphasized that although the airplanes were synthesized, the modified engines were operational (although not flightworthy) and have been delivered to and tested by NASA-Lewis personnel. Results of the program were extensively discussed at the General Aviation Propulsion Conference held at the Lewis Research Facility in November 1979, and indicated

that major goals were met. Noticeably TSFC goals were not met under most conditions. However, all noise goals (which represented a 90% reduction in noise footprint) and most emissions goals were met.

Since a major thrust of the QCGAT program was to demonstrate large-engine technology transfers to small-engines, it appears that the program was quite successful. Certainly, the noise goals achieved are extremely impressive.

4.7 SUMMARY OF THE TECHNOLOGY EVALUATION

Several significant points made earlier in this chapter are repeated here for emphasis. Finally, a list of attractive and unattractive technologies will be disucssed.

4.7.1 Features of the Evaluation Technique

(1) The rating yardstick used for Airplane A and Airplane B reflect a concensus of opinion both in the identification of relevant categories as well as in their quantification.

(2) Responses to the three rounds of the survey to quantify the categories (Survey 2) ranged from 70% to 95%.

(3) Only comparable technologies should be evaluated under the present technique. For example, high pressure, timed, fuel injection should not be compared with stratified charge reciprocating engines.

(4) The relative figures of merit generated by different raters display significant stability in ranking different technologies despite differences in magnitude noted between raters.

(5) Large changes in relative figures of merit between technologies are not observed when relative benefits are perturbed about an expected value. However, such changes may be expected if the state-of-the-art improves and results in an unforeseen application scenario.

(6) The four technologies in the crashworthiness group appear somewhat underrated. This is attributable to the fact that improvements are restricted to only the crashworthiness category, and that this category had relatively low weights for both Airplane A and Airplane B.

(7) Small differences in figures of merit should not be interpreted to rank one technology over another.

(8) The ranking of technologies by figures of merit does not reflect risk in the present analysis.

4.7.2 Attractive Technologies

(1) The GATE engine and the stratified charge rotary combustion engine dominate the rankings for Airplane A as shown in Table 4.9 and offer significant advantages to Airplane B as shown in Table 4.10.

(2) All propulsion engines offer benefits to both airplanes.

(3) Fiberglass, Kevlar, and graphite composites are all extremely attractive provided certification procedures are refined and a modest decrease in price is noted.

(4) Aerodynamic concepts such as natural laminar flow airfoils, spoilers with full span flaps, and low/medium speed airfoils appear extremely attractive.

(5) Integrated avionics systems which alleviate pilot workload such as DAAS and Digital Data Links are very attractive.

A very important consideration which deserves mention at this point is that many technologies which were eliminated from consideration due to the criteria of Section 4.2.3 are directly inferred from the list of attractive technologies just defined. For example, improved fuel injection, improved turbochargers, variable timed ignition systems, and ceramic technology are all implied for the improved positive displacement engines. Also, improvements in computational aerodynamics are required in order to permit three dimensional wing-body-tail analyses as well as wing-spoiler-flap analyses.

4.7.3 Unattractive Technologies

(1) Area navigation concepts such as LORAN C and OMEGA are fairly unattractive to the user although they offer significant savings in operations and maintenance expenses for the ground sites.

(2) Active controls, Fly-by-Wire, and Fly-by-Light are extremely unattractive to both Airplane A and Airplane B, as are HUD's, Doppler, and Inertial Navigation.

CHAPTER 5

DESIGN STUDIES

The design studies illustrate the direct and synergistic impacts of advanced technologies by comparing advanced and current technology airplanes that have been designed to the same specifications.

5.1 DESIGN SPECIFICATIONS

The statement of work specified that conventional and canard configurations be developed for two types of airplanes incorporating appropriate advanced technologies. The preliminary specifications given are as follows:

(1) Design conventional and canard configurations for:
   (a) A small airplane with at least a 6-passenger cabin (including pilots), and
   (b) A large airplane with at least a 12-passenger cabin (excluding pilots).

(2) Performance objectives are:
   (a) Maximum $L/D \geq 18$
   (b) Cruise speed ≥ 250 kt
   (c) Landing speed ≤ 60 kt

For design purposes, the two airplane types were more narrowly defined. The "small" airplane is defined as a 6-passenger (including pilots) single engine business and/or personal airplane and corresponds to Airplane A of Chapter 4. The "large" airplane is defined as a 19-passenger (excluding pilots) commuter airliner and corresponds to Airplane B of Chapter 4. The two types of airplanes are refered to as the "6-passenger" and "commuter" in this chapter.

5.1.1 6-Passenger Design Specifications

Characteristics of existing 6-passenger airplanes were used as guidelines in completing the 6-passenger design specifications. As shown in Table 5.1, the resulting specifications were split into "required" and "desired" sets. This was done because $L/D \geq 18$ strongly conflicts with $V_{stall} \leq 60$ kt. Furthermore, since it was felt that landing and takeoff distances are much more important than the speeds involved, the stall speed requirements were relaxed.

5.1.2 Commuter Design Specifications

The characteristics of existing commuter aircraft were used as guidelines in establishing the commuter design specifications. Again, the resulting specifications were divided into "required" and "desired" sets. The "desired" requirements for the commuter were relaxed extensively because of its operating envelope. Commuter aircraft operate at low altitudes, making a desired L/D of 18 extremely difficult to attain. Furthermore, a landing speed of less than 60 knots is somewhat unrealistic in the size of commuters typical of this study. Balanced field length, together with landing distance, is more important than landing speed. The resulting specifications follow in Table 4.5.2.

Table 5.1. 6-Passenger Design Specifications

Required: (1) Seating for 6 persons (including 2 crew) with baggage.

(2) $V_{cruise} \geq 250$ kt at gross weight.

(3) Range $\geq$ 900 nm with 45 min. reserves carrying 6 passengers and baggage.

(4) Takeoff distance over a 10.7 m obstacle $\leq$ 610 m, sea level (ISA) and maximum gross weight.

(5) Landing distance over a 15.2 m obstacle $\leq$ 610 m, sea level (ISA) and maximum gross weight.

(6) Meet FAR 23 requirements except for V_{stall} as noted in (8).

Desired: (7) Maximum L/D $\geq$ 18 cruise.

(8) $V_{stall} \leq 60$ kt in the landing configuration at maximum gross weight and sea level (ISA).

5.2 TECHNOLOGY INTEGRATION

A major preliminary task performed during the course of the design study was the identification of those technologies to be incorporated into the designs. The technology evaluation of Chapter 4 was helpful in this respect and served as a guideline in selecting particular technologies.

Table 5.2. Commuter Design Specifications

Required: (1) Seating for 21 persons (including 2 crew) with baggage.

(2) $V_{cruise} \geq 250$ kt at maximum takeoff weight at 3050 m MSL (ISA).

(3) 2000 nm ferry range where ferry range is determined for full fuel + 2 crew (only) at 250 kt with 45 min. reserves.

(4) Segmented range of nine 87 nm legs without refueling with a 60% load factor (12 pax) and with 45 min. reserves.

(5) Single leg range of at least 400 nm at 100% load factor with 45 min. reserves.

(6) Balanced field length of 1370 m or less at sea level (ISA) and maximum takeoff weight.

(7) Meet FAR part 25 requirements.

Desired: (8) (a) Maximum $L/D \geq 18$ at cruise.

(b) $V_{stall} \leq 60$ kt in the landing configuration at maximum gross weight

It should be noted that the impact of many of the evaluated technologies cannot be determined by design studies. For example, while the impact of composite materials may be evaluated, the effects of load limiting seats and CRT displays are much harder to quantify. In general, only technologies which directly influence the mission performance of an airplane are capable of being analyzed.

5.2.1 6-Passenger Technology Integration

As one would expect, the highest ranking technologies identified in the analysis of Chapter 4 were in the areas of propulsion, structures, and aerodynamics. Specific technologies from each of these areas were selected and are termed "Primary Technologies" in that they directly influence airplane performance. Other technologies which do not directly influence airplane performance were also incorporated and are termed "Secondary Technologies." Table 5.3 lists the Primary and Secondary Technologies which were incorporated into the advanced technology 6-passenger airplanes.

The reasons for selecting the technologies in Table 5.3 are as follows:

(1) Spoilers and Full Span Fowler Flaps

Trade studies (see Section 5.3.1) showed that high wing loadings (1915 to 2394 N/m^2) markedly improve cruise efficiency but degrade takeoff and landing performance. The obvious solution here is to utilize spoilers for primary roll control and free the trailing edge of the wing for full span flaps. Fowler flaps are used because they provide high lift and low drag at small deflections (for takeoff) and higher lift and drag at large deflections (for landing).

Table 5.3. 6-Passenger Advanced Technologies

Primary Technologies*	Secondary Technologies*
Spoilers for roll control	Load limiting seats
Full span Fowler flaps	Energy absorbing floor
Advanced natural laminar flow airfoil	Improved restraints
Kevlar and/or graphite composite structure	Integrated avionics and displays
Stratified charge, highly turbocharged rotary combustion engine	Integrated low-cost fluidic wing leveler
Quiet, efficient propeller technology	

*Primary Technologies are those which directly influence airplane performance while Secondary Technologies do not.

(2) Advanced Natural Laminar Flow Airfoil

Preliminary data show that computer generated natural laminar flow (NLF) airfoils have low-drag characteristics approaching those of NACA 6-series airfoils and maximum lift coefficients resembling those of the turbulent-flow NASA LS-series airfoils, which are also computer generated. Furthermore, the advanced NLF airfoils are far less sensitive to roughness (in terms of maximum lift coefficient) than the NACA 6-series airfoils.

(2) Kevlar and/or Graphite Composite Structure

Advanced composites can significantly reduce structural weight while providing a stiff and aerodynamically smooth surface. Several studies indicate that major cost savings are possible due to a reduction in the number of parts and man-hours required for production.

(4) Stratified Charge, Highly Turbocharged Rotary Combustion (RC) Engine

This engine is characterized by a high power to weight ratio, good specific fuel consumption, and liquid cooling. The RC engine was selected instead of the GATE turboprop primarily because the former is undergoing tests while the latter is a paper study. Furthermore, the GATE engine is evolving into a higher horsepower category than required for the 6-passenger airplane.

(5) Quiet-Efficient Propeller Technology

This includes computer generated blade sections, optimized planforms, composite blades, etc. Cruise efficiency gains are relatively small (2-3%) but significant improvements in takeoff and climb efficiencies and noise characteristics are possible.

(6) Load Limiting Seats and Energy Absorbing Floor

These technologies can reduce peak vertical g-loadings by 50% and therefore greatly reduce the risk of death or injury in the event of a crash. Little or no weight and cost penalties are expected.

(7) Improved Restraints

Improved restraints are a minor technology in terms of airplane weight and cost but greatly enhance survivability by insuring that the occupant remains in his seat during a crash. If load limiting seats are used, effective restraints become mandatory. The only problems identified appear to be those assoicated with comfort and ease of use.

(8) Integrated Avionics and Displays

While not directly influencing performance, this technology can improve the utility and flexibility of an airplane and can be considered to increase safety since it has the potential to substantially reduce pilot workload. The degree of sophistication of the system as applied to the 6-passenger airplane has not been defined but the capabilities of the technology in general are illustrated by the NASA Ames PCAAS and DAAS studies.

(9) Integrated Low-Cost Fluidic Wing Leveler

This wing leveler is visualized as a basic part of the airplane. Because most airplanes are not spirally stable, this technology can significantly improve safety, particularly in IFR conditions by reducing pilot workload. This system is commercially available to the homebuilt market for less than $200.

5.2.2 Commuter Technology Integration

The discussions of advanced technologies integrated into the 6-passenger designs apply to the commuter designs. Identical technologies were integrated with two exceptions: (1) powerplant and (2) airfoil. Table 5.4 presents the advanced technologies incorporated into the commuter design.

Table 5.4. Commuter Advanced Technologies

Primary Technologies*	Secondary Technologies*
Spoilers for roll control	Load limiting seats
Full span Fowler flaps	Energy absorbing floor
Advanced low-speed airfoil	Improved restraints
Kevlar and/or graphite composite structure	Integrated avionics and displays
GATE technology turboprop engine	
Efficient propeller technology	

*Primary Technologies are those which directly influence aircraft while Secondary Technologies do not.

The technologies not previously discussed but applicable to the commuter are:

(1) GATE technology turboprop engine.

This engine was selected because of its high power-to-weight ratio, low purchase price, and good specific fuel consumption. Other advantages attributed to turboprops include high reliability and long engine lifetimes.

(2) Advanced low-speed airfoil.

The advanced NASA low-speed airfoils (LS-series) have characteristics similar to the original GA(W) series of

airfoils and exhibit good maximum lift characteristics together with improved pitching moment characteristics. Also, the thickness of the low-speed section assists in maintaining low wing weights while providing a high volume for fuel.

5.3 PARAMETRIC TRADE STUDIES

Parametric trade studies were conducted to establish the impact of basic airplane parameters (wing loading, aspect ratio, power loading, etc.) on mission performance.

5.3.1 6-Passenger Trade Studies

Three types of trade studies were conducted covering cruise, taekoff, and landing performance. Detailed derivations may be found in Appendix C.1.

The cruise trades were formulated to show the affective power loading ($[\eta_p$ P/W], hp/lb) required to cruise at 250 kt as a function of wing loading (W/S), effective aspect ratio (Ae), zero lift drag coefficient (C_{D_o}), and altitude. It quickly became apparent that the high L/D requirement necessitated high cruising altitudes. Figures 5.1 and 5.2 present the cruise trades for altitudes of 6100 m and 9140 m, respectively.

The takeoff trades were expressed in terms of wing loading (W/S) and power loading (P/W) required for a 610 m takeoff distance over a 15.2 m obstacle. (This requirement was later changed to a 610 m takeoff distance over a 10.7 m obstacle.) The requirement proved to be a very strong function of the maximum takeoff lift coefficient ($C_{L_{max_{TO}}}$) and a very weak function of aspect ratio (A) and zero lift drag coefficient (C_{D_o}). These characteristics led to a fairly simple representation of the takeoff problem as shown in Figure 5.3.

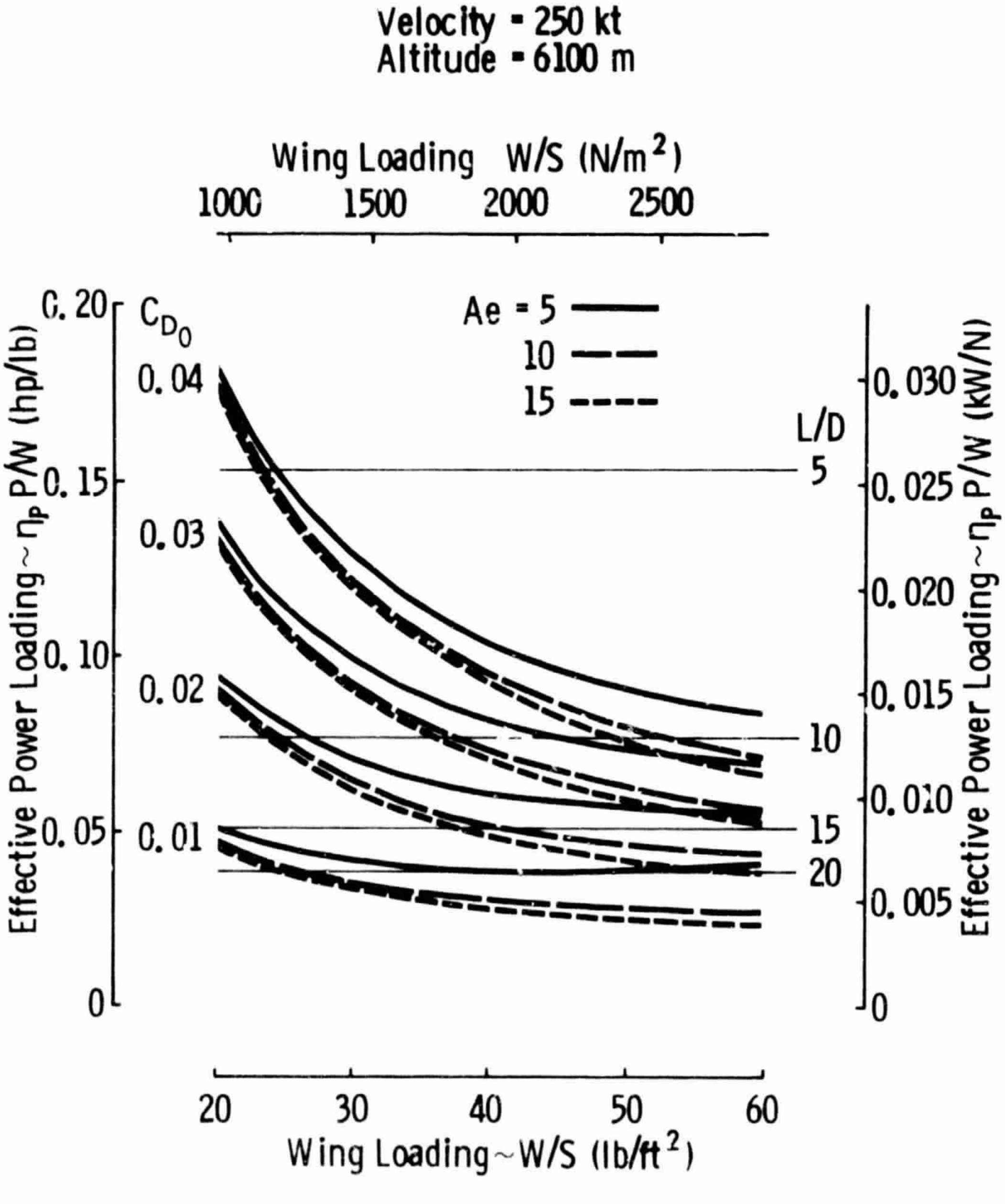


Fig. 5.1. 6-Passenger Cruise Trade Studies (at 6100 m)

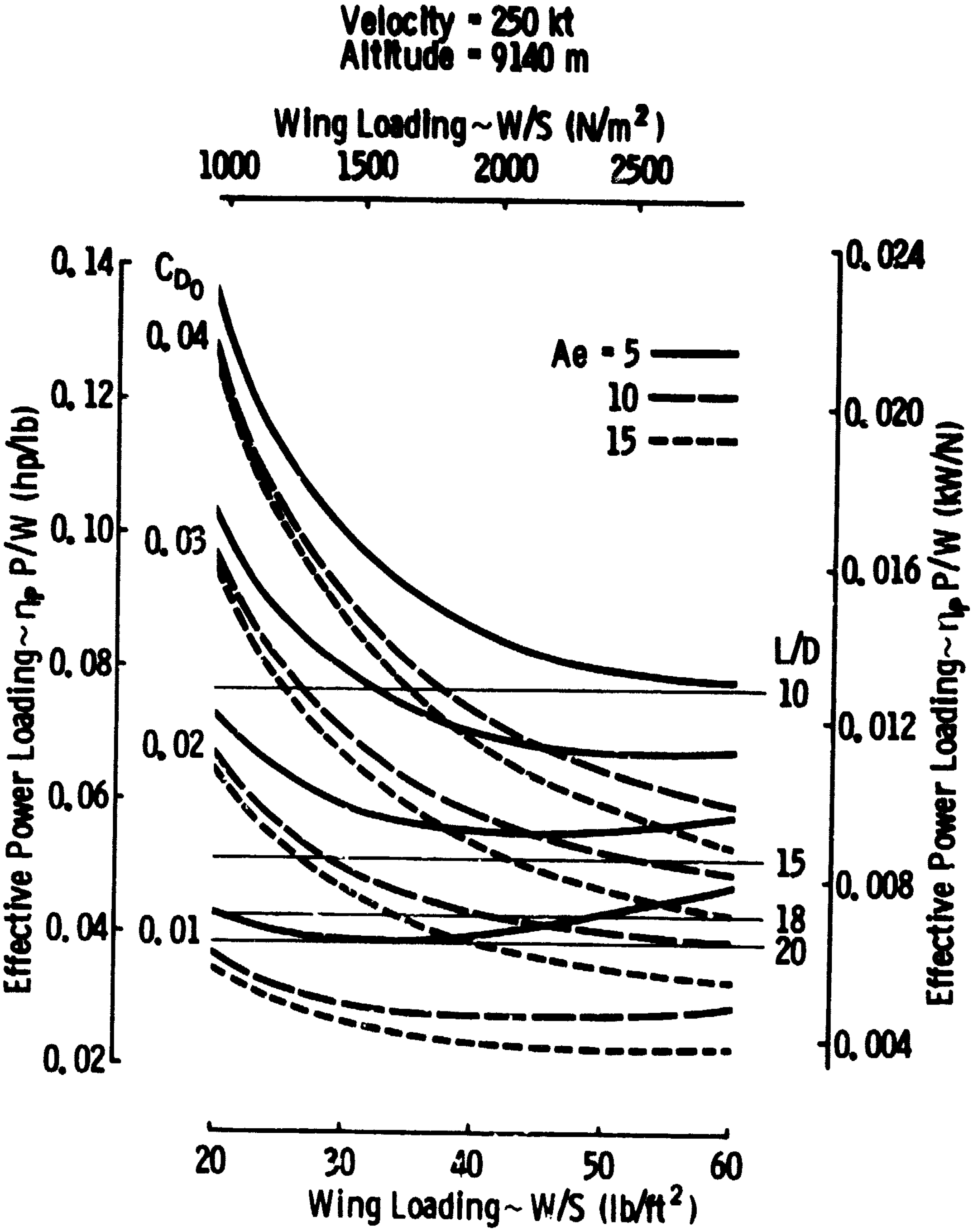


Fig. 5.2. 6-Passenger Cruise Trade Studies (at 9140 m)

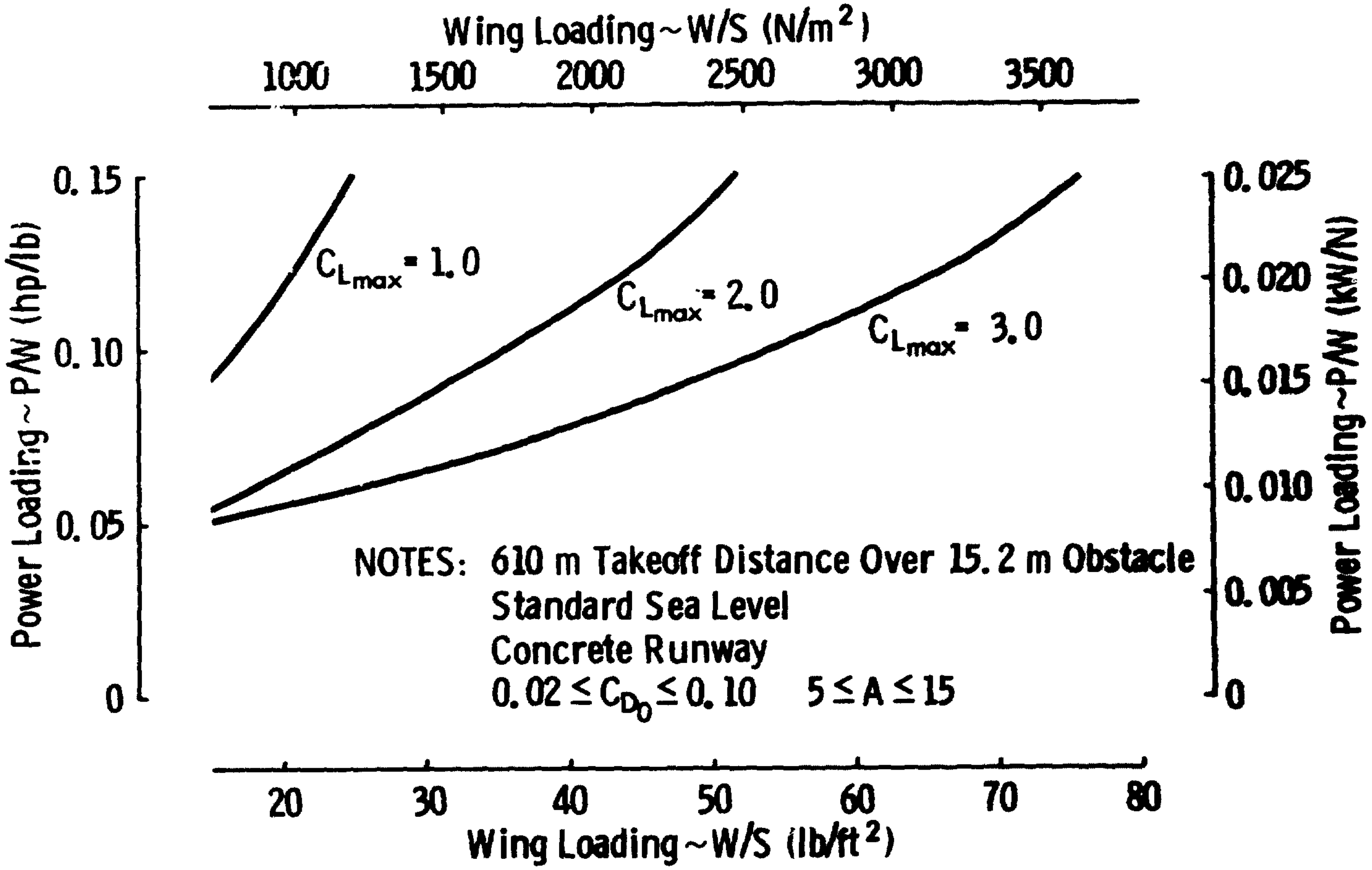


Fig. 5.3. 6-Passenger Takeoff Trade Studies

The landing trades show wing loadings and maximum landing lift coefficients ($C_{L_{max_{LDG}}}$) required for a 610 m landing distance over a 15.2 m obstacle and for a stall speed of 60 kt. Figure 5.4 gives the results of the landing trade study.

The trade studies of Figures 5.1-5.4 are summarized in Table 5.5.

As a result of the trade studies, it was decided that relaxing the $V_{stall} \leq 60$ kt requirement was justified since it would otherwise arbitrarily restrict the application of advanced technologies. Airplane parameters and design goals for the advanced technology 6-Passenger airplanes were established as follows:

Parameters:

$W/S = 2155\ N/m^2\ (45\ lb/ft^2)$

$A = 11$

$h_{cruise} = 9144\ m\ (30{,}000\ ft)$

Goals:

$C_{D_o} \leq .02$

$e \geq .75$

$C_{L_{max_{TO}}} \geq 2.5$ and $C_{D_{o_{TO}}} \leq .10$

$C_{L_{max_{LDG}}} \geq 3.0$

5.3.2 Commuter Trade Studies

Two types of trade studies were conducted for the commuter aircraft and consisted of cruise and balanced field length performance. Detailed derivations are included in Appendix C.2.

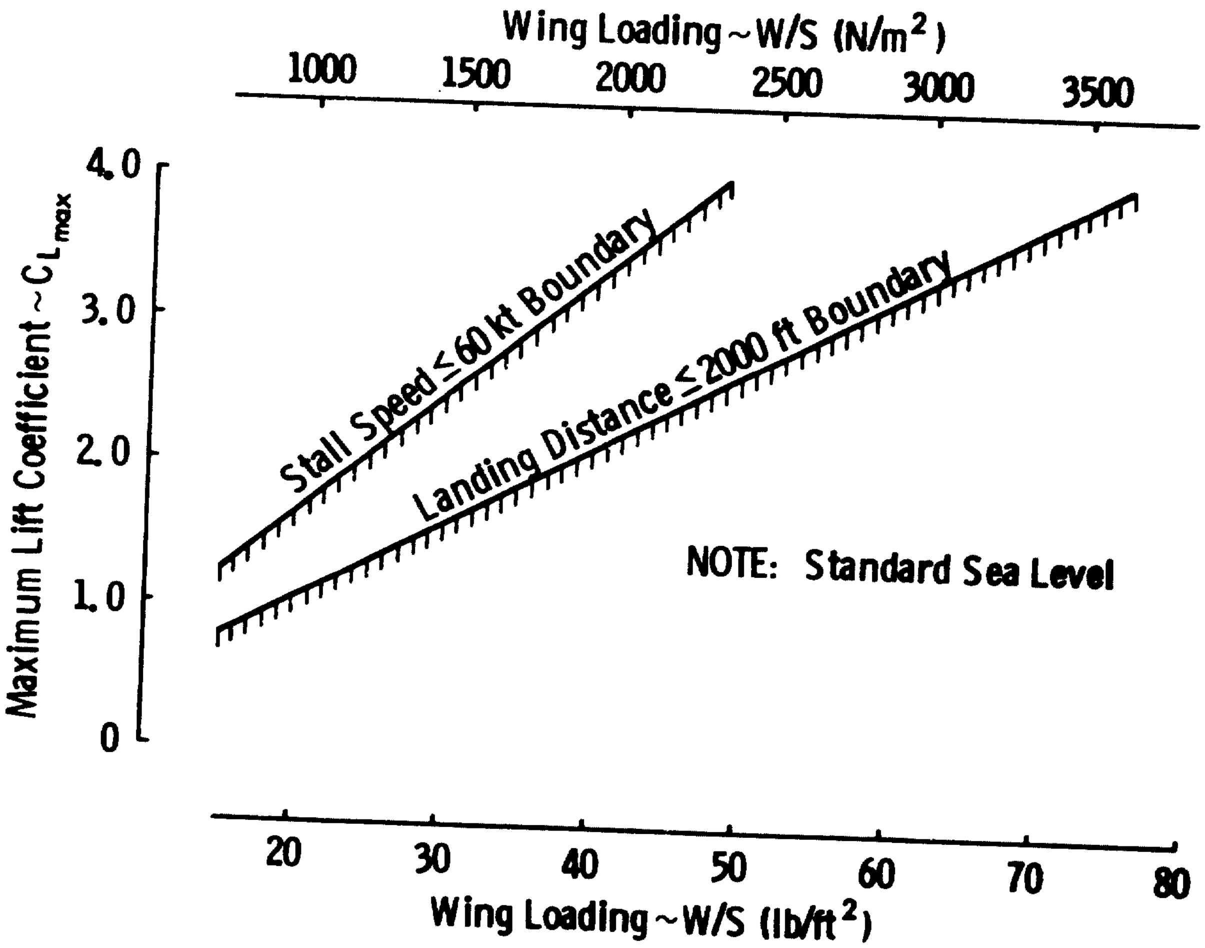


Fig. 5.4. 6-Passenger Landing Trade Studies

Table 5.5. 6-Passenger Trade Study Summary

CRUISE TRADE STUDY
Current high performance single engine airplanes typically have $C_{D_o} \approx .02$, $Ae \approx 5.5$, and $W/S \approx 1005$ N/m^2 which results in $L/D = 11$ at 9140 m. $L/D = 18$ requires much higher W/S (2155 N/m^2) and larger Ae (80) for $C_{D_o} = .02$, and $C_{D_o} = .02$ is very difficult to achieve with $W/S = 2155$ N/m^2.
TAKEOFF TRADE STUDY
P/W required for constant W/S is a very strong function of $C_{L_{max_{TO}}}$. Because cruise requirements demand high W/S, advanced flap technology (full span Fowler flaps) becomes a necessity if reasonable P/W is to be maintained.
LANDING TRADE STUDY
$V_{stall} \leq 60$ kt is a very limiting requirement compared to the 610 m landing distance requirement. If the V_{stall} requirement is adopted, it becomes the critical factor in selecting W/S. If the landing distance requirement is used instead, the takeoff distance requirement becomes critical.

Similar to the 6-passenger studies, the commuter cruise studies show the effective power loading (η_p P/W) required to cruise at 250 kt and 3050 m as a function of wing loading (W/S), effective aspect ratio (Ae) and zero lift drag coefficient (C_{D_o}). Figure 5.5 presents the cruise trade studies.

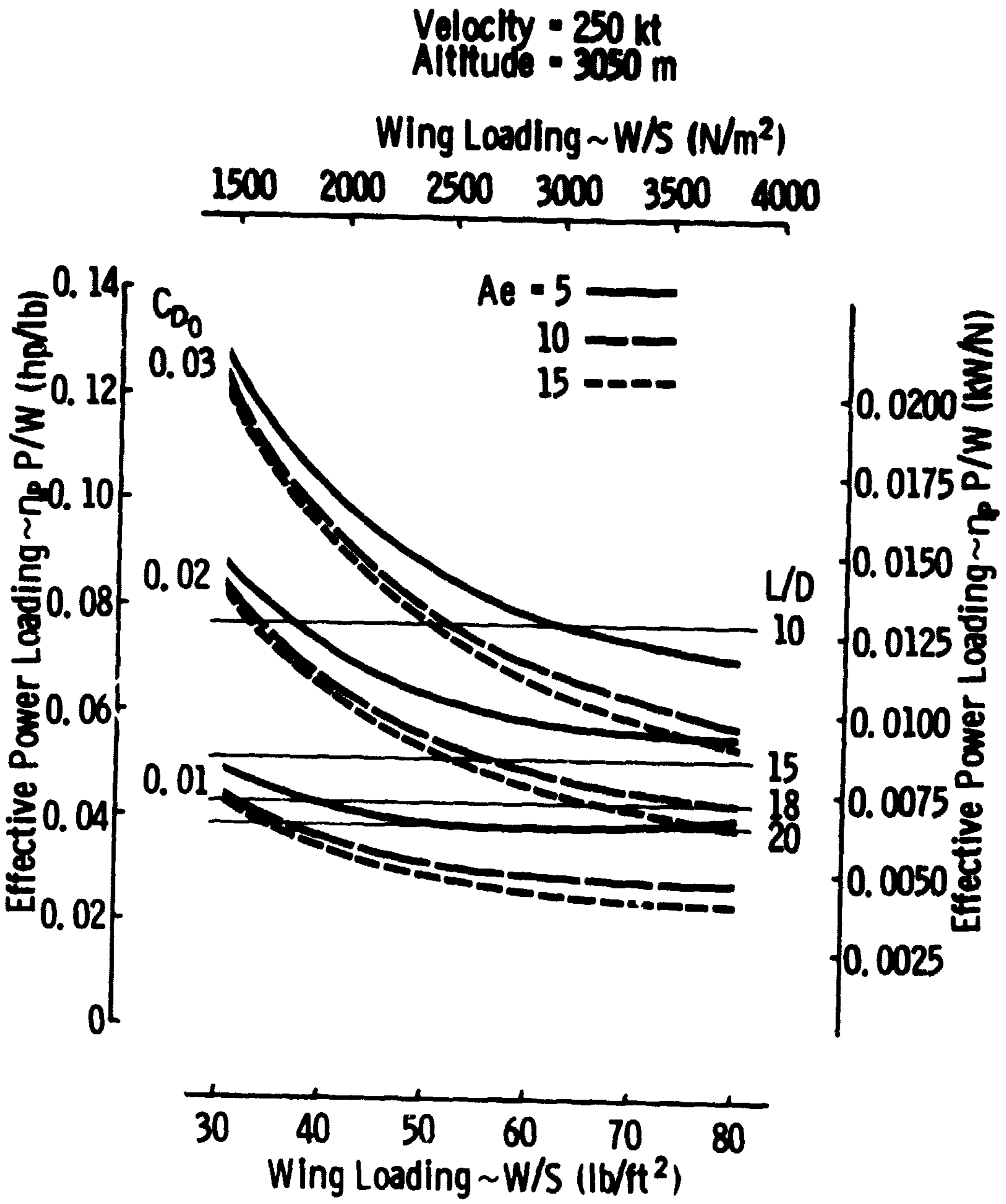


Fig. 5.5. Commuter Cruise Trade Studies

The balanced field length studies were developed in terms of C_{D_0}, effective aspect ratio Ae, maximum lift coefficient in takeoff configuration ($C_{L_{max_{TO}}}$), and effective power loading (η_p P/W). The studies show that balanced field length is dependent primarily on $C_{L_{max_{TO}}}$ and (η_p P/W). Results of this study are presented as Figures 5.6, 5.7, and 5.8, and were developed for values of C_{D_0} = .075 and Ae = 10.

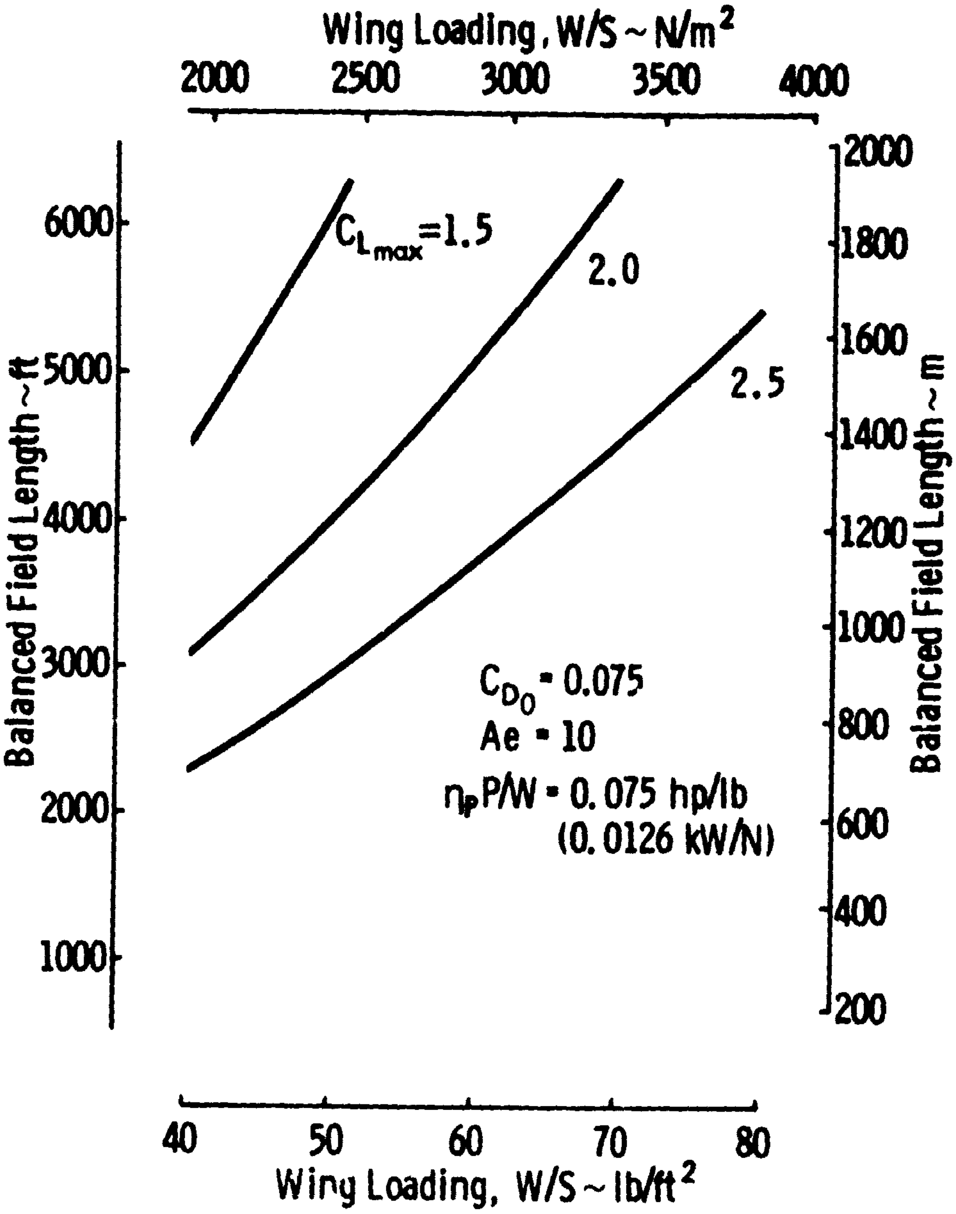


Fig. 5.6. Commuter Balanced Field Length Studies

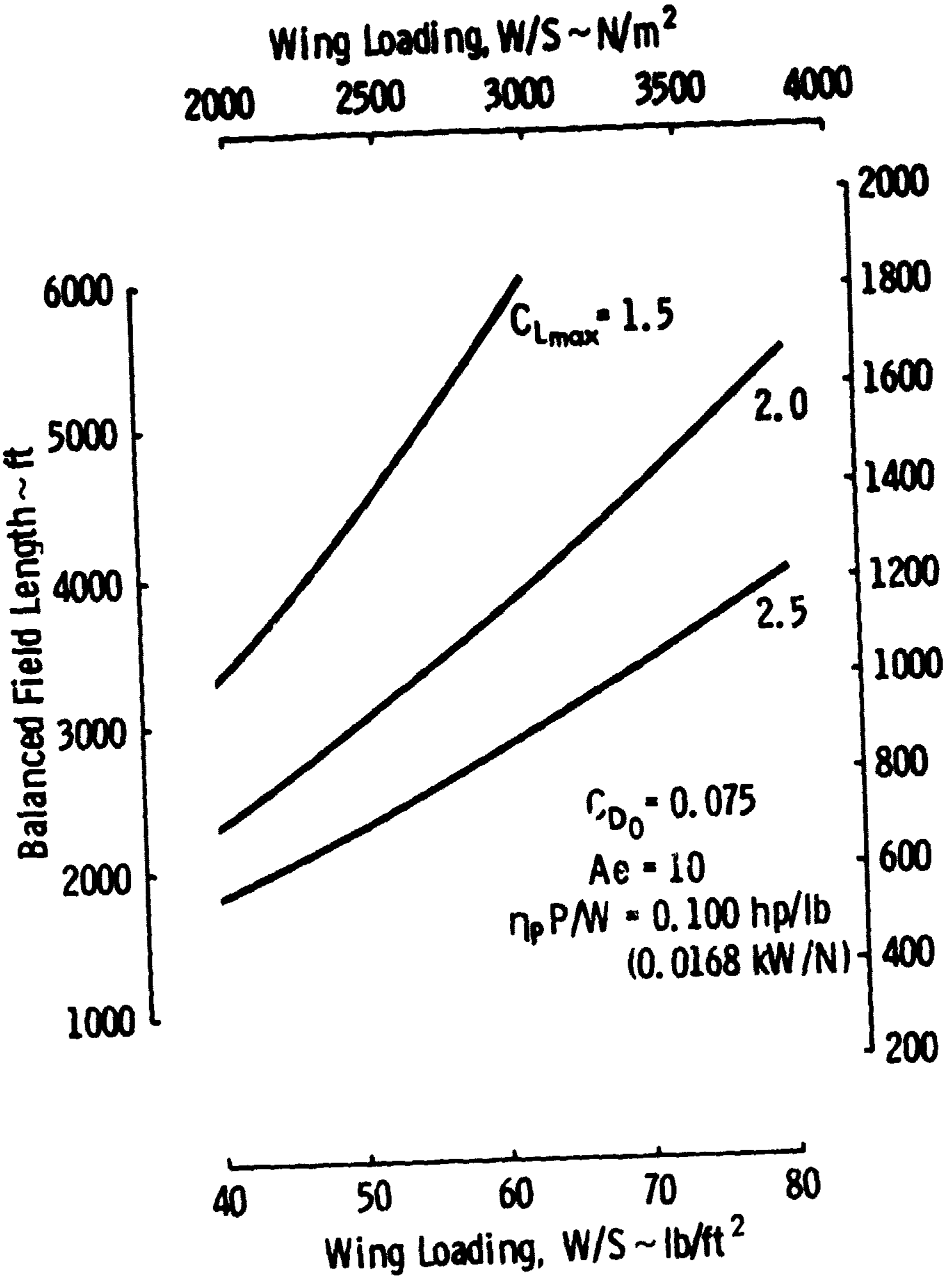


Fig. 5.7. Commuter Balanced Field Length Studies

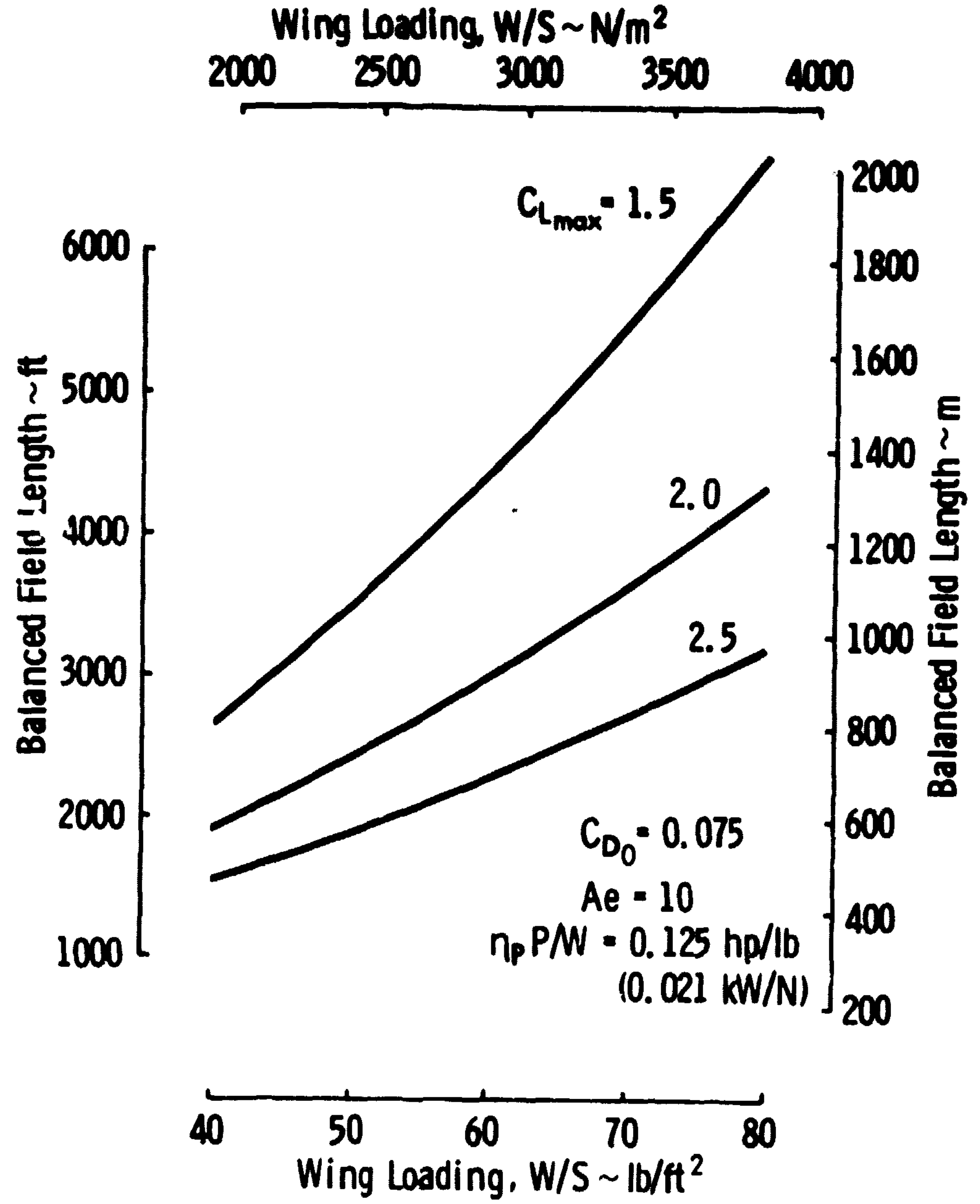


Fig. 5.8. Commuter Balanced Field length Studies.

Observations resulting from an examination of these figures appear in Table 5.6.

Table 5.6. Commuter Trade Study Summary

CRUISE TRADE STUDIES
Current commuters have values of $C_{D_o} \simeq .025$, $Ae \simeq 6.0$, and $W/S \simeq 2155\ N/m^2$, at a cruise altitude of 3050 m. **L/D = 18 demands extremely low values of C_{D_o} ($\simeq .02$), coupled with high wing loadings ($\simeq 3352\ N/m^2$). As was the case with** the 6-passenger design a $C_{D_o} \approx .02$ appears very difficult to achieve under conditions of high wing loadings.
BALANCED FIELD LENGTH
Because of the high wing loadings desired in cruise flight, advanced flap technology is required (full span Fowler flaps). High $C_{L_{max}}$ in takeoff allows lower power loadings for takeoff and thereby maintains a more reasonable difference between cruise and takeoff power requirements.

These results dictated relaxation of two of the original specifications. First, the requirement for $V_{stall} \leq 60$ kt is not practical for the commuter aircraft since these aircraft (in the 18-19 passenger range) typically are not constrained by this requirement. A survey for a commuter traffic model presented in Reference 44 showed that 93% of the airports in use had effective runway lengths of 1220 m or greater, where effective length is defined as the actual runway length corrected to sea level standard conditions. Hence, balanced field length as opposed to stall speed is more critical in the determination of accessible airports. Second, the L/D requirement of 18 was relaxed to a value of 12 due to a desired cruise altitude of 3050 m.

This altitude was selected because available data indicated that the bulk of the commuter market could be accessed without having to cruise at higher altitudes. Figure 5.5 clearly indicates that L/D ≈ 12 is a more realistic goal. The design goals established for the commuter aircraft were:

Parameters:

$W/S = 3112\ N/m^2$

$A = 12$

Goals:

$C_{D_o} \approx .020 - .025$

$e \approx .75$

$C_{L_{max_{TO}}} = 2.5$

5.4 CONCEPTUAL DESIGNS

This section describes the conceptual design of conventional and canard configurations for the 6-passenger and commuter airplanes which incorporate the advanced technologies discussed in Section 5.2. Current technology baseline airplanes were also established to provide a basis for comparison of the advanced technology designs.

The project staff was aided in this effort by the senior design class of the Aerospace Engineering Department at the University of Kansas. The additional manpower proved valuable to the design effort and assisted in identifying unforeseen difficulties associated with technology integration and configuration analysis.

5.4.1 6-Passenger Designs

A current technology baseline, an advanced technology conventionally configured vehicle, and a canard configuration were synthesized.

All three designs utilize the same basic cabin, which seats six passengers (all facing forward), and has a baggage area behind the rear seats. The cabin, which is illustrated in Figure 5.9, is somewhat idealized since it was common to all three designs. A more involved design effort would probably result in a more rounded cross-section with contours more closely matched to the configuration in question.

Design of the 6-Passenger airplanes followed the methods outlined below. Detailed procedures may be found in Appendix C.

(1) Preliminary Sizing

An initial gross weight was estimated using the Breguet range equation and the wing was sized accordingly. Tail areas were sized with tail volume coefficients obtained from similar types of existing airplanes.

(2) Weight and Balance

Component weights were calculated giving an improved weight estimate and providing center of gravity information.

(3) Horizontal Tail Sizing

The horizontal tail area required was determined from static margin and takeoff rotation requirements.

NOTES: (1) Scale: 1/40

(2) All dimensions are inside dimensions

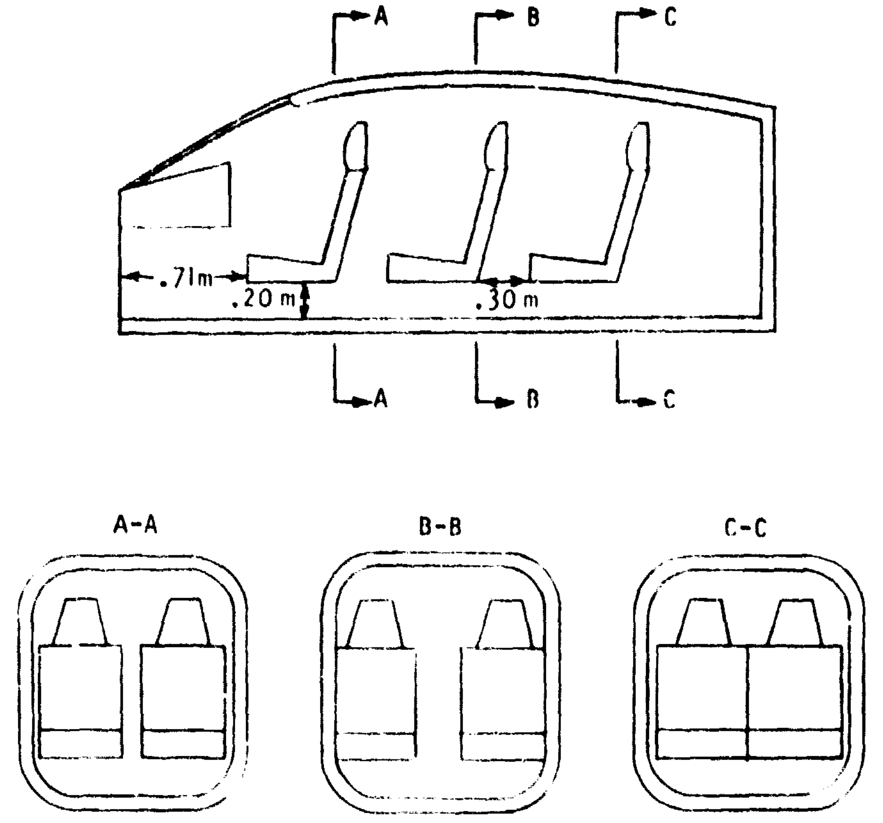
(3) Cabin length = .66 m

(4) Max cabin width = 1.17 m

(5) Max cabin height = 1.27 m

(6) Cabin wall thickness = .08 m

(7) Seat pitch = .66 m



Cabin Width = 1.12 m
Cabin Height = 1.22 m
Seat Width = .46 m

Cabin Width = 1.17 m
Cabin Height = 1.27 m
Seat Width = .46 m
Aisle Width = .25 m

Cabin Width = 1.12 m
Cabin Height = 1.22 m
Seat Width = .51 m

Fig. 5.9. 6-Passenger Cabin Layout

(4) **Aerodynamics**

Airplane wetted area and zero lift drag coefficient were calculated.

(5) **Final Sizing**

GASP (General Aviation Synthesis Program) was used to "fly" the airplane. Engine size and gross weight were adjusted to meet the design specifications. Prior to the actual sizing, GASP weight and drag routines were calibrated against the manual calculations.

The three 6-Passenger designs are discussed separately in the following sections.

5.4.1.1 Current Technology Baseline. The 6-Passenger current technology baseline (6PAXBL) provides a basis of comparison for the advanced technology airplane.

In designing 6PAXBL, characteristics of current high performance, single engine, general aviation airplanes were retained as much as possible. The major exception was that a 7620 m cruise altitude was assumed so that the power required at cruise would not result in an exceptionally large engine. Specifications for this airplane are those shown in Table 5.1 with the exception of the L/D $\geq$ 18 goal. 6PAXBL has the following characteristics:

(1) Geared, fuel injected, turbocharged, air-cooled, 6-cylinder (opposed) reciprocating engine.

(2) Conventional aluminum structure.

(3) Partial span, single-slotted flaps.

(4) Conventional control surfaces.

(5) Cruise altitude of 7620 m; pressurized to maintain a 2440 m cabin.

(6) NACA 64_2-A215 airfoil.

(7) $W/S = 1053.4\ N/m^2$ $(22\ lb/ft^2)$.

(8) $A = 7.5$.

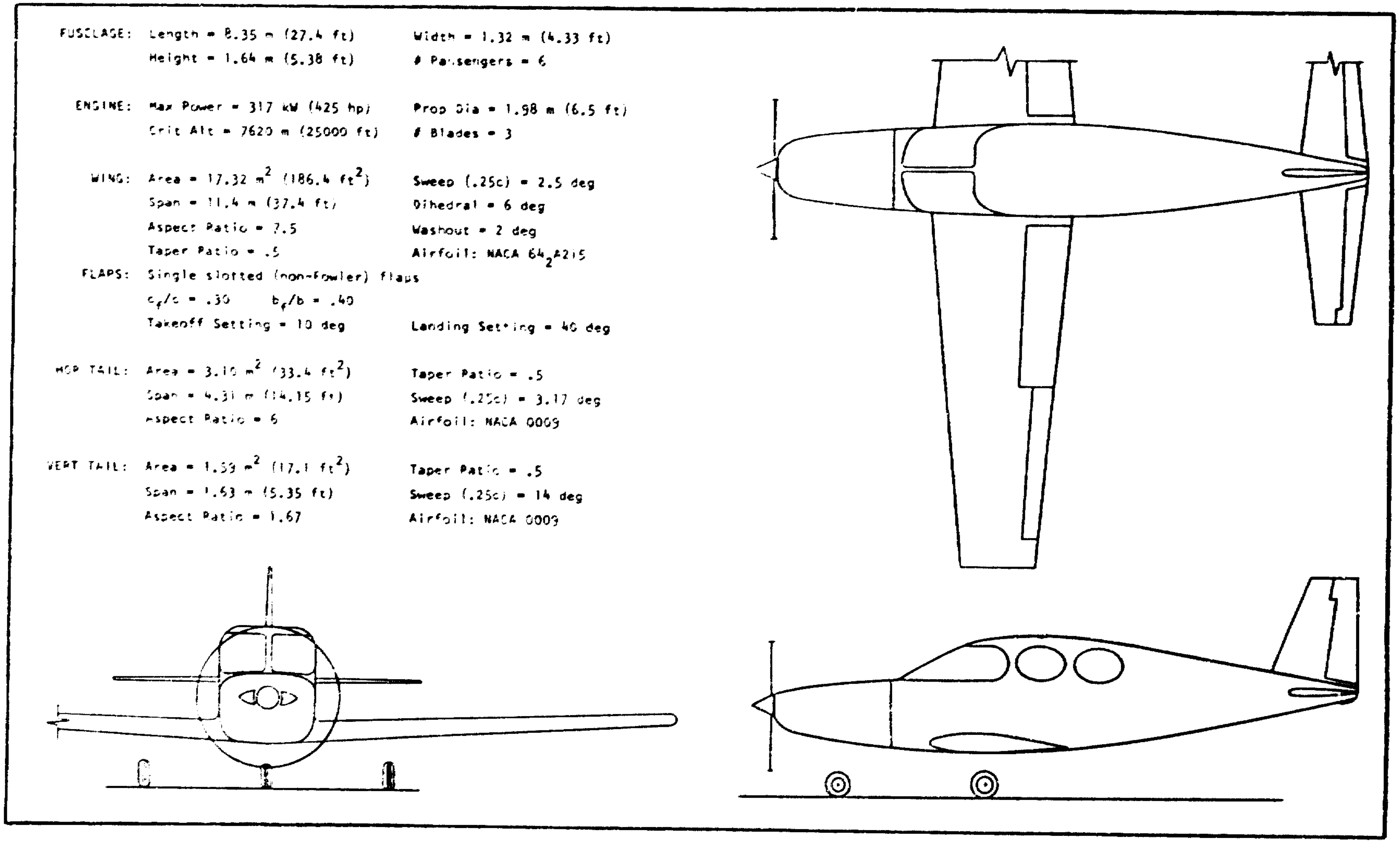
The design procedures discussed in Section 5.4.1 resulted in the 6PAXBL design shown in Figure 5.10 and Table 5.7 summarizes the characteristics and performance of this airplane.

Referring to Table 5.7 one notes that 6PAXBL is a high performance airplane which has speed, payload, and range characteristics more similar to those of the Bellanca Skyrocket than to those of more conventional general aviation airplanes. A comparison of 6PAXBL to the advanced technology designs and to existing airplanes is discussed in Section 5.5.

5.4.1.2 Advanced Technology Conventional Configuration.

The 6-Passenger conventional configuration, advanced technology airplane (6PAXAD) incorporates the technologies listed in Table 5.3. The trade studies of Section 5.3.1 were used to define the basic airplane parameters.

No real problems were encountered in the conceptual design of 6PAXAD but detailed design of the flap and spoiler systems would be complicated by the small size of the wing. The general characteristics of this airplane are as follows:



FUSELAGE: Length = 8.35 m (27.4 ft) Width = 1.32 m (4.33 ft)
Height = 1.64 m (5.38 ft) # Passengers = 6

ENGINE: Max Power = 317 kW (425 hp) Prop Dia = 1.98 m (6.5 ft)
Crit Alt = 7620 m (25000 ft) # Blades = 3

WING: Area = 17.32 m^2 (186.4 ft^2) Sweep (.25c) = 2.5 deg
Span = 11.4 m (37.4 ft) Dihedral = 6 deg
Aspect Ratio = 7.5 Washout = 2 deg
Taper Ratio = .5 Airfoil: NACA 64_2A215

FLAPS: Single slotted (non-Fowler) flaps
$c_f/c = .30$ $b_f/b = .40$
Takeoff Setting = 10 deg Landing Setting = 40 deg

HOR TAIL: Area = 3.10 m^2 (33.4 ft^2) Taper Ratio = .5
Span = 4.31 m (14.15 ft) Sweep (.25c) = 3.17 deg
Aspect Ratio = 6 Airfoil: NACA 0009

VERT TAIL: Area = 1.59 m^2 (17.1 ft^2) Taper Ratio = .5
Span = 1.63 m (5.35 ft) Sweep (.25c) = 14 deg
Aspect Ratio = 1.67 Airfoil: NACA 0009

Fig. 5.10. Current Technology 6-Passenger Design

Table 5.7. 6-Passenger Current Technology Baseline Characteristics

WEIGHTS

Gross = 1859.8 kg (4100 lb)

Payload = 544.3 kb (1200 lb)

Empty = 1051.4 kg (2318 lb)

Fuel (max payload) = 264 kg (582 lb)

ENGINE

Geared, fuel injected, turbocharged, air-cooled 6-cylinder (opposed) reciprocating

Max Power = 317 kW (425 hp)

Critical Altitude = 7620 m (25,000 ft)

Cruise BSFC = $.274 \frac{kg}{kW\text{-}hr}$ ($.450 \frac{lb}{hp\text{-}hr}$)

Dry Specific Weight = .894 kg/kW (1.47 lb/hp)

TBO = 1800 hr

PERFORMANCE

V_{cruise} = 250 kt (75% power, gross weight)[1]

Range = 900 nm + 45 min. reserves (250 kt, 544.3 kg (1200 lb) payload)[2]

L/D = 11.7 (250 kt, gross weight)[1]

V_{stall} = 58.3 kt (flaps 40°)

Takeoff dist. over 10.7 m (35 ft) obstacle = 540 m (1771 ft) (flaps 10°)[2]

Landing dist. over 15.2 m (50 ft) obstacle = 351 m (1152 ft) (flaps 40°)[2]

[1] 7620 m (25,000 ft) altitude

[2] Sea level, gross weight

(1) Geared, stratified charge, highly turbocharged, liquid cooled, 2-rotor, rotary combustion engine.

(2) Composite (Kevlar and/or graphite) structure.

(3) Full span single-slotted Flower flaps.

(4) Spoilers for roll control.

(5) Cruise altitude of 9140 m; pressurized to maintain a 2440 m cabin.

(6) NASA advanced natural laminar flow airfoil.

(7) W/S = 2154.6 N/m^2 (45 lb/ft^2)

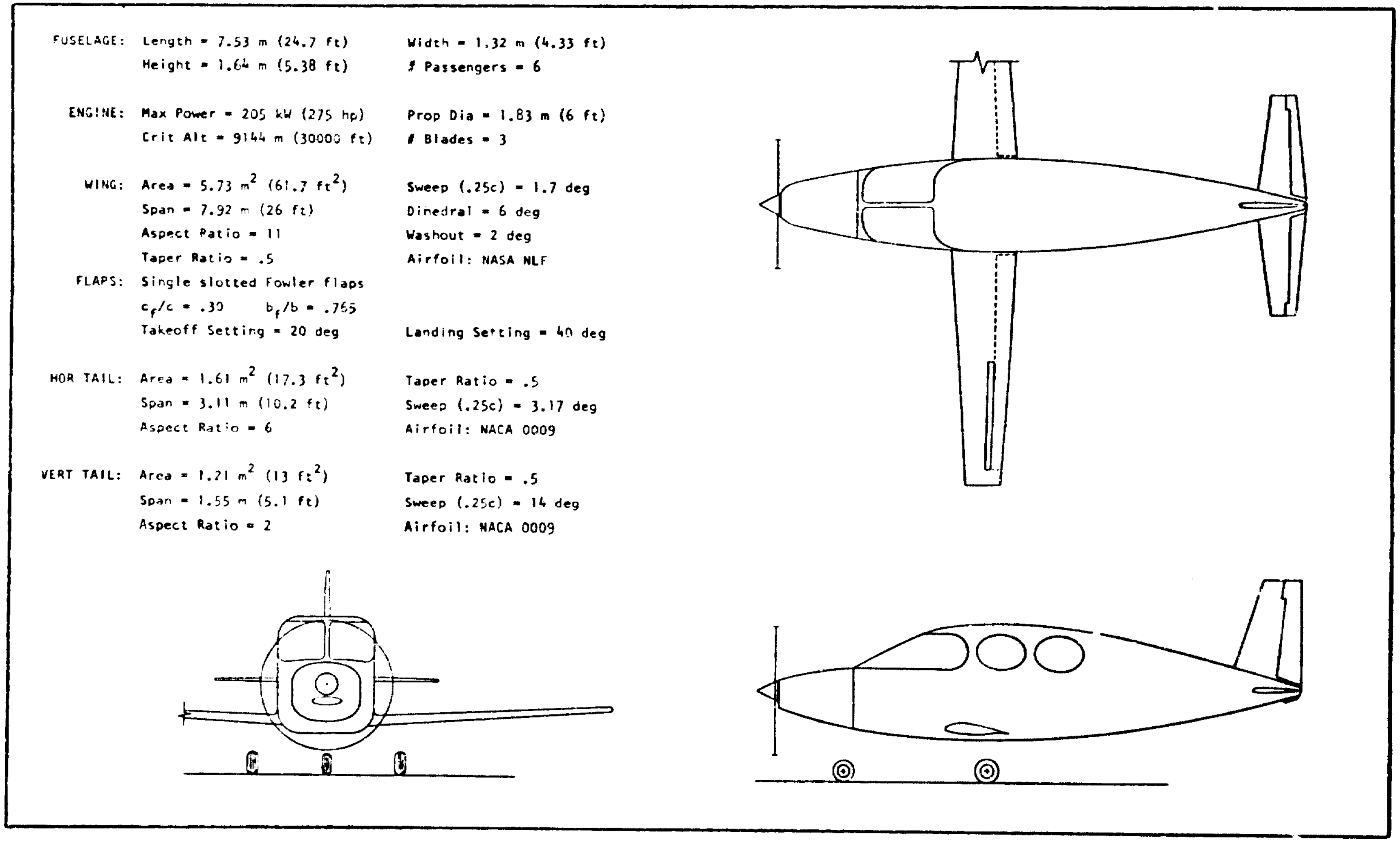
(8) A = 11

Here, the design procedures previously discussed in Section 5.4.1 resulted in the 6PAXAD design shown in Figure 5.11 and Table 5.8 summarizes its characteristics and performance.

Table 5.8 shows that the 6PAXAD design meets the required specifications of Table 5.1 but does not have the desired L/D $\geq$ 18 or $V_{stall} \leq$ 60 kt. A detailed discussion of 6PAXAD together with a comparison with 6PAXBL is presented in Section 5.5.

5.4.1.3 Advanced Technology Canard Configuration. The 6-Passenger canard configuration, advanced tehcnology airplane (6PAXC) incorporates the technologies listed in Table 5.3 and the trade studies of Section 5.3.1 were again used to define the basic airplane parameters.

Several problems were encountered in the design of 6PAXC. First, methods for sizing the canard and for calculating induced drag were lacking. Second, GASP will not handle canards. For



FUSELAGE:	Length = 7.53 m (24.7 ft)	Width = 1.32 m (4.33 ft)
	Height = 1.64 m (5.38 ft)	# Passengers = 6
ENGINE:	Max Power = 205 kW (275 hp)	Prop Dia = 1.83 m (6 ft)
	Crit Alt = 9144 m (30000 ft)	# Blades = 3
WING:	Area = 5.73 m^2 (61.7 ft^2)	Sweep (.25c) = 1.7 deg
	Span = 7.92 m (26 ft)	Dihedral = 6 deg
	Aspect Ratio = 11	Washout = 2 deg
	Taper Ratio = .5	Airfoil: NASA NLF
FLAPS:	Single slotted Fowler flaps	
	c_f/c = .30 b_f/b = .765	
	Takeoff Setting = 20 deg	Landing Setting = 40 deg
HOR TAIL:	Area = 1.61 m^2 (17.3 ft^2)	Taper Ratio = .5
	Span = 3.11 m (10.2 ft)	Sweep (.25c) = 3.17 deg
	Aspect Ratio = 6	Airfoil: NACA 0009
VERT TAIL:	Area = 1.21 m^2 (13 ft^2)	Taper Ratio = .5
	Span = 1.55 m (5.1 ft)	Sweep (.25c) = 14 deg
	Aspect Ratio = 2	Airfoil: NACA 0009

Fig. 5.11. Advanced Technology Conventional Configuration 6-Passenger Design

Table 5.8. 6-Passenger Advanced Technology Conventional Configuration Characteristics

WEIGHTS

Gross = 1258.7 kg (2775 lb)   Payload = 544.3 kg (1200 lb)

Empty = 582 kg (1283 lb)   Fuel (max payload) = 132.5 kg (292 lb)

ENGINE

Geared, stratified charge, highly turbocharged, liquid-cooled 2-rotor, rotary combustion

Max Power = 205 kW (275 hp)

Critical Altitude = 9144 m (30,000 ft)

Cruise BSFC = $.231 \frac{\text{kg}}{\text{kW-hr}}$ ($.38 \frac{\text{lb}}{\text{hp-hr}}$)

Dry Specific Weight = .45 kg/kW (.74 lb/hp)

TBO = 3000 hr

PERFORMANCE

V_{cruise} = 250 kt (75% power, gross weight)[1]

Range = 900 nm + 45 min. reserves (250 kt, 544.3 kg (1200 lb) payload)[2]

L/D = 14.2 (250 kt, gross weight)[1]

V_{stall} = 64.5 kt (flaps 40°)[2]

Takeoff dist. over 10.7 m (35 ft) obstacle = 610 m (1999 ft) (flaps 20°)[2]

Landing dist. over 15.2 m (50 ft) obstacle = 406 m (1332 ft) (flaps 40°)[2]

[1] 9144 m (30,000 ft) altitude

[2] Sea level, gross weight

these reasons, 6PAXC cannot legitimately be compared to 6PAXBL or 6PAXAD, and as presented here, must be considered only as a possible configuration and not as a refined design. These problems are discussed in greater detail in Section 5.4.3.

General characteristics of the canard design are the same as those of 6PAXAD as follows:

(1) Geared, stratified charge, highly turbocharged, liquid cooled, 2-rotor, rotary combustion engine.

(2) Composite (Kevlar and/or graphite) structure.

(3) Full span single-slotted Fowler flaps.

(4) Spoilers for roll control.

(5) Cruise altitude of 9140 m; pressurized to maintain a 2440 m cabin.

(6) NASA advanced natural laminar flow airfoil.

(7) $W/S = 2154.6 \text{ N/m}^2$ (45 lb/ft^2)

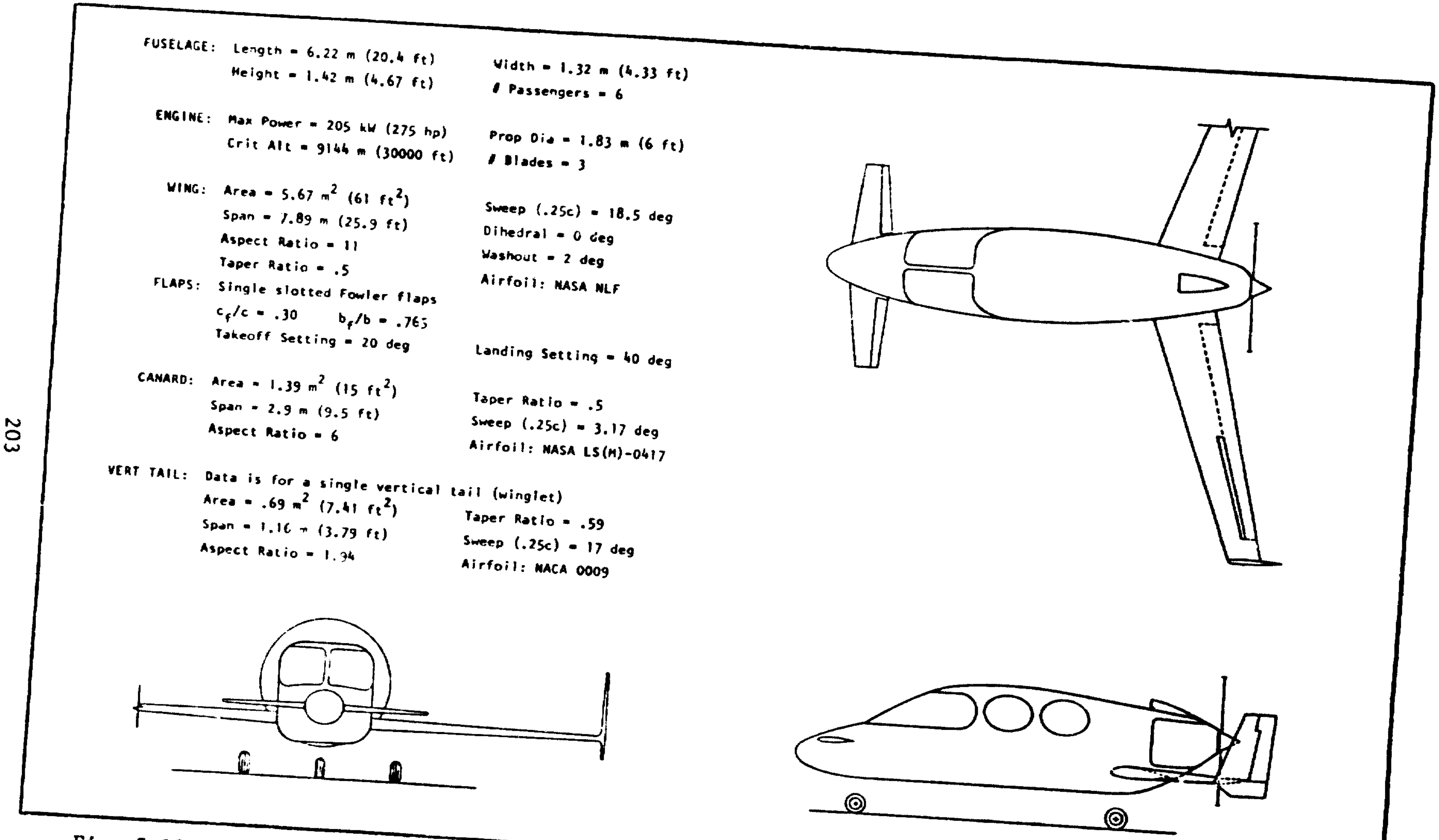
(8) $A = 11$

The full span flaps called for may create a trim problem but the extent of the problem, if it exists, was not investigated due to the previously mentioned lack of reliable analysis techniques.

Figure 5.12 presents a 3-view of the advanced technology canard configuration.

5.4.2 Commuter Designs

An advanced technology conventional configuration and an advanced technology canard configuration were synthesized. A third existing aircraft was selected as a baseline for comparison.



FUSELAGE: Length = 6.22 m (20.4 ft)
Height = 1.42 m (4.67 ft)
Width = 1.32 m (4.33 ft)
# Passengers = 6

ENGINE: Max Power = 205 kW (275 hp)
Crit Alt = 9144 m (30000 ft)
Prop Dia = 1.83 m (6 ft)
Blades = 3

WING: Area = 5.67 m^2 (61 ft^2)
Span = 7.89 m (25.9 ft)
Aspect Ratio = 11
Taper Ratio = .5
Sweep (.25c) = 18.5 deg
Dihedral = 0 deg
Washout = 2 deg
Airfoil: NASA NLF

FLAPS: Single slotted Fowler flaps
c_f/c = .30 b_f/b = .765
Takeoff Setting = 20 deg
Landing Setting = 40 deg

CANARD: Area = 1.39 m^2 (15 ft^2)
Span = 2.9 m (9.5 ft)
Aspect Ratio = 6
Taper Ratio = .5
Sweep (.25c) = 3.17 deg
Airfoil: NASA LS(M)-0417

VERT TAIL: Data is for a single vertical tail (winglet)
Area = .69 m^2 (7.41 ft^2)
Span = 1.16 m (3.79 ft)
Aspect Ratio = 1.94
Taper Ratio = .59
Sweep (.25c) = 17 deg
Airfoil: NACA 0009

Fig. 5.12. Advanced Technology Canard Configuration 6-Passenger Design

The existing aircraft selected has a 19 passenger capability and was selected because it is one of very few aircraft specifically designed as a commuter.

Both advanced technology conceptual designs utilize the same fuselage interior. Accommodations are included for 19 passengers (sitting three abreast) and two pilots. Additional space is included for cabin furnishings and a flight attendant. A baggage/cargo area is included behind the passenger area, with access through an upward opening cargo door. The passenger area of the aircraft is entered through a smaller door at the front of the cabin. Figure 5.13 presents this interior arrangement.

Design of the advanced technology aircraft followed the procedures outlined below. Detailed data and calculations may be found in Appendix C.2.

(1) Preliminary Sizing

The gross weight of each of the advanced designs was matched to the baseline aircraft. Tail areas were determined initially by minimum static stability requirements.

(2) Weight and Balance

A detailed weight and balance calculation was performed for each of the designs because interior furnishings and accommodations for these aircraft constitute a large portion of the aircraft weight.

(3) Horizontal Tail Sizing

The horizontal tail was sized for static margin and rotation requirements.

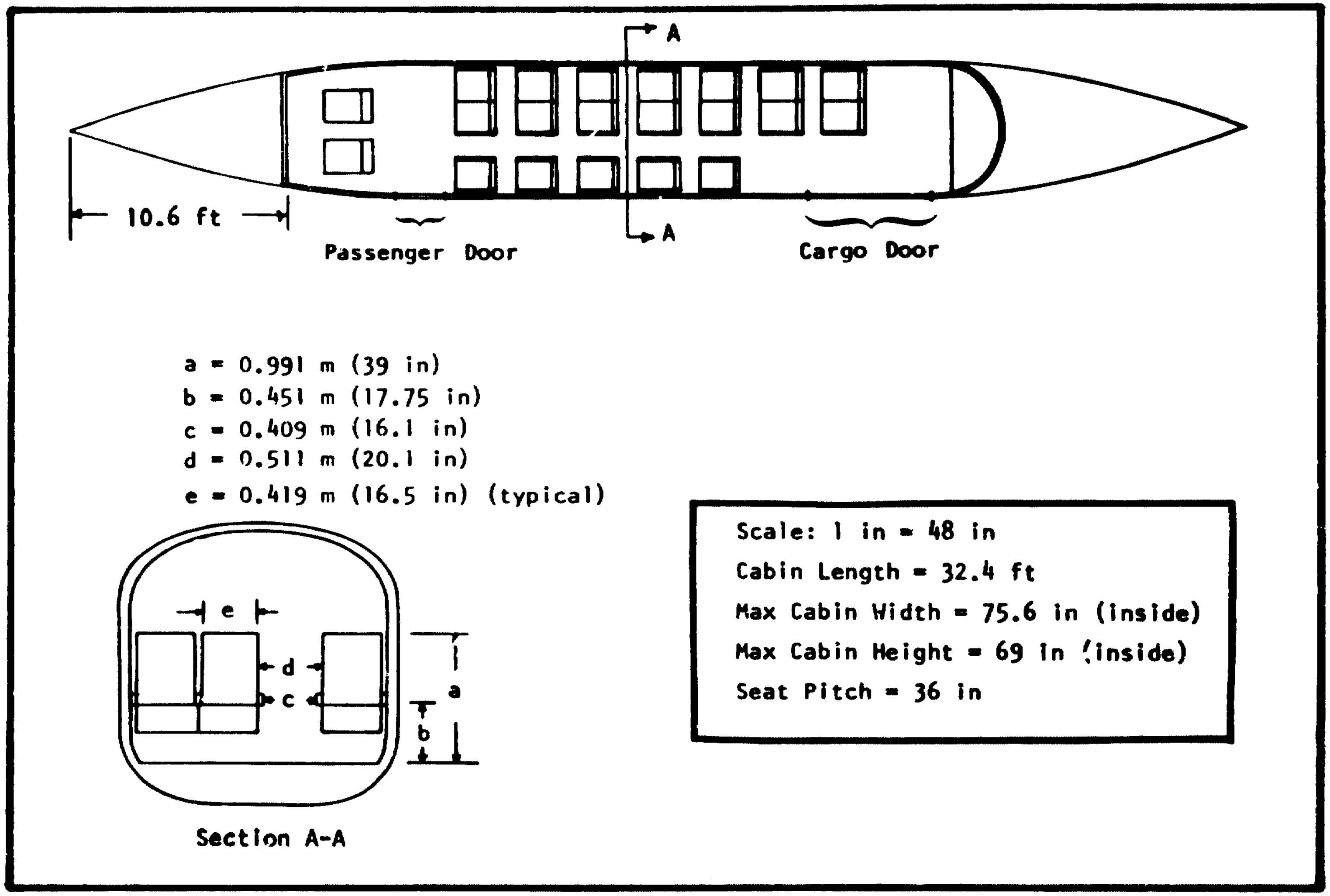


Fig. 5.13. Commuter Cabin Layout

(4) **Aerodynamics**

Airplane wetted area and zero lift drag coefficient were calculated.

(5) **Final Sizing**

GASP was used to perform the mission analysis of the aircraft. Here, gross weight was maintained while engine size was adjusted to meet design specifications. Two specific missions were analyzed. The first involved a single leg mission at gross weight, while the second was characterized by nine 87 nm legs at a 60% load factor. Both missions were flown at 3048 m. Prior to mission analysis, GASP was calibrated to obtain the drag and weight characteristics which were predicted through manual calculations.

The two advanced designs and the baseline aircraft are discussed separately in the following sections.

5.4.2.1 Current Technology Baseline. The aircraft utilized for the current technology baseline (COMBL) appears in Figure 5.14.

The characteristics of COMBL are:

(1) Twin turboprop engines.

(2) Conventional aluminum structure.

(3) Partial span, double-slotted flaps.

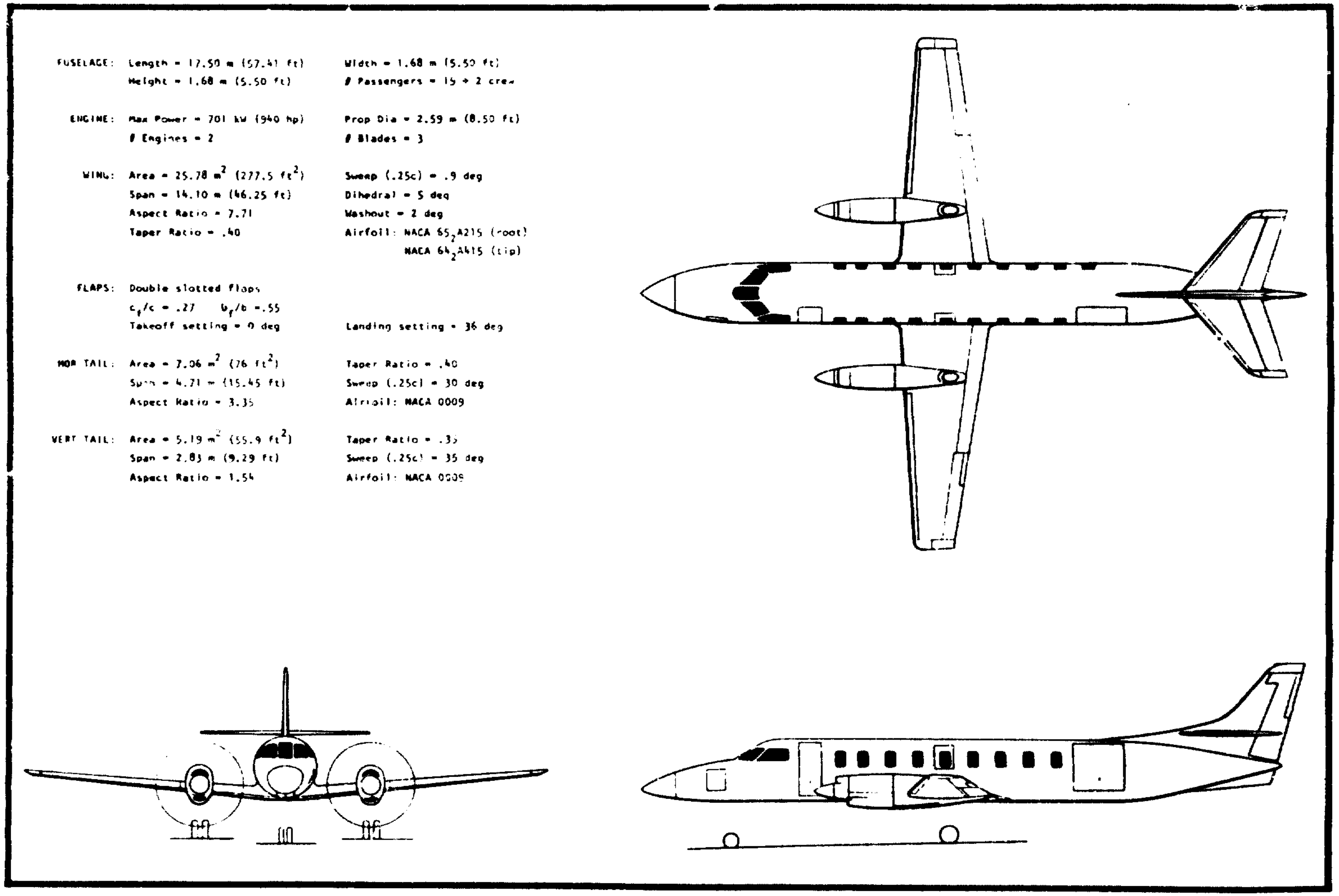
(4) Conventional control surfaces.

(5) Cruise altitude = 3048 m.

(6) NASA 65_2A215 at the root, NACA 64_2A415 at the tip.

(7) W/S = 2157 N/m2

(8) A = 7.71



FUSELAGE: Length = 17.50 m (57.41 ft) Width = 1.68 m (5.50 ft)
Height = 1.68 m (5.50 ft) # Passengers = 15 + 2 crew

ENGINE: Max Power = 701 kW (940 hp) Prop Dia = 2.59 m (8.50 ft)
Engines = 2 # Blades = 3

WING: Area = 25.78 m^2 (277.5 ft^2) Sweep (.25c) = .9 deg
Span = 14.10 m (46.25 ft) Dihedral = 5 deg
Aspect Ratio = 7.71 Washout = 2 deg
Taper Ratio = .40 Airfoil: NACA 65_2A215 (root)
NACA 64_2A415 (tip)

FLAPS: Double slotted flaps
$c_f/c = .27$ $b_f/b = .55$
Takeoff setting = 0 deg Landing setting = 36 deg

HOR TAIL: Area = 7.06 m^2 (76 ft^2) Taper Ratio = .40
Span = 4.71 m (15.45 ft) Sweep (.25c) = 30 deg
Aspect Ratio = 3.35 Airfoil: NACA 0009

VERT TAIL: Area = 5.19 m^2 (55.9 ft^2) Taper Ratio = .35
Span = 2.83 m (9.29 ft) Sweep (.25c) = 35 deg
Aspect Ratio = 1.54 Airfoil: NACA 0009

Fig. 5.14. Commuter Baseline Configuration

The performance characteristics of COMBL are summarized in Table 5.9.

Table 5.9. Commuter Current Technology Baseline Characteristics

WEIGHTS

Gross = 5670 kg (12500 lb)

Empty = 3379 kg (7450 lb)

Max Fuel Weight = 1969 kg (4342 lb)

ENGINES

Turboprop with emergency methanol injection

Max Power 708.4 kW (950 hp)

Cruise BSFC = $.335 \frac{\text{kg}}{\text{kW-hr}}$ $(.55 \frac{\text{lb}}{\text{hp-hr}})$

Dry Specific Weight = 4.36 kW/kg (2.65 hp/lb)

TBO = 3000 hr

PERFORMANCE

V_{cruise} = 250 kt @ 60% power, 3048 m (10,000 ft), 5670 kg (12,500 lb)

L/D = 10.44 [3048 m (10,000 ft), 5670 kg (12,500 lb)]

V_{stall} = 87 kt (flaps 36°, sea level, 5670 kg (12,500 lb))

Takeoff Distance over 10.7 m (35 ft) obstacle = 914 m (3000 ft) (flaps 0°, sea level, 5670 kg (12,500 lb))

Landing Distance over 15.2 m (50 ft) obstacle = 897 m (2944 ft) (flaps 36°, sea level, 5670 kg (12,500 lb))

Balanced Field Length = 1149 m (3771 ft)(takeoff configuration, 5670 kg (12,500 lb))

Single Engine Service Ceiling = 3962 m (13,000 ft) (5670 kg (12,500 lb))

The performance characteristics of COMBL are summarized in Table 5.9.

Table 5.9. Commuter Current Technology Baseline Characteristics

WEIGHTS

Gross = 5670 kg (12500 lb)

Empty = 3379 kg (7450 lb)

Max Fuel Weight = 1969 kg (4342 lb)

ENGINES

Turboprop with emergency methanol injection

Max Power 708.4 kW (950 hp)

Cruise BSFC = $.335 \frac{\text{kg}}{\text{kW-hr}}$ $(.55 \frac{\text{lb}}{\text{hp-hr}})$

Dry Specific Weight = 4.36 kW/kg (2.65 hp/lb)

TBO = 3000 hr

PERFORMANCE

V_{cruise} = 250 kt @ 60% power, 3048 m (10,000 ft), 5670 kg (12,500 lb)

L/D = 10.44 [3048 m (10,000 ft), 5670 kg (12,500 lb)]

V_{stall} = 87 kt (flaps 36°, sea level, 5670 kg (12,500 lb))

Takeoff Distance over 10.7 m (35 ft) obstacle = 914 m (3000 ft) (flaps 0°, sea level, 5670 kg (12,500 lb))

Landing Distance over 15.2 m (50 ft) obstacle = 897 m (2944 ft) (flaps 36°, sea level, 5670 kg (12,500 lb))

Balanced Field Length = 1149 m (3771 ft)(takeoff configuration, 5670 kg (12,500 lb))

Single Engine Service Ceiling = 3962 m (13,000 ft) (5670 kg (12,500 lb))

5.4.2.2 Conventional Configuration Advanced Technology Commuter.

The conventional configuration, advanced technology commuter (ADCOM) incorporates the technologies listed in Table 5.4. The trade studies of Section 5.3.2 were used as guidelines for the definition of the basic airplane parameters.

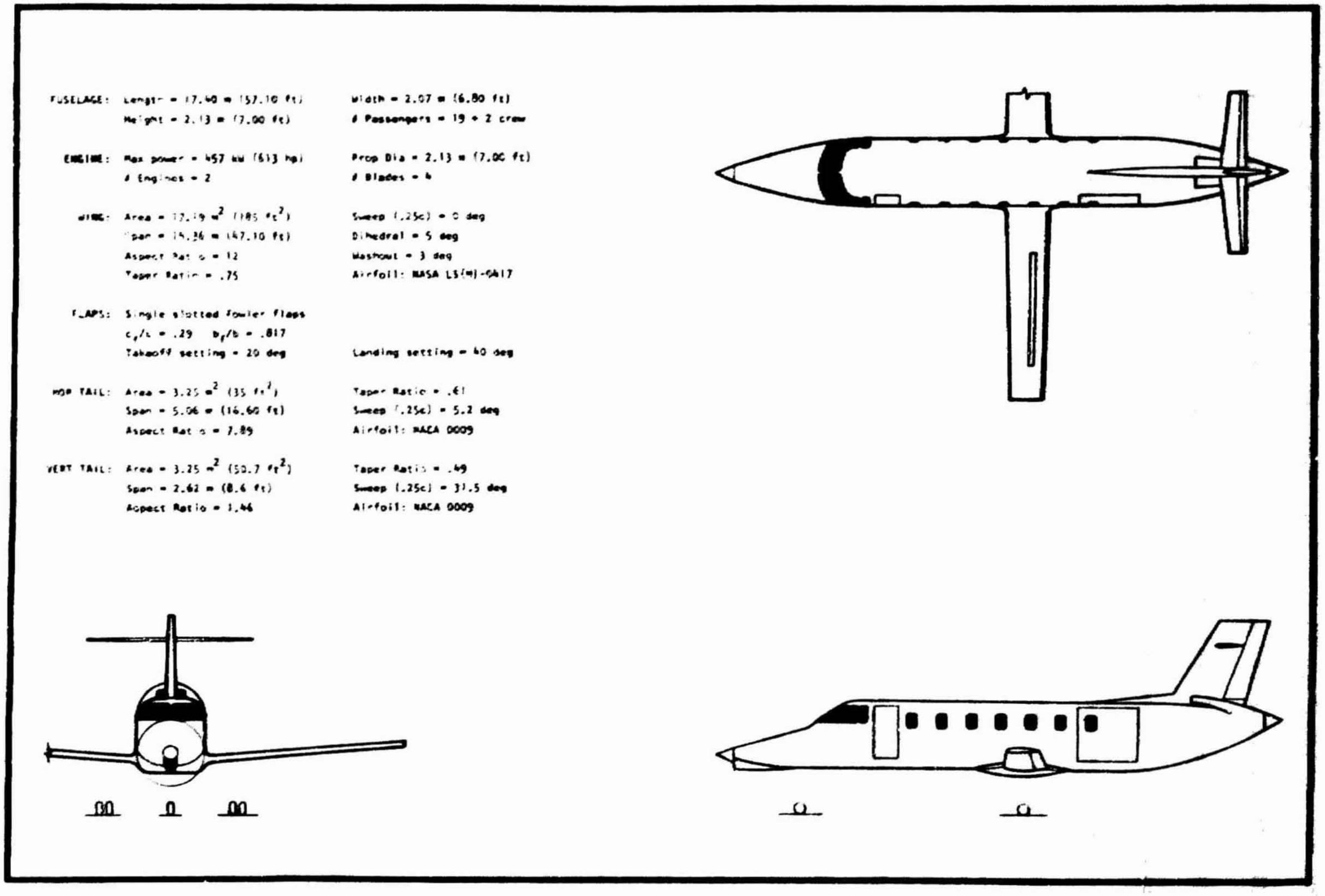
The conceptual design of ADCOM proceeded rather smoothly, and only one major difficulty was encountered. Because of the small wing size, the wing volume available for fuel became critical. However, a manual calculation using conservative approximations revealed that available wing volume could accommodate the mission fuel. Figure 5.15 presents a 3-view of ADCOM.

Also, the characteristics of ADCOM are presented in Table 5.10.

5.4.2.3 Canard Configured Advanced Technology Commuter.

The problems encountered with the 6-Passenger canard design also hampered the commuter canard design. Initial sizing and wing/canard location were determined utilizing conventional configuration analysis methods. For this reason, the advanced technology canard commuter (ADCOMCN) should closely approximate the results which could be expected from more sophisticated methods. However, lacking verification, this canard should not be compared with the advanced technology conventional configuration (ADCOM) or the baseline aircraft (COMBL).

Figure 5.16 presents a 3-view of ADCOMCN, which is characterized by the following:



FUSELAGE: Length = 17.40 m (57.10 ft)
Height = 2.13 m (7.00 ft)
Width = 2.07 m (6.80 ft)
# Passengers = 19 + 2 crew

ENGINE: Max power = 457 kW (613 hp)
Engines = 2
Prop Dia = 2.13 m (7.00 ft)
Blades = 4

WING: Area = 17.19 m^2 (185 ft^2)
Span = 14.36 m (47.10 ft)
Aspect Ratio = 12
Taper Ratio = .75
Sweep (.25c) = 0 deg
Dihedral = 5 deg
Washout = 3 deg
Airfoil: NASA LS(M)-0417

FLAPS: Single slotted Fowler flaps
c_f/c = .29 b_f/b = .817
Takeoff setting = 20 deg
Landing setting = 40 deg

HOR TAIL: Area = 3.25 m^2 (35 ft^2)
Span = 5.06 m (16.60 ft)
Aspect Ratio = 7.89
Taper Ratio = .61
Sweep (.25c) = 5.2 deg
Airfoil: NACA 0009

VERT TAIL: Area = 3.25 m^2 (50.7 ft^2)
Span = 2.62 m (8.6 ft)
Aspect Ratio = 1.46
Taper Ratio = .49
Sweep (.25c) = 31.5 deg
Airfoil: NACA 0009

Fig. 5.15. Advanced Technology Commuter Conventional Configuration

Table 5.10. Advanced Technology Conventional Configuration Commuter Characteristics

WEIGHTS

Gross = 3706 kg (12,580 lb)

Empty = 3058 kg (6,742 lb)

Max Payload = 1724 kg (3800 lb)

ENGINES

GATE Turboprop

Max Power = 457 kW (613 hp)

Cruise BSFC = .274 $\frac{\text{kg}}{\text{kW-hr}}$ (.45 $\frac{\text{lb}}{\text{hp-hr}}$)

Dry Specific Weight = 3.29 kW/kg (2.0 hp/lb)

TBO = 3000 hr

PERFORMANCE

V_{cruise} = 250 kt @ 70% power, 3048 m (10,000 ft), 5706 kg (12,580 lb)

L/D = 12.5 @ 5706 kg (12,580 lb), 3048 m (10,000 ft)

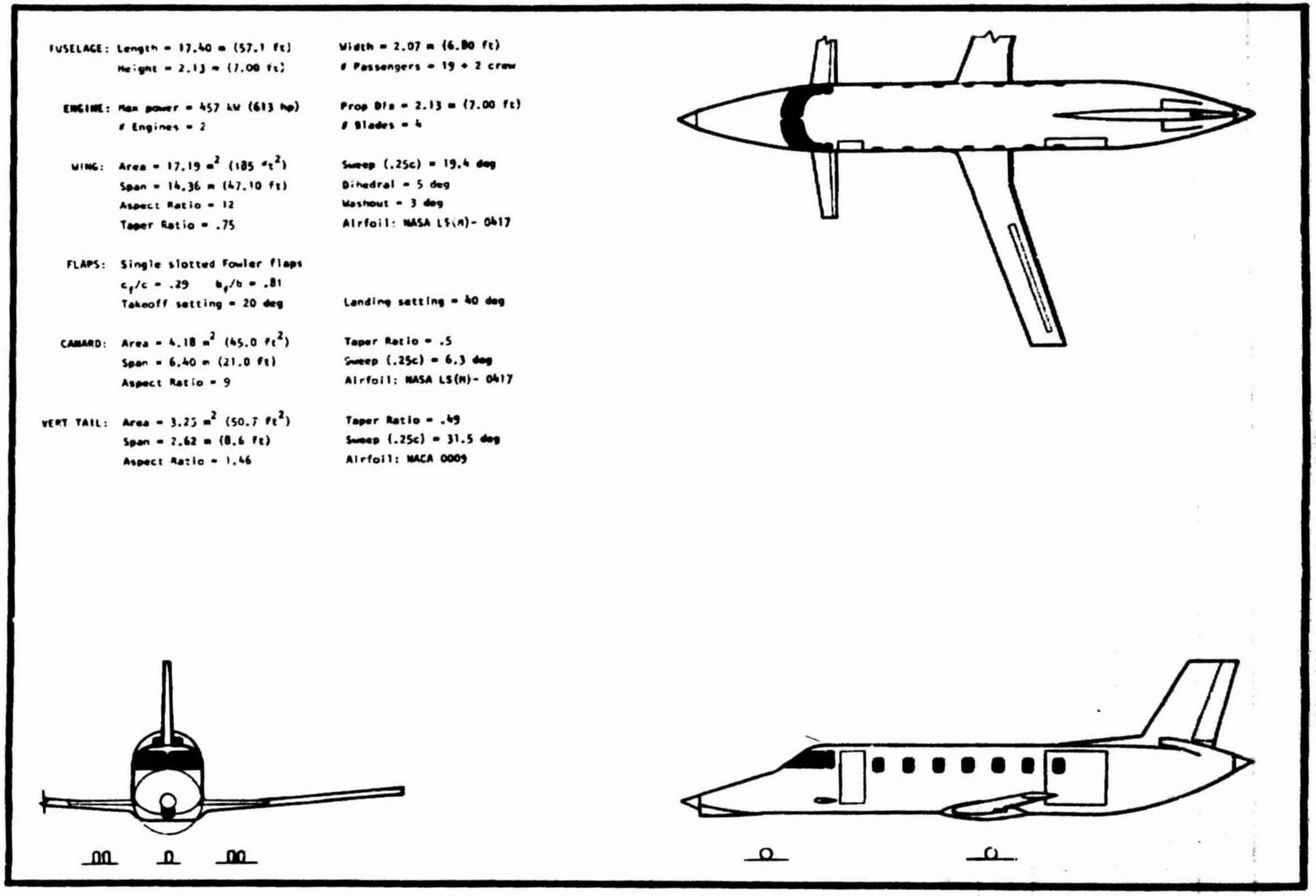
V_{stall} = 84 kt (flaps 40°, sea level, 5706 kg (12,580 lb))

Takeoff Distance over 10.7 (35 ft) obstacle = 1047 m (3600 ft) (flaps 20°, sea level, 5706 kg (12,580 lb))

Landing Distance over 15.2 m (50 ft) obstacle = 588 m (1930 ft) (flaps 40°, sea level, 5606 kg (12,580 lb))

Balanced Field Length = 1097 m (3600 ft) (flaps 20°, sea level, 5706 kg (12,580 lb))

Single Engine Service Ceiling = 2475 m (8120 ft) 5706 kg (12,580 lb)



FUSELAGE: Length = 17.40 m (57.1 ft)
Height = 2.13 m (7.00 ft)
Width = 2.07 m (6.80 ft)
# Passengers = 19 + 2 crew

ENGINE: Max power = 457 kW (613 hp)
Engines = 2
Prop Dia = 2.13 m (7.00 ft)
Blades = 4

WING: Area = 17.19 m^2 (185 ft^2)
Span = 14.36 m (47.10 ft)
Aspect Ratio = 12
Taper Ratio = .75
Sweep (.25c) = 19.4 deg
Dihedral = 5 deg
Washout = 3 deg
Airfoil: NASA LS(M)- 0417

FLAPS: Single slotted Fowler flaps
c_f/c = .29 b_f/b = .81
Takeoff setting = 20 deg
Landing setting = 40 deg

CANARD: Area = 4.18 m^2 (45.0 ft^2)
Span = 6.40 m (21.0 ft)
Aspect Ratio = 9
Taper Ratio = .5
Sweep (.25c) = 6.3 deg
Airfoil: NASA LS(M)- 0417

VERT TAIL: Area = 3.25 m^2 (50.7 ft^2)
Span = 2.62 m (8.6 ft)
Aspect Ratio = 1.46
Taper Ratio = .49
Sweep (.25c) = 31.5 deg
Airfoil: NACA 0009

Fig. 5.16. Advanced Technology Commuter Canard Configuration

(1) Twin turboprop engines.

(2) Composite (Kevlar and/or graphite) structure.

(3) Full span, single-slotted Fowler flaps.

(4) Spoilers for roll control.

(5) Cruise altitude = 3048 m.

(6) LS(M) - 0417 low-speed airfoil.

(7) $W/S = 3259\ N/m^2$.

(8) $A = 12$

Both the conventional and canard advanced technology configurations utilize the same fuselage, with the same geometrical parameters for the wing, with the exception of sweep.

The canard configuration does offer some interesting side effects in configuration analysis. Conventional methods of analysis indicated that wing sweep was required to properly balance the aircraft while maintaining an aerodynamic center location that was acceptable from a static longitudinal stability standpoint.

Although wing weight generally increases with the addition of sweep, increasing the wing root chord such that the wing trailing edge sweep may be reduced to zero (as when a "Yehudi" is incorporated) will allow the relocation of the main landing gear from within the torque box to a position aft of the rear spar. The resulting torque box weight savings may be expected to offset the weight penalty incurred through wing sweep.

Additional characteristics of the canard are examined in Section 5.4.3.

5.4.3 Canard Analysis Problems

Development of the 6-passenger and commuter canard configurations was halted because of an absence of reliable canard analysis methods. The difficulty here lies in the fact that present methods do not account for the effects of wake deformation from the canard on the main (aft) wing. Although this situation does not pose severe limitations at low angles-of-attack or when the canard is not highly loaded, it was suspected that non-short-coupled canards under either of these conditions would display characteristics which would be significantly different than those predicted by present methods.

Initial attempts to rectify the situation involved the use of the Quasi Vortex Lattice Method (QVLM) of Lan (Ref. 116). Here, the configuration of Figure 5.17 (Ref. 68) was used as a validation case. This particular configuration was wind tunnel tested at the NASA Langley Research Center under conditions similar to the flight regime of the advanced technology canard configurations. Although QVLM does not model a deformed wake, this effect was expected to be minimal at low angles-of-attack due to the short-coupled nature of the test configuration. Leading edge separation was assumed at the higher angles of attack, and the strakes were not included in the QVLM-tested configuration.

Figure 5.18 illustrates the results of the computer analysis where fairly good agreement with the tunnel data is noted. Here, the observed differences are believed to result from augmented vortex lift generated on the wing by canard vortices. However,

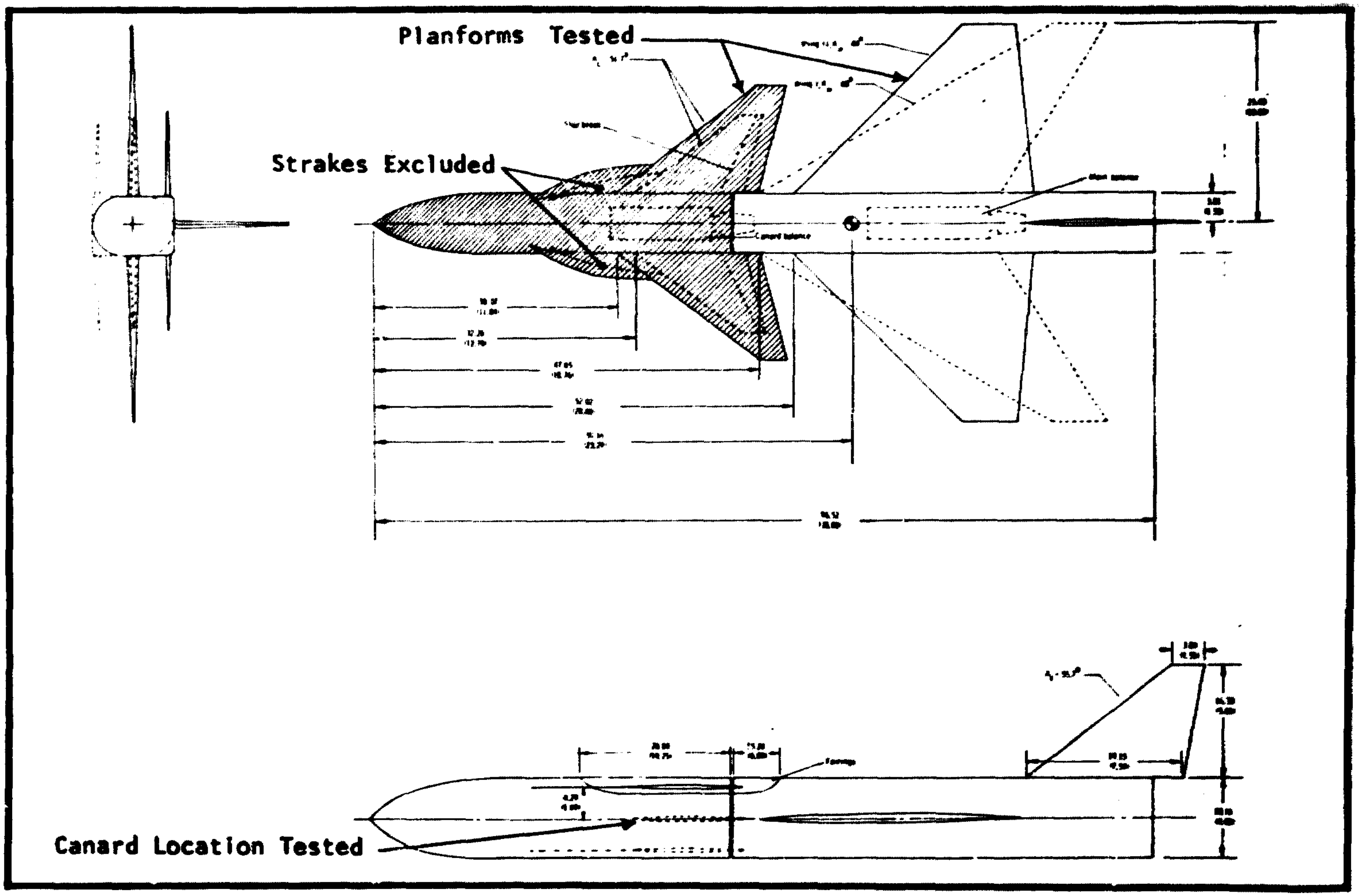


Fig. 5.17. QVLM Validation Configuration

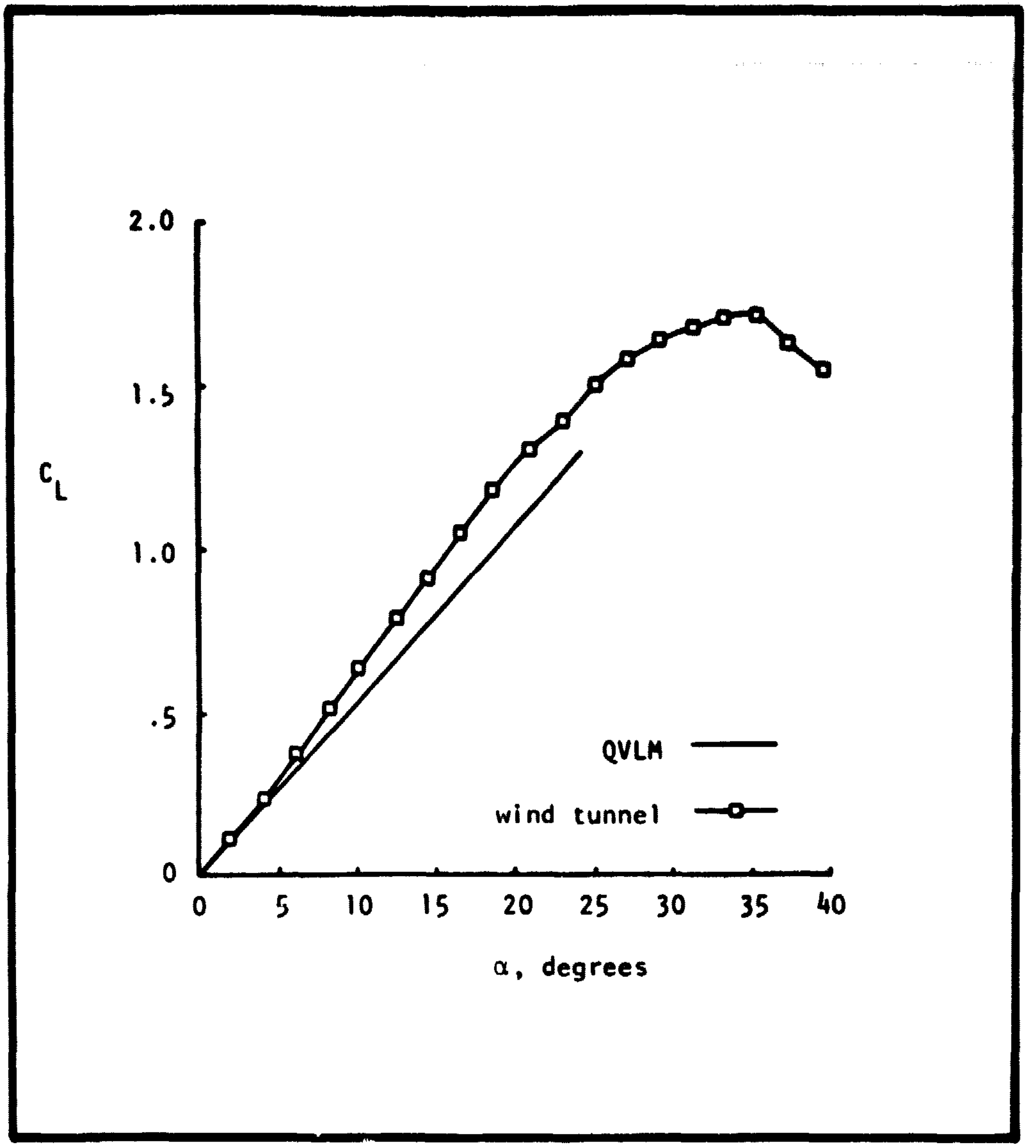


Fig. 5.18. Comparison of Experimental and QVLM Results for the Validation Configuration

further attempts to test QVLM on non-short-coupled configurations were hampered by an absence of published wind tunnel results for these configurations. Furthermore, an investigation of conventional vortex lattice methods (VLM) indicated that all of those codes which were examined employed undeformed, planar wakes. These observations, together with the following three points, led eventually to a decision to halt further canard analysis.

(1) GASP results for the conventional configurations reflected angles-of-attack on the order of 8° to 10° under certain low speed flight conditions.

(2) Preliminary canard configurations appeared to favor non-short-coupled canards.

(3) Current successful high aspect ratio canard configurations are characterized by very heavily loaded canards.

5.5 DESIGN STUDY SUMMARY

This section summarizes the results of the design study. Advanced and current technology airplanes are compared using GASP and a parametric analysis. As previously mentioned, the canard configurations were not fully developed and are therefore omitted in these comparisons.

5.5.1 GASP Comparisons

The impact of advanced technologies on the airplanes which were analyzed proved quite dramatic. GASP provided some very interesting and useful information, especially since it accounts for synergistic effects.

5.5.1.1 6-Passenger Designs. Data for the current and advanced technology designs were presented in Tables 5.7 and 5.8 respectively. Table 5.11 summarizes the characteristics of the two airplanes, and emphasizes those quantities which illustrate the impact of advanced technologies.

Table 5.11. 6-Passenger Comparison by GASP

	Current Technology	Advanced Technology
Wing Loading	1053.6 N/m^2 (22 lb/ft^2)	2154.6 N/m^2 (45 lb/ft^2)
Power Loading	57.56 N/kW (9.65 lb/hp)	59.65 N/kW (10.0 lb/hp)
Aspect Ratio	7.5	11
Wetted Area	67.71 m^2 (728.8 ft^2)	40.37 m^2 (434.5 ft^2)
Gross Weight	1859.8 kg (4100 lb)	1258.7 kg (2775 lb)
Empty Weight	1051.4 kg (2318 lb)	582 kg (1283 lb)
Empty/Gross	.565	.462
V_{stall}[1]	108 km/hr (58.3 kt)	110.5 km/hr (64.5 kt)
Takeoff Dist.[2]	540 m (1771 ft)	609 m (1999 ft)
Landing Dist.[1]	351 m (1152 ft)	406 m (1332 ft)
Lift/Drag[3]	11.7	14.2
Fuel Required[4]	264 kg (582 lb)	132.5 kg (292 lb)
Avg. Cruise Fuel Eff.[5]	.84 km/kg (12.1 $\frac{nm}{gal}$)	1.80 km/kg (25.9 $\frac{nm}{gal}$)

[1] Sea level, gross weight, landing flaps.

[2] Sea level, gross weight, takeoff flaps.

[3] Cruise altitude, 250 kt, gross weight.

[4] 900 nm + 45 min. reserves, 250 kt, 544.3 kg (1200 lb) payload

[5] Cruise altitude, 250 kt, mid-weight.

Refering to Table 5.11, the integration of advanced technologies (see Table 5.3) had the following results:

(1) Wetted area is reduced by 40%.

(2) Maximum gross weight is reduced by 32%.

(3) Empty to gross weight ratio is lowered by 18%.

(4) Lift to drag ratio is increased by 21%.

(5) Fuel required is reduced by 50%.

(6) Average cruise fuel efficiency is increased by 114%.

(7) Takeoff distance is increased by 13%*.

(8) Landing distance is increased by 16%*.

(9) Stall speed is increased by 11%.

*Requirements were still met or exceeded.

In the current analysis, it is not possible to single out exactly how much a given technology benefits the airplane; the effects are highly synergistic. For example increasing wing loading (with help of full span flaps) decreases wetted area and wing weight which allows a smaller engine which decreases weight and fuel consumption, which again allows a smaller wing, etc.

Ideally, GASP could be used to investigate the impacts of individual technologies and various combinations of technologies but this proved to be beyond the scope of the current study. The problem was overcome by using a parametric method of comparison as discussed in Section 5.5.2.

5.5.1.2 Commuter Designs. Table 5.12 summarizes the configuration characteristics of the two designs which were analyzed and displays those quantities most affected by advanced technology integration.

Table 5.12. Commuter Comparison by GASP

Design Gross Weight		
	Current Technology	Advanced Technology
Wing Loading	2155 N/m^2 (45 lb/ft^2)	3279 N/m^2 (68 lb/ft^2)
Power Loading	4.07 kg/kW (6.69 lb/hp)	6.63 kg/kW (10.9 lb/hp)
Aspect Ratio	7.71	12
Lift/Drag	10.44	12.55
Wetted Area	165.2 m^2 (1778.7 ft^2)	136.5 m^2 (1469.2 ft^2)
Max. Gross Weight	5670 kg (12,500 lb)	5706 kg (12,580 lb)
Empty Weight	3379 kg (7,450 lb)	3058 kg (6,742 lb)
Empty/Gross	.596	.536

The results of technology integration into the commuter aircraft are:

(1) Wetted area is reduced by 17%.

(2) Empty to gross weight ratio lowered by 10%.

(3) Lift to drag ratio increased 20%.

Performance comparisons of the aircraft were obtained from the GASP analysis of the multi-leg mission, where a 60% load factor was assumed for each aircraft and the remaining weight was allowed for fuel. Recent FAA regulations (Ref. 215) allow COMBL a zero-fuel weight of 5675 kg, or a gross weight of 6356 kg. A comparison of ADCOM with respect to COMBL (with additional fuel) allows a realistic evaluation of advanced technology incorporation

into a commuter operation. Table 5.13 summarizes the performance characteristics of the two aircraft.

Table 5.13. Comparison of Baseline and Advanced Technology Commuters for the Multi Mission*

	COMBL	ADCOM
Max. Gross Weight	6350 kg (14,000 lb)	5289 kg (11,660 lb)
Payload	1089 kg (2,400 lb)	1089 kg (2,400 lb)
Takeoff Distance	1113 m (3,650 ft)	1091 m (3,580 ft)
Landing Distance	967 m (3,173 ft)	579 m (1,900 ft)
Balanced Field Length	1345 m (4,412 ft)	1006 m (3,300 ft)
Single Engine Service Ceiling	3094 m (10,150 ft)	3094 m (10,150 ft)
Fuel Required 45 min. reserve	1311 kg (2,890 lb) 216 kg res (477 lb res)	782 kg (1,723 lb) 127 kg res (279 lb res)
Time Required	4.84 hrs	5.0 hrs

* Nine 87 nm legs, including taxi, takeoff, climb, and cruise.

The effect of technology integration on the performance characteristics of the commuter aircraft are:

(1) Maximum gross weight is reduced by 17%.

(2) Takeoff distance is virtually matched.

(3) Landing distance is reduced 40%.

(4) Balanced field length is reduced 25%.

(5) Single-engine service ceiling is matched.

(6) Fuel required is reduced 40%.

(7) Mission time is increased 3%.

5.5.2 Parametric Comparisons

A measure of airplane cruise efficiency termed "Range Factor" (RF) was derived using the Breguet range equation with an expression for lift to drag ratio. RF is defined as pound (payload) miles per gallon of fuel and is a function of range (R), altitude (h), velocity (V), empty to gross weight ratio (W_E/W_G), effective aspect ratio (Ae), zero lift drag coefficient (C_{D_o}), effective specific fuel consumption (sfc/η_p), and wing loading (W/S).

Since the independent variables are functions of technology the RF will illustrate the impacts of advanced technologies. Derivation of RF may be found in Appendix C.

5.5.2.1 6-Passenger Designs. The RF comparisons were done for four different technology baselines defined as follows:

(1) Current technology non-turbocharged baseline
  - non-turbocharged reciprocating engine.
  - conventional aluminum structure.
  - conventional controls and control surfaces.

(2) Current technology turbocharged baseline
  - turbocharged reciprocating engine.
  - conventional aluminum structure.
  - conventional controls and control surfaces.

(3) Low risk advanced technology baseline
  - Advanced turbocharged reciprocating engine; lower sfc and higher critical altitude.

- conventional aluminum structure.
- spoilers for roll control; full span single-slotted Fowler flaps.
- moderately increased wing loading and aspect ratio.

(4) High risk advanced technology baseline

- advanced, stratified charge, highly turbocharged rotary combustion engine.
- composite structure.
- spoilers for roll control; full span single-slotted Fowler flaps.
- high wing loading and aspect ratio.

The RF variables for baselines (1) and (2) are determined by averaging data for various existing 6-passenger single engine airplanes. No designs were established for baseline (3) so the RF variables were estimated using available data. The RF variables for baseline (4) are obtained from the GASP designed advanced technology airplane (6PAXAD). Table 5.14 presents the data used in the RF comparisons.

Range factor is plotted as a function of speed for each of the technology baselines in Figure 5.19. Range has been normalized to 900 nm + 45 min. reserves to make the comparisons consistent.

Table 5.14. Data Used for 6-Passenger Range Factor Comparisons

Variables	Technology Baselines			
	(1)	(2)	(3)	(4)
h (m) (ft)	2,133.6 7,000	6,096 20,000	7,620 25,000	9,144 30,000
W_E/W_G	.590	.595	.565	.462
A	6.57	7.08	10	11
e	.7	.7	.7	.7
C_{D_o}	.0226	.0226	.0250	.0286
SFC $(\frac{kg}{kW\text{-}hr})$ $(\frac{lb}{hp\text{-}hr})$	.260 .428	.271 .445	.231 .380	.231 .380
η_p	.85	.85	.85	.85
W/S (N/m^2) (lb/ft^2)	969.56 20.25	1035.63 21.63	1635.63 35	2154.57 45

The technology impacts illustrated in Figure 5.19 are very interesting and are summarized as follows:

(1) Turbocharging allows baseline (2) airplanes to cruise at higher altitudes than baseline (1) airplanes and thus increases RF at typical cruise speeds. Maximum RF occurs at a higher speed but is slightly lower.

(2) The low risk technologies, baseline (3), increase maximum RF very significantly and cause RF_{max} to occur at a higher speed.

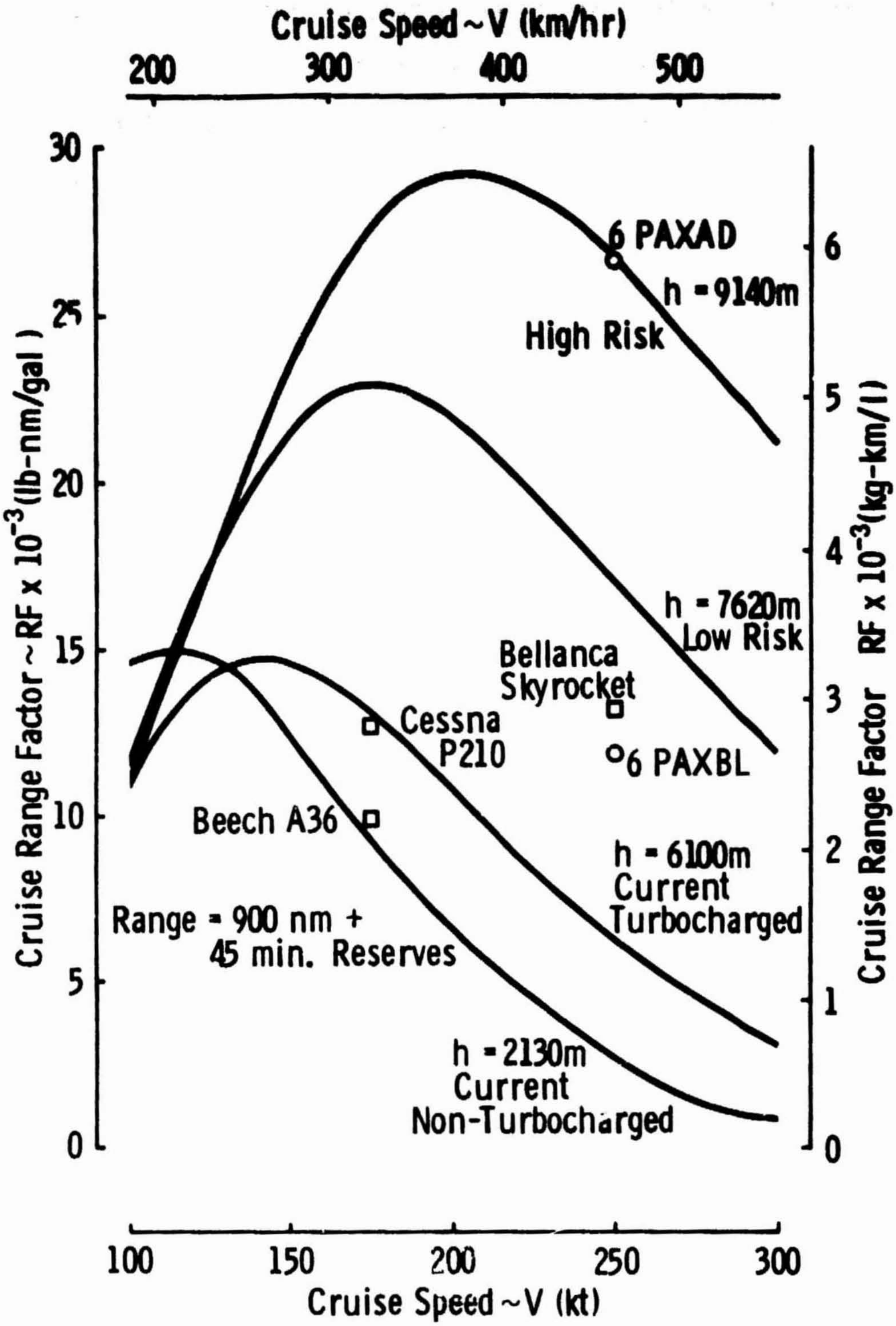


Fig. 5.19. 6-Passenger Range Factor Comparisons

(3) The high risk technologies, baseline (4), further increase RF_{max} and shift RF_{max} to a higher speed.

(4) The GASP designed current technology baseline (6PAXBL) is much more efficient at 250 kt than baseline (2) due to lower C_{D_o}, lower W_E/W_G, and higher cruise altitude.

(5) GASP comparisons between the advanced technology (6PAXAD) and current technology (6PAXBL) designs as discussed in Section 5.5.1.1 are validated.

5.5.2.2 <u>Commuter Designs</u>. RF comparisons were made for four technology baselines:

(1) Current technology baseline
- turboprop engines.
- conventional aluminum structure.
- conventional control surfaces.

(2) Low risk advanced technology baseline
- turboprop engines.
- conventional aluminum structure.
- spoilers for roll control, full span single-slotted Fowler flaps.
- High wing loading and high aspect ratio.

(3) Medium risk advanced technology baseline
- turboprop engine.
- composite structure.
- spoilers for roll control; full span single-slotted Fowler flaps.
- high wing loading and high aspect ratio.

(4) **High risk advanced technology baseline**

- **GATE technology engines.**
- **composite structures.**
- **spoilers for roll control; full span single-slotted Fowler flaps.**
- **high wing loading and high aspect ratio.**

The variables for the RF baseline, (1), were taken from COMBL. The high risk baseline, (4), was developed using the characteristics of ADCOM. The low risk technology baseline, (2), was developed using variables common to the other two baselines by integrating the drag characteristics and high wing loadings of ADCOM with the propulsion and structural characteristics of COMBL. The medium risk technology baseline, (3), was developed by integrating composite structures into baseline (2).

The variables used in the RF analyses follow in Table 5.15.

The results of the comparison appear in Figure 5.20, where range factor RF is shown as a function of speed for a single leg range of 800 nm.

The technology impacts are:

(1) The current technology baseline state-of-the-art is fairly high. Incorporation of low risk technologies will not substantially benefit the performance of the aircraft.

(2) High risk technologies offer substantial performance improvements for this size of commuter aircraft. Fuel efficiency is more than doubled, while low risk technology offers only a 30%

improvement over the current state-of-the-art. The GATE engine provides a greater improvement in efficiency than the integration of composites.

Table 5.15. Data Used for Commuter Range Factor Comparisons

Variables	Technology Baselines			
	(1)	(2)	(3)	(4)
h (m) (ft)	3048 10,000	3048 10,000	3048 10,000	3048 10,000
W_E/W_G	.596	.596	.536	.536
A	7.71	12	12	12
e	.81	.71	.71	.71
C_{D_o}	.0253	.0268	.0268	.0268
sfc $(\frac{kg}{kW/hr})$ $(\frac{lb}{hp/hr})$	.335 .551	.335 .551	.335 .551	.274 .450
η_p	.88	.88	.87	.87
W/S (N/m^2) (lb/ft^2)	2154 45	3256 68	3256 68	3256 68

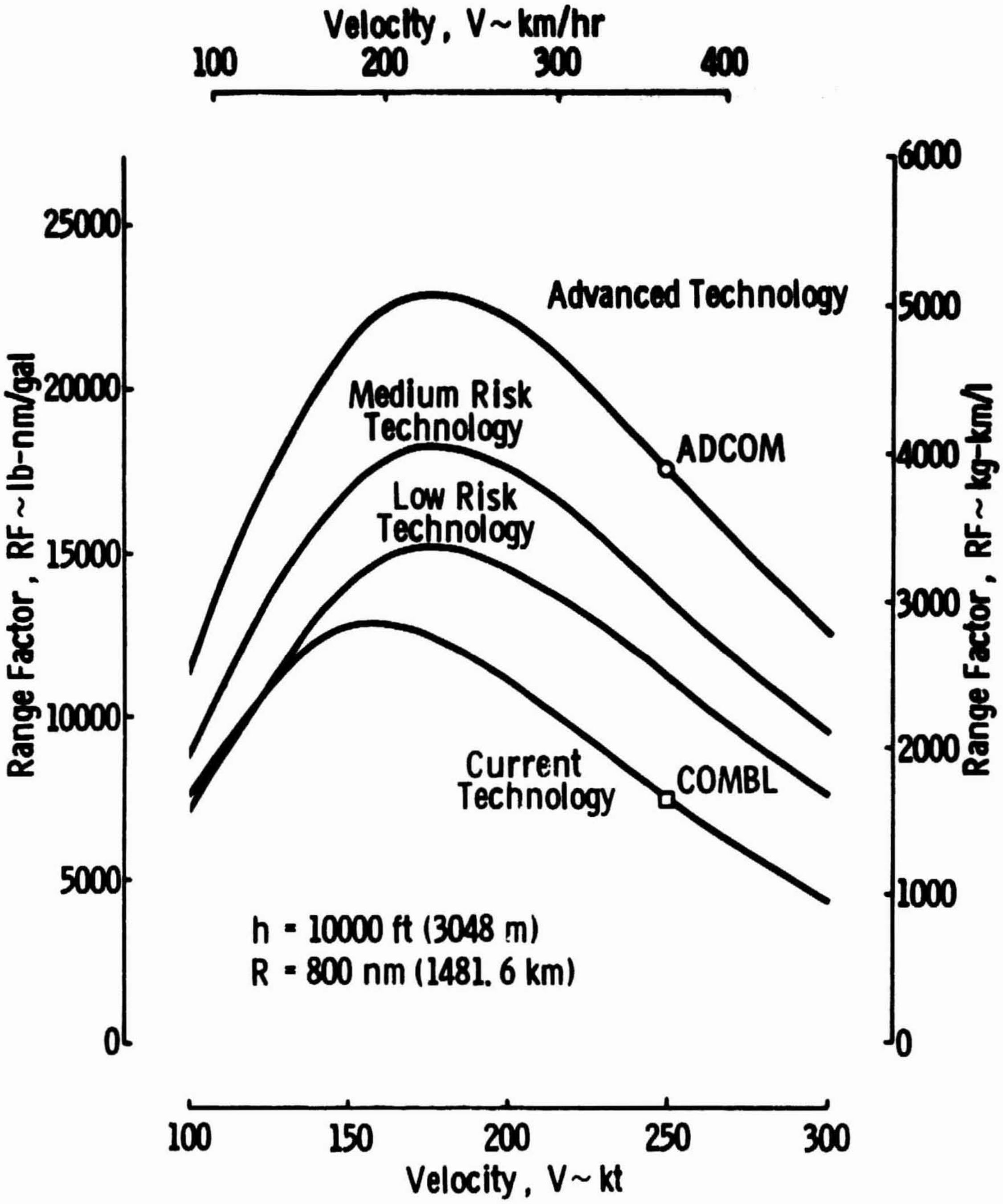


Fig. 5.20. Commuter Range Factor Comparisons

CHAPTER 6

GENERAL AVIATION SYNTHESIS PROGRAM

This program, developed by the NASA-Ames Research Center under the supervision of Thomas L. Galloway, has been discussed in the literature as early as 1973 (Ref. 64), been utilized in several vehicle trade studies of 1975 vintage (e.g. Ref. 80 and 153), and more recently been used by some of the manufacturers who participated in the General Aviation Turbine Engine (GATE) studies. As of this writing, it is still receiving significant attention, and ongoing improvements to the code appear to signal even greater versatility and applicability to the particular synthesis problems faced by general aviation.

6.1 PROGRAM FAMILIARITY

Gaining familiarity with the program's capabilities was given a high priority during the early phases of the research effort. Here, the continuous and extensive support rendered by Galloway proved invaluable. Through his assistance, extensive familiarity with the program logic was gained in a relatively short period of time.

The program is particularly versatile and the user is offered a wide range of input variables with which to define significant vehicle, propulsion system, and mission parameters. Vehicle sizing as well as propulsion system sizing are available as standard options, and user-specified inputs allow for various capabilities of the program to be exercised. For example, during the actual employment of GASP, sizing the vehicle and propulsion system vs mission parameters without actually exercising the mission trajectory options proved to be particularly cost effective.

Three uniquely different types of program executions will be referred to throughout this chapter. Accordingly they will be defined here for clarification.

(1) Short Run - execute only the vehicle weight, drag, and propulsion system sizing options without trajectory definition. This is a standard program option.

(2) Standard Run - proceed with the short run and continue with trajectory definition. This is also a standard program option.

(3) Commuter Run - execute successive legs where gross takeoff weight and fuel remaining at the beginning of each leg are derived from the preceeding leg. This is a non-standard option and represents a modification by the present research team as discussed in Section 6.2.3.

6.1.1 Canard Configurations

GASP does not possess the capability to handle canards. By this, it is meant that GASP will not allow for the investigation of possible reductions in induced drag due to the upload on the forward tail nor will it make any allowance for structural weights which may differ due to different span loadings and/or fuselage bending moments. The underlying factor for this shortcoming is simply a lack of canard data which would allow for the development and incorporation of empirical weight and/or aerodynamic equations.

6.1.2 Propulsion System Sizing

GASP synthesizes vehicles with either a "rubber" engine or a fixed propulsion system based on user-specified inputs. The very attractive "rubber" engine feature of this program allowed for rotary combustion, reciprocating, and turbine powered configurations to be matched with a propeller and sized for different vehicles.

6.1.3 Drag and Weight Calculations

The program will compute both a drag polar and a component weight breakdown. It also provides the user with sufficient input capability to generate specific drag and weight characteristics. For the evaluation at hand, aerodynamic and weight characteristics were manually calculated and then compared against results generated by GASP. Although aerodynamic coefficients showed reasonably good agreement, structural component weights for the current technology 6-passenger airplane did not. Since consistent results were required for the technology evaluation comparisons, it was decided to incorporate manually calculated drag and weight characteristics for all computer runs. This required that several short runs be made to size the propulsion system as well as obtain desired weight and drag characteristics, where the latter characteristics were obtained through inputs already provided for in the program.

6.2 PROGRAM MODIFICATIONS

Three modifications were made to GASP in order to allow for its maximum utilization.

6.2.1 Twin Engine Centerline Thrust

The first involved the addition of an input variable which would allow for a twin engine vehicle to be configured with centerline thrust in a tractor-pusher arrangement. No aerodynamic changes were accounted for. However, this modification allowed for the retention of preliminary tail sizing and longitudinal balancing options which already exist in GASP. Structural weights and the drag of the wing and fuselage could be expected to change when engines are removed from the wing and added to the fuselage.

6.2.2 Brake Specific Fuel Consumption (BSFC)

GASP computes a scaled BSFC for a given propulsion system type and applies this figure to compute range and/or fuel used during various mission segments. Although one manufacturer provided a subroutine which reflected the SFC's of its GATE proposal, a decision was made to modify the program and allow a user-specified input to correct the computed BSFC to a desired level. Hence, after the propulsion system was sized over several short runs, this input was applied to adjust the BSFC to different levels based on technology forecasts for different engines.

6.2.3 Commuter Mission Profile

The two most attractive features of GASP lie in its propulsion system sizing algorithm and its fairly sophisticated trajectory analysis for takeoff, climb, and acceleration. This latter feature is lost, however, when a commuter is analyzed because only one leg can be flown at a time. Although the program does possess the versatility to examine missions at other than takeoff gross weights with full fuel, subsequent commuter legs must be individually loaded and executed after previous leg weights have been determined.

To overcome this difficulty and still utilize the full potential of GASP, an extensive modification was made to the program. Three major goals of this modification were to (1) insure that every GASP computational methodology be retained, (2) insure that all GASP capabilities be retained, and (3) keep the modification totally transparent to the user.

At present, all three goals appear to have been achieved. One variable has been added to the original namelist called $INGASP and acts as a switch. Test runs of the program with this switch on or off allows all of those program capabilities actually used in the present research to be accessed and utilized. With the switch on, an additional namelist containing only seven variables (three are 10-element arrays) is read. Here, up to ten legs at different altitudes, Mach numbers, and ranges may be specified together with any range-correcting options. Once GASP enters the mission profile analysis phase, each specified leg is analyzed utilizing only GASP methods. Three fuel weights for each leg are computed as in the original program, and the remaining design fuel quantity together with the landing weight are transferred to the next leg as initial values. Failure to meet all specified legs results in an error message identifying the accumulated successful leg completions and the point of fuel exhaustion or, if elected, vehicle resizing together with a further analysis of the mission trajectory. Although simple in concept, the reader who is familiar with the lateral and highly interrelated structure of GASP will recognize that this modification ultimately controls the majority of the 72 subroutines in the program.

Numerous commuter runs were made to test the validity of this modification. The most successful of these involved a nine-leg specification of 161 km (87 nm) each for the Swearingen Metro. Each subsequent leg reflected anticipated reductions in time-to-climb and range-in climb, and the final leg resulted in a 5.6 km (3 nm) difference from an expected range which had been predicted in a scenario generated for a commuter study performed in Reference 215.

6.3 PROGRAM BENCHMARKS

In order to validate the use of GASP, the program was benchmarked against two vehicles whose characteristics were manually calculated.

In the case of the 6-passenger airplane, a new vehicle representing current reciprocating engine technology with a conventional

aluminum structure was designed and analyzed. Several short runs were made to verify weight, drag, fuel capacity, and propulsion characteristics. The final standard run over a desired 1667 km (900 nm) range resulted in a 9 km (5 nm) deficiency.

When a similar analysis was performed for the commuter, the resulting vehicle had almost identical characteristics with those shown for Example A in Volume I of the published GASP documentation. This latter airplane had a gross weight of 5675 kg (12,500 lb) and a range of 1117 km (603 nm) at 3048 m (10,000 ft) with a 45 minute reserve. The example data were subsequently modified by calculating available fuel volume and then limiting gross weight to approximately 6356 kg (14,000 lb) based on compromises between available fuel volume and a zero fuel weight of 5675 kg (12,500 lb) with a payload of 19 passengers. Commuter runs were then made with excellent agreement between results and manual calculations.

In all cases, significant differences between expected and GASP-generated structural weights were noted. Some concern was expressed by the present research team over the unusually high aspect ratios (on the order of 12) which were being examined. Manual computations, however, reflected good agreement between the methods of Nicolai (Ref. 154), Torenbeek (Ref. 214), and those of one airframe manufacturer. Consequently, inputs to GASP were adjusted over several short runs until desired component weights resulted. These correction factors were then considered constant for subsequent investigations of advanced technology vehicles. It must be noted that this decision to use manually generated data does not reflect an opinion that the GASP methodology is incorrect. Rather, since comparisons between current and advanced technologies were being conducted, it was felt that the above procedure would yield more consistent results.

Differences in drag characteristics between expected and GASP-generated values were small. However, drag computations were also adjusted for the baseline vehicles over several short runs until desired values were obtained. These correction factors were then also considered constant for the investigation of advanced technology vehicles.

It is significant that these correction factors are already provided for in the GASP input list. Hence, the adaptability of GASP is not degraded due to input limitations.

6.4 USE OF GASP

The results obtained from the use of GASP are reflected in the performance and trade studies discussed previously in Chapter 5. Additional data are presented in Appendix C.

6.5 RESULTS OF GASP IMPLEMENTATION

The use of GASP contributed markedly to the productivity of this research effort and allowed for the analysis of several airplane configurations in a rapid and orderly manner. The wide range of inputs already provided in the basic program presents the user with attractive options for vehicle definition, and the propulsion sizing and trajectory definition capabilities offer significant contributions to General Aviation aircraft synthesis capabilities.

CHAPTER 7

RESULTS

7.1 OVERVIEW OF TASKS PERFORMED

This research, which spanned 12 months, was pursued in an attempt to identify those advanced technologies which, when integrated into general aviation airplanes, would offer significant improvements in safety, performance, efficiency, and utility. In order to achieve this primary goal, several diverse and otherwise independent tasks were performed. These may be broadly grouped as follows:

(1) A thorough and in-depth data base was established.
    (a) 31 manufacturers were visited.
    (b) 3 NASA research centers were visited.
    (c) 6 professional meetings were attended.
    (d) A detailed literature search was performed.

(2) A technology evaluation technique was developed, tested, and evaluated. This technique needed to reflect the consensus of the general aviation community, be broad enough to consider all aspects of a technology's impact, be relatively sensitive to differences in a technology's potential benefit, and display a degree of stability.
    (a) Survey 1 was a Delphi survey used to identify the measurements of a technology's impact (category identification). 17 categories were identified after four rounds

of the survey were completed.

(b) Survey 2 was a Delphi survey used to quantify the measurements (category rating). Three rounds were used to establish the ratings (category weights).

(c) Pessimistic, Likely, Optimistic, and Expected relative benefits were determined and examined to establish the stability of the evaluation technique (PLOE studies).

(d) A factor analysis was performed for the relative benefit matrix to determine the suitability of the selected categories.

(e) The effect of different raters was examined.

(f) An analysis of variations in the Empty Weight category rating was performed because it appeared that the definition of this category and/or its impact on payload was not adequately defined to Survey 2 participants.

(3) The effects of integrated technologies on two classes of airplanes were examined. Both airplanes were specified to cruise at 250 knots. Airplane A was synthesized as a 6-passenger, high performance, personal/business airplane. Airplane B was synthesized as a 19-passenger commuter.

(4) The General Aviation Synthesis Program (GASP) was evaluated, modified, and used to investigate the effects of technology integration on Airplanes A and B. It is emphasized here that the modifications were made only to adapt the program to the study at hand and do not reflect deficiencies in

the program.

(5) A modified version of the Quasi Vortex Lattice Method (QVLM) was used to investigate canard configurations. Here, the modification allowed the investigation of the effects of a forward tail on an aft main wing. Fairly good agreement was noted for a short-coupled canard, but non-short-coupled configurations were not evaluated due to an absence of wind tunnel data.

7.2 RESULTS OF TASKS PERFORMED

The results of the separate tasks identified in Section 7.1 are summarized below according to major areas of emphasis.

7.2.1 Manufacturer and Research Center Visits

All visits contributed immeasureably to the data base required for the technology evaluation. Manufacturers contributed significantly by sharing their views of both advanced technology development as well as of NASA research in general. Comments regarding technologies requiring further study and recommendations for further NASA research may be found in Appendix A. However, the following opinions and perceptions of the manufacturers are emphasized here.

(1) NASA research should be confined to basic research, whereas product development should be left to manufacturers.

(2) High risk technologies such as those encountered in propulsion require NASA funding if they are to materialize as hardware.

(3) Certification and product liability costs are often far greater than those costs incurred in the actual development of a technology.

7.2.2 Technology Evaluation

An evaluation technique based on a linear compensatory model was successfully developed, tested, and implemented. This model reflects the opinions of the general aviation community both in the identification of categories to be used as measurement devices as well as in the determination of the relative importance of these categories.

Two sets of category weights were developed as part of this research. The first was for a 6-passenger, high performance, personal/business airplane, and the second was for a 19-passenger commuter.

7.2.2.1 Attractive Technologies. The following technologies appear to be attractive to general aviation.

(1) All propulsion technologies. The GATE turboprop and Stratified Charge Rotary Combustion Engine were distinctly ahead of all other technologies considered for Airplane A.

(2) Fiberglass, Kevlar, and graphite composite materials. Certification procedures must reflect the latest composite test data, however, to preclude overly restrictive requirements from nullifying otherwise significant weight reductions. Designs will also need to incorporate proven methods for lightning protection. Only areas most vulnerable to lightning

strikes need protection, such as tips of wings and tail surfaces or any relatively sharp pointed projection. Promising methods for protection include flame sprayed aluminum coating, external conductors or diverters, and embedded aluminum or copper wire mesh.

(3) Natural laminar flow airfoils, spoilers with full span Fowler flaps, and low/medium speed airfoils. Development of these technologies requires improvements in computational aerodynamics.

(4) Advanced integrated avionics systems which reduce pilot workload.

7.2.2.2 Unattractive Technologies. The following technologies appear unattractive.

(1) Area navigation concepts such as Loran C and Omega.

(2) Active controls, fly-by-wire, and fly-by-light.

(3) HUD's, Doppler navigation, and inertial navigation.

7.2.2.3 Technologies Not Examined. Technologies with significant potential but not evaluated due to their inapplicability to Airplane A and/or B include the following:

(1) Propfan

(2) Quiet, Clean General Aviation Turbine engine (QCGAT).

7.2.3 Design Studies

Design trade studies for both airplanes reflect significant performance gains resulting from the integration of new technologies. Here, the synergistic effects of composites, aerodynamics, and propulsion technologies were examined. The resulting airplanes displayed marked improvements in performance, operating cost, and empty weight and served to verify the predictions evolving from the Evaluation Technique. Lighter aircraft with higher wing loadings and improved propulsion systems showed 40% to 50% reductions in fuel used.

7.2.4 GASP

The use of GASP aided immensely in the evaluation of the impact of advanced technologies. Here, manual calculations for weight and drag were input, and the program was used to size the vehicle and propulsion system, and to evaluate mission performance. Its versatility promises significant benefits for general aviation synthesis.

7.2.5 QVLM

Although this analysis tool reflected fairly good agreement for the one configuration evaluated, the inability of this method as well as conventional VLM methods to model a deformed wake was perceived to be a shortcoming to the investigation of non-short-coupled canard configurations.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The identification and integration of certain advanced technologies can have significant and profound impact on future general aviation airplanes. The results of the present study suggest that it may be possible to integrate certain high-risk technologies into two low-speed general aviation airplanes and realize substantial fuel savings while improving safety, comfort, and performance. These fuel savings alone represent significant reductions in the cost of owning and operating an airplane.

The initial cost of the airplanes, however, is expected to be high. Developments which would substantially lower purchase price include:

(1) A NASA commitment to develop advanced propulsion system technologies specifically for general aviation.

(2) A requirement by the automotive and trucking industry for more sophisticated and efficient turbochargers.

(3) A similar requirement by the automotive industry for large supplies of Kevlar and graphite composites.

(4) The development of a substantial data base for composites which would lead to better-defined certification requirements.

The key to the improved performance and efficiency of the 6-passenger light single-engine airplane investigated lies in increased wing loading. Higher aspect ratios, a NASA natural laminar flow airfoil, lighter weight through the use of composites, and improved propulsion systems also contributed significantly. Since wing loading is constrained by stall speed requirements of 61 kt for this class of airplanes, a re-examination of this requirement appears warranted.

Improvements in commuter efficiencies, while not as great as experienced by the 6-passenger airplane, were still dramatic. Improved propulsion systems, higher aspect ratios and wing loadings, lighter structural weights through the use of composites, and the incorporation of a NASA low-speed airfoil, all contributed significantly to the improvements enjoyed by this vehicle.

8.2 RECOMMENDATIONS

Those technologies identified in Chapter 4 and repeated in Section 7.2.2.1 should be pursued. Additionally, those technologies which improve the crashworthiness of an airplane (seats, restraints, floor, fuel tanks) should receive continued attention by both NASA and the FAA.

Computational methods which allow for the more accurate aerodynamic analysis of wing-body-tail configurations (both fore and aft tail) should be developed. Finally, verified prediction techniques for wing-spoiler-flap configurations should also be developed.

Integrated avionics systems and related technologies designed to reduce pilot workload must be pursued. This implies that a vigorous human factors research program directed towards an analysis of the pilot-airplane-flight environment interface should also be conducted.

While the Ames DAAS concept and the Princeton Advanced Research Airplane appear well suited to investigate the effects of advanced avionics, advanced aerodynamic technologies must be actively and carefully investigated and flight tested in order to establish a verified data base for the integration of these technologies. Furthermore, although advanced propulsion systems play a key role in the present research, significant benefits to general aviation appear possible through the incorporation of only aerodynamic technologies.

The research of advanced technology general aviation airplanes should be continued. While the separate technologies all require development, an integrated test vehicle should be pursued in order to realistically investigate the actual benefits realizeable through the synergistic effects of the different technologies. In view of the fairly long lead times which are characteristic of the aviation industry, research should be directed as soon as possible to a high-aerodynamic-technology vehicle. Such a vehicle would be characterized by composite structures (for both weight and surface finish), advanced airfoils, higher wing loadings, and higher aspect ratios.

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APPENDIX A

NOTES FROM VISITS TO MANUFACTURERS AND RESEARCH CENTERS

This appendix contains notes generated by the research team during the course of visits to 31 manufacturers and three research centers. The notes have been edited to a certain degree and the names of manufacturers have been deleted. They are included as a part of this report because comments, ideas, and opinions gained from the visits were of extreme value to the present research effort. Also, it is hoped that certain views expressed from time to time may now be made a matter of public record in a form more accessible to the general aviation community than previously possible.

It must be emphasized that this appendix contains the views of those persons visited and do not necessarily reflect the opinions of the authors of this report. In those cases where technologies which were evaluated as part of this research are discussed, the reader is advised to refer to Chapter 4 for further information. Also, when a statement attributing some characteristic of "Company B" appears under a discussion for "Company A", the statement reflects Company A's view of Company B's position, involvement, or action.

A.1 AIRFRAME MANUFACTURERS

A.1.1 Company A

I. Powerplants and Propulsion

The real need here is powerplants up to and including the 746 kw (1000 HP) range.

Liquid Cooling

The major advantage is as a configuration tool. The engine and radiator can be placed independently of each other in the aircraft. Might possibly reduce cooling drag.

More efficient; cooling liquid can be used to heat the cabin.

On a direct weight and cost comparison with air-cooled engines, liquid cooling will weigh more and cost more. Excess cost can be returned in performance gains and configuration allowances.

Increases TBO of the engine by cooling the cylinders more evenly and thereby allowing closer tolerances between components.

Diesel Engines

High fuel tolerance. Will burn practically anything.

Excellent fuel efficiency.

Could suffer a weight problem.

Stratified Charge Engines

Higher fuel efficiency.

Low emissions.

Rotary Engines

Offers advantages in size and smoothness of operation.

Coupled with a stratified charge mixture, fuel consumption can be lowered to conventional aircraft engine levels.

Turbocharging

Current aircraft turbochargers are not matched to engines. They are simply diesel truck turbochargers which are "tacked on" to airplane engines.

If turbochargers were optimized for aircraft, 3047 m (10,000 ft) could be added to current ceilings.

This improvement is one of the most realistic and achievable goals for the present.

Increased TBO's

Turbine engines have the potential for 5000 to 7000 hour TBO's with careful monitoring. Without it, 3500 hour TBO's are still possible. However, a strict maintenance schedule may be too expensive and time consuming.

Current reciprocating engines have TBO's of only 2000 hours. The high-powered, 6 cylinder injected engine is a real maintenance problem.

Liquid cooling is essential to increasing TBO's. It allows closer tolerances. If not liquid cooled, TBO's of current reciprocating engines could still be increased by the installation and incorporation of larger bearings and by adding 50 lbs of structural "beef-up" to the engine.

Improved Ignition and Carburetion

Current aircraft reciprocating engines need spark advance incorporated into them. Presently, they have none. At least mechanical advances should be used.

Electronic control with a manual backup for throttle and mixture would increase range by 20%. (Note that best power and economy occur at two different operating points.)

A combination of these would greatly improve engine life and fuel economy.

Propellers

Propellers can be improved by utilizing thinner airfoils tailored to the span of the blade.

Composite construction of blades would increase the damage tolerance of the propeller.

Noise reduction is required. One way of accomplishing this is to sweep the blade tips.

Emphasis was placed on economics, schedules, and judgement vs analysis during the design phase. Cost is the most important underlying factor.

The skill of the labor force is an important consideration. "Planes must be built by folks, not craftsmen."

II. Structures

Metal-to-metal bonding

This is a current technology for general aviation, both on secondary and primary structures.

This company currently bonds 4000 to 6000 subassemblies per month.

Composites

Composites are used extensively, but in secondary structure only.

Use of composites in primary structures is constrained by the FAA. The FAA requires two times the normal factor of safety of 1.5. This added strength requirement eliminates any weight savings from composites.

Aluminum is still used because of its low cost.

Prediction Methods

A flight test flutter prediction method is needed. Must allow real time flutter analysis.

A good noise prediction method is needed, both for internal and external noise.

A high frequency loads analysis method is needed for the 70 to 100 Hz range.

III. Aerodynamics

Required Prediction Methods

Tail effectiveness as a function of tail and wing location, both longitudinally and vertically.

A method for examining the fuselage-nacelle channel on twins is required. Providing low-speed inboard lift is a key requirement. Must eliminate tail buffet. A good potential flow model would probably solve the problem.

An accurate method for predicting hinge moments for ailerons, flaps, and spoilers is needed.

Tailored Airfoil Sections

Sections should be generated for the specific task instead of being picked out of a handbook. Tailoring the section can reduce drag by as much as 35 counts.

GA(W) wing (airfoil) is difficult to manufacture.

OSU airfoil service is not used because of an inhouse capability for generating airfoil sections.

IV. Systems

Suggested Methods for Anti-Icing

Microwave, but interferrence with MLS may be possible.

Sonic and pulsating methods.

Avionics

Primary emphasis in this area should be placed on reducing pilot workload. This requires simplified avionics.

Engine Condition Monitors

Some are currently in operation.

Suggested engine particles be monitored, and that microphones be used for detecting unusual sounds.

V. Canards

Not a good airplane and doesn't compete with this manufacturer's product line. Present canards are "neat" airplanes, but shouldn't be considered a utility airplane.

Locating the landing gear and fuel will be difficult.

Trim difficulties expected when flaps are incorporated on the aft wing.

A.1.2 Company B

I. Propulsion

NASA-Lewis Research Programs

Company B would like to see the four major programs for General Aviation continued: (1) GATE, (2) Stratified Charge Reciprocating Engine, (3) Stratified Charge Rotary Combustion Engine, (4) Advanced Diesel.

Also want to see continued propeller studies, with emphasis on weight, composites, noise, and efficiency.

Currently is involved with the GAP program: (1) Agricultural aircraft, (2) Turboprops, (3) Light single engine aircraft.

Mentioned the Ames cooling drag project and expressed interest in it.

Noise

Keenly interested in exterior and interior noise research. Supports the noise reduction tests at KU and LaRC.

Suggested possibility of electro-static cancellation of interior noise.

Turbocharging

Current turbochargers need to be optimized.

Fuels and alternate power sources

More research needed on alternate fuels for General Aviation.

Suggested NASA investigate alternate power sources.

Lockheed is doing work on battery development: Lithium Hydroxide, Hydrogen Peroxide. Might have significant advantages for aviation applications, especially if electric propulsion becomes a possibility.

Liquid Cooling

Sees major advantages here.

50% increase in TBO's is required in order to make this attractive.

Improved Ignition and Carburetion

Sees a definite need here, but feels that very basic research is required to fully assess benefits of advancing timing as well as better mixture and throttle control.

This company was involved in a timing change study.

Turboprops and Turbofans

Visualizes the 149 kw - 373 kw (200 -500 HP) range becoming a reality for turbines.

Turbofans cannot match the efficiency of turboprops below a 400 knot flight regime.

Rotary Combustion Engine

Not much interest here.

II. Crashworthiness and Safety

Crashworthiness

Further work required here, particularly with respect to composites. Composites splinter and release energy all at once as opposed to aluminum which can crush and dissipate loads.

Safety

An investigation of the stall/spin problem is needed now. Since the simplest way to prevent a spin is to prevent the stall, incorporate active stall prevention. Don't give the pilot the ability to stall.

III. Aerodynamics

GA(W) sections

Feels as though this section was oversold. Wing-body interference problems outweigh benefits. Aft loaded sections cause problems with wing-body interference/separation as well as with trim drag due to pitching moment characteristics. Control surfaces tend to float.

OSU Computer Service

Company B uses the service.

This company would like to see results of programs like ATLIT and Redhawk disseminated more quickly.

IV. Structures

Composites

FAA certification is a problem, but this is to be expected because there are severe technical problems with the incorporation of composites.

A General Aviation composites study is required (comprehensive) over a 15 year period. All aspects, such as manufacturing, aging, environmental effects, should be addressed. Moisture absorption is a problem.

NASA should support composite tests for General Aviation much like the programs for commercial transports.

Composites are utilized in secondary structure only. Lack of sufficient data precludes use in primary structure.

Stiffness characteristics as opposed to strength should be verified.

Investigate possible implementation in engines. Good potential for weight savings there.

Has great concern for crashworthiness aspects.

V. Systems

Aircraft systems, if improved, offer potential for substantial gains. Tradeoffs in dollars, weight, and side effects are significant.

Electrical

Areas such as generators, alternators, and starters need more attention. Antennas can be greatly improved.

Fly-by-Wire and Fly-by-Light

Despite anticipated certification difficulties, outlook is optimistic for fly-by-wire.

Fly-by-light has little application.

SSSA and Active controls

Gust alleviation systems offer substantial benefits. Ride Quality is second to gust alleviation. Active flutter suppression might be attractive.

SSSA would be good as a wing leveler, yaw damper, or total autopilot control. Certification problems might be encountered.

Avionics

Digital data links between the aircraft and ground are required for reducing cockpit noise, voice communication, and pilot workload.

A real need exists for advanced integrated displays in the cockpit.

Digital data links with the ground could also provide weather information and collision avoidance.

CRT displays could make IFR flight as easy as VFR.

Key to advanced avionics is effective integration of advanced microprocessors. Required if advanced systems like engine controls are to be incorporated.

More efficient heating and cooling for the cabin is desirable. Better air cycle systems should be developed with better efficiencies. The same is needed for electric, hydraulic, and pneumatic systems.

VI. Canards

This company is neutral toward canard configurations. Some points expressed include:

Might be an attractive solution to stall/spin problems.

Might impair visibility from the cockpit.

Notes: (1) Be energy conscious.

(2) Research institutions should solve the technical problems. Industry will solve the production and certification problems if the technology has enough merit.

A.1.3 Company C

I. Cost

New Technologies

New technologies are attractive only if low cost.

An increase in purchase price is allowable only when a decrease in life cycle costs are realized. Price is not too important in the high performance category of airplanes.

II. Flight Demonstrator

Reduced Noise

Use mufflers.

Explore Boeing method for acoustic paneling in the inlets of turbine engines.

Drag Reduction

Increase aspect ratio. Negligible benefit expected for small aircraft due to increase in weight.

Perform a general clean-up of the exterior surfaces.

Configuration

Explore canards and tandem wings and determine if the benefits claimed really exist.

Winglets

Utilize for lateral-directional control.

Explore the effects of variable geometry winglets.

High Lift Devices

Explore different high lift devices and determine what is most effective for reducing approach and landing speeds.

III. Structures

Composites

No composites are used by this company except for fiberglass radomes and fairings.

Graphite corrodes metal rivets.

Crashworthiness aspects need to be explored.

Major problem is a lack of data on fatigue, manufacturing methods, inspectability, and certification requirements.

Composites are a difficult endeavor for manufacturers to pursue due to costs and certification difficulties. Here, a manufacturer must gain experience with secondary structures before pursuing more ambitious projects.

Bonding

The military has had problems with field servicing and maintenance of bonded structures.

No bonding is used by this company.

IV. Systems

Fly-by-wire and Fiber Optics

Fiber optics offer potential weight savings.

Interference problems hamper electronic systems. EMI shielding doubles conventional wire weight. Fiber optics, however, are free of radio interference.

Active Controls

Hampered by expensive redundancies.

May pay off in ride control for aircraft with low wing loadings. Load control can be effective in reducing weight of the vertical fin and high aspect ratio wings.

This company is uncertain about the application of active controls to general aviation aircraft.

Batteries

New lead-acid batteries are better in cost and weight than NICADs.

V. Computational Methods and Research

Airfoils

Work with NASA has been helpful in comparing codes.

The OSU facility has not been used.

NASTRAN

Used with good correlation noted.

Flutter

Free play and friction in flight controls and their effect on flutter need to be studied. What are allowable tolerances here?

Aileron "buzz" needs to be studied.

VI. Propulsion

TBO

One problem known to exist with a particular turbofan is a degradation in maintenance where typical values experienced reflect

300 hours between inspection and overhaul of the hot section.
900 hours between inspection and overhaul of the gearbox.

By comparison, a turbojet presently in use has a 4000 hour TBO.

Note: Engineering support costs and certification costs amount to 10 to 100 times the cost of the technology itself.

A.1.4 Company D

I. Propulsion

Liquid Cooling

No major advantages. While it would improve TBO, only a 1% improvement in cooling drag reduction could be attained.

Rotary Combustion Engine

Development of this engine should be pursued.

At present, the engine suffers from high SFC, high weight, and is not as smooth as expected. The following potentials could be realized if the rotary were pursued:

Weight savings.
Fuel consumption comparable to current recips.
Good turbocharging candidate.

Diesel

Excellent fuel efficiency.

A 2-cycle supercharged diesel is known to be receiving attention.

GATE Turbine Engine

Definitely worth pursuing.

The 373 kw (500 hp) size should be emphasized. A flat rating would make it compatible with present high performance single engine applications.

GATE resulted in little new technology identification.

Do not pursue very small turbines on the order of 75 kw (100 hp).

Cost is expected to be high, on the order of 5:1 vs reciprocating engines.

II. Configurations

Configuration research is a waste of time. It is mature as a result of 75 years of evolution.

III. Airfoils

GA(W)

Mixed views were expressed for this class of airfoils. The section is sensitive to contours, leakage, and interference, and is heavily aft-loaded.

OSU Airfoil Service

Never really supported the service.

Airfoils developed by Hicks at NASA Ames are good.

IV. Structures

Composites

Very little composites are used by this company. Further research appears dictated before this technology gains acceptance in general aviation.

Companies D & E)

Bonding

Bonding is used on stringers, doors, cowls, and other secondary structures. It is not used on primary structures.

Advantages: smooth contours, better appearance, stiffer, and saves on labor.

Disadvantages: Costly to tool up for, and has field repair problems.

Few problems with delamination have been experienced.

V. Controls

Fly-by-wire and Fiber Optics

Not seen as a possibility in general aviation in the foreseeable future.

Weight savings would not offset the cost penalty for general aviation.

Not enthusiastic towards active control systems, SSSA, etc., at all.

However, a gust alleviation system to improve ride quality might be attractive to general aviation.

VI. Avionics and Electronics

Integrated Avionics and Microprocessors

Expect cost disadvantages due to redundancy requirements.

Advanced avionics might be attractive to the market. On the other hand, today's avionics may already be too advanced.

A.1.5 Company E

I. Structures

Metal Bonding

Prime fastening method to replace riveting.

Major advantages: reduction in man-hours and reduces surface roughness.

Major problems: lack of understanding of life cycle. Implementation by a manufacturer requires a large capital outlay. Environmental effects, especially humidity, are of major concern

Inspectability, repairability, and maintainability are also questionable.

No bonding is used by this company.

Better adhesives which are less pressure sensitive are needed, with attendant research of properties.

Bonding distributes loads more effectively and has better fatigue properties.

Composites

Use will possibly replace metal bonding, but is expected to occur later.

General aviation will see primary structures composed of composite materials in about 20 years.

Concern was expressed about carbon in a crash environment.

This company had a fiberglass door on one of their aircraft but had to replace it with a metal one because the original was not stiff enough.

Company B utilized a honeycomb structure in the belly of one of their aircraft for crashworthiness energy absorption.

II. Propulsion

GATE

Company F is following the developments of this program.

Appears that fuel problems facing the country will have major impact on this program.

Expects to see smaller turbines in general aviation by the late 1980's.

Diesel Engines

Have much promise because of excellent specific fuel consumption characteristics.

Diesels might be more attractive and beneficial to general aviation than turbine engines.

Liquid Cooling

Absolute necessity for higher power-density engines. 400 hp is the limit for air cooled engines. Uneven cooling is a serious problem with air cooled systems during rapid descents.

Should significantly increase TBO by reducing cyclic thermal loads and allowing the manufacture of a "tighter" engine.

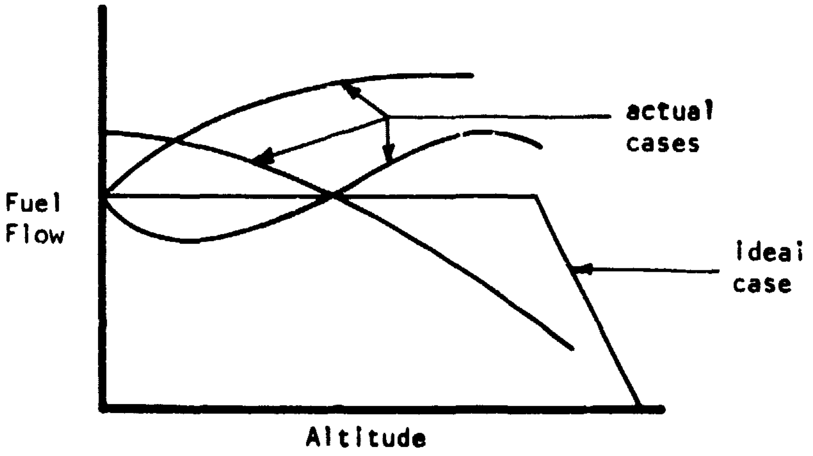
Should significantly reduce cooling drag and simplify engine/airframe integration.

Development of this technology will probably require government funding.

Fuel Controls

Considered to be a very near term objective.

Examined an auto-mixture control for use but found the controls unreliable and inconsistent as shown below.



Rotary Combustion Engine

Unsure of real benefits in this area.

Stratified charge, however, has real potential.

Propellers

Has experienced problems with vibration and blade flutter on some propellers which required a change.

Turbocharging

Can anticipate installation problems on smaller engines. Not much of a selection available. They are not optimized. Current systems are structurally sound, and have displayed excellent reliability.

Turboprops

Does not see demand in general aviation airplanes under 6 place, pressurized, single engine versions.

Studies of weight savings of turboprops is misleading because of the requirement for additional equipment such as radios, pressurization, etc. for the aircraft to operate in the ideal and efficient environment for the turboprop.

Engines currently used by this company are 4 and 6 cylinder models, with TBO's ranging up to 2000 hours. Turbocharging reduces TBO down to the 1000 to 1200 hour range.

III. Aerodynamics

Wing Loadings

Expects higher W/S to appear in general aviation. A major problem with high W/S is the high power required to cope with the associated high C_L's.

Airfoils

Aft loaded airfoils cause interference problems.

Likes the OSU center and is maintaining contact.

Not highly interested in airfoil refinements.

Computational Aerodynamics

Methods should be used to design aft fuselage sections and examine cooling drag.

Stall/Spin

If aircraft are made stall-proof, they will not spin. Question of how to stall-proof an airplane is significant. Incorporating a stick pusher, or limiting elevator power are effective but limit part of the performance envelope.

Canards

Believes the following advantages exist: reduced wetted area, possible gust alleviation, lower fuselage weight.

Company I has realized gains from reduction of cooling drag and rerating engines to 75% power.

IV. Flight Controls and Avionics

Very interested in microprocessor integration into aircraft systems.

Flight Controls

Impressed with the SSSA approach.

Gust alleviation is a good candidate for advanced active control.

Fly-by-wire and light offer substantial weight savings. Multiplexing with fiber optics would reduce wire bundle weight significantly.

Active controls will be needed in the future.

Avionics and Displays

In 1971-72, this company performed a study of a HUD with a side stick force controller. The study was constrained by cost. NASA could further investigate these areas.

The Omega navigation system is good but does not provide terminal guidance. It needs government support for a fully integrated system to be developed.

Single-pilot IFR workload is much too high. What is needed is a visual, automated communication mode rather than present verbal methods. This would improve the workload and accuracy of information transfer.

V. Crashworthiness

Definitely needs more work. Seats are not designed for energy absorption.

Ag planes are good crashworthiness examples. Roll cage, good seat belts, and shoulder harnesses.

More realistic design specifications are needed.

VI. Noise

More attention should be and will be paid to noise in the future design of aircraft. Low level pressurization offers some potential for interior noise reduction.

A.1.6 Company F

General philosophies for building aircraft:

> "Keep it simple. Eliminate systems. Make it easy to fly."

I. Structures

Composites should be pursued.

II. Configuration and Aerodynamics

Canard

Allows lower gross weight and less wetted area. The wetted area of a canard configuration can be 2/3 that of a comparable conventional aircraft.

For a push-pull canard configuration, the fuselage has two inflection points in bending moment. This allows for a much lighter fuselage.

Wing Sweep with Winglets

Allows winglets to be used for directional stability.

Get C_{ℓ_β} without dihedral.

Sells airplanes (looks good).

Wing Strakes

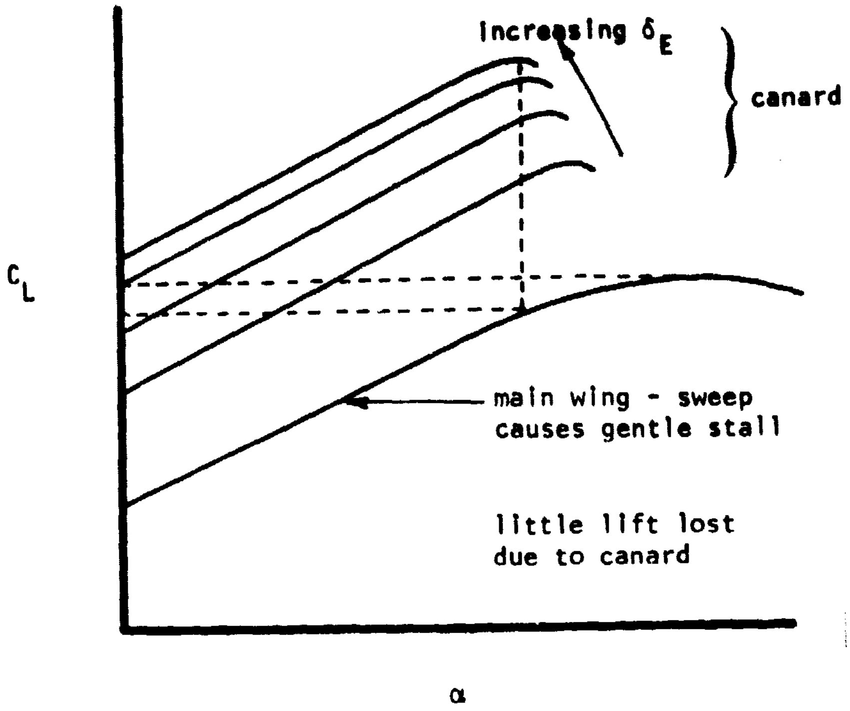
Provides volume for fuel and interior cabin space for elbows.

(Company F)

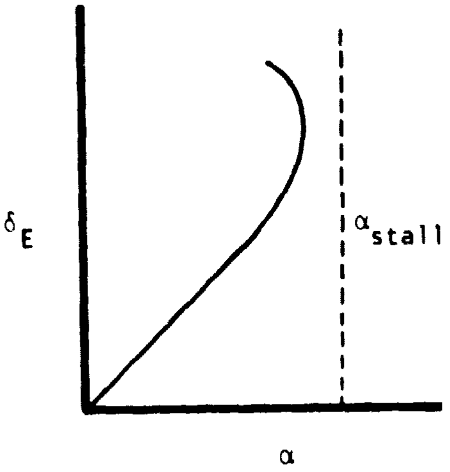
Aerodynamics of Canard Configurations

The wing tip is in upwash and results in localized low to negative induced drag. With the tips loaded up, the winglets work well.

Care must be exercised in selecting the proper airfoil section for a highly loaded canard. W/S of the canard can be twice that of the main wing, and the canard and wing can carry a 50/50 load distribution.



When the trim requirements for a canard with the lift characteristics of the previous figure are examined, it can be seen that the main wing cannot be stalled.



Efficiency Factor

Effective $e > 1$ when total area is counted in $A = b^2/S$.

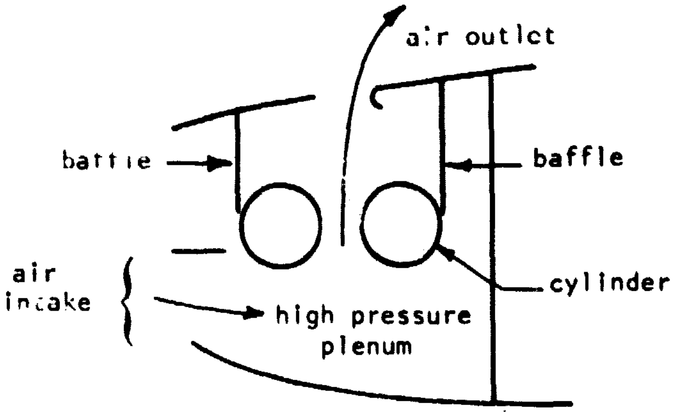
$$b = b_w \quad \text{and} \quad S = S_{canard} + S_{wing}$$

III. Engine Cooling

Updraft Cooling

Produces much more uniform cooling of the cylinders, which could increase TBO significantly. Possible problem with oil spray from the engine degrading cabin forward view.

The cooling air is only slightly affected when passing over the exhaust manifold first.



IV. Avionics, Systems, and Displays

Very interested in HUD's, improved displays, warning annunciators. Much improvement is needed here.

Would like to see an angle-of-attack indicator.

Avionics need improvement in price and reliability.

Fuel indicators are terrible. Should be non-linear and very accurate for the last 30 to 60 minutes of available fuel.

A.1.7 Company G

I. Propulsion

GATE Studies

Particularly interested in a 280 kw (275 hp) unit and another on the order of 746 kw (1000 hp).

Endorses GATE with reservations. Recommends that the range of sizes of GATE be well defined.

Aircraft Engines

Believes that the low bypass turbofan still offers more efficient thrust at high operating altitudes.

A variable bypass engine is needed with a capability for bypass ratios of .2 to .3 at 41,000 ft.

Noise is a big problem with low bypass engines but variable bypass would help.

If the GATE studies are accurate, a successful single engine turboprop will materialize.

II. Aerodynamics and Stability and Control

Wing Development

A design by this company incorporated a supercritical high aspect ratio wing (8). The new wing design proved to be too expensive for production so an existing wing was modified. It was not clear if production of an entirely new wing was cost prohibitive, or whether production problems associated with the supercritical wing were prohibitive.

The wing modification for the design consists of the following: the aft 60% of the existing wing was retained. The front 40% was replaced with a computer generated section. Each wing tip was extended 3 feet, and winglets were added. These modifications resulted in a 17% increase in L/D at cruise.

When used, winglets accounted for a 3% to 4% reduction in drag, and modifications of an existing wing resulted in a 230 lb weight penalty.

Light Aircraft

A modified 64-A215 had leading edge stall problems. Hence, a highly cambered (drooped) leading edge was incorporated which corrected the problem by maintaining flow attachment at the leading edge.

The Whitcomb airfoils could have problems with spins because of high leading edge suction. The high suction on the drooped airfoil on one plane aggravates spin characteristics.

Expressed interest in an airfoil section developed at the University of Illinois. It is reported to produce leading edge stall without the normally associated effects, and could have possibilities with spin-proofing or control during post-stall maneuvers.

More work needs to be done with airfoil design for general aviation. Forward camber is more attractive than aft camber.

T-tails are good for resolving spin problems.

High Speed Aircraft Control

Spoilers are used for primary lateral control.

Although direct lift control is not used, it has excellent technical merit.

III. Structures

Bonding

No bonding is used at highly loaded joints.

Feels that the ideal extent of bonding should be about 1/2 of what is currently in use on a particular light airplane.

Delamination at the trailing edges of wings, etc., and its causes (e.g. moisture) must be examined.

Since large portions of an aircraft are bonded at once, a parts shortage can halt the bonding process.

Multiple stage bonding can weaken old joints.

Quality control is a major problem, and strict environmental conditions must be maintained at all times.

Bonding has allowed the construction of a very simple airframe which also costs less.

Composites

Certification is a major problem associated with composites. NASA needs to work on certification criteria that are suited to composites, particularly where primary structures are involved.

Composites have primary advantages of

(1) Weight reduction
(2) Cost reduction
(3) Ability to accommodate complex shapes

Composites in propellers will yield better uniformity.

Honeycomb

Used extensively in the cabin area of the fuselage on one light aircraft.

Only used in floor and radome of a particular high speed aircraft.

IV. Systems

Flight Controls

Digital flight controls look good but are not being pursued at the moment.

Avionics

Panel mounted systems are more attractive than remote ones in terms of lighter weight, less complexity and lower cost.

V. Research By NASA

Recommends methods be developed for determining the effects of humidity on flight test results. No methods currently exist, nor is it accounted for in certification.

A.1.8 Company H

I. Aerodynamics and Configuration

T-Tails

T tails were designed for market appeal, and any performance gained is an "extra".

T tails can provide for less trim change while improving power-on stability.

GA(W)-1

Designs can suffer from wing-body interference. However, they produce high C_L's and gentle stall characteristics.

Canards

Not convinced about the benefits of a canard.

Cooling Drag

Twin engine aircraft with a third engine mounted in the nose of the aircraft can be (have been) used for cooling drag determination.

II. Bonding

Some bonding is utilized in cowls. Further bonding is being incorporated slowly.

III. NASA Involvement With General Aviation

NASA should be very selective in their entrance into general aviation and should confine their work to basic research as opposed to providing industrial guidance.

A.1.9 Company I

I. Propulsion

Air Cooled Engines

There are no near term alternatives to air-cooled engines.

Variable timing and electronic ignition will be utilized when required and when their flexibility and reliability are proven.

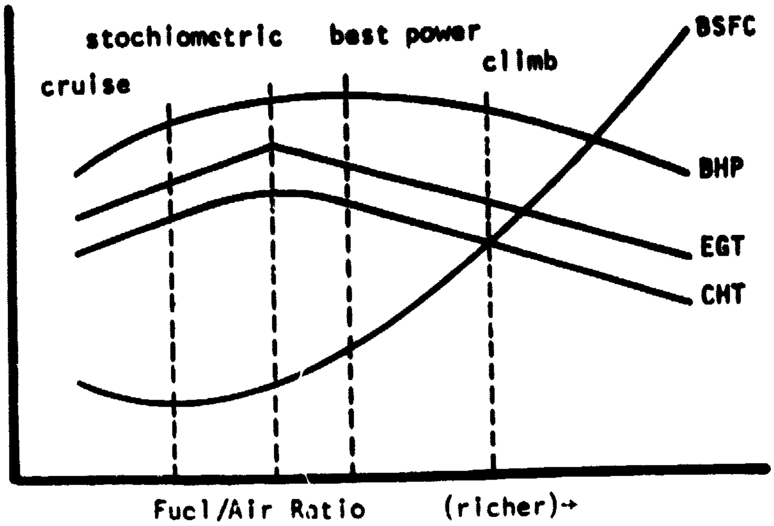
The automotive industry is not the leader of technology, but the leader of marketing.

An automatic system is needed to properly maintain correct mixture settings for best efficiency in cruise.

Operating an engine lean of peak results in cooler operation. (see sketch on next page)

Cooling design methods exist, but cooling requirements for general aviation engines are not specified in enough detail. Major problems with cooling drag lie in (1) inlets which are too large, (2) exhaust vents which are not well analyzed, and (3) lack of an efficient diffuser (plenum).

(Company I)



Engine Operating Characteristics

Definition of cooling drag: the momentum loss of air required to cool the engine.

Liquid Cooling

Could be done without a weight penalty over air cooled systems.

It is more efficient from a cooling drag standpoint.

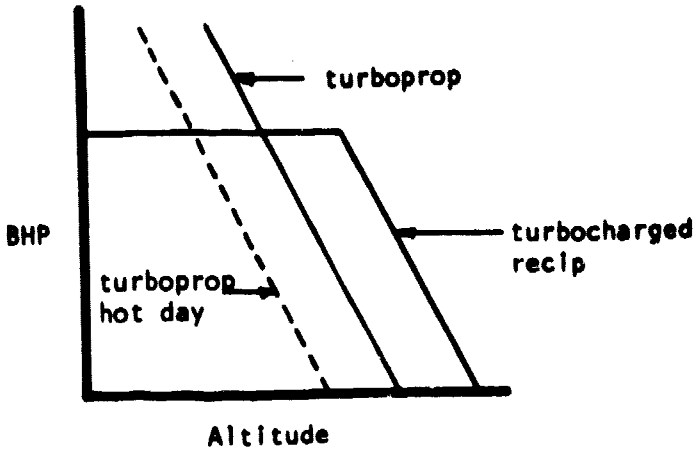
The high reliability required results in increased cost.

Turbines

Use only for justified purposes.

The turbocharged reciprocating engine offers some advantages over the turboprop. As an example, see the figure at the top of the next page.

A larger turboprop must be used to retain hot day performance and to offset a relatively high lapse rate.



Reciprocating Engine vs Turboprop Performance.

II. Aerodynamics

High Wing Loadings

Face the following problems

(1) Public reluctance to accept the handling qualities associated with higher cruise speeds.
(2) Landing and takeoff distances are increased.
(3) High wing loading generally requires high power loading.

High W/S requires effective flap systems, and possibly even full span flaps with spoiler roll control.

The general aviation data base for full span Fowlers with spoiler roll control is small.

Some effective wing area is regained for takeoff with moderately deflected Fowlers, but is accompanied by a (small) drag increase.

Natural Laminar Flow

Studies need to be done on effects of contour shape tolerances and surface finishing.

Eppler's work on airfoils is encouraged and supported.

III. Safety and Crashworthiness

Deicing and Anti-icing

More work should be done in the search for an icephobic surface coating.

Weather

Studies of severe weather structural response and damage limiting methods should be pursued.

More research regarding lightning strikes is needed.

Crashworthiness

Definitely needs more work. NASA should continue its present research in this area.

Specific areas which merit study: fuel containment, engine compartment fire containment, effect of composites, heat tolerant metals.

IV. Noise

Possible methods for reduction include

1. Vibration damping.
2. Quiet, yet power-effective mufflers.
3. Quieter propellers.
4. Sound damping in the cabin.
5. Variable transmission and/or gearing systems for the engine/propeller interface. Could be attractive for certain applications by holding propeller rpm constant while allowing engine rpm to vary.

V. Operations

ATC

Would like to see NASA involved more in the conceptual stages of ATC planning.

New basic concepts which allow for the optimized use of inertial nav and RNAV are needed. These would help fuel efficiency quite a bit.

Flight Manuals

More standardization of flight manuals for aircraft is needed. GAMA is working on this.

VI. Flight Test

Flight Test Pilots

The technical capabilities of test pilots needs to be improved through better training.

Management needs to be more aware of the functions, qualifications, expertise, and capabilities of test pilots.

Instrumentation

Good thrust and torque meters are needed to determine performance accurately.

More development is needed on the vortex generating airspeed sensor. Airspeed measurement without disturbing the flow field requires development.

A humidity detection device is needed to improve the accuracy of engine operating parameters.

VII. General Comments

FAA regulatory procedures are overly restrictive. Also, the regions are autonomous, and certification requirements based on the interpretation of a regulation by one region may differ substantially from those of another region.

NASA may want to hold a seminar to educate management on the availability of high technologies.

NASA may also want to educate the younger engineering generation on older (pre-1954) documents.

Management and marketing decisions can conflict with technology and result in bad airplanes.

Most general aviation airplanes aren't designed. Rather, they are just built.

Product liability is the worst problem confronting the industry.

Regarding airfoils, NASA should publish data for realistic flight conditions in addition to those for "smooth airfoils", etc.

Rewrite the Pratt and Whitney reciprocating engine manuals (circa 1940-1945) for application to general aviation. They are good.

Anything that makes aero design more of a science and less of an art will be an important area of research.

A. 1. 10 Company J

I. Operational Environment

The critical area for advancement is not the vehicle, but the operational environment. i.e., the pilot's interface with the systems must be improved.

Pilots need clearances, weather, and traffic advisories, which are currently obtained verbally. These should ideally be communicated visually.

Solutions

Develop data links from the ground to the aircraft.

If these problems were solved using the data link and CRT display, it would eliminate unnecessary voice communications, radar sets, and possible collision avoidance equipment. The system would reduce work load and be more efficient.

II. Composites

Cost and certification are the most serious problems.

III. Propulsion

Available turbochargers are not optimized for aircraft use. General aviation is constrained to off-the-shelf equipment.

IV. Liability

Plagued by nuisance suits. Even if the company is innocent, it still costs money. This is a big factor for a small company.

10% of the vehicle cost is liability insurance.

A.1.11 Company K

Company K developed a single-engine, very high performance aircraft employing a composite structure.

I. Structures

Composite construction of the aircraft is not advanced technology. The material used (fiberglass) has been available since the 1950's.

Composite structure allows a significant reduction in parts count. This should cut costs.

The fuselage is constructed in halves. The left half is outfitted with all bulkheads, engine mount, and internal hardware. After this is done, the right half is bonded to it. This method should reduce labor costs significantly since construction time is reduced. It allows the worker to outfit the aircraft easily without having to crawl through the fuselage shell as is required with conventional aircraft manufacturing processes.

The aircraft is not particularly lighter than existing aircraft.

The major construction material is a fiberglass honeycomb sandwich.

II. Aerodynamics

No advanced technology. All airfoil sections are NACA sections.

Wing loading is relatively low and on the order of 20 to 30 psf.

This airplane is aerodynamically clean. Lack of joint lines and protrusions, together with a "slick" surface finish which the composite construction allows, creates a very low-drag airframe.

With 298 (400 hp) and 6 passengers, the aircraft is capable of 261 kt cruise at 6096 m (20,000 ft).

A.2 PROPULSION MANUFACTURERS

A.2.1 Company L

I. Advanced Airfoil Sections

Currently working on an airfoil section with Ohio State to develop a thinner section that produces greater maximum lift to reduce weight.

Want to maintain current cruise efficiency ($\eta_p = .9$) while improving low-speed performance. The goal is an efficiency of .7 to .75 in climb.

Doesn't believe that cruise efficiency can be improved. Thus they are concentrating on the low-speed regime.

(Company L)

II. Blade Planform/Configuration

Blade number is increasing in twins. Single engine aircraft will remain with 2 or 3 bladed propellers because of weight and engine characteristics.

The Q-tip reduces noise while generally maintaining rpm. Performance is not improved.

Proplets are not winglets. Rather, they are Q-tips bent in the opposite direction.

III. Materials

Composite blades are made with Kevlar.

The composite blade was designed to twice the strength of a comparable aluminum blade. This conservatism in strength was a safeguard for certification. After certification, plans for reducing strength and weight to more realistic values may be undertaken.

The composite blade costs 2 1/2 times as much as an aluminum blade but weighs half as much.

Costs of the composite blade appear more favorable each day. The cost of Kevlar is declining and the price of aluminum is increasing. In addition, when strength is reduced to realistic levels, the removal of Kevlar will reduce costs even more.

For the composite propeller configuration, the propeller assembly weight is divided equally between hub and blade weights.

IV. GAP Program

Five different blade designs are undergoing testing for acoustics. These propellers are all 1/2 scale, and are currently being wind tunnel tested. A full scale test is expected to follow.

V. Operations

For reciprocating engine propellers, one must forego cruise airfoils to allow for vibration. Example: Use Clark Y instead of a 16 series section.

For turbine aircraft, vibration is not as great a problem, and the most efficient airfoil can be used.

Blade erosion has proven to be no more of a problem for the composite blades than for aluminum blades.

Five bladed propellers are performing well. When more than three blades are used, however, vibration considerations impact more heavily on the design.

VI. NASA Research

Need studies on propeller characteristics when used for reverse thrust.

A.2.2 Company M

I. GAP Studies

Purpose

Identify technologies that will reduce fuel costs.
Identify technologies that improve noise characteristics.

Technology Elements include weight, noise, cost, life, airframe integration, and emphasize "clean sheet" airplane design.

II. Technologies Applicable to Propellers

Advanced Airfoils

Looking at ARAD characteristics over their entire performance range.

Utilizing computer-aided design of airfoils.

Comparing L/D, C_L, etc. of Clark Y, GA(W), current in-house designs, and ARAD.

Current cruise efficiency stands at $\eta_p \simeq 85\%$ to 87%. Advanced airfoils offer 1% to 2% efficiency increase, and also help relieve compressibility losses.

Improved Propeller-Nacelle Integration

Looking primarily at a performance improvement.

Engine shape is a significant parameter.

Using potential flow analysis to determine what the nacelle effects are on the propeller flow field.

Possibly realize a 3% to 4% increase in efficiency.

Design Optimization

Blade sweep. Also, reduce t/c through the use of composites.

Composite Materials

Screening materials. Looking for optimized materials and the manufacturing techniques required in a production environment.

Composites offer the greatest value in fatigue life and low weight but have large penalties in cost, both in acquisition and in processing.

Effects of tip speed: Diameter and rpm tradeoffs.

Effect of number of blades

Effect of blade loading on noise

Current blade loadings are designed for performance and are not optimized for noise.

III. Areas Where Greatest Gains Can Be Made in Propeller Technology

Advanced Airfoils

Propeller/Nacelle Integration

Compressibility Studies

Current losses are on the order of 1% to 5%.

Sweep of 45° at the tips can gain half of the losses back.

A combination of tip sweep and advanced airfoils should gain most of the losses back.

Believes 90% installed efficiency can be realized compared to the current levels of 85% to 87%.

Analysis of propellers done with a 3-D strip computer code, based on a 2-D method by North Carolina State and Lockheed.

IV. NASA Research and Funding

Composites

Investigate materials and processes.

Establish time criteria for fatigue testing, etc.

Develop and substantiate data.

A.2.3 Company N

I. Propulsion

Q-Fan

Work was halted because of lack of industry interest.

Prop-fan

Designed for higher Mach application: .55 and above.

Features

- Area-ruled spinner.
- Swept blade shape.
- Integrated nacelle shape.
- High power loading.

Objectives

- 5% to 10% savings in DOC.
- 20% reduction in fuel consumption at M = .8.

Sweeping blades appropriately can cancel noise at the source. Works well for the prop-fan, but the effects on conventional propellers is unknown.

The prop-fan doesn't really represent difficult structural problems. Metal spar, foam leading edge and trailing edge, composite shell.

It has better performance on takeoff than a turbofan.

The integral spar with shell is designed primarily for safety. Damage to a blade will not result in failure of the complete propeller.

II. Environmental Control Systems

Goals

Reduce power requirements.
Reduce Life Cycle Costs (LCC) for entire aircraft system.

A variable air-cycle system was produced for a fighter aircraft, with a broad range of applicability in mind.

The system saved 817 kg on a 28150 kg aircraft, and also saved .37 cubic meter of internal space, or 40% of the environmental control system compartment.

Reliability of the variable cycle system is just about as good as a conventional system even though it has more moving parts.

Recirculation can save 30% of a 373 kw power requirement.

Air cycle is lighter than vapor cycle, but requires more power.

III. Air Bearings

Offer great promise for high speed rotary machinery.

Have more load capability at high speeds, but tend to fail at low speeds (just the opposite of ball bearings).

Have the potential for greater reliability. No maintenance.

Systems are heavy and cost more than ball bearings.

IV. Micro-Electronics

Engine Control Systems

Total electronic controls for engines utilizing no mechanical parts or backup systems for operation.

Engine control systems will have to control more functions and more accurately.

For small engines, cost is the important factor. This company produces the engine controls for a current small turbofan at approximately $3 to $4 thousand per unit.

Controls synchronize, synchrophase, and control fuel flow of the engines. Results in a 7% to 15% improvement in sfc.

Fly-by-wire and Fiber Optic Systems

For flight controls and engine controls.

Distributed microprocessors seem more likely than a single computer.

When developing fly-by-light and digital controls, the following points must first be considered.

(1) How much redundancy is required for the mission, and what methods for redundancy will work best for the situation.
(2) Policing the system is difficult, because failure determination requires much complexity.

Advanced Data Diagnostic Systems

Airborne integrated data system. Monitors health of aircraft systems and engines.

Will also be applied to flight profile monitoring.

General aviation could use at least an engine monitoring system.

At first, the system will probably be ground based. As more electronic systems (microprocessors) appear on aircraft, onboard monitoring systems will emerge.

A.2.4 Company O

I. General Aviation Engine Market

The total piston engine market in general aviation is $250 to $300 million per year.

$25 to $30 million would be required to start from scratch with a new engine and take it to production.

Technology must be cost effective for the manufacturer.

Liability

Is a problem within the industry. A company may pay over $3 million per year for liability insurance.

General aviation engines today are very sophisticated and not World War II products.

(Company O)

II. New Technologies

Improved Fuel Injection

The fuel injection system currently used is simple, low cost, and reliable, but does not compensate for atmospheric density changes.

Fuel injection could be improved to provide for density compensation so that fuel consumption could be reduced 3% to 4% during takeoffs, landings, and climbs.

Variable Timing

Offers the potential of a 3 1/2% increase in fuel economy.

Metallurgy

Methods need to be developed for lower cost production of titanium. It is an abundant element.

If engines were designed with titanium, a 30% weight reduction over current engines could be realized.

If the goal of 1.6 kw/kg (1 hp/lb) is to be realized, titanium must be utilized.

III. Ideas On Advanced General Aviation Engines

Diesel Engine: No such thing as an "uncooled engine".

Rotary Combustion Engine: Will never be feasible because of the following reasons:

(1) low volume sales.

(2) complex tool-up and machining.

GATE Engines:

The following is a comparison between a reciprocating ngine (turbocharged) and a GATE turboprop.

Engine	**Power, kw (HP)**	**Altitude**
Company O	**242-231 (325-310)**	**Sea Level**
Company O	**186 (250)**	**7620 m (25,000 ft)**
GATE Turboprop	**269 (360)**	**7620 m (25,000 ft)**
GATE Turboprop	**500 (670)**	**Sea level**

Turbocharged Reciprocating Engine vs GATE Turboprop

By this comparison, GATE doesn't look that good.

Derating (flat rating) will already affect the turboprop. Utilizing it at an off design point degrades the fuel specifics.

The hot day performance of a turboprop is not as good as a turbocharged reciprocating engine.

The GATE engine costs are unrealistic. The projected market is totally unrealistic. For example, a currently produced comparable turboprop engine costs roughly $50,000, compared to an existing reciprocating engine which is $25,000. Both have similar sea level horsepower. The costs of the turboprop have been amortized for years, and it still costs a lot. How will a small turbine, utilizing advanced technology, cost anywhere near a current reciprocating engine?

The "real world" factors of marketing and aesthetics need to be accounted for in design.

A.2.5 Company P

I. Marketing

Technology of no use unless

It satisfies a need.

Developer can afford it.

It's profitable to the user.

It's introduced at the right time.

(Company P)

Turboprop Mature Market Priorities

Price - Very sensitive at equal hp.

HP - Wants more horsepower at same $/hp.

Reliability and product support.

SFC (but not so important, since other factors contribute to DOC.)

TBO and other maintenance costs.

Operating characteristics.

Weight.

Turboprop New Market Priorities

SFC - Emotional as well as economical issue.

Price.

Reliability and product support.

TBO and other maintenance costs.

Operating characteristics.

Weight.

Engine Targets : 1490 kw (2000 hp) -- .262 kg/kw-hr sfc
522 kw (700 hp) -- .27 kg/kw-hr sfc
224 kw (300 hp) -- .32 kg/kw-hr sfc

Turboshaft Priorities

SFC @ 60% power (installed), @ low altitude.

Weight (installed).

Price.

Reliability and product support.

TBO and other maintenance costs.

Operating characteristics.

Brand name.

Price importance is inversely proportional to gross weight.

Turbine Engine Market

Customers	1978	1985
Corporate	58%	65%
Utility, commuter, & paramilitary	16%	27%
Military	16%	4%
Civil Helicopters	10%	4%

Sales: Forecasting a 5.8% growth rate for turbine aircraft over the next ten years.

Turbofan Priorities

Thrust: Speed improvement.

SFC: Range improvement.

Price.

II. Advanced Design

GATE Studies

Goal was to use high technology but obtain lower costs. This goal is contradictory.

Marketing Considerations

Not favorable for small turboprop -- high volume but low dollar sales.

Market penetration of a 224 kw (300 hp) engine at 5000 units/yr for $20 thousand = $100 million/yr. This is small for Company P considering an anticipated $50 million development cost. For $100 million, can develop a 1491 kw (2000 hp) turboprop, and make more on less volume of sales. The development costs are not much different for a small or a large engine.

The only way a small turboprop will be developed is through NASA sponsorship of research and development.

III. Aerodynamic Research

Concerned with compressors, combustors, and turbines.

Compressors

Centrifugal Compressors

Pressure ratios of 7 to 11.

Current engine with centrifugal compressor gained four points in η and 7% in sfc.

Always looking for better shapes.

Does extensive computational aerodynamics work in the design and analysis of compressors.

Axial Compressors

Maximum pressure ratio for 2 stages is approximately 2.

Looking at a rotating hub with stators cantilevered from outer ring. This reduces the stall margin.

IV. Mechanical Research

Looking at:
- Structures.
- Cooled turbine.
- Fan blade foreign object damage.
- Reduction gearbox.
- Rotor fragment containment.
- High Dn (diameter x speed) roller bearing Technology.
- Journal bearing technology.
- Supercritical rotor dynamics technology.

Structures Technology

In-house finite element programs supposedly better than NASTRAN. Finite element programs used for:

- Transient dynamic analysis.
- Contact analysis.
- Mode shapes.

Also, experimentally determining mode shapes via a holographic analysis is attractive.

(Company P)

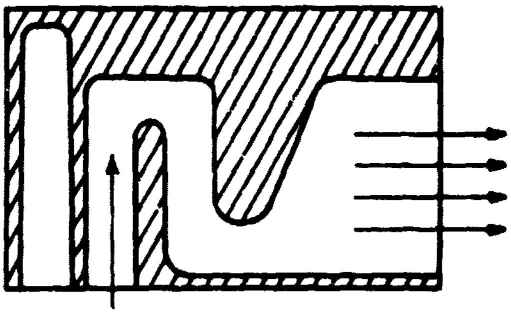
Finite element program for turbine blades has 12,000 degrees-of-freedom.

Also can analyze effects of flange leakage and foreign object ingestion.

Cooling Technology

Used 12,000 degree-of-freedom model for one blade.

TIT 1170°C (2140° F) but blade temperature is 977° C (1790° F).



Cool turbine blade with integral air channels as shown above.

Gearboxes

Engine rpm's as high as 30,000.

Vibration is a big problem in gearboxes.

Matched gearing and indexing can reduce vibration by 50%.

Increasing the thickness of the shaft usually helps reduce overall flexibility.

IV. Prop-Fans and Variable Pitch Fans

Prop-fan offers efficiencies of .8 at Mach = .8.

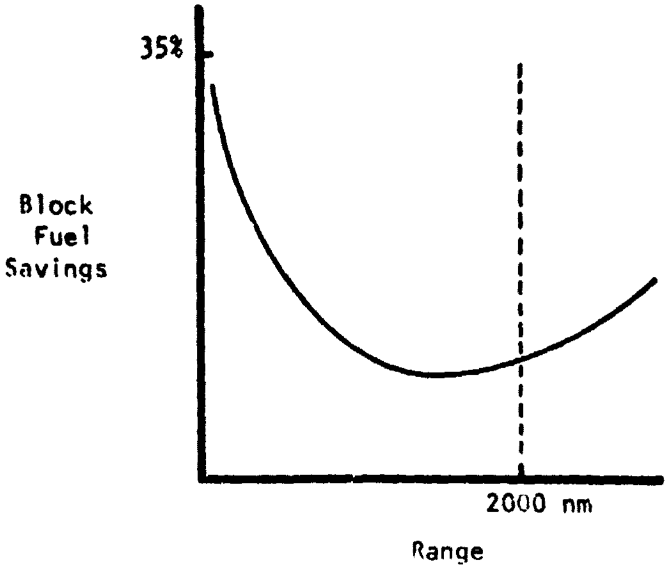
Also attractive for short to medium range aircraft.

Directly challenges turbofan.

Variable pitch fan (VPF) challenges medium-speed turboprops.

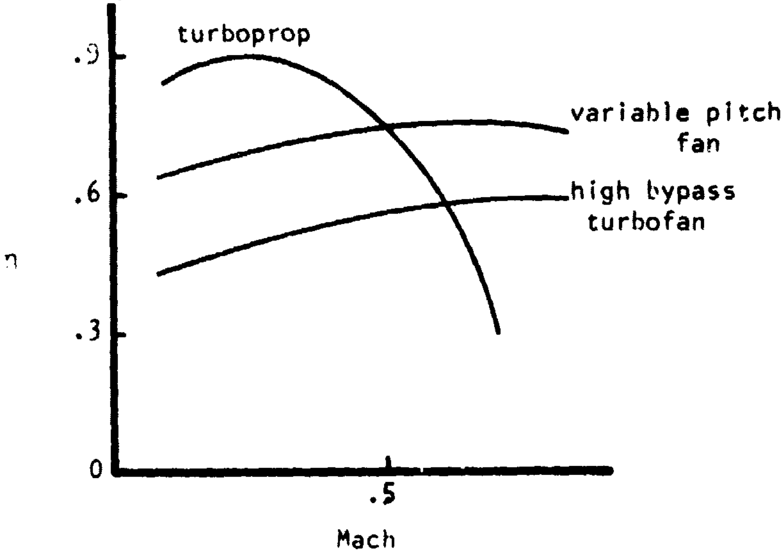
Recommendations

Investigate prop-fan application to small business aircraft for Mach numbers of .7 to .8.



Prop-Fan Savings vs Turbofan.

Investigate variable pitch fan application to commuter aircraft.



Variable Pitch Fan, Turboprop, and Turbofan Efficiencies.

(Company P)

VI. High Efficiency Propellers

Propeller Research

Blade design, afterbody effects, airfoils, nacelles, and inlet effects, control, hub design, materials, all require study.

Need propeller developments to match engine developments.

Tradeoffs

As velocity increases, propulsive efficiencies become more significant.

With conventional airfoils, a large diameter is required for high efficiency. For noise reduction, need to reduce diameter and/or rpm.

Commuters need high thrust/power for takeoff, possibly attained by compromising cruise performance.

Areas under review

More efficient airfoils.

Noise (FAR 36 near and far field).

Optimization.

Integration of spinner and nacelle.

Increasing number of blades

Advantages	Disadvantages
reduce diameter	complex hub
shorter undercarriage	higher cost
reduce engine-out problems (thrust-line closer to c.g.)	higher weight
increase high speed efficiency	
looks better	
lowers noise	
engine speed goes up but torque goes down	

Anticipated work needed for

High speeds - increase propfan efficiencies.
Low speeds - increase turboprop efficiencies.

Noise

Free-turbine propeller has cruise noise advantages (variable propeller speeds).

Research

Direct towards maximum fuel economy.

Apply (integrate) new technologies in areas of:

Airfoil shapes,
Materials and construction, and
Control concepts.

VII. Fuels

A main thrust is that engines be able to use a wide range of fuels. Specifically applicable for turbines and diesels.

Tar sands may be important as a fuel source.

VIII. Materials

Priorities

Safety, inspection, and simplicity.

Low first cost.

Weight.

Effects on fuel economy.

Durability/cost tradeoffs in defining desired TBO's.

Influencing Factors

Increased energy cost affects materials cost.

Increased fuel cost requires increased efficiency.

Supply of critical materials such as chromium, cobalt, and tantalum could be a problem.

Chromium - 95% comes from Rhodesia and South Africa. Used for corrosion resistance and strength.

Cobalt - replaceable at a cost.

Tantalum - used for oxidation resistance in turbine blades.

New and/or Alternate Materials

Ceramics - Reliability.

Substitutes - Nickel for cobalt.
Aluminum for chromium or
Molybdenum for chromium.
Columbium for tantalum.
No substitute for titanium in impellers.

Reduce Input Materials for Lower Costs.

Powdered metal is expensive, and costs twice that of bar stock.

Castings - need better non-destructive testing even when using hot isostatic pressing.

Mixed processes - diffusion bonding or friction welding of castings and forgings.

Note: Forgings have a high rejection rate:
Keep 15% and discard 85%.

Improved Corrosion Resistance Methods

Rapid solidification rate (RSR) - single crystals.

Better coatings.

Areas for Further Research

Improve non-destructive testing.

Improve confidence in

Powdered metal technology.

Casting methods.

Extension of engine life.

A.2.6 Company Q

I. Significant points made during preliminary briefing

Reciprocating engine performance and operations are often adversely affected by enroute as well as destination weather.

Turbine engines are lighter, more reliable, faster, and less susceptible to enroute weather than their reciprocating counterparts. Also, they are not subject to cooling drag.

The disadvantages of a turbine include cost, and higher specific fuel consumption. The latter is offset somewhat by the elimination of cooling drag.

If turbines are to get any cheaper, broad usage must be found.

Turbines are still not the answer to all segments of general aviation: best over 150-186 kw (200-250 hp).

General aviation accident rates are much higher for reciprocating powered aircraft than for turbines.

II. Comments on General Aviation

Businessmen like quiet working atmosphere in aircraft (more productive use of time).

Corporate passengers like long range, comfortable, over-the-weather flying capability.

General aviation's major drawback is cost. New technology must be incorporated without large price increases.

III. GATE Project

Design Philosophy

Traditional - reduce parts count, and make the remaining parts more efficient.

Cheaper production, commonality.

Cost Factors - high expense

Rotation speed - affects life, shaft dynamics and bearing suspensions

High tip speeds create high stresses in compressor and turbine blades.

Precision: surface finish is critical.

Low volume production, tooling costs, and required research and development (R & D).

Cost Solution

The solution is lower rotational speed.

Multi-stage axial compressor (5-6 stages).

Again, the low speed of the turbine reduces stresses (50% in the turbine blades).

Shaft fuel injection, with centrifugal fuel nozzels (low-pressure system).

The net result is a much lighter weight turboprop, compared to a reciprocating engine (a 224 kw reciprocating engine weights 272 kg). Smoother, quieter, no cooling drag, smaller nacelle, jet fuel, competitive BSFC, and longer TBO's, are all advantages over the reciprocating engine. Costs $19,000 on a large-scale production basis.

Turbofan Concept

Turbofan utilizes a common hot core with the turboprop.

Add 3-stage low-pressure compressor and fan, and a 3-stage low-pressure turbine.

Bypass ratio = 5 to 5.5:1; thrust = 4.319 KN; weight = 84 kg; sfc = 40.5 kg/KN-hr at SL, 69.44 kg/KN-hr at 9140 m with 1.113 KN thrust.

Forecasting a TBO of 10,000 hours (aircraft life).

Priced at $23,000 with several thousand/year production run.

GATE Realization

Minimum time required to get the GATE engine to a demonstrator level is 3-4 years (optimistic), 5-6 years for certification.

There are no plans for turboprop hardware at Company Q currently. The cost of development to demonstration would probably be under $10 million.

However, if NASA doesn't fund additional GATE work, industry probably won't pursue it.

Small turbine development led to a low cost turbojet. The unit cost $2000 for a 1000 unit production run in 1976. It was designed for 30 minutes to 1 hour of life at 35,000 rpm. The engine has been tested up to 18 hours, and has a TSFC of 132.6 compared to 117.3 kg/KN-hr of another similar engine. Life of the engine is limited by the use of grease-packed bearings.

60% of the cost of this turbojet was in the turbine.

Simple compressor concept is proven by this turbojet with only minimal compromises in aerodynamics. TSFC goes up, but not unreasonably. The reduction in performance results from lower pressure ratios.

Turbine design is flexible:

build to high stress - long life.
build to low stress - lower initial cost.

GATE turboprop description

6-stage axial compressor, 1-stage centrifugal compressor, 4-stage turbine.

low gearing

1.02 m (40 in) long, weighs 72.6 kg (160 lb) without starter.

12.5 pressure ratio, 1010° C TIT, 280 kw (376 hp) and 0.356 KN (80 lb) thrust.

IV. Current Work

Military application

A broad production base for a current small turbofan might be realized from a likely contract.

Another small turbofan used in a different program is derated 10% to 15%.

Utilizes oil lubricated bearings and could benefit general aviation through spinoffs.

A.2.7 Company R

Developing rotary combustion engines for aircraft and other vehicles.

I. Rotary Configuration

Rotor system is simple and easily adaptable to different sizes.

Size (displacement) can be changed by

(1) increasing width of rotor.
(2) adding rotors.
(3) increasing diameter of rotors.

Item 3 is the least attractive, because apex speed is a factor. Items 1 and 2 are easy.

4 rotors is an attractive maximum. Allows the engine case to be built in two parts, each with two rotors. In this manner, the crankshaft does not have to be split for the timing mechanism. This keeps cost down.

Wide rotors are not very desirable (current model is 3 inches wide) because of crankshaft bending under loads.

II. Seals

Unique apex and side seals are incorporated which resolved previous seal problems.

The seals are sintered ferrous metal, which is very compatible with the trochoidal surface coating. Compatibility is the key. Trochoidal coating is high cost and applied with a detonation gun.

Other less costly methods exist, including plasma spray and chrome.

In a test of seals, this company found

(1) their trochoidal surface showed imperceptible wear.
(2) their apex seal wear after 2000 hours was very low and forecast to last 5000 hours.

This test was, however, performed at a lower BMEP than expected for aircraft.

(Company R)

III. General Comments on Rotary Combustion

(1) lower weight.
(2) lower cost.
(3) multi-fuel capability - not restricted to AVGAS.

3000 hour TBO for the aircraft rotary combustion engine is a viable goal.

Lower cost due to simpler system and easy adaptation to different sizes. Reciprocating engine manufacturing is cost-constrained (or cost-fixed) by lot sizes of production runs.

The rotary engine OEM cost will be better than for a similar technology level reciprocating engine. At the worst, it will be the same.

Now running a military contract for development of a rotary engine. In addition, they have contracted an airframe manufacturer to do sizing studies utilizing their aircraft rotary engine.

Engines are liquid cooled although air cooling has been demonstrated. The liquid cooled engines are lighter than equivalent reciprocating engines, even with coolant and radiators. Therefore, they offer advantages both in cooling drag and weight.

IV. Charge Stratification

Main research effort.

Uses an unthrottled, direct fuel injection approach with much success.

Fuel injection is followed by secondary air ingestion.

Uses one injector for the pilot flame ($\simeq$ 10% of fuel) and a second injector for 90% of the fuel which controls power output.

Already demonstrated excellent emissions and fuel economy in a surface vehicle.

V. Aircraft Engine

Was testing a 246 kw (330 hp), 127 kg (280 lb) engine, but not at the moment. It is expected to be run again.

An earlier NASA report documents studies of an aircraft rotary engine which was

(1) a gasoline engine.
(2) not stratified-charged.
(3) normally aspirated.

Present preliminary analysis indicates that the above engine, when modified to stratified charge capability, will meet emissions, have wide-cut fuel capability, and have a BSFC ≃ 0.24 kg/kw-hr (.4 lb/hp/hr). (NASA goal is 0.23.)

VI. Suggestions for NASA (areas NASA could help in)

(1) More mutual effort (or an atmosphere of) between NASA and the manufacturers.

(2) Stratified charge combustion modeling.

(3) Basic research on materials - higher speeds and loads will require better wear rates.

(4) Materials research of high temperature cast aluminum - specific data on low cycle thermal fatigue.

(5) Improved turbocharging.

A.2.8 Company S

Background: Developing an advanced technology turboshaft engine for military helicopter applications.

One of two companies developing this engine.

I. Objectives

SFC = .55, at 358 kw (480 ESHP) (60%).

Relatively easy to change turbine and apply to a turboprop vehicle for 75% power at cruise altitude.

Requirements - the engine component design should not contain any design features (inherent limitations) that would preclude the engine from obtaining an FAA certification.

Front drive characteristic specifically designed so that it could be adapted to turboprop application.

Present contract funds research through 500 hours of testing, but not through certification. Would like to see NASA fund the certification phase.

If certification is attempted, the engine could possibly be certified by 1984.

This is a high technology engine and, even if mass produced, could never get below $56 to $60/kw ($75 to $80/lb).

II. Highlights

(1) Designed for SFC of .33 kg/kw-hr (.55 lb/hp/hr) power at sea level.

(2) This 597 kw (800 ESHP) engine is to have a dry weight of 90.8 kg (200 lb). Includes a FOD device at inlet, which would not be required for civil use.

(3) Must have provisions for customer bleed air (pressurization, etc.)

(4) Must have 7.5 kw continuous drive pad for accessory pack.

(5) Operation for 5 mins without oil at 75% power.

(6) Modular assembly/disassembly.

III. Noise

Comment: anything on a flight schedule (commuter) must meet already mandated emissions standards and about-to-be-mandated noise standards.

A.2.9 Company T

I. Advanced Materials and Processes

(1) Directionally solidified turbine blade. Exothermically cooled. Produces a 2.42% sfc improvement.

(2) Abradable seals. produces a 10:1 wear ratio with turbines, compressors, or any component that requires close tolerances.

(3) Single crystal turbine blades. Eliminates grain boundary strengthening alloys. Provides stronger blades. Allows higher blade and TIT temperatures (1092° C [2000° F] for blades), and no surface coatings or blade cooling is required.

II. Turbine Engines

Compared to large turbine engines, small turbines have less efficient components. Manufacturers cannot afford the complexity of seals, clearances, and components required to get the same efficiencies, temperatures, and pressure ratios as are found in larger turbine engines.

Turboprop business aircraft requirements:

(1) increased altitude and horsepower.
(2) increased component efficiencies and operating temperatures.
(3) propeller noise reduction.
(4) high horsepower propellers.
(5) STAT studies (see Appendix A.5.1)

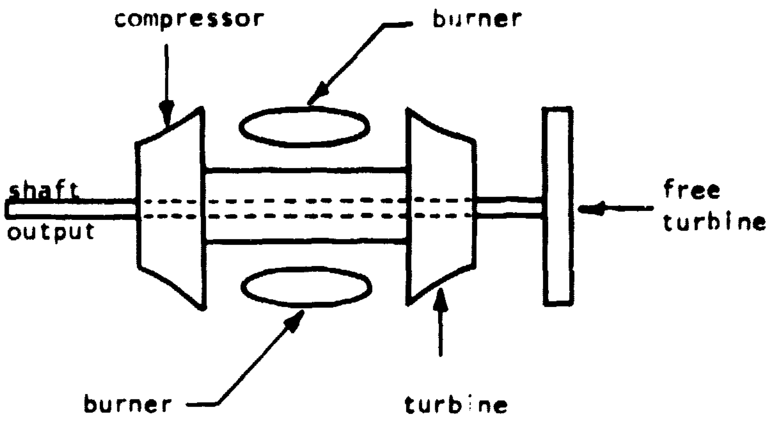
III GATE Program

As engine horsepower is decreased, the turbine engine is less competitive with respect to the reciprocating engine. One company representative, however, believes that the light, fixed wing aircraft market is an ultimate customer for the turbine.

Application of the small turbine is best suited to the light-to-medium weight category of pressurized, twin engine aircraft.

Features:

(1) laser hardened gears.
(2) single stage compressor.
(3) free turbine (see figure below). A single shaft is 2% to 3% less expensive than a twin shaft, free turbine configuration, but the twin shaft has a larger market with helicopter applications.



Twin Shaft, Free Turbine Configuration.

(4) a turbine inlet temperature (TIT) of 1203° C.
(5) an aircooled laminated centrifugal turbine. This technology allows the incorporation of very complex cooling air paths within the turbine, unattainable by other fabrication techniques.

Results of GATE study were:

(1) overall efficiency ($\Delta\eta$) increased 9.8%.
(2) SFC was reduced 7.4%.
(3) unit cost was reduced 21%. In a production run of 7,000 to 10,000 units per year, the projected cost of each engine was $15,000. 40% of the total reduction is attributable to a 40% reduction of turbine cost, and 24% of the total reduction to the forecast production rate.
(4) cost was predicted through GASP by the following proportionality:

$$\text{cost} \propto (\text{hp})^{.68}$$

Four engines were examined in the study: a turbojet, turboshaft, turboprop, and turbofan. The turboprop is more applicable than the fan to twin engine aircraft in the 242-298 kw (325-400 hp) range.

Cruise and takeoff criteria favor the turboprop over the jets. SFC is worse than for reciprocating engines, but the difference is returned in weight and size reduction. Seat-miles/gallon increases substantially.

IV. Recommended Areas of Emphasis for Research

(1) Energy efficient engines with improved SFC.
(2) Alternate fuels research.
(3) Establish durability evaluation methods (Example: methods for predicting engine life and TBO).
(4) Bird strike design methodology. A method is required for designing turbofans of all sizes to survive bird strikes and still operate.
(5) Pursue GATE.

Propulsion groups should examine high performance, low cost turboprops, advanced engine cycles, and component improvements in efficiency and manufacturing techniques.

A.3 AVIONICS AND AUTOPILOT MANUFACTURERS

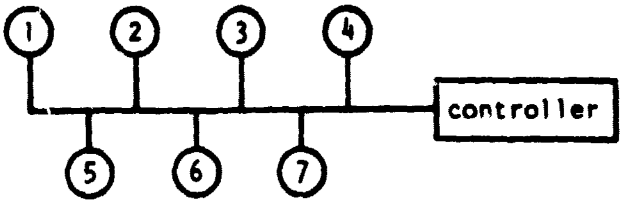
A.3.1 Company U

I. Integrated Avionics

Multiplexed systems

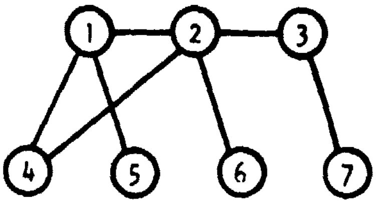
The military is evaluating the "1553" multiplexing bus.

Multiplexing should not be incorporated into general aviation avionics systems.



Multiplexed System (military)

(numbers indicate individual avionics units. i.e. navigation radio, communication radio, Automatic Direction Finder, etc.)



Broadcast System (ARINC)

Multiplexing has some serious disadvantages:

(1) expensive.
(2) if the controller fails, the entire system fails.
(3) requires triplex lines and receivers for redundancy.

Multiple connection between data sources and sinks is not necessary as shown in the broadcast system. If one unit fails, the entire system does not fail.

System costs

The primary costs in avionics are displays and sensors.

Low volume production increases unit costs.

Cost reduction in avionics demands that low cost sensors be developed.

New sensing methods should be explored: optical sensors and low cost solid state sensors.

The automotive industry has not been very helpful in these areas since they do not appear to be pursuing advanced technology.

II. Electronic Instrumentation

Displays

Color displays can be as economically produced as monochromatic displays.

Multifunction displays offer great promise.

Mean time between failure (MTBF) of the units can be doubled if operating temperatures are decreased 11° C (15° F).

Currently developing high resolution color CRT displays for commercial airlines.

Built-in-test

Has some advantages if its design is not overly complex.

Results obtainable depend largely on the innovation of the designer.

III. Advanced Technologies

Digital technology will filter down to general aviation with low cost computers. As electronics cost decrease, capabilities increase.

Airframers still decide on which major systems to incorporate or pursue.

Electronic fuel controllers show promise if they can lower life cycle costs.

IV. Navigation Systems

Omega - VLF

Not accurate enough for domestic service.

Loran C

Incomplete airspace coverage.

In addition, 100 to 200 kHz power line transmission control signals interfere with its performance.

Global Positioning System

GPS has the ability to fulfill the roles of VOR, DME, RNAV, and possibly category I approaches.

GPS can be made attractive to a very large group of customers which includes general aviation. It is very cost effective.

It offers up to 10 meter accuracy with the most sophisticated equipment, but only 200 meters for the less sophisticated equipment.

The key to GPS is integrating it into the current navigation system.

In the 80's, a GPS system could possibly cost less than VOR-DME for equal performance.

Antennas are not a restrictive problem. A 15 cm diameter, 2.5 cm thick antenna should suffice for general aviation operations.

V. Suggestions for NASA

NASA should sponsor research, but avoid in-house development. Industry (avionics) will develop technologies and concepts.

A.3.2 Company V

I. Current Avionics Trends

Industry is leaning towards installation of complete systems produced by one manufacturer. Today's systems cannot be easily interfaced.

OEM's will set requirements for systems integration by the "common harness" concept.

Integrated systems (or units) are evolving and already appearing on the market. Example unit: VOR receiver, DME, RNAV (4 waypoint), ILS, Glideslope.

II. Comments from the Company

Does not want standardization of avionics in general aviation. This tends to destroy the competitiveness of the avionics market. If all the units look and operate similarly, freedom of design and competitive motivation could be lost.

Avionics products are governed by the inertia of the pilot market. Pilots resist new changes to the current products, and will not buy units with radical differences from the norm because of their lack of understanding of the products. Because of this, avionics products that require operations training are not favored by the manufacturers.

III. Research for NASA

Human factors research is needed on the cockpit environment.

Research is needed on "display by exception" because of the limited panel space in general aviation aircraft.

A.3.3 Company W

I. Integration

Integration of systems is inevitable, and is already occuring.

Integration of avionics has some serious drawbacks. For example, power supplies must be redundant.

II. Cost Drivers in Avionics

Actual electronic component cost is decreasing.

The level of sophistication in usage requirements (50 to 25 kHz spacing, better filters) has increased. This increases costs.

Requirements for increased reliability of units, certification, and labor wages increase costs.

III. New Technologies

Health monitoring of the engine is not difficult, but low cost sensors must be developed to make the idea feasible and practical.

Monitoring by exception would greatly reduce pilot workload.

Digital operation is eminent and is currently being incorporated into avionics. However, Company U autopilots are analog systems.

IV. Suggestions for NASA Research

(1) Human factors and pilot workload in the cockpit.
(2) Pilot displays.
(3) Low cost sensors
(4) Standardization of cockpit layout and controls.
(5) However, since aviation is not a crucial national problem, NASA might better concern itself with energy research.

A.3.4 Company X

I. Displays

A market exists for better displays even at a higher price.

Visualizes CRT's replacing mechanical HSI's.

CRT's will become a part of this company's avionics products because more functions can be integrated into a compact display space. The cost will be high, however.

NASA should research methods for replacing expensive mechanical instrumentation.

Significant reductions in price would be achieved if the market volume was doubled or tripled.

10% of sales is devoted to research and development.

The DAAS program is good only for demonstration. Regardless of DAAS, integrated avionics technology will develop within the industry.

II. Fiber Optics

Fiber optics show great promise by replacing heavy wire bundles and eliminating interference. However, fiber optics require a standard bus for operation.

Improvement of mechanical connectors for fiber optics will promote the integration of the technology.

III. Electronic Flight Controls

Absolute dependence on electronics is becoming economically feasible. Quadruple redundancy can achieve extreme reliability.

Fly-by-wire technology can be expected in this market, but only slowly.

Separate Surface Stability Augmentation (SSSA) shows a lot of promise.

IV. Product Liability

This is a problem for this company (like any other company), but they have yet to pay any product liability claims.

V. FAA Certification

Has good experience with their FAA regional office. However, sometimes the FAA does not know how to approach new technology. They attempt to test new technologies with old methods, sometimes nullifying any advantages.

Lightning is not a problem for this company's products.

A.3.5 Company Y

Avionics is a $435 million/year business. Company Y controls 45% of the market. Most customers are corporations.

Caters to the market and produces airline-quality products for general aviation users.

Specialities: attitude and heading displays and sensors
air data computers, displays, and sensors
automatic flight control.

I. Projections for Technology. The following are likely:

More integration of functional features with regard to information acquisition and displays.

More digital computation and interface.

Strapdown AHRS (Attitude Heading Reference System)

Flexible vs free floating gyros (for cost savings)

CRT displays will replace conventional ADI, HSI, and eventually the entire panel.

Management systems

Long Range NAV

Energy management including autothrottle, fuel controls, and flight control systems.

GPS

Too expensive, though highly accurate.

Controlled by the military. Not available for 7-10 years.

Antennas are unwieldy.

Collision Avoidance System. Interesting because of computer application.

II. Future in Flight Controls

Looks 5 years ahead. 10 years is too far downstream.

One of the most difficult tasks is to service obsolete systems. New systems appear continuously, and old systems are expensive to maintain.

In general aviation today, the airframer or the user integrates the system. In the future, only the airframe manufacturer will integrate systems due to complexity and lack of standardization.

Because analog system capabilities are almost saturated, digital technology is attractive because of its increased functional capability, reliability, and accuracy. Company Y does not produce digital systems currently, but is exploring the technology.

The emphasis on size and weight is a unique problem to general aviation. The bus interface will allow lower weight.

III. Navigation and Energy Management

Autoland

Too expensive for general aviation. Category II approaches are impractical for general aviation pilots because of FAA maintenance and training requirements.

Stability augmentation/load alleviation requires faster actuators.

Greater automation: digital systems appear promising, but requires more power.

Fly-by-wire and fiber optics are not being pursued. They are not cost effective. Even boosted systems require a cable backup.

Navigation management capabilities and results (result of onboard computers)

Integration of navigation sensors (INS, Omega, VOR/DME).

Full ATC data base, including charts and plates.

Flight planning.

Reduced workload.

Energy management capabilities (result of onboard computers)

Improved fuel and engine efficiency.

Flight manual storage.

Automatic engine control.

IV Air Data Systems: (see following figures)

A.3.6 Company Z

I. Current Products and Technology

Manufactures flight control systems for general aviation, primarily for those aircraft weighing 5765 kg and under

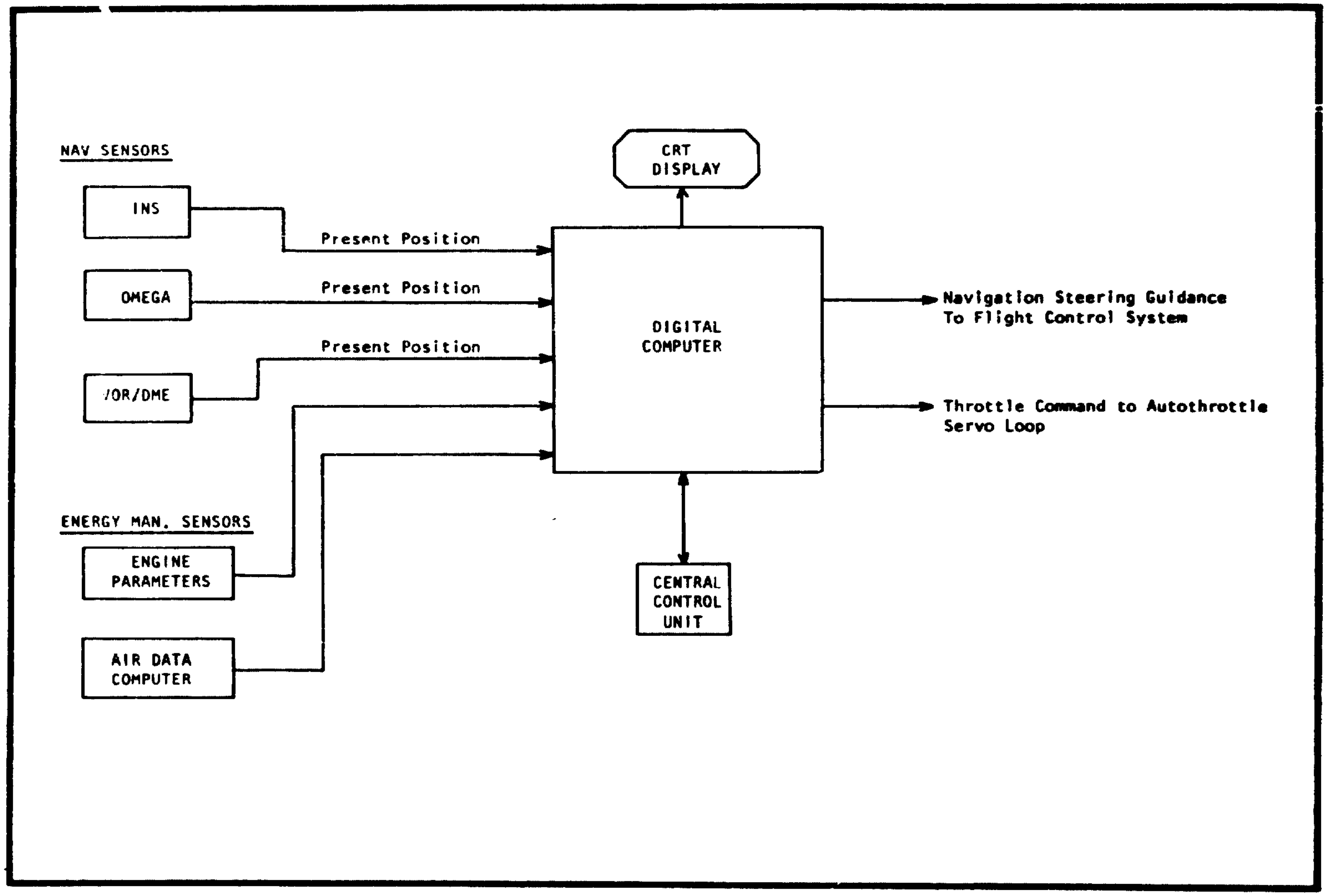
Utilizes a single rate gyro, which is powered pneumatically and electrically for redundancy.

Invented the tilted gyro turn coordinator.

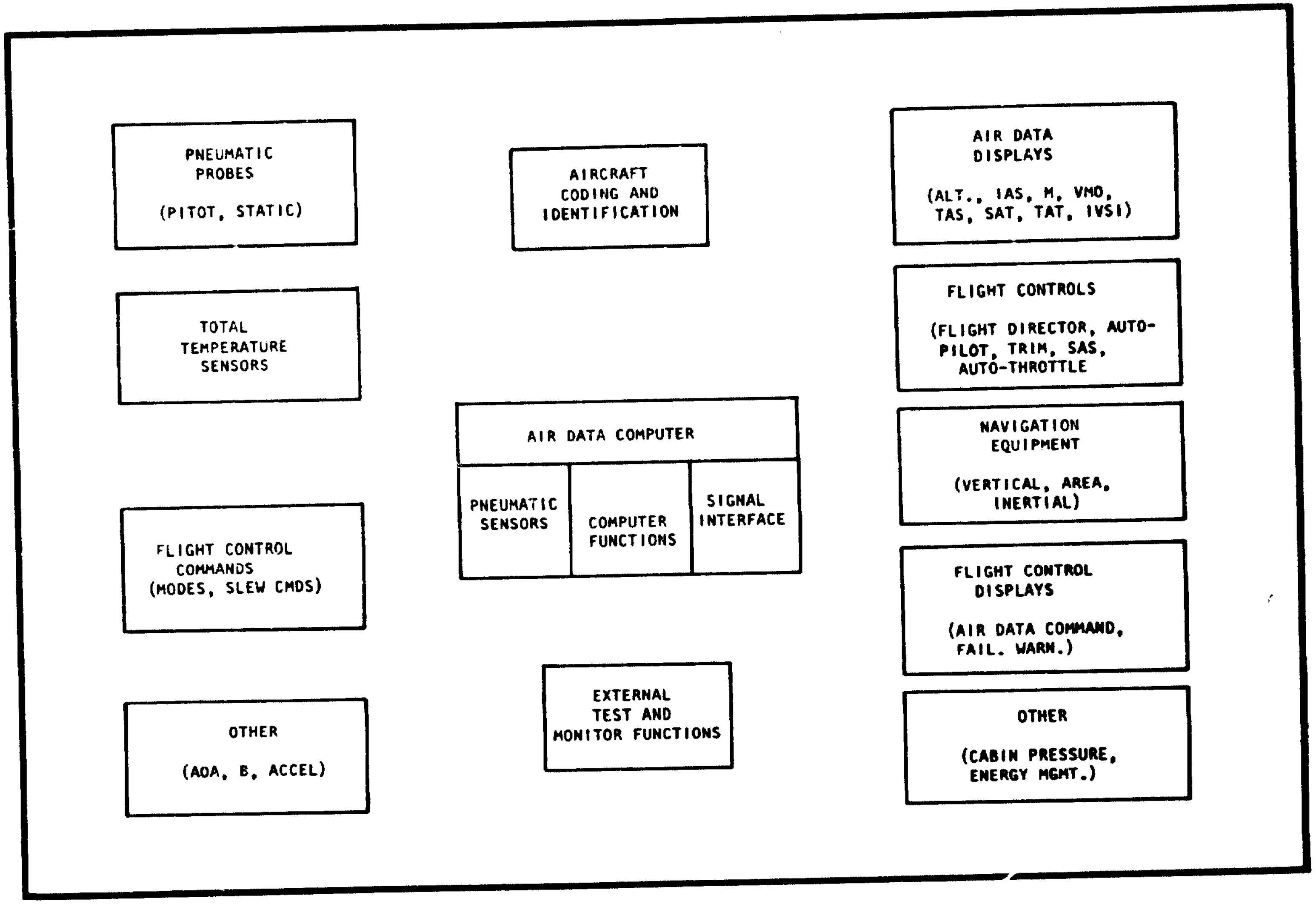
Double power system on gyro is more stable. Each power supply modulates the other when a power surge is experienced.

Uses 400 Hz A.C. electric drive and pneumatics. The gyros regulate valves which control pneumatic servos for the autopilot.

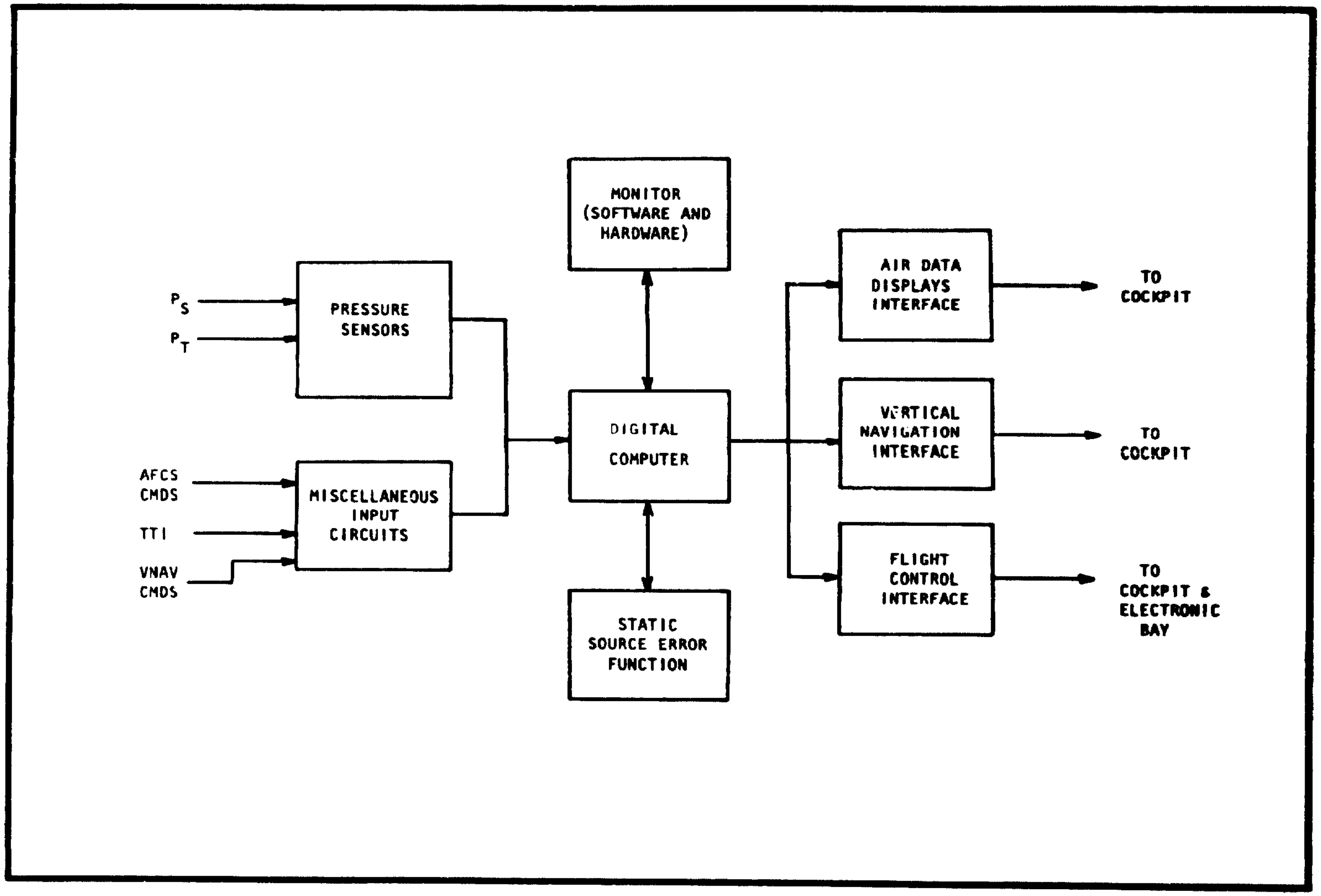
If the electrical system fails, the wing leveler function still operates because the entire system from gyro to servo is totally pneumatic.



Navigation/Energy Management System



The Air Data System



Digital Air Data Computer Basic Block Diagram

II. New Technologies

Will not incorporate digital technology into their analog products. The cost of recertification is too prohibitive.

Digital systems do not offer the redundancy of pneumatic systems, where the former is only electrical and the latter is pneumatic-electric.

Cost also prohibits switching from pneumatic to electric actuators.

Pneumatic system has advantages: altitude compensation, no electric current drain, and smoother operation.

Familiar with the fluidic rate sensor research at Langley, but does not perceive future applications of the technology.

Advanced displays

HUD's, CRT's, are excellent for reducing pilot workload.

Transition from IFR to VFR flight is dangerous. CRT displays could alleviate this problem. A HUD allows for a safer transition.

Fiber optics. No foreseeable applications at this company.

III. Certification

A serious problem.

Certification procedures make minor product improvement changes unattractive to this company due to excessive (and therefore expensive) delays.

Weeks of preparation by the company followed by delays and then a trivial flight test damage the image of the FAA and the certification process.

Has over 260 STC's. Any major change on the autopilots would require a new STC for each aircraft: phenomenal cost for a small company.

A.3.7 Company AA

I. Current Products

Produce flight directors, HSI's, autopilots, turn and bank indicators, and yaw dampers.

Present products are analog-digital hybrids. Utilizes many integrated circuits.

Uses a strain-gage, piezo-resistive pressure transducer for altitude hold input.

Autopilot actuators are DC servos with infinite resolution and a slipclutch.

II. Advanced Technologies and Problems

CRT's. Waiting to examine the success of this technology in the commercial aircraft market.

SSSA. Not pursuing this technology. Conservatism and product liability are the major drawbacks. (Conservatism on the part of the airframe manufacturers.)

Problems with new technologies:

> Field service. Retards the incorporation of microprocessors into their products. The field maintenance skill level is not high enough to support this technology.
>
> User misuse and lack of understanding. Pilots do not read the users manual and they do not know how to use some of the features of the autopilots.
>
> Product liability. Liability cases are so far-reaching today that small companies must exercise caution when introducing new products. Product liability severely inhibits new technology, innovation, and advanced products. Recently hired a full-time accident investigator.

Flight Directors. One representative of this company was not convinced of the benefits of flight directors. Pilots are attracted to the HSI commands and do not maintain outside surveillance.

3% of sales is returned for internal research and development.

A.4 SYSTEMS MANUFACTURERS

A.4.1 Company BB

I. Controls

Digital Flight Controls: Looking at a distributed microprocessor.

Fly-by-wire: Already developed a fly-by-wire system. Utilizing a failsafe 3 motor common control drive.

Fiber optics: A fiber optic control system has been developed and flown.

II. Composite Structures

Control Hardware

Developed filament-wound graphite push-pull rods.

Developed injection molded composite bell crank.
Cost analysis:

Composite bellcrank -- $11.15
Equivalent magnesium bellcrank -- $75.00
Illustrates a savings of 85% due to composite material.

Airframe

Currently under contract to NASA-Langley Research Center to evaluate composite airframe components in the field.

Evaluating graphite and Kevlar. Graphite is utilized in controls and surfaces. Kevlar application is primarily in doors and fairings. Stiffness is not a restrictive problem of these composites, but their non-isentropic properties must be recognized.

Graphite hazard: filaments of graphite are released in a crash environment and infiltrate electronics, causing short circuits.

III. Displays

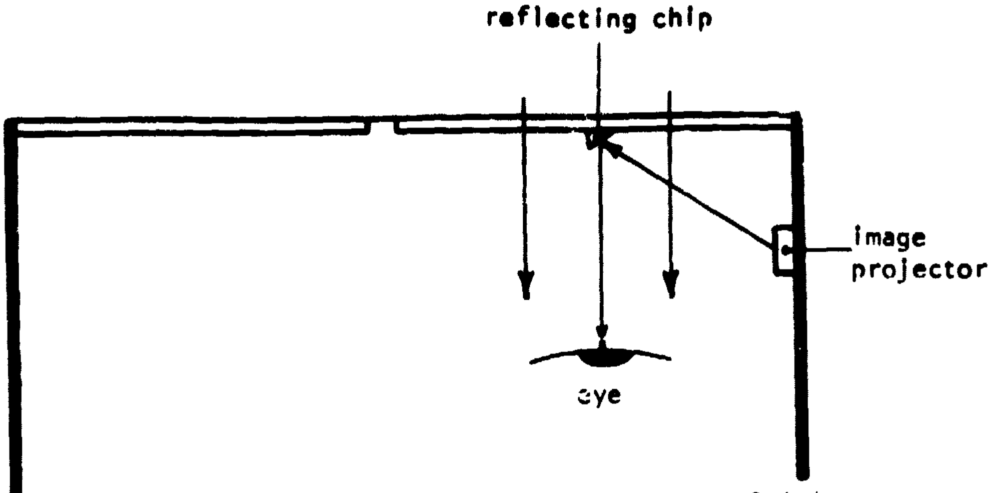
Heads Up Displays (HUD) and Head Mounted Display (HMD)

HUD's are extremely useful in an IFR environment.

HMD's are more versatile than HUD's. Allow unrestricted movement and are simpler and lighter.

Current CRT head mounted displays are heavy, cumbersome, require a helmet mounting, and are not commercially viable. They also block peripheral vision and have a monocular presentation.

Developed the micro-HUD. A small reflecting chip is mounted onto glasses, directly in front of the eye.



Top View of Eye Glasses. Also See Section 4.5.6.4 for photograph.

Method has broad applications. Has potential to cut cost over current HUD's by a factor of 4. Dynamic display capability obtained through a vibrating fiber optic display. (see figure on next page.) Mechanically vibrated optics, with timed light impulses, creates dynamic images, similar to CRT's.

IV. Fiber Optics

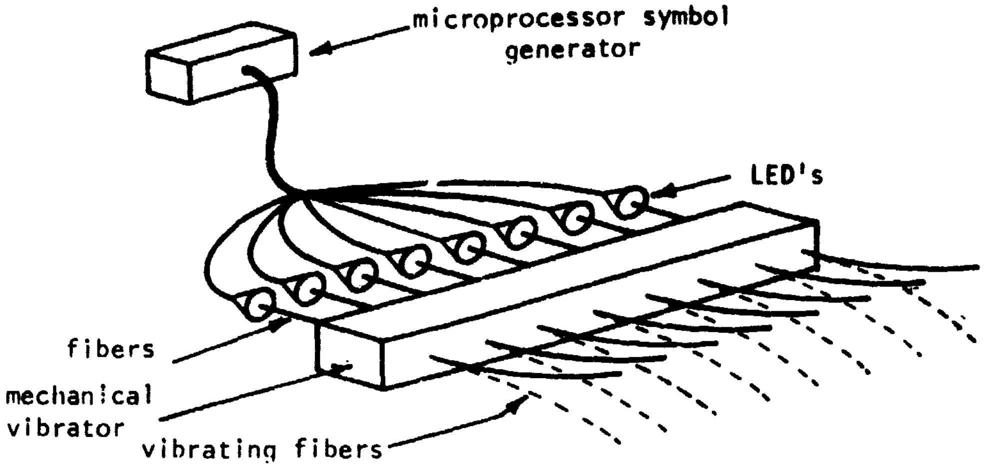
Lightning strike benefits

Aircraft that have composite structures and utilize fly-by-wire are vulnerable to lightning strikes. Current will destroy the system.

Fiber optics are non-conducting and would not be as vulnerable to a current surge from lightning.

Structural monitoring

Fiber optics can be imbedded within the composite material matrix for structural monitoring.



Vibrating Fiber Optic System With Microprocessor Symbol Generator.

Scanning the fibers with a microprocessor, a signal delay or lack of signal from a fiber would indicate a possible failure developing within the material it was imbedded in.

Signal carrying

Fiber optics have a wider bandwidth, allowing more signals or data to be passed along them as compared to wires.

A.4.2 Company CC

Deals with control of vehicles, from aircraft to mopeds.

I. Avionics

PCAAS

Projected technologies were studied, but current technology was utilized for the demonstration program to minimize costs.

GPS system

A GPS antenna may be too large for incorporation into a general aviation airframe.

II. Control Systems

Microprocessor systems

Electronics for advanced control systems are available at low cost. The problem of cost for controls stem from the sensors, the displays, and the actuators.

NASA should investigate low cost sensors and actuators.

Fluidics

Are impaired by temperature variation because of thermistor control.

Because of sensitivity to temperature, fluidics cannot meet the TSO temperature requirements.

III. Safety

Spiral

A wing leveler should be provided for general aviation aircraft.

Some aircraft have apparent spiral modes with different time constants than the actual spiral mode. These result from lateral out-of-trim conditions.

An old NASA study suggests utilizing a centering spring to relieve the problem.

Very speed sensitive. Also, aircraft may diverge in one direction and not the other. Characteristics also differ from plane to plane.

FAA crash studies

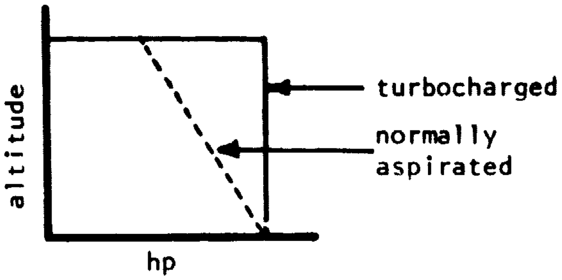
Compiled complete crash statistics over a 10 year period for single engine, multi-engine, and retractable gear categories.

The single engine retractable gear aircraft was involved in the largest percentage of crash incidents. One aircraft, however, was equipped with a wing leveler and remained accident free.

A.4.3 Company DD

I. Turbocharging and Engine Control

The match point for aircraft engines is matching the turbocharger to the aircraft flight envelope.



The truck diesel engine turbocharger provides a production base of over 1 million units per year.

Microprocessors are applicable to aircraft engines only if total control is exercised: simultaneous control of mixture, manifold pressure, and rpm.

Turbochargers are generally overdesigned and will (must) match engine TBO.

The most significant improvement forecast for turbochargers is the incorporation of air bearings. However, most of the turbocharger advanced technologies (air bearings, ceramic wheels, sheet metal housings) are too costly.

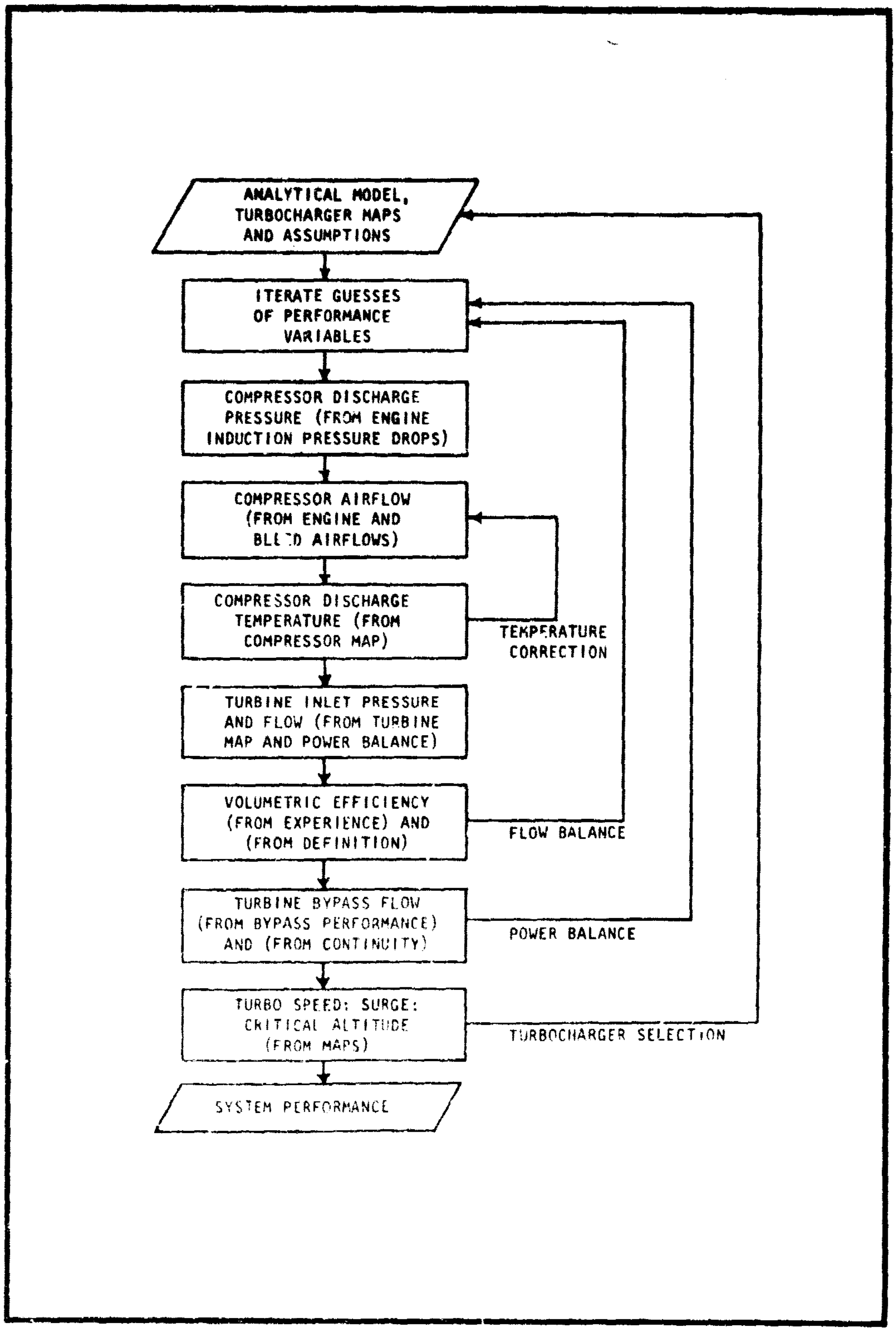
Current aircraft turbochargers have been labeled "just a truck turbocharger". This turbocharger, however, covers a wide power range and allows for low cost because of the diesel engine production base.

A.4.4 Company EE

Produces actuators for commercial aircraft and large business jets at the rate of 2 to 3 units per month for each type.

I. Hydraulic Flight Control Actuators

Actuators are "tailored" to each application. They are designed for a specific aircraft type. General "off the shelf" hardware is not available.



Turbocharger Design Logic

Actuators are very sophisticated because of redundancy requirements.

Actuators must be located at the surface for production of maximum power.

"Custom" actuators of these types and sophistication are too expensive for general aviation application.

A.5 NASA RESEARCH CENTERS

A.5.1 Ames Research Center

I. Avionics

Improved guidance and navigation based on VOR/DME. Emphasis here is on improved systems which use VOR/DME.

System is based on 2 VOR/DME systems, where the receivers scan for close proximity stations. One difficulty lies in the fact that it takes 5 seconds to lock and interpret a VOR signal. Hence, the time to search for acceptal signals can be prohibitive. An alternative would be the incorporation of a computer which stores the last station and signal to speed up the scanning process.

A further difficulty lies in storage requirements. Inputting station longitudes and latitudes is very time consuming. VOR stations which broadcast their position (longitude and latitude)in addition to radial information eliminate the requirement to load this data to memory, and would greatly enhance the attractiveness of the scanning mode.

Scanning results could be incorporated with air data to greatly enhance navigation guidance.

Pilot Interface with Avionics

Each capability added to avionics today will affect pilot workload by a factor of 4. Hence, emphasis is being directed toward simplifying the pilot workload involved with the use of avionics.

For example, improved navigation capabilities (scanning) requires loading station locations. Development of an "electronic map" allows the pilot to input station locations by either a light pen, a matrixed optical system surrounding the map display, or by a touch-

(Ames Research Center)

sensitive screen. The map display system described here is currently flying in a Cessna 402 at Ames.

Low-cost electronic map display with touch input system could be the interface between pilot and navigation system in advanced avionics for general aviation. NASA Ames Research Center is using this map-covered X-Y plotter (upper right) and programmable calculator (left center) to study the display/interface concept and verify the performance of a scan-tuned VOR/DME navigation system. To simulate a touch input system, the Ames Research Center is using a digitizing system that consists of the spark pen in the operator's hand and microphonic pickups along the top and left edges of the plotter. The calculator controls the VOR and DME receivers and performs the Kalman filtering needed to determine present position from radionavigation and air data sensor outputs. The calculator and plotter are Hewlett Packard 9825A and 9862A units, respectively.

(Ref. 50)

This photo is of the light pen. Also demonstrated was a map overlay which is inserted over a touch-sensitive very thin plastic grid of wires. This grid sheet is laid over the CRT with the map over it. The sheet is manufactured by a company that makes touch-sensitive keyboards for microwave ovens. The large number of grids per sheet and small number manufactured resulted in a cost of $1200 for three grid sheets. Costs would be much lower for a production run.

This touch sensitive map has been installed in a Cessna 402.

To locate points on the map, the pilot touches the map location. The plotter arm moves to the input point and marks the map. Then a query is returned: OK? The pilot responds by touching "YES" or "NO" on the screen. If required, the pilot is allowed to improve his map point by responding to "LEFT/RIGHT" queries and "UP/DOWN" queries. As such, he can quickly, accurately, and reliably load what amounts to an RNAV flight plan without having to load radial/DME waypoints.

The matrixed optical system, where light beams form a grid in front of the CRT screen, is shown on the following page. Placing a finger on the CRT display interrupts a light beam and results in an input to the computer. The weight and balance system is shown where (1) the particular airplane loading capabilities for the particular 402 exists in the software package (fuel/baggage mix in tip tanks and nacelles, and passenger seating configuration), (2) the white dot in the envelope as well as the airplane representation changes to show what (e.g.) 50 lbs in the left nacelle will do to the envelope as well as to the available volume in the nacelle. The system is virtually error proof, simple, and fast.

Replacement of gyros with other sensors

Replacement is accomplished with a 3 axis magnetometer which senses accelerations and integrates outputs about 3 axes to derive pitch, roll, and yaw.

Pressure transducers are also receiving attention

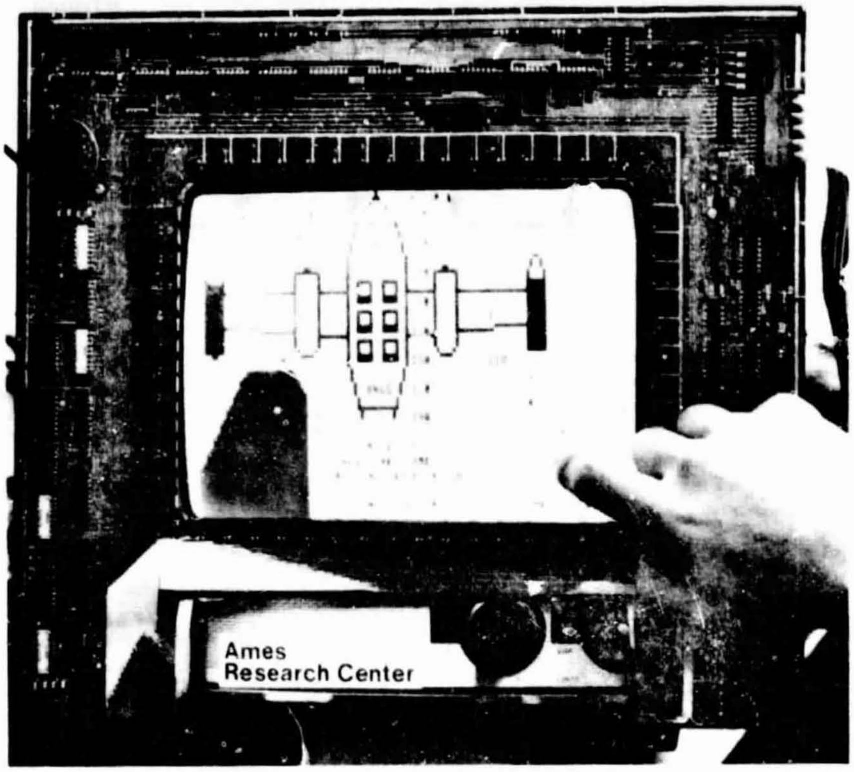
Silicon chip pressure transducers using piezoelectric crystals in membranes cost around $12.

A shed vortex airspeed measurement device based on the principle of airspeed being proportional to the frequency of shed vortices is installed and working on the Cessna 402.

Common bus

Reduces weight, simplifies interface of components, and allows multiplexing of signals. Implies standard bus (note: general aviation is not required to meet ARINC standards).

(Ames Research Center)



Touch input system for an electronic display allows a pilot to communicate with an avionics system by touching the appropriate location on the face of the display. Seen here is a modified Carroll Engineering Co. unit in use at NASA Ames Research Center for concept research and evaluation. A program stored in a programmable calculator guides the pilot through a task — a weight and balance routine in this illustration — by presenting messages and cues to which the pilot responds by touching "keyboard" digits, functions such as "clear," or words such as "pounds" or "gallons" that designate units of measurement. When the operator's finger touches an input point, it interrupts two light beams intersecting at right angles at that point — elements of a light grid established over the face of the display by linear arrays of light emitting diodes along two adjacent edges of the display. Interruption of the beams is sensed by photo-detectors along the two opposite edges, feeding position information to the calculator for processing and dissemination as required by the avionics system. The display unit used here is a Kaiser Aerospace FP-50 flight director.

(Ref. 50)

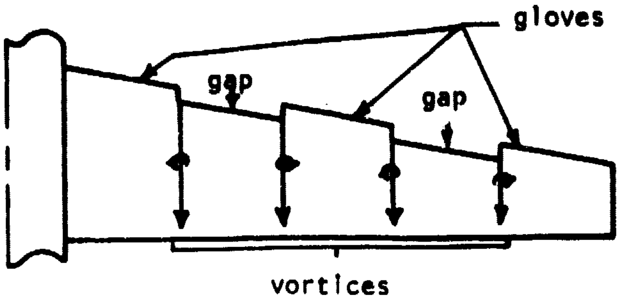
II. Stall/Spin

The key to spin avoidance lies in the prevention of spin entry and not in spin recovery.

Research is based on leading edge gloves and gaps.

See sketch on next page.

(Ames Research Center)



Vortices generated at higher angles of attack affect separation characteristics.

Thus far:

R/C model with the modified wing will not spin.

Grumman American Yankee has vastly improved spin characteristics in flight test configuration.

Needs:

Theoretical basis needs to be developed.

Twin engine configurations need to be examined (for channel flow study).

III. Cooling Drag

Assess level of cooling drag

Cooling drag is defined as any drag resulting from pumping air through a nacelle (or cowl).

Utilizing a Seneca wing and a Cessna 402 nacelle for the test configuration. The baseline was established by (1) modifying the nacelle to eliminate trailing edge separation, (2) streamlining the front of the nacelle for low drag, (3) sealing the air inlets and the exhaust openings, and (4) removing the propeller. This configuration established the low drag baseline.

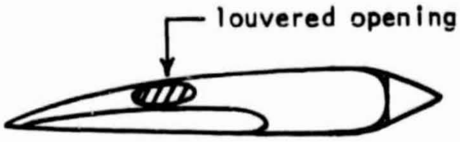
Compared to the original configuration, a 13% drag reduction was realized.

(Ames Research Center)

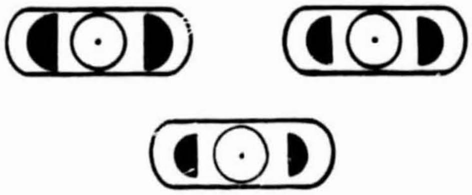
Reducing the air mass flow rate required for cooling does not reduce drag much.

Optimize and Investigate different nacelle shapes

Eliminate cowl flap. Replace with louvered opening.



Evaluated three inlet sizes.



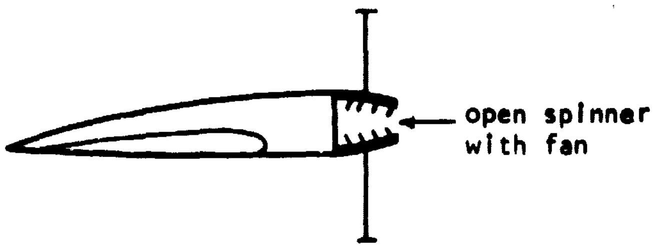
Single, low inlet produced the best results.

better at high angle of attack.

allows optimized nacelle shape.

(Ames Research Center)

Better nacelle shape at front.



IV. STAT

STAT is the Small Transport Aircraft Technology program which is aimed at investigating aircraft for the following range of specifications:

15 - 80 passengers

50 - 100 nm legs

Includes design studies of airframe, engine, and propeller, with specific studies of

high/low speed compatibility

good ride quality

low noise

identification of high cost features.

Overview of STAT

Will emphasize aerodynamic analysis and include:

Analytical methods for improved performance predictions for multi-element high lift devices.

Wind tunnel programs to examine turboprop slip stream effects on wing configuration.

Propulsion system research to define improvements in turboprop and turboshaft engines.

Structural research to identify cost reductions in manufacturing through the use of advanced aluminum alloys.

Avionics research to yield improved IFR capabilities.

Aircraft flight control systems:

- **fly-by-wire**
- **fly-by-light**
- **integrated electronics**
- **digital controls**
- **fail safe and fail passive controls (already incorporated in V/STOL and helicopter aircraft)**

Improved icing protection.

Ways to reduce commuter prices to $55,000/seat.

May also examine bonding/composites because of the costs associated with fasteners (rivets).

Typical specifications that STAT would cover: turboprop, 50 passengers, 250 kts.

V. Aerodynamics

General comments

Drag reduction at high speed involves delaying M_{div}.

Drag reduction at low speed essentially lies in improving $C_{L_{max}}$.

Computer codes:

FLO 22 - transonic wing on wall

FLO 28 - transonic wing on body

Full potential flow wing-body with attached flow and no small disturbances.

Natural Laminar Flow Control (NLFC)

6-series airfoil sections are examples of NLFC.

NLFC is achieved by reducing adverse pressure gradients over the airfoil.

Surface coatings are implied.

Very Mach dependent.

6-series has good cruise with wide drag bucket, but adverse stall characteristics.

NLFC may not be practical due to bugs, insects, etc.

NLFC is difficult to evaluate in the wind tunnel due to tunnel effects.

Comments on GA(W) airfoil

Use of 2D data without regard for the wing-body junction may lead to flow separation there.

Best use of a GA(W) wing might be on a high wing configuration, where the wing upper surface doesn't intersect the fuselage.

A.5.2 Langley Research Center

I. Crash Dynamics

Crashworthiness Design

Seats

Energy absorbing seats can reduce peak vertical "g" loadings by 50%.

Wire bending (translating a loop along wire) is a very efficient way to absorb energy.

One of the most promising crashworthiness features together with improved restraints.

Do not locate seats over wing spars.

Seat pan is very important. Current pans collapse. Must be designed with regard to the rest of the seat for good crashworthiness.

Industry builds seat for comfort (thick cushions compress too much and cause belts to loosen).

Restraints

Must be anchored to seat with the seat firmly anchored to the floor.

Inertia reels are sometimes unreliable. Incorporated largely for ease of entry/exit. Ideally, a restraint holds the occupant firmly in his seat, and the seat and structure absorb energy.

Lateral movement of occupants is best controlled by a double harness (seat mounted).

(Langley Research Center)

Structure

Floor/subfloor should be made crushable to absorb energy. Aside from vertical stroking of the seat, this is the only other area where stroking distance exists to absorb energy.

Fire prevention

Military work on fuel containment is quite successful and technology transfer is needed.

Fuel treatment to reduce vaporization has some potential.

Foam in the fueltanks costs 1% to 2% of tank volume but can contain fuel and prevent spraying.

II. Composites

Composite types

Advanced composites include graphite, Kevlar, and boron. Glass is not considered an advanced composite. Graphite and boron are probably too expensive for general aviation.

Testing

Flight Service: Aircraft with test samples include:

L1011, Boeing 737 - Kevlar.
CH-54 - graphite stiffeners.
Bell 206 - Kevlar doors, fairing.
C-130 wing box - boron/epoxy.
DC-10 rudder, Boeing 737 spoiler skins - graphite/epoxy.

Worldwide ground based exposure.

Problems with composites

Lightning strike

Graphite suffers only from localized damage.

Kevlar and glass are more of a problem.

Composites do not attract lightning any more than metal structures.

Metal honeycomb with composite skins could compromise safety since a clear path for the strike to dissipate may not be available.

Solutions are possible by using any external conducting path such as wire screens.

Moisture absorption/high temperature

Matrix absorbs about 1% moisture by weight.

Paint absorbs about 3% moisture by weight.

High temperature and/or moisture weakens matrix.

Miscellaneous

Generally impervious to fuels.

Composite manufacturers: Dupont, Hercules, 3M, Union Carbide.

III. 3D Aerodynamics

See next page for 3D aerodynamics progress.

Currently working on wing/canard design and wing/fuselage interaction.

IV. 2D Aerodynamics

Turbulent flow shapes

Tend to be aft loaded.

Control surface floating is not a problem.

Industry is wary of aft-loaded airfoils.

Natural Laminar Flow

Goal: Attainment of $C_{L_{max}}$ equivalent to that of the turbulent flow airfoils while maintaining the low drag of the NACA 6-series sections.

Thickness and moment constraints also exist.

Bellanca Skyrocket airfoil: $t/c = 15\%$, $C_{D_o} = .006$, $c_{\ell_{max}} = 1.8$.

C-5

Advances in 3-D Aerodynamics

Shape	Flow Type	Analysis						Design		
		Steady			Unsteady			Steady		
		Sub	Trans	Super	Sub	Trans	Super	Sub	Trans	Super
Airfoils	Inviscid	+	+	+	+	+	+	+	+	+
	Viscous	+	+	-	[+]	-	-	+	+	-
Wings	Inviscid	+	+	+	+	[+]	+	+	-	+
	Viscous	[+]	[+]	-	-	-	-	-	-	-
	LE Vortex	[+]	-	[+]	[+]	-	-	[+]	-	-
Complete Aircraft	Inviscid	+	[+]	+	[+]	-	[+]	-	-	[+]
	Viscous	-	-	-	-	-	-	-	-	-
	LE Vortex	[+]	-	[+]	[+]	-	-	-	-	-

+ Available
[+] Not mature yet
- Not available

$c_{\ell_{max}}$ is not sensitive to roughness.

Drag is moderately to significantly sensitive to roughness.

Maintenance of airfoil contours (ripple-free) is more important than bugs, insects, dirt, etc. Flat spots are bad.

Low speed airfoils ($M \leq .4$)

Improve symmetrical airfoils with control surfaces.

Attempting to reduce pitching moment. One example (LS(M)-0417), when compared to the GA(W)-1, shows:

$\Delta c_{\ell_{max}} = +.22$

c_{d_o} is reduced

c_m shows a 30% reduction

slightly worse stall

c_d lower in climb.

Medium speed airfoils ($M \leq .7$)

Examing two airfoils: 13% and 17% t/c

Retains excellent low speed characteristics

Improved c_m, same $c_{\ell_{max}}$, and less c_d than old NACA sections.

V. Avionics and Controls

Current programs

T-30 (Sabre business jet) will be equipped to study pilot-ATC interface. Digital and analog systems will be included.

The heart of the system is a digital Bendix 910.

A conventional analog autopilot is included.

Fully programmable color CRT display.

MLS, curved approaches, will require more than conventional flight director.

Fluidics

Low cost, highly reliable, rate sensors for autopilots.

The wing leveler is inexpensive, simple, and performs well. An $85 model for homebuilts is available commercially.

Examining a 2-axis wing leveler and heading hold autopilot

Working with Cessna and Piper on a fluidic autopilot.

Looking at an all-fluidic airplane for demonstration.

Pilot workload - single pilot IFR

A simulator is an important tool for human factors research.

Unconventional controllers show promise. Example: side stick controller.

Integrate displays and instrumentation.

DABS - Discrete Address Beacon System - automatic uplink and downlink data flow.

Exploring the speech synthesis problem.

Langley has a general aviation simulator programmed to study these problems and possible solutions to them.

VI. Stall/Spin Research

Tools

Spin tunnel (Re $\simeq$ 80,000 to 90,000) - Only steady-state spin conditions can be examined. Spin entry cannot. Have encountered problems with small scale effects of the test models.

R/C models, 1/5 scale.

Wind tunnel models.

Full scale wind tunnel.

Flight test.

(Langley Research Center)

Simulation - A data base is required to develop this.

Airplanes

Yankee
Sundowner
Cessna 172
Piper T-tail prototype

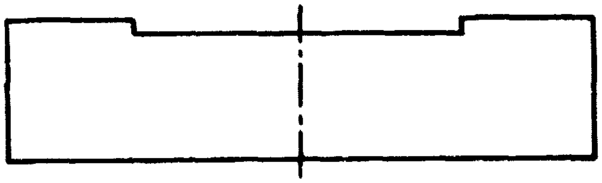
Configuration Effects

Drooped leading edge

Full span application of this modification aggravated the spinning characteristics of the test aircraft. Spins became unrecoverable.

Can improve spinning characteristics if (1) the modification covers 50% - 60% of the outboard span and (2) ends in a sharp break near the mid-span of the wing.

The modification appears to require a chord extension.



More testing must be performed to establish the benefits of this modification to different aircraft types.

A.5.3 Lewis Research Center

I. GATE

Purpose

Study application of advanced technology to small turbines to determine utility of small turbines in general aviation.

Overall goal is 20% increase in performance and a 50% reduction in cost (to $50/hp).

Company participants (4)

Detroit Diesel Allison

Garrett AiResearch

Teledyne Continental

Williams Research

Garrett, Williams, and Teledyne approached the problem with the low cost idea, and reduced the cost of turbine engines by 50% at forecast production levels.

Allison's front end costs were higher but DOC was greatly improved through sophistication.

Some viewpoints of GATE

Must be advocated to NASA headquarters.

Began two years ago. Now investigating a hardware program, costing $60 million with two contractors producing test engines.

Low cost potential exists, although at high risk for the manufacturer. Hardware production will not occur soon, if at all, without NASA funding.

The demonstration engine would not run until 5 to 6 years after funds are allocated.

Main drawback is high risk, and that risk will not be acceptable to industry without NASA funding.

(Lewis Research Center)

II. Positive Displacement Engines

General aviation positive displacement engine research

Program goals

Improved fuel economy, weight and drag reduction.

Major Thrusts

Lean operation of conventional engines

Improved fuel injection

Improved cooling

Advanced combustion chamber and modeling

Definition of alternative engine systems (advanced spark ignition, light weight diesel, stratified charge rotary combustion)

Advanced combustion techniques. e.g. adiabatic

High speed/high pressure fuel injection

Continued upgrading of facilities, instrumentation, and analytical/diagnostic capabilities

Aircraft Fuel Injection

Objective: Establish requirements of an improved fuel injection system for leaner operation.

Approach: Determine effects of spray quality on engine performance and emissions.

Droplet size, distribution, and velocity

Spray pattern

Injection timing and duration

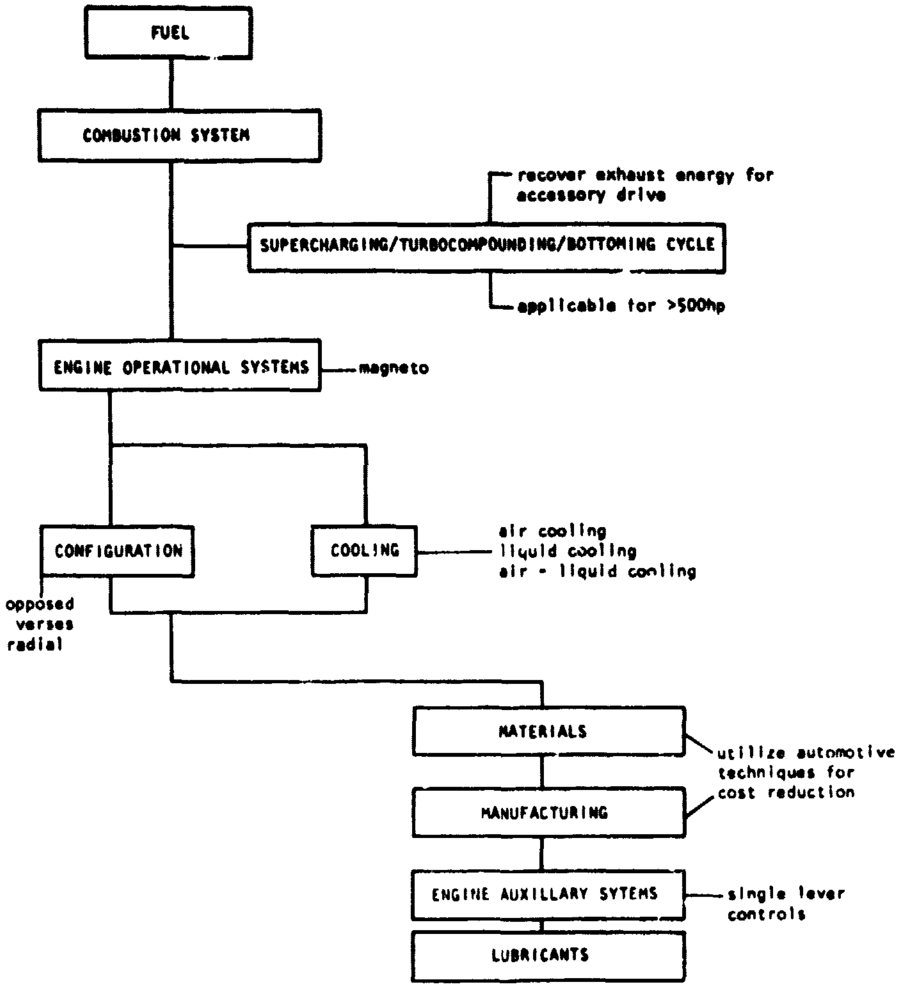
Nozzle position.

How: Manifold flow visualization tests, injector characterization tests, engine combustion tests (using commercial and test engines.)

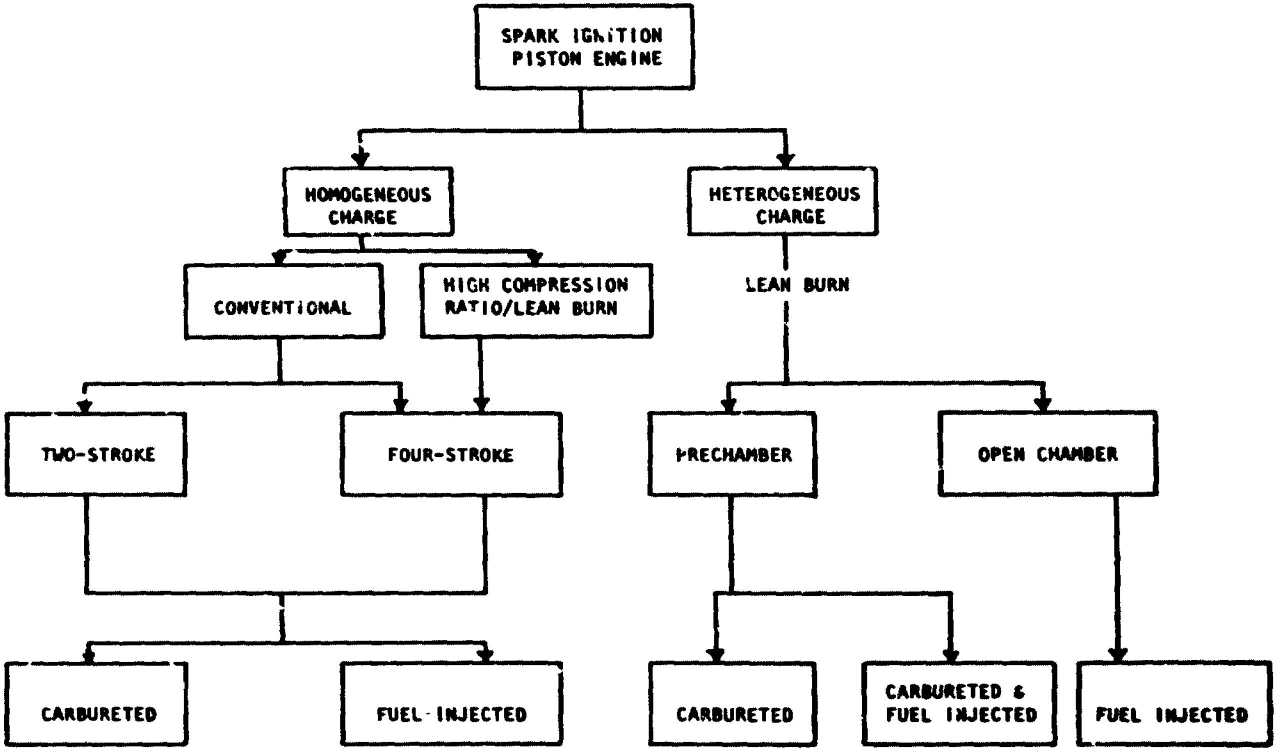
(Lewis Research Center)

Advanced spark ignition aircraft piston engine design study.

- **Technology analysis and design candidate evaluation.**
  - **Define expected technology base for an advanced spark ignition aircraft piston engine for the late 1980 time period.**
  - **Evaluate candidate design items against criteria to choose most likely advanced technology for engine design.**
  - Recommend new or augmented technology programs.
- Fuels for advanced spark ignition aircraft piston engine.
  - Near term: 100 LL AVGAS or wide-cut version (homogeneous charge combustion)
  - Far term: kerosene base commercial jet fuel (Jet A). (stratified charge combustion).
- Homogeneous charge.
  - Conventional:
    - Compression ratio (thermal efficiency) is detonation limited to approximately 8.5-9.0 to 1.
    - Fuel economy at higher power is materials (temperature) limited.
  - High Compression Ratio Lean Burn (HCRLB)
    - Increased compression ratio (increased thermal efficiency) is possible with 100 octane fuel to approximately 12 to 1.
    - Lower exhaust gas temperatures improve valve and valve guide durability.
    - Minimal hardware changes to conventional engine produce significant results.
    - Expect greater than 10% increase in fuel economy.



Advanced Technology Base Items Hierarchical Structure. (Teledyne Continental Motors)



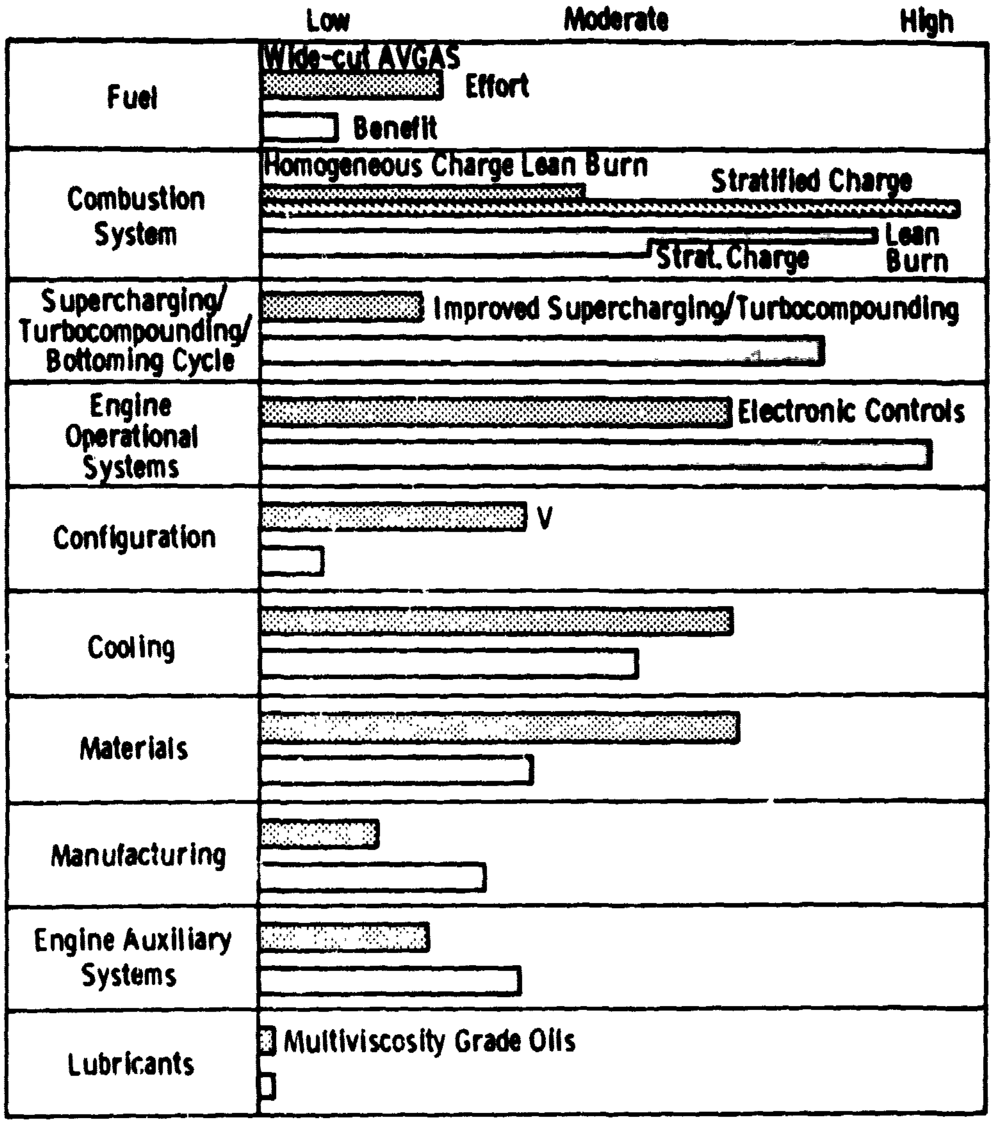
Simple Morphology of Combustion Systems Evaluated **(Teledyne Continental Motors)**

- **Engine operational systems.**
  - **Fuel delivery systems.**
    - **Electronic fuel injection.**
    - **Electronic fuel control (mechanical fuel system, tweaked electrical system)**
    - **Electronic air control (controls engine performance by control of air flow).**
    - Direct cylinder injection.
  - Ignition systems.
    - Breakerless, continuously variable timing.
    - Breakerless, stepped timing.
- Engine Auxiliary systems.
  - Single-lever control.
    - Servo-mechanical.
    - Servo-electrical/electronic.
  - Electric power generation.
    - High speed, brushless alternator.
    - Single-unit starter motor/generator.
  - Engine driven air conditioning
    - Rovac, air-to-air heat exchanger (rotary compressor, saves weight by 50%)

Design and technology features.

- High Compression Ratio Lean Burn engine (HCRLB)
  - Six-cylinder, horizontally opposed, air/oil cooled.
  - 12:1 compression ratio, lean burn, 100 octane avgas.
  - Turbocharged for critical altitude of 10,670 m.
  - Naturally aspirated version also made available (without turbocharger only).

ADVANCED SPARK-IGNITION AIRCRAFT PISTON ENGINE ADVANCED TECHNOLOGY ITEM EFFORT VS. BENEFIT



(Teledyne Continental Motors)

Electronic microcomputer single-lever control system.

Target weight of 373 kw version is 163 kg.

Gear-driven propshaft - 0.75:1 (partly for noise).

Minimum 2000 hour TBO.

Compatible with common-cylinder family concept (down to 4 cylinders).

Stratified Charge

Six-cylinder horizontally opposed, air/oil cooled.

12:1 compression ratio, stratified charge, kerojet fuel.

Turbocharged for critical altitude of 10,670 m.

Naturally aspirated version also made available.

Electronic microcomputer single-lever control system.

Target weight of 373 kw version is 136 kg (highly turbocharged).

Gear-driven propshaft - 0.7:1

Minimum 2500 hour TBO.

Compatible with common-cylinder family concept.

Rotary engine program.

Candidate for future general aviation use.

Assess current state of the art.

Look into advanced rotary engine designs.

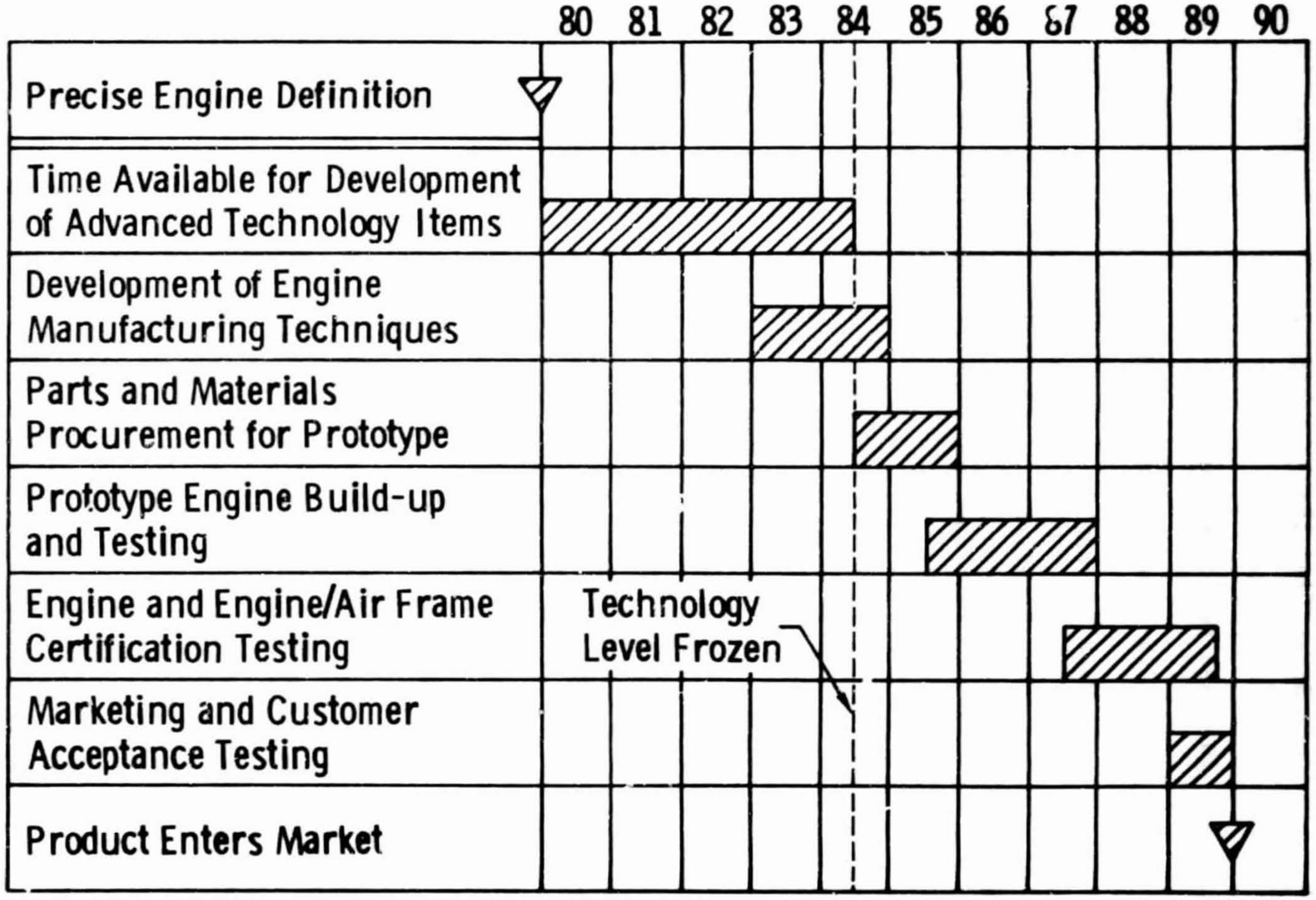
Program status:

RC 2-75 Curtiss Wright engine tests - completed.

Modified RC 2-75 test contract - in progress.

NASA in-house rotary engine test - just starting.

ADVANCED SPARK - IGNITION AIRCRAFT PISTON ENGINE TECHNOLOGY BASE CHRONOLOGY (OPTIMISTIC)



(Teledyne Continental Motors)

(Lewis Research Center)

"clean sheet" rotary engine design - just starting

Curtiss Wright 1119 kw stratified charge engine tests - in progress. (land vehicle)

Stratified charge engine tests - future (aircraft)

In-house rotary engine.

- 1978 Mazda, 2 rotors, 75 kw at 7000 rpm.
- Test Program:
  - Baseline - carbureted.
  - Tear down and install combustion instrumentation.
  - Repeat baseline.
  - Autotronic fuel control and multispark ignition.
    - Leaning study.
    - Ignition effects on combustion.
  - Thermal barrier coatings.
  - Turbocharging.
  - Stratified charge - simplified system.

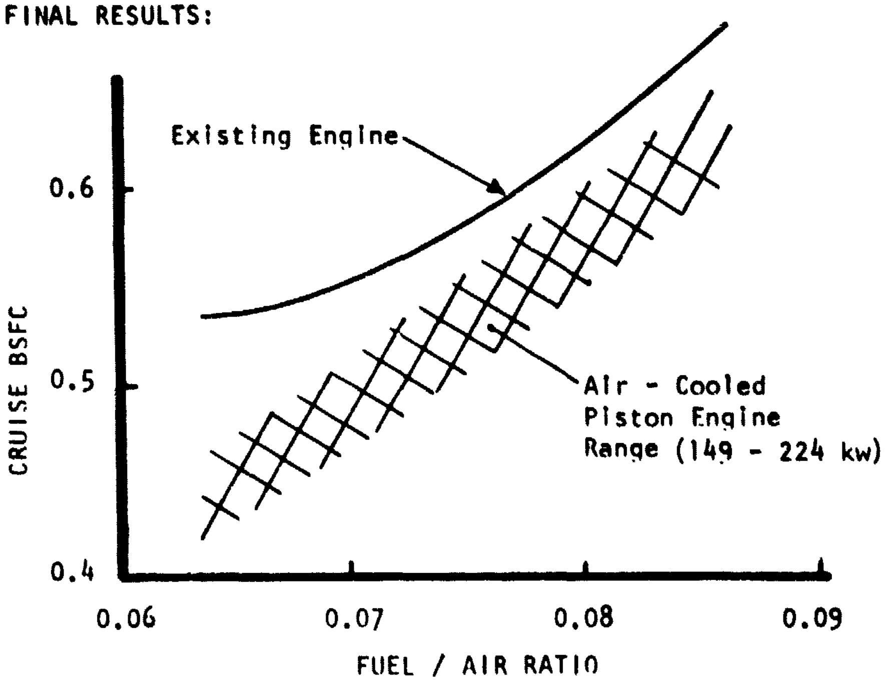
"Clean sheet" rotary design study.

- Contractor: Curtiss-Wright Corporation
- Date: June 11, 1979 - June 11, 1980
- Goals:
  - 1 lb/hp at takeoff power.
  - BSFC $\leq$ .23 kg/kw/hr at 75% cruise.
  - Operate efficiently on 110/130 octane plus one or more alternative fuels.
  - Meet 1979 EPA piston aircraft emission standards.

APPROACH:

- **TEST EXISTING ENGINE PERFORMANCE AND EMISSIONS**
- **DEFINE PHYSICAL CHARACTERISTICS INCLUDING SCALING EFFECTS**

FINAL RESULTS:



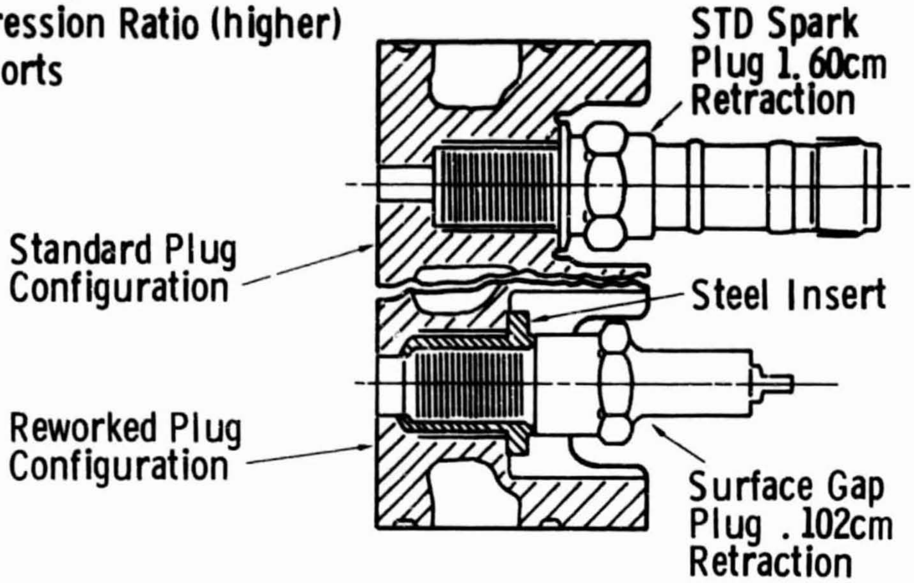
	EMISSIONS-% OF STD			WEIGHT**
	HC	CO	NO_x	KG/KW
EXISTING ENGINE	139*	89	57	.77
ENGINE RANGE	60-240	180-360	10-50	.85 - 1.09

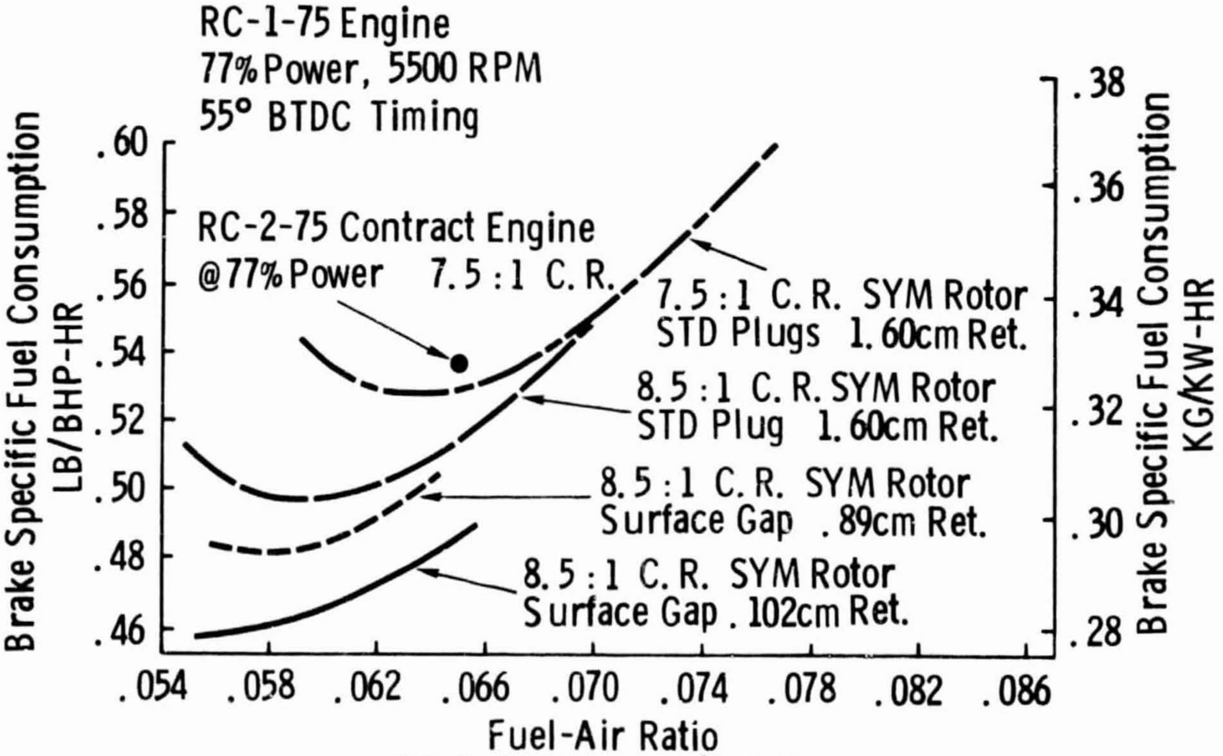
* 85% from taxi & idle
** Includes cooling system

Rotary Engine Characterization

EFFECT OF ENGINE MODIFICATIONS

- Spark Plug Location (closer)
- Compression Ratio (higher)
- Side Ports





RC-1-75 SFC vs. F/A Ratio

Manufacturing costs comparable or less than current aircraft engines.

Maintenance and overall life cycle costs lower than current reciprocating engines.

Altitude capability equal to current engines.

Use SCRC 4-350 as baseline engine.

Conceptually design engine.

Engine/airframe integration.

Identify new technology items which offer a significant payoff.

Diesel engine program

Objective: Develop in-house research and technical base to assess potential alternative engine candidates for future general aviation use.

Potential benefits.

50% reduction in life cycle cost.

25%-40% reduction in fuel consumption.

10%-30% reduction in specific weight.

50% reduced specific size.

Improved reliability through fewer moving parts.

Broad range of usable fuels.

Engine description.

2 cycle, radial diesel (6 cylinder rated at 298 kw (flat)).

3500 rpm geared to 2400 rpm for the propeller.

Uncooled, adiabatic engine. High technology insulated cylinders.

Minimum cooling configuration greatly reduces cooling drag. Cooling is required for the turbocharger and oil.

2 cycle operation results in 93° C lower EGT.

Evaluating a 149 kw and a 298 kw aluminum finned, cooled engine. 149 kw version is 4 cylinder, with a BSFC of .213 to .219 kg/kw/hr.

For the 298 kw, uncooled version, cruise BSFC is .195 kg/kw/hr. At 6100 m and full power, BSFC is expected to be on the order of .213 to .219 kg/kw/hr.

The diesel operates best at full power but obtains its best BSFC at 75% to 80% power.

III. Propeller Technology

Candidate Propulsion systems (4)

- Turboprop
- Propfan
- Variable pitch fan
- Turbofan

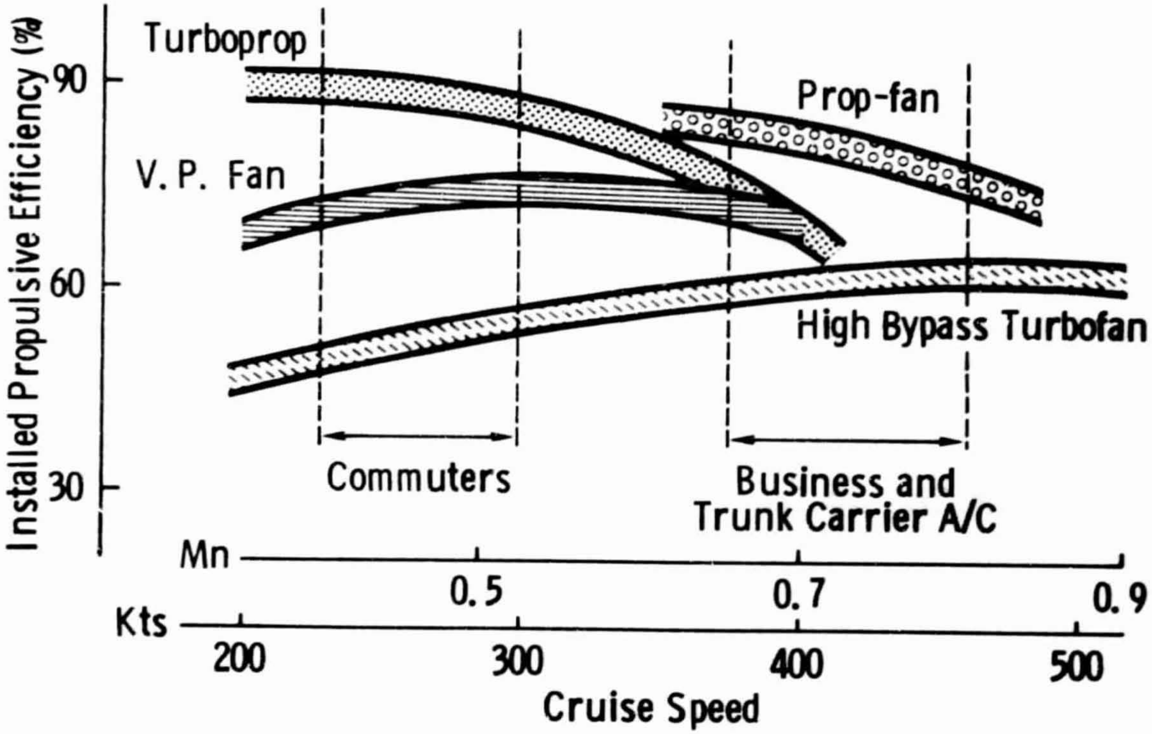
Parametric comparison of a small aircraft to a large aircraft:

	small	large
$C_{L_{max}}$	1.7	3.0
W_{max} (kg)	5675	363200
S (m^2)	29.97	511
W/S (N/m^2)	1867	6990
C_L (min drag)	.7	.7
q_{stall} (N/m^2)	1101	2327
$q_{L/D_{max}}$ (N/m^2)	2681	10055
L/D_{max}	13	19

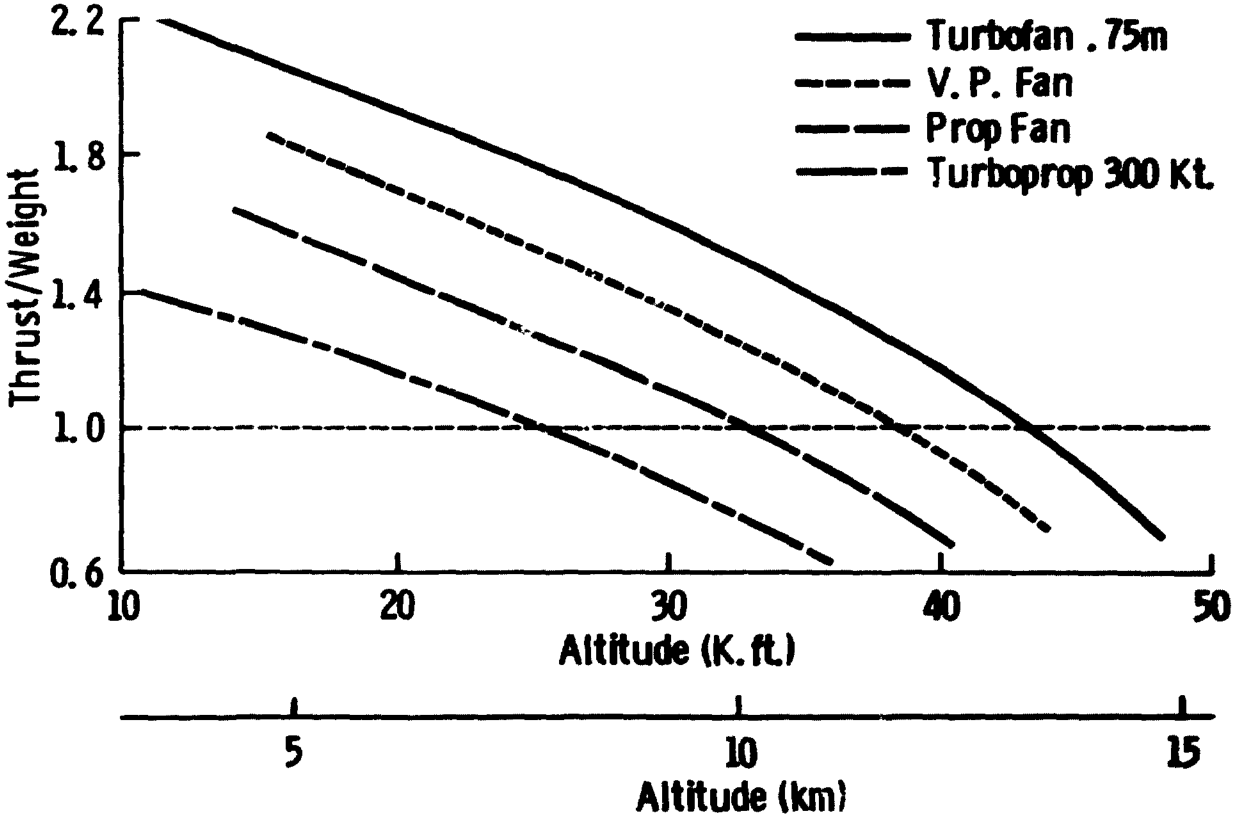
Relative to a large aircraft, general aviation aircraft require propulsion systems having:

- high cruise thrust at altitude
- high engine thrust/weight ratio
- low specific fuel consumption

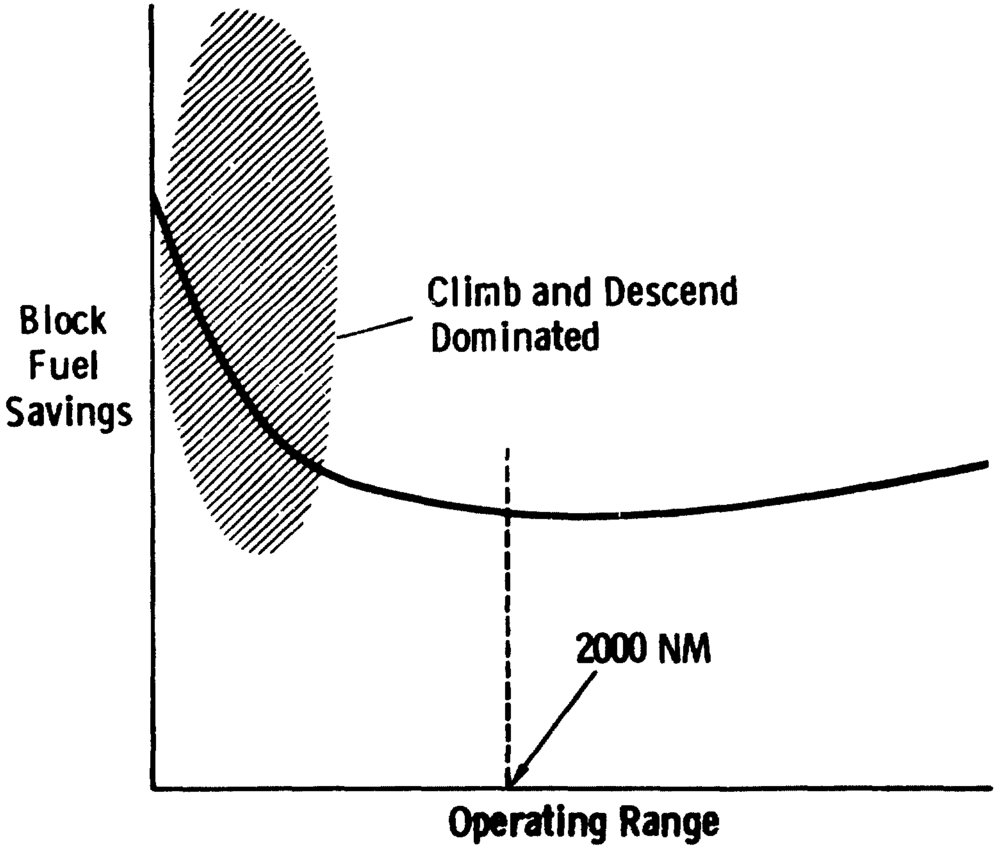
INSTALLED PROPULSIVE EFFICIENCY AT CRUISE



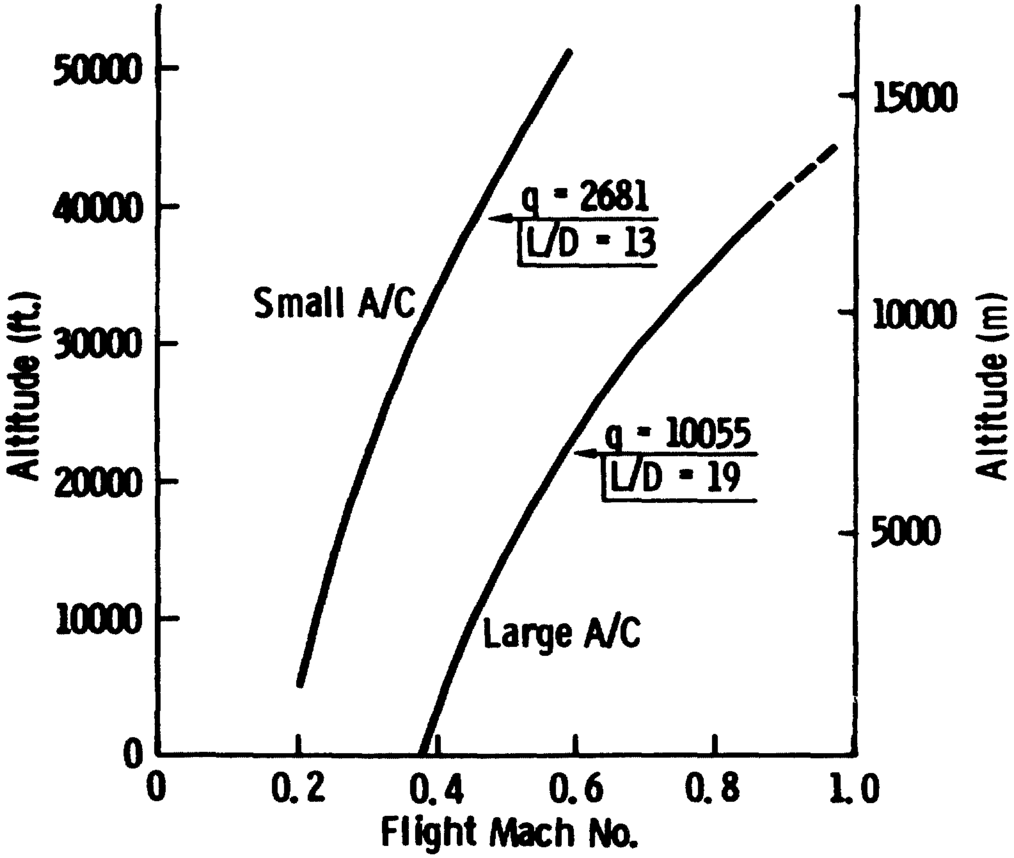
TURBOFAN -
HIGHEST THRUST/WEIGHT



PROP FAN
FUEL SAVING TRENDS RELATIVE TO TURBOFANS



MAX. L/D SPEED VS. ALTITUDE FOR "SMALL" AND "LARGE" AIRCRAFT



Propulsion system comparisons

Propfans: High speed - challenges the turbofan.

Variable pitch fan: Intermediate speed - challenges the turbeprop.

Recommend two feasibility studies

(1) Propfan application to small business aircraft (Mach = .7 to .8).

(2) Variable pitch fan application to commuter aircraft.

General Aviation Propeller (GAP) program

Background

NACA propeller research ended in the 1950's.

Advanced turboprop of 1975 at M = .8.

GAP - technology for lower speed general aviation.

Goals

Reduce fuel used by 8% to 9%.

Lower noise by 5 to 10 dB.

Improved safety through use of composites for strength.

Current design practice

40 years of experience.

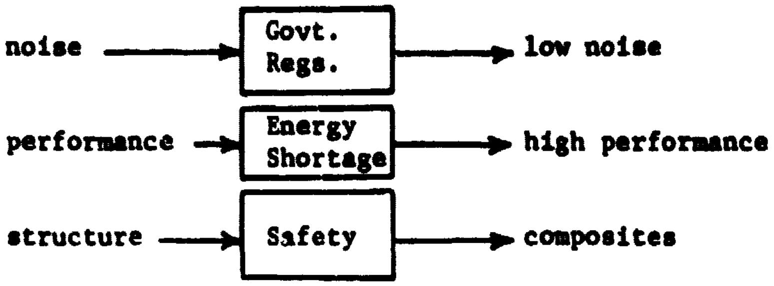
Aluminum construction.

Few blade designs: cut down or extend tip.
add blades.

Aircraft integration: "cut and try" process.

Design Trends:

Current Practice	Future
very low cost	
non-optimum	optimized



Program participants

Cost/benefit study - McCauley

Improved performance concepts - Purdue

Aero-acoustic methodologies - OSU

Advanced propeller balance - contract

McCauley GAP cost/benefit study

Task I: Identify advanced technologies and cost/benefit.

Task II: Optimum configurations and mission analysis.

Task III: Technology assessment and program plan.

Aircraft Categories:

(1) Reciprocating engine, 261 kw, 250 kts.

(2) Turboprop, 746 kw.

(3) Aerial application, 186-746 kw.

McCauley Study Team:

McCauley - Performance and coordination.

Cessna Pawnee - Aircraft and mission analysis.

Ohio State - Noise and performance.

Materials Science Corporation - Composites.

Improved Performance Concepts

Swept lifting line analysis.

Improved testing techniques - laser Doppler velocimeter.

New concepts - proplets, swept blades.

Propeller aero-acoustic methodologies

Phase 1: Predict and test 1.52 m diameter models

Airfoil technology - Clark Y, NACA 16, GAW-2, ARA-D.

Phase 2: Flight test comparison.

Phase 3: Improved methodologies and verification.

Team: Ohio State
Rockwell International
Hartzell
Hank Borst
Dowty

Small Transport Aircraft Technology (STAT)

Lewis Research Center Capabilities

Propulsion system performance

Noise

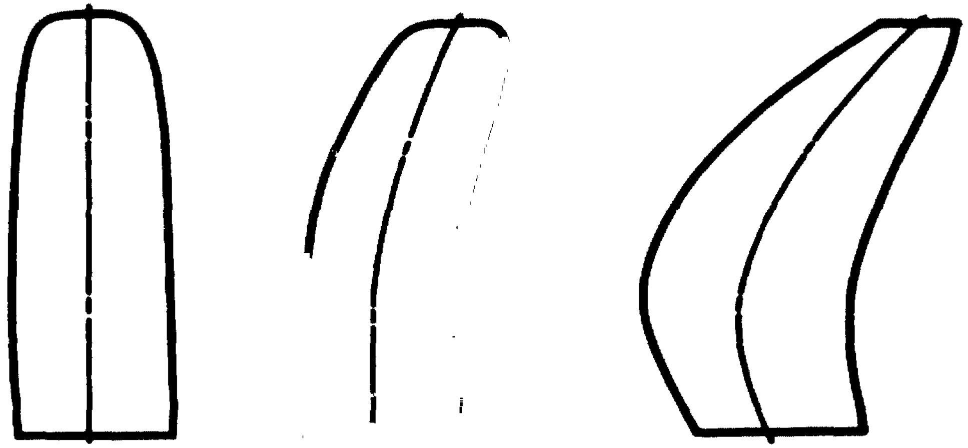
Icing Studies

Propeller aeroelastics.

FY 1979 Plans

Engine and propeller studies.

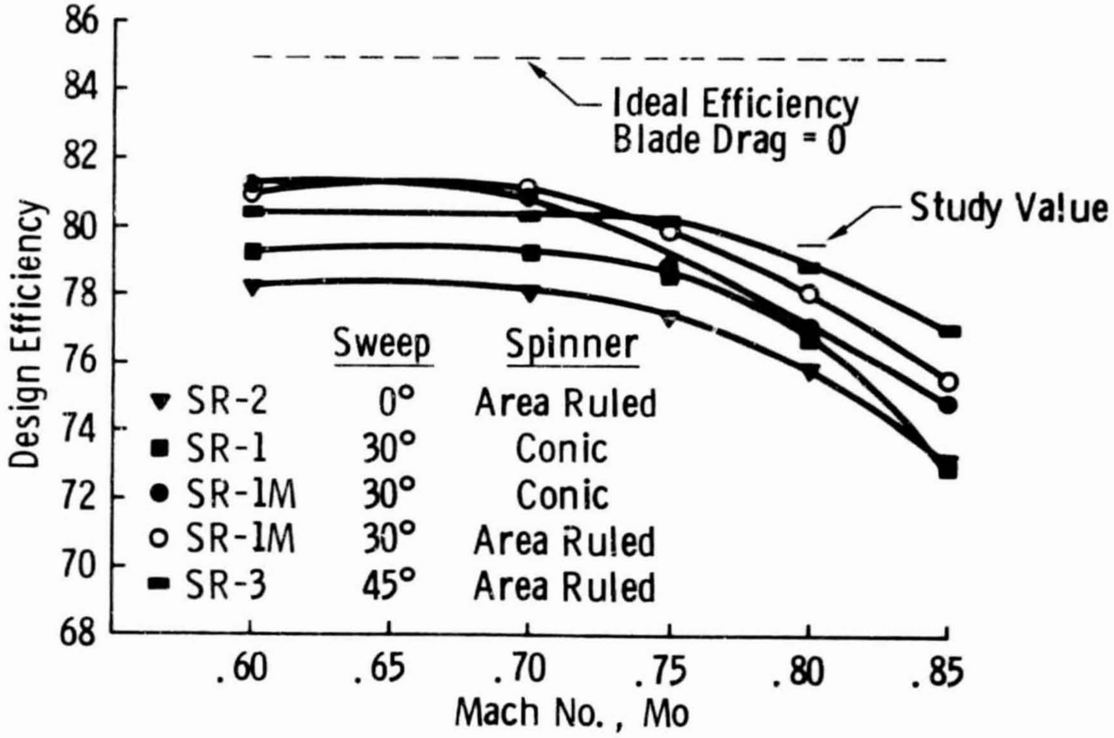
PROPELLER MODEL COMPARISON



	SR-2	SR-1, 1M	SR-3
Tip Speed, m/sec (ft/sec)	244 (800)	244 (800)	244 (800)
Power Loading, kW/m^2 (hp/ft^2)	301 (37.5)	301 (37.5)	301 (37.5)
No. of Blades	8	8	8
Tip Sweep Angle, deg	0	30	45
Design Eff, %	77	79	81
Design Noise Level, dB	143	143	137

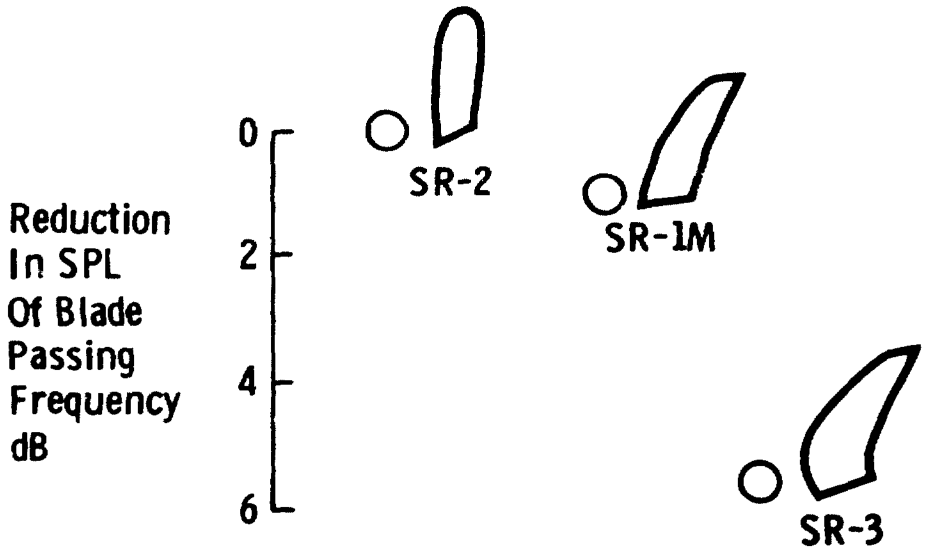
HIGH SPEED PROPELLER PERFORMANCE SUMMARY

$J = 3.06$ $C_P = 1.7$ $D = 24.5''$



NOISE COMPARISON OF PROPELLERS

$M_0 = 0.8$ Design Conditions



APPENDIX B

TECHNOLOGY EVALUATION

Five significant aspects of the technology evaluation are discussed in this appendix. Although all are briefly mentioned in Chapter 4, they are amplified here to further define the basis for the results of the technology evaluation.

Section B.1 discusses the Category Selection Survey (Survey 1) and describes how the 17 evaluation categories were selected.

Section B.2 describes the Category Rating Survey (Survey 2) and describes how the relative importance of the 17 evaluation categories were established. Histograms of round 3 and mean category rating trends are included.

Section B.3 describes the Candidate Technology Identification process. 81 deleted technologies (137 Preliminary Candidate Technologies - 56 Final Candidate Technologies) are briefly discussed.

Section B.4 addresses the PLOE studies which were performed as part of the analysis of the selected Evaluation Technique. Complete tables for the pessimistic, likely, and optimistic scenarios are presented for both airplanes. Also, the results of this study are graphically presented for both airplanes.

Finally, Section B.5 examines the effect of Empty Weight category ratings of 0 and 9.5 vs the computed ratings of 4.340 and 5.657 (for Airplanes A and B respectively) on the technology rankings.

B.1 CATEGORY SELECTION SURVEY

The category selection survey was based on the Delphi method which involves sequential rounds of written communication in which the group response from one round is fed back to participants for consideration in the next round. The participants were the project staff and members of the University of Kansas Aerospace Engineering Department Faculty. Four survey rounds were required to obtain satisfactory convergence and round-to-round feedback consisted of participant comments and participant voting (in the form of an "average" list) from the previous round.

The first round established a large category list with definitions for each category. This list and definitions were refined in subsequent rounds to arrive at the final category list of 17 categories. Participants rated their own confidence in their responses with a confidence level, CL, $(0 \leq CL \leq 10)$ which was used to weight the voting.

An average list was established after each round by compiling a list of the "N" most-voted categories where N was the average number of categories in the participant lists. When two categories in the average list appeared to directly overlap, the category with the smaller number of votes was deleted and the next most voted category was added.

Variations in the average list were small after the first round and convergence was assumed after the fourth round. Tables B.1 through B.4 present the average lists of rounds 1 through 4 respectively.

Table B.1. Round 1 Average Category List

Category	Votes
Safety	5
Fuel Efficiency	4
Purchase Price	4
Reliability	4
Survivability	4
Empty Weight	3
Exterior Noise	3
Handling Qualities	3
Interior Noise	3
Maintenance Cost	3
Pilot Workload	3
Range	3
Stall Speed	3

Maximum number of votes = 8 (no confidence levels)

The final list of categories was obtained by checking the fourth round average list against the three selection criteria as discussed in Section 4.1.2. This resulted in a final category list which differs from the fourth round average list in three respects.

(1) The categories of "Payload" and "Empty Weight" overlap. Hence "Payload", having fewer votes, was deleted from the list.

Table B.2. Round 2 Average Category List

Category	Votes
Purchase Price	54.5
Exterior Noise	53.5
Fuel Efficiency	49.0
Emissions	46.5
Reliability	46.5
Direct Operating Cost	44.5
Payload	44.5
Overall Pilot Workload	39.5
Safety	39.5
Survivability	39.5
Takeoff/Landing Performance	39.5
Interior Noise	39.0
Range	37.5
Cruise Speed	30.0
Ride Qualities	30.0
Static Comfort	30.0
Empty Weight	24.0
Lift/Drag Ratio	22.0

Maximum number of votes = 63.5 (includes confidence levels)

(2) "Overall Pilot Workload" was changed to "Pilot Workload" for clarity, but the former's definition was retained.

Table B.3. Round 3 Average Category List

Category	Votes
Direct Operating Cost	52.5
Emissions	52.5
Exterior Noise	52.5
Fuel Efficiency	52.5
Overall Pilot Workload	52.5
Purchase Price	52.5
Reliability	52.5
Safety	52.5
Takeoff/Landing Performance	52.5
Empty Weight	43.5
Interior Noise	43.5
Ride Qualities	43.5
Static Comfort	43.5
Survivability	42.5
Cruise Speed	35.5
Range	33.5
Payload	25.5

Maximum number of votes = 52.5(includes confidence levels)

(3) The definitions of all of the categories were reviewed and refined if necessary.

The final category list (17 categories) used in the evaluation technique is presented in Table B.5.

Table B.4. Round 4 Average Category List

Category	Votes
Cruise Speed.	53.5
Direct Operating Cost	53.5
Emissions	53.5
Exterior Noise.	53.5
Fuel Efficiency	53.5
Interior Noise.	53.5
Overall Pilot Workload.	53.5
Purchase Price.	53.5
Reliability	53.5
Ride Qualities.	53.5
Safety.	53.5
Static Comfort.	53.5
Takeoff/Landing Performance . .	53.5
Empty Weight.	44.5
Range	44.5
Ceiling	28.0
Crashworthiness	28.0
Payload	24.5

Maximum number of votes = 53.5 (includes confidence levels)

Table B.5. Final Category List Used In The Evaluation Technique

Category	Definition
Ceiling	Altitude at which the maximum rate of climb is .51 m/s (service ceiling).
Crashworthiness	The characteristics of an airplane which determine the level of occupant protection in the event of a crash.
Cruise Speed	Maximum continuous cruise speed.
Direct Operating Cost	All costs directly attributable to flying and keeping an airplane operational. All scheduled and unscheduled maintenance costs and fuel costs are included.
Emissions	Pollutants produced during the operation of an airplane. Does not include noise.
Empty Weight	Airplane weight without fuel, crew, and payload.
Exterior Noise	Noise perceived at ground level due to the operation of an airplane.
Fuel Efficiency	Airplane cruise efficiency measured in air-miles per pound-fuel.
Interior Noise	Noise perceived by the occupants of an airplane.
Pilot Workload	The amount of time, concentration, and effort a pilot must devote to the safe operation of an airplane. This includes the effects of airplane handling qualities.

Table B.5. Final Category List Used In The Evaluation Technique (Concluded)

Category	Definition
Purchase Price	The price paid for a new airplane by the user, including avionics and equipment costs.
Range	The distance an airplane can fly without refueling while allowing for appropriate fuel reserves.
Reliability	A measure of the probability of failure of an airplane component or system.
Ride Qualities	A measure of the effects of aircraft motion on the smoothness and comfort of the ride experienced by the occupants.
Safety	A measure of an airplane's inherent characteristics which reduce the probability of an accident.
Static Comfort	A measure of an airplane's inherent comfort. This includes roominess, seat comfort, ventilation, decor, ease of entry, etc.
Takeoff/Landing Performance	This parameter includes takeoff and landing speeds, field length requirements, and rates-of-climb and descent.

B.2 CATEGORY RATING SURVEY

The category rating survey was based on the Delphi Method which involves sequential rounds of written communication in which the group response from one round is fed back to participants for consideration in the next round. The 42 participants involved in this survey represent General Aviation manufacturers, user groups, university faculty, NASA centers, and project staff. A complete listing of the participants is given in Chapter 4.

Three survey rounds were required and the round-to-round feedback consisted of participant voting and comments. Participant voting was represented by "mean" and "corrected mean" category ratings and voting distributions in the form of histograms.

The mean category ratings for each airplane are simply weighted averages computed using Equation B.1.

$$\bar{R}_j = \frac{\sum_{i=1}^{n} (R_{ij})(CL_i)}{\sum_{i=1}^{n} (CL_i)} \qquad (B.1)$$

where $\bar{R}_j$ = the mean rating ($0 \leq \bar{R}_j \leq 10$) of category j.

n = the number of participants.

R_{ij} = the rating ($0 \leq R_{ij} \leq 10$) given category j by participant i.

CL_i = the confidence level ($0 \leq CL_i \leq 1$) of participant i.

The corrected mean category ratings for both airplanes were obtained by multiplying the mean rating by the ratio of the maximum possible rating (10) to the maximum mean rating as shown by Equation B.2.

$$\bar{R}_{cj} = \left(\frac{10}{\bar{R}_{max}}\right) \bar{R}_j \tag{B.2}$$

where $\bar{R}_{cj}$ = the corrected mean rating ($0 \leq \bar{R}_{cj} \leq 10$) of category j.

$\bar{R}_{max}$ = the maximum mean category rating ($0 \leq \bar{R}_{max} \leq 10$)

$\bar{R}_j$ = the mean rating ($0 \leq \bar{R}_j \leq 10$) of category j.

The histograms show the number of votes each rating received in a given category as shown by Equation B.3.

$$V_{jk} = \sum_{i=1}^{n} (T_{ijk})(CL_i) \tag{B.3}$$

where V_{jk} = the number of votes in category j for rating k.

n = the number of participants.

T_{ijk} = the voting indicator of participant i in category j for rating k (T_{ijk} = 1 for yes, 0 for no).

CL_i = the confidence level of participant i.

Note: V_{ij} is rounded to the nearest 0.5 for histogram plotting purposes.

Figure B.1 presents the mean and corrected mean category ratings and the histograms from round 3. The round-to-round trends of the mean ratings are illustrated in Figure B.2.

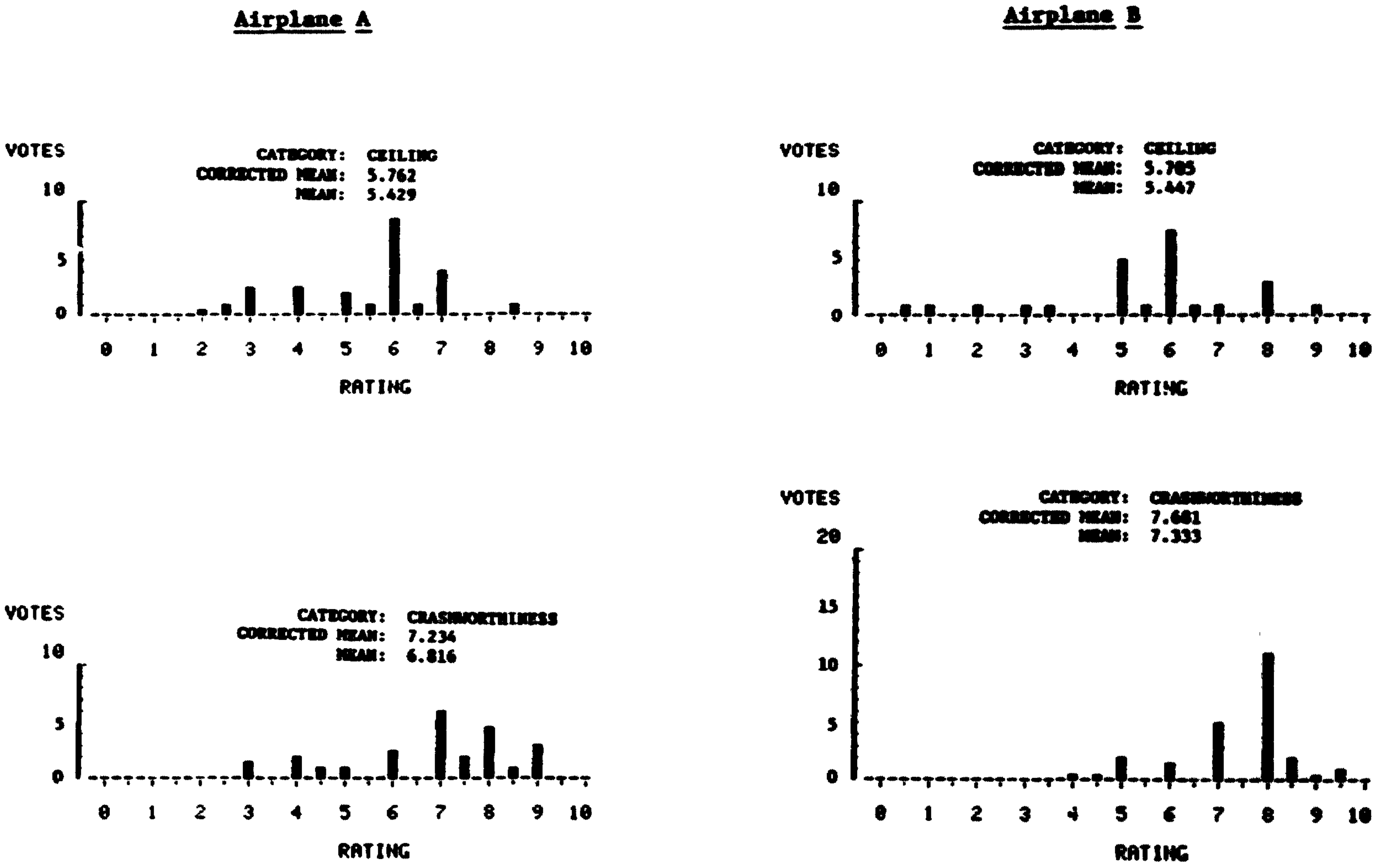


Fig. B.1. Results of Round 3 of the Category Rating Survey

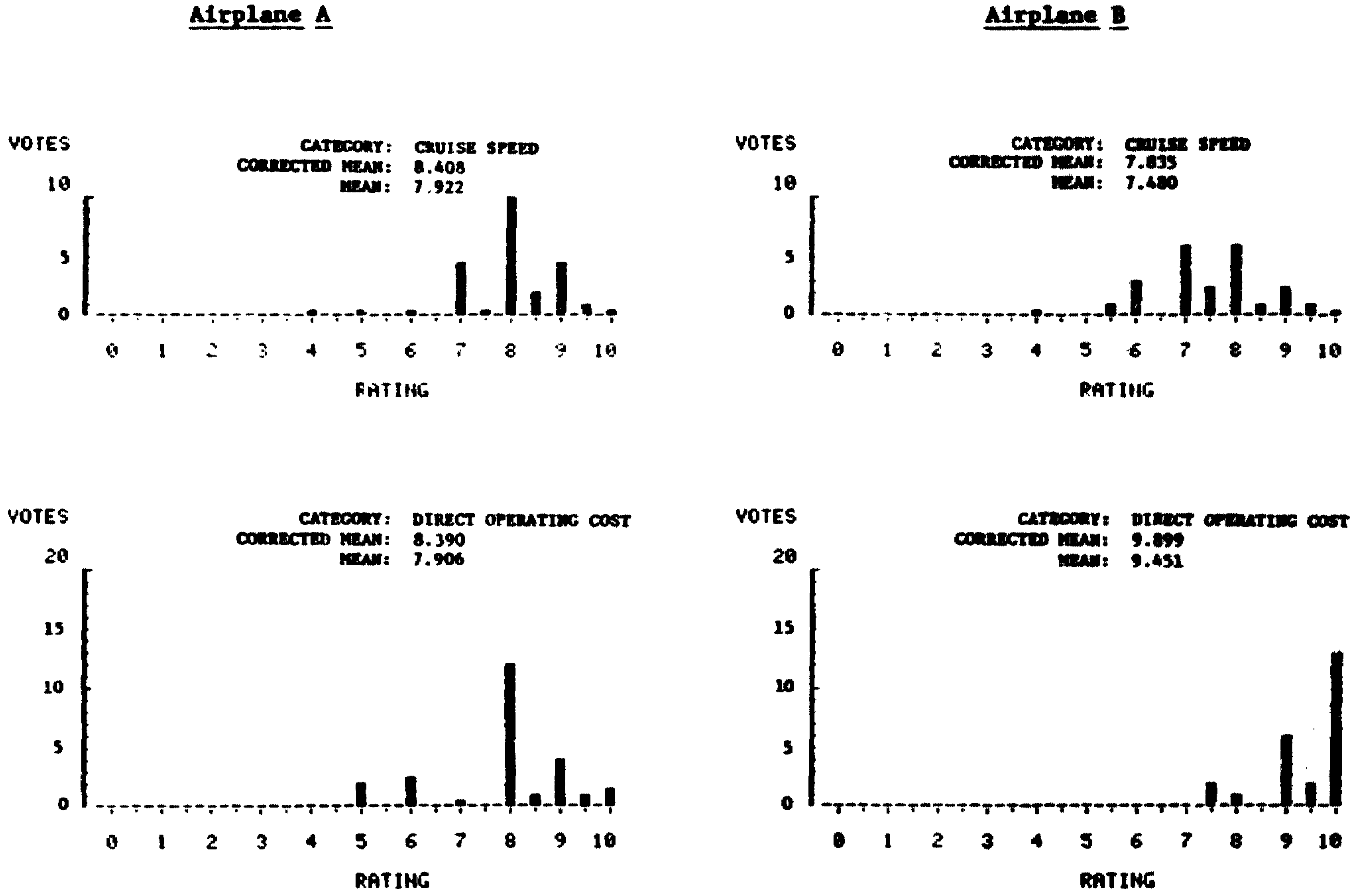


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

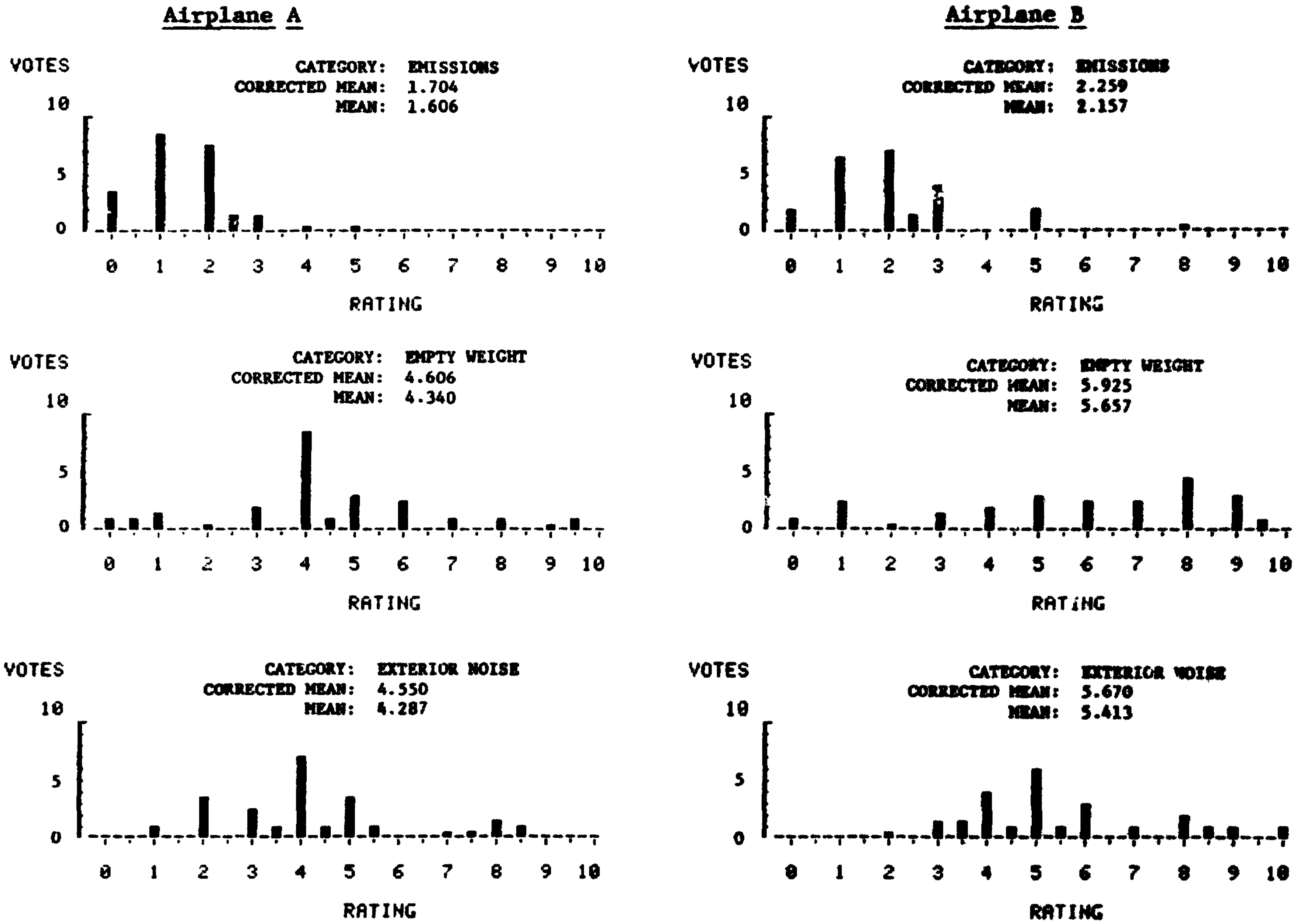


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

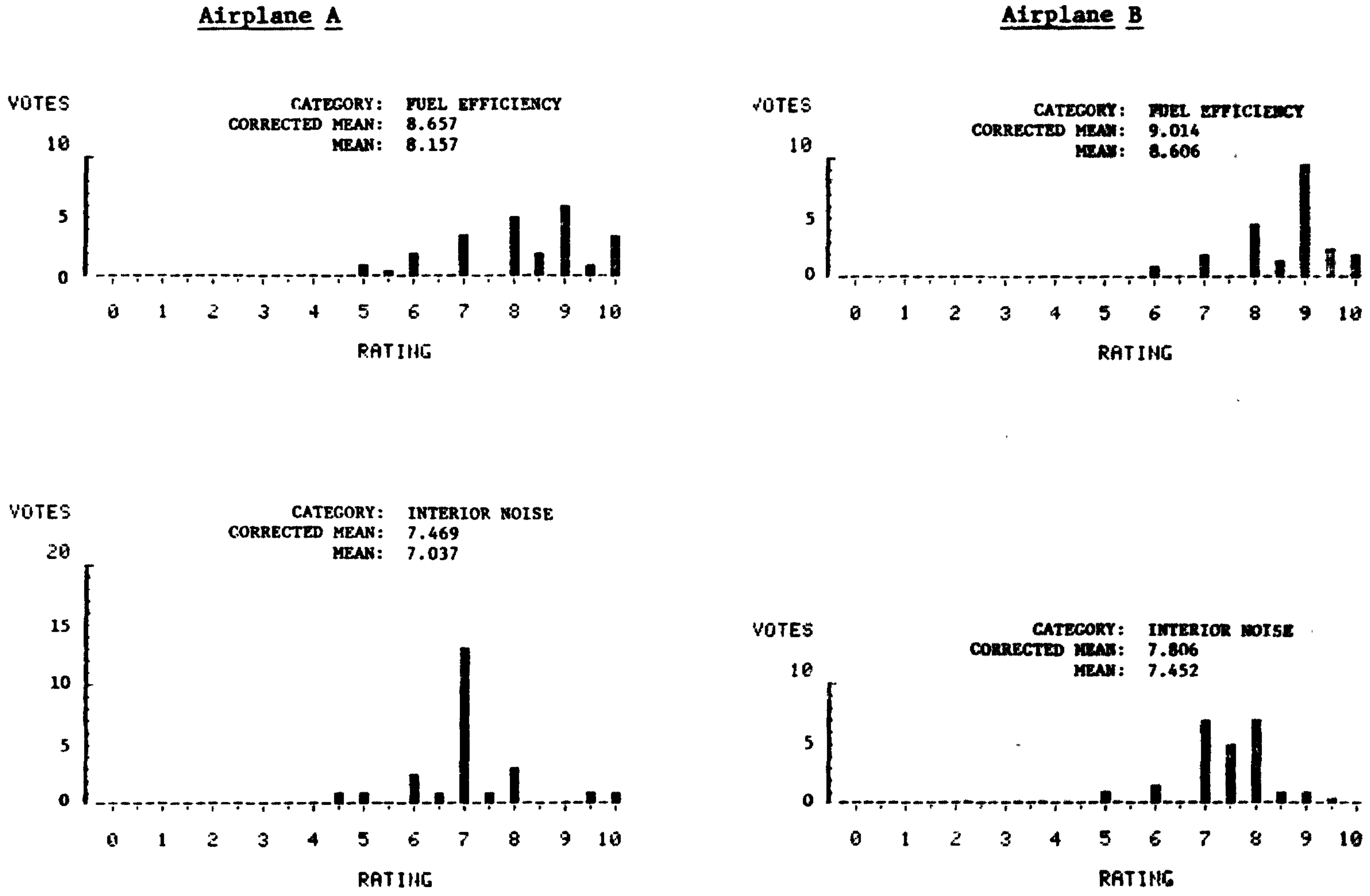


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

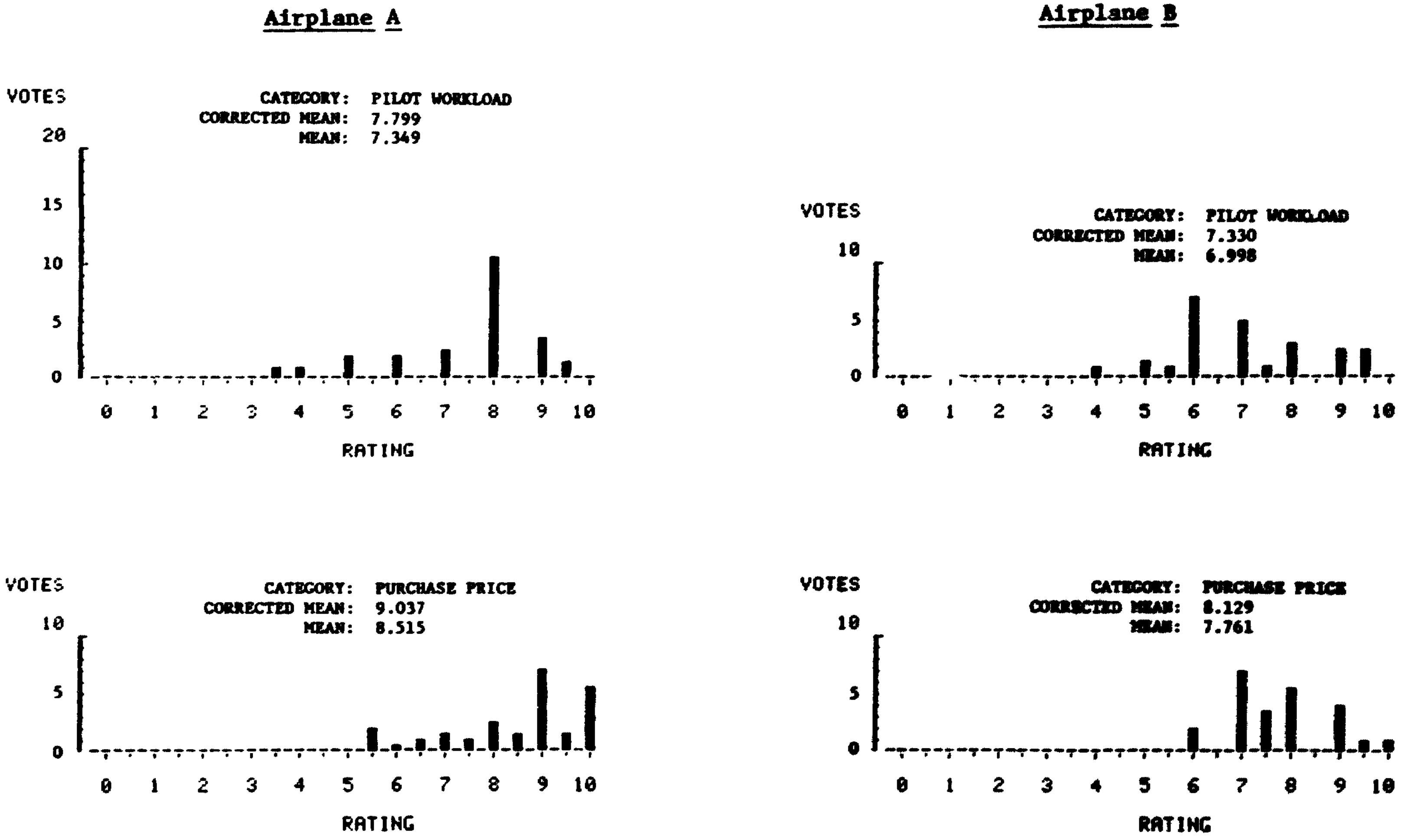


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

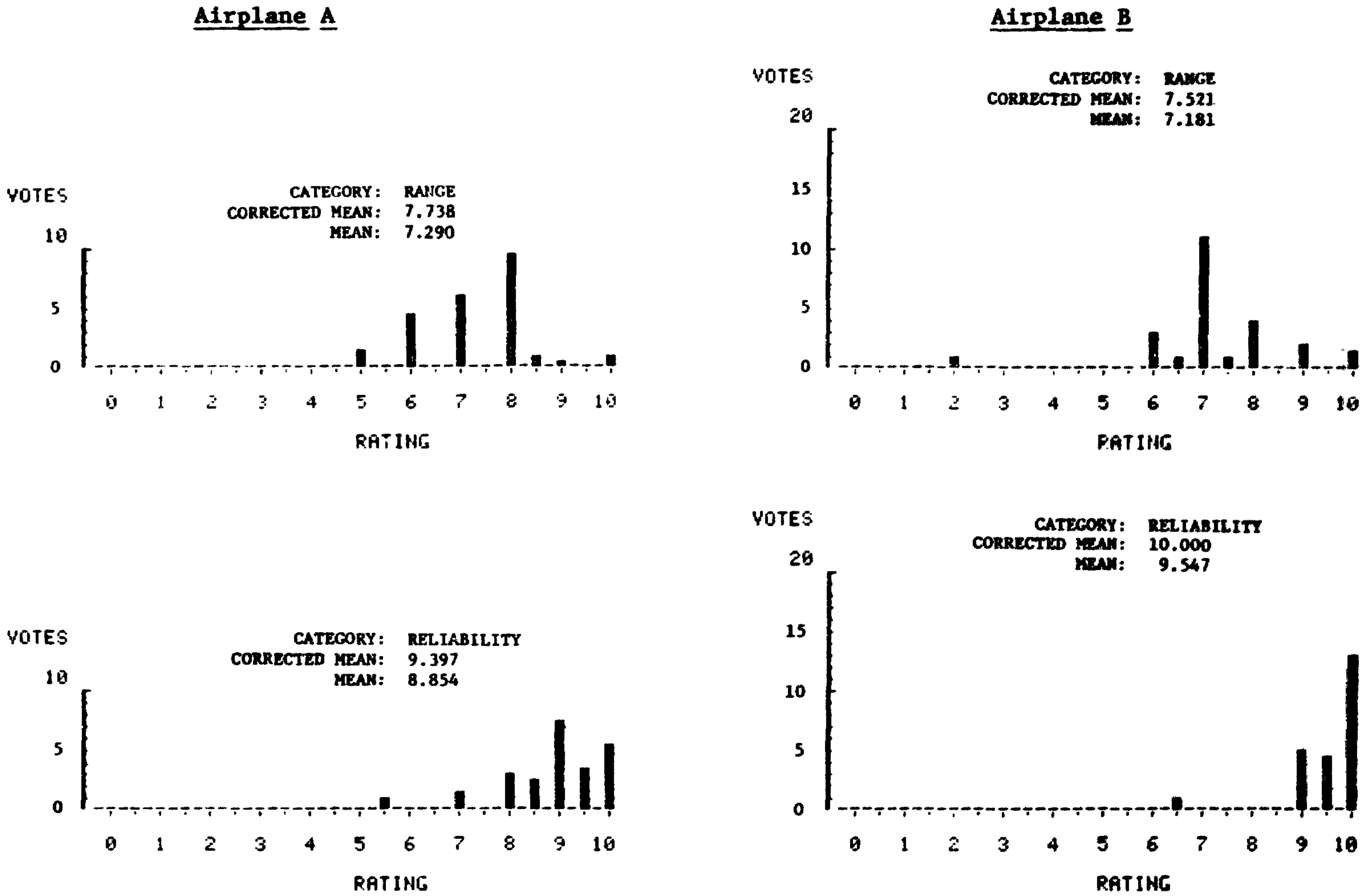


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

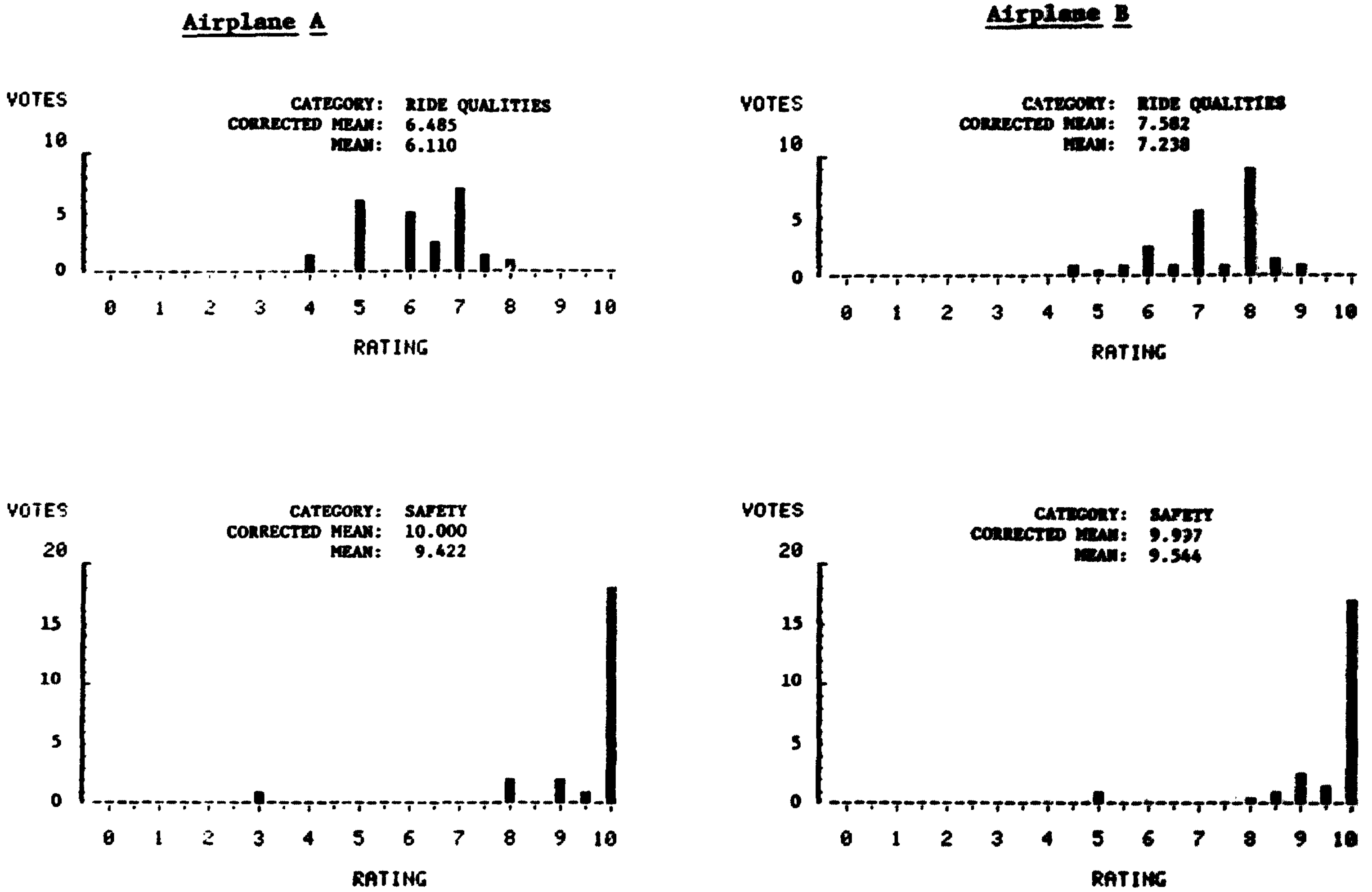


Fig. B.1. Results of Round 3 of the Category Rating Survey (continued)

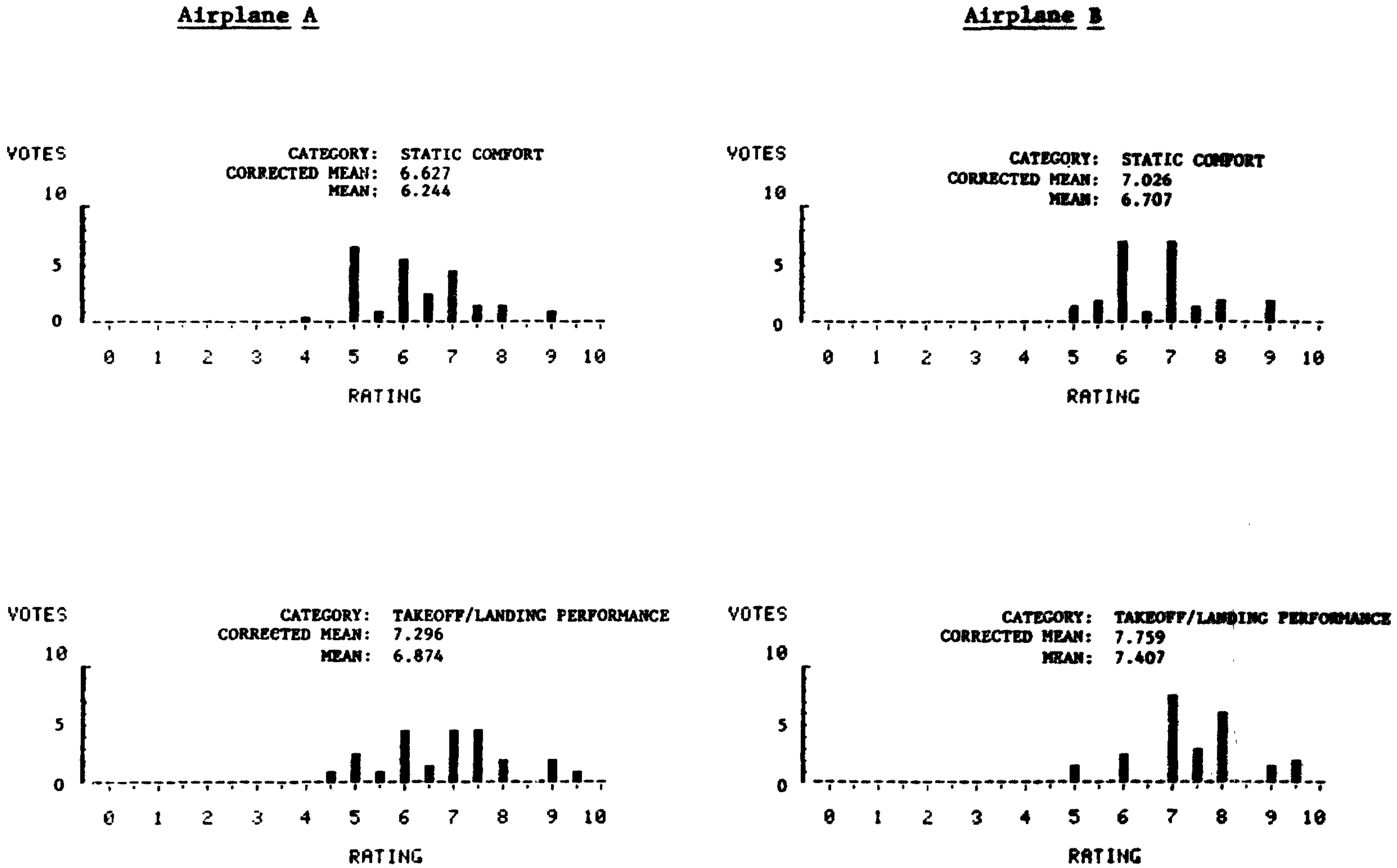


Fig. B.1. Results of Round 3 of the Category Rating Survey (concluded)

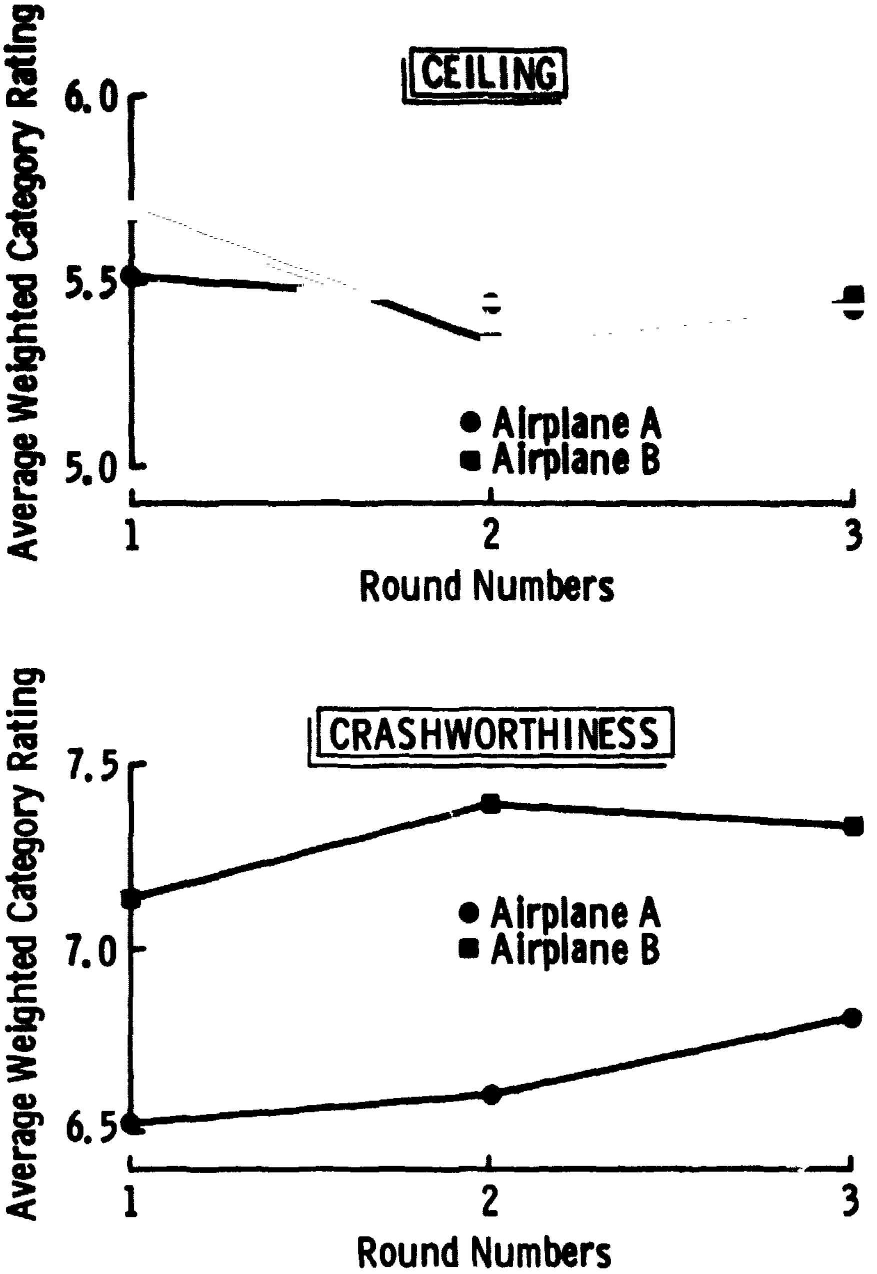


Fig. B.2. Mean Category Rating Trends.

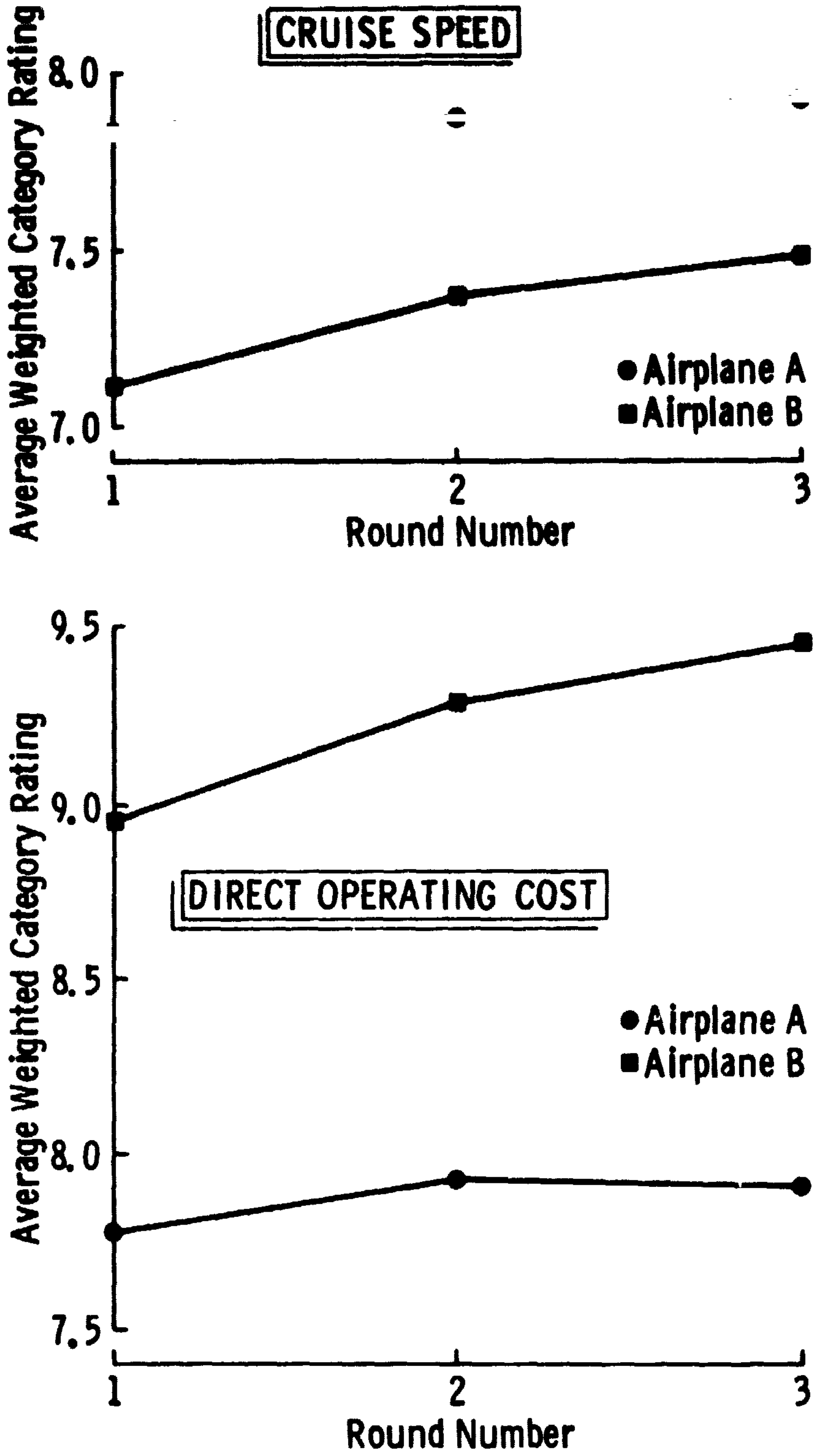


Fig. B.2. Mean Category Rating Trends (continued)

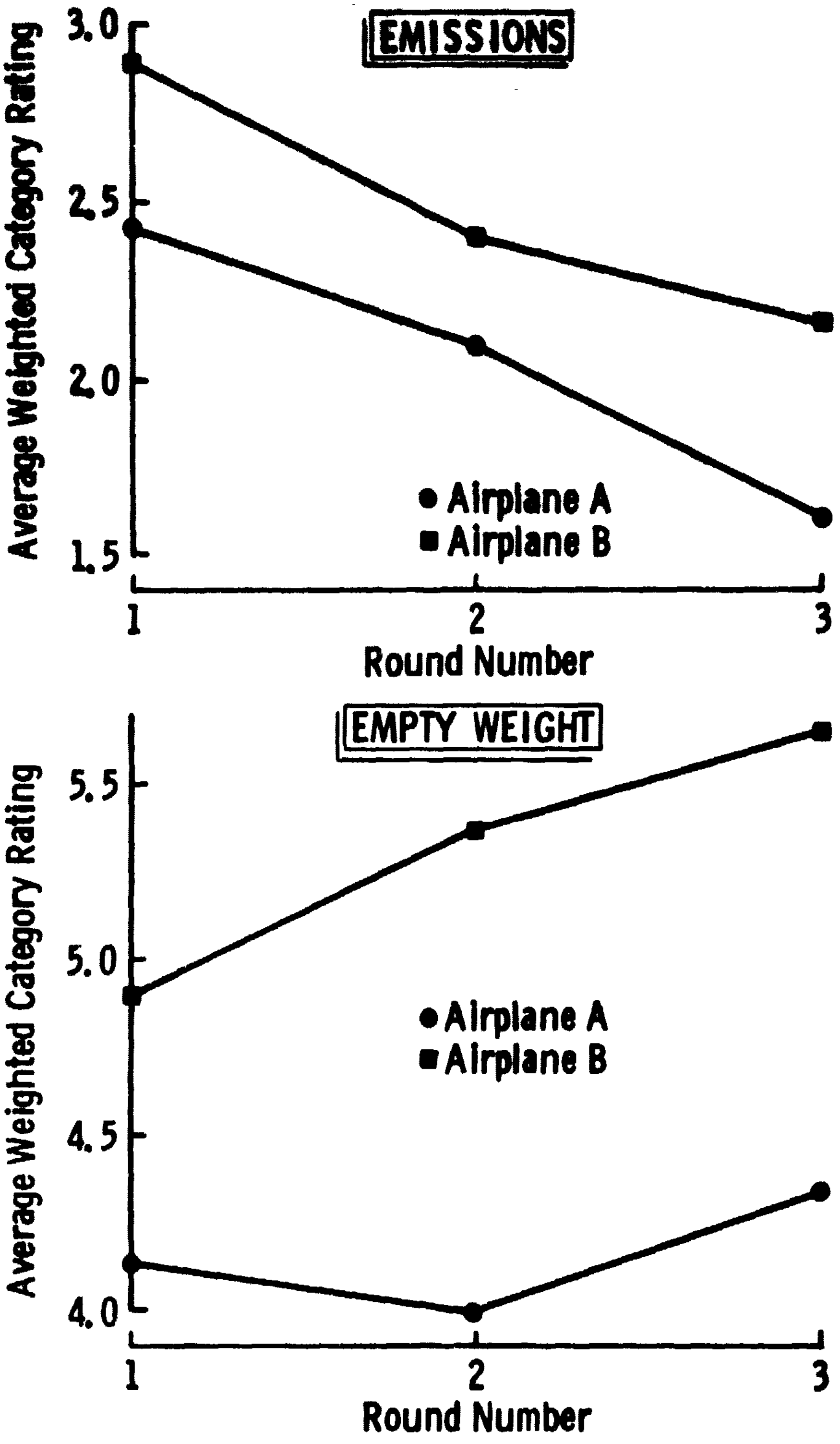


Fig. B.2. Mean Category Rating Trends (continued)

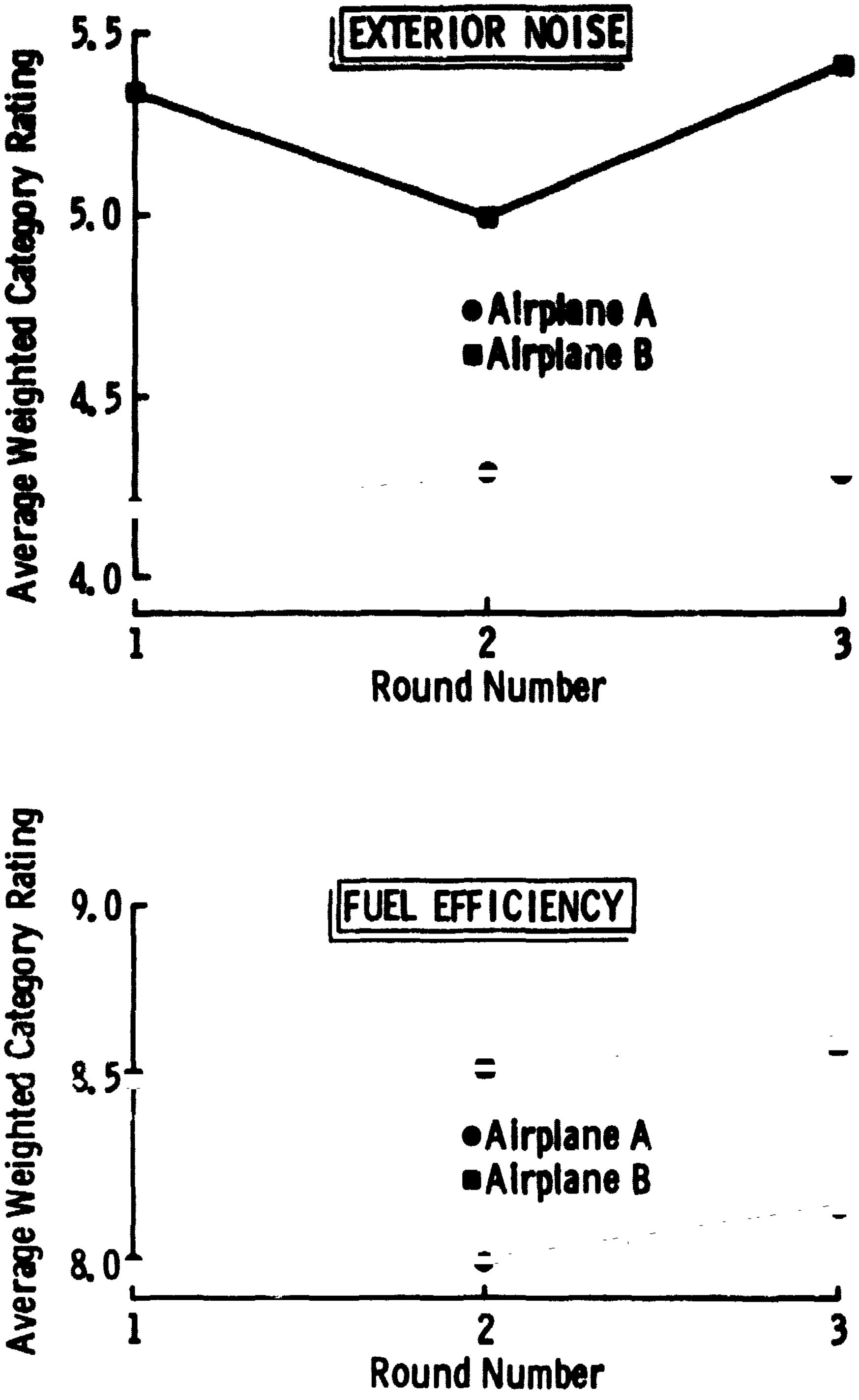


Fig. B.2. Mean Category Rating Trends (continued)

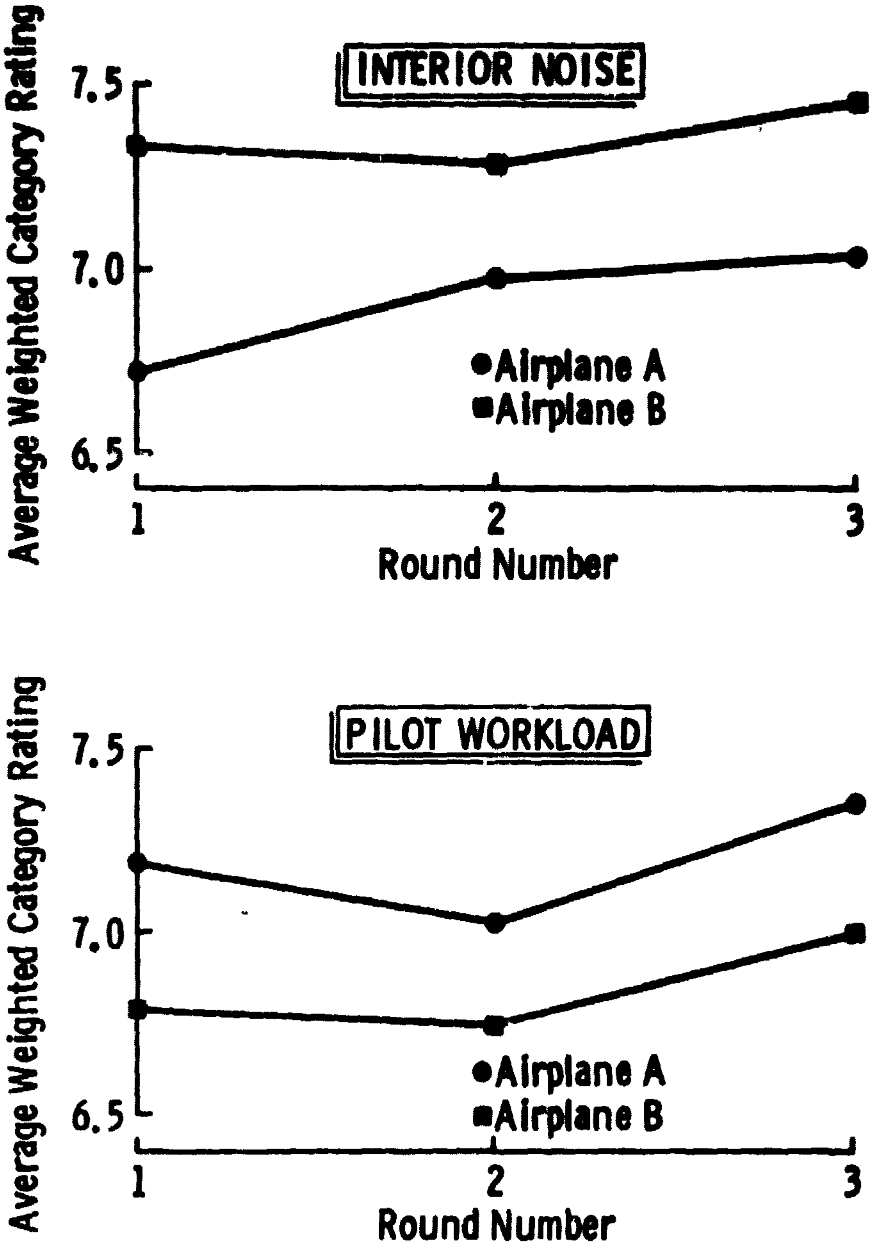


Fig. B.2. Mean Category Rating Trends (continued)

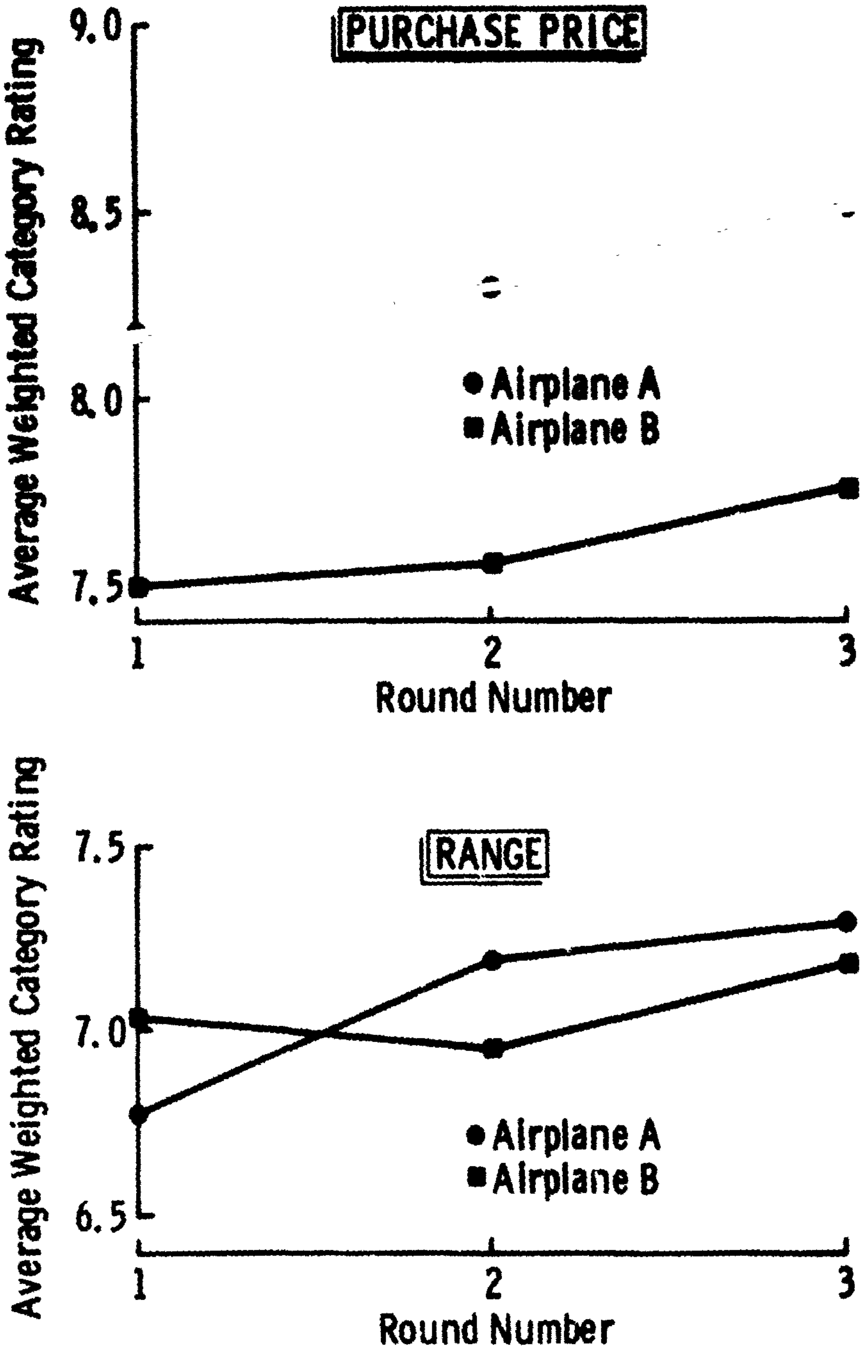


Fig. B.2. Mean Category Rating Trends (continued)

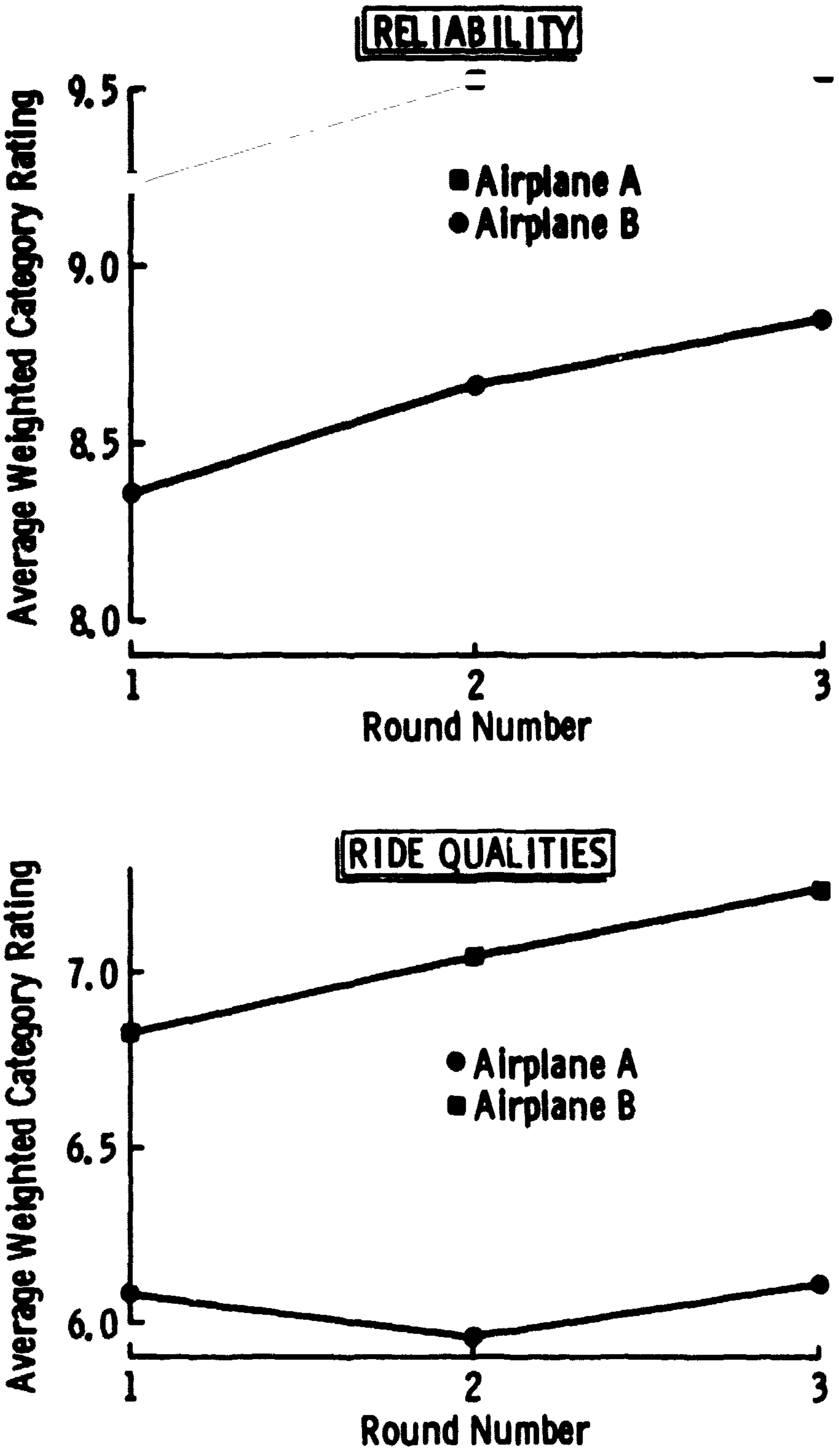


Fig. B.2. Mean Category Rating Trends (continued)

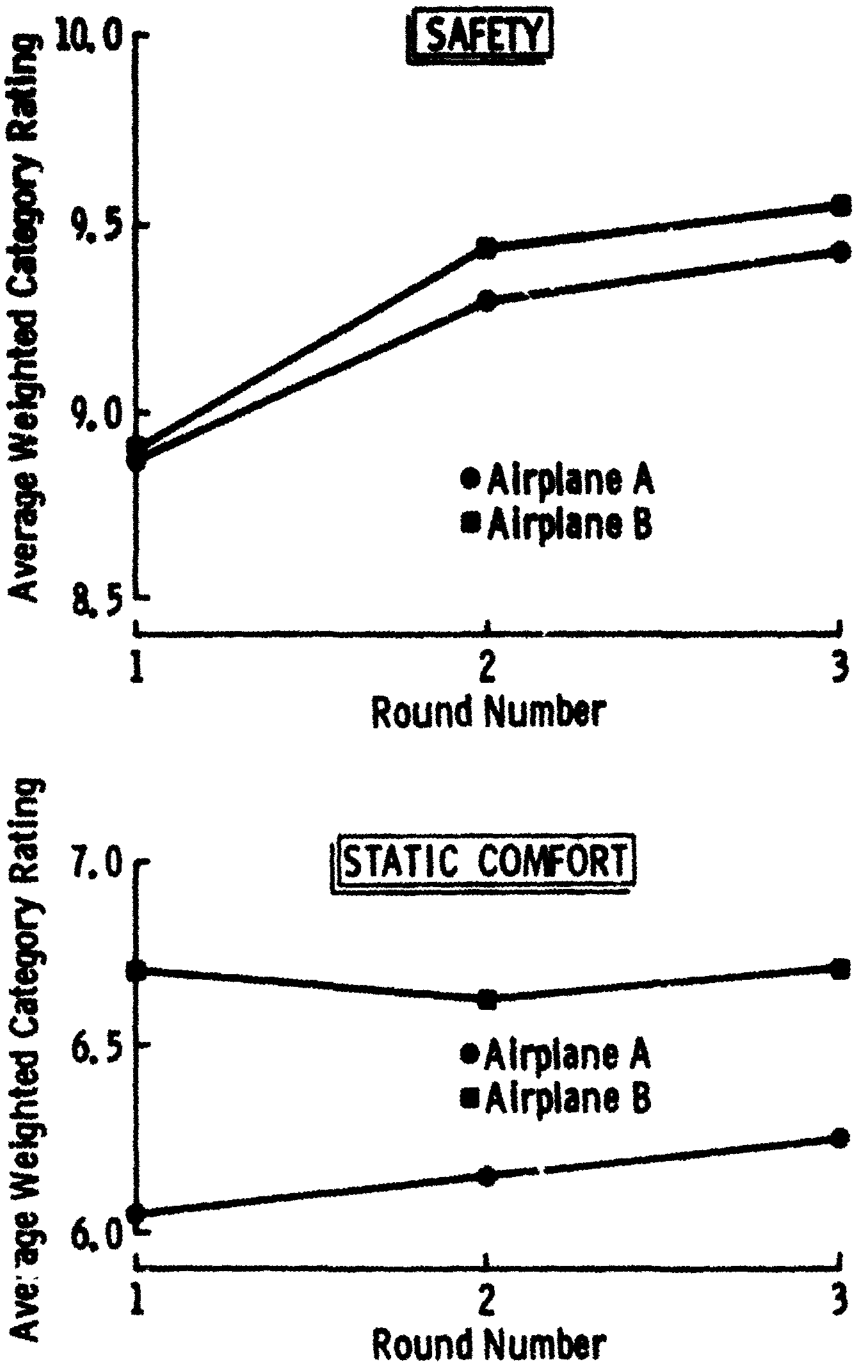


Fig. B.2. Mean Category Rating Trends (continued)

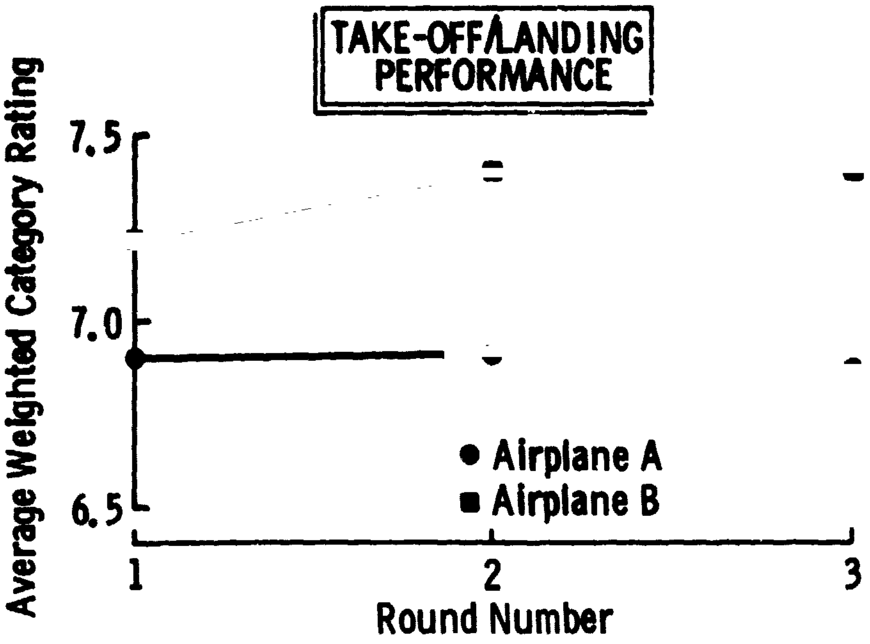


Fig. B.2. Mean Category Rating Trends (concluded)

As mentioned previously, three rounds were required to obtain satisfactory convergence. The convergence criterion used is that suggested in Reference 125 and is based on the stability of participant voting. The procedure is as follows:

(1) Calculate the total number of rating changes (TNC) in a category between two successive rounds. TNC_i is the <u>number of participants</u> who changed their rating of category i between two rounds.

(2) Calculate the total percent change (TPC)

$$TPC_i = (\frac{TNC_i}{n})\,100 \qquad (B.4)$$

where TPC_i = the total percent change in category i.

TNC_i = the total number of rating changes in category i.

n = the number of participants.

(3) If $TPC_i \leq 15\%$, then category i can be considered stable.

Note: Only those participants who responded in two successive rounds can be included in this analysis.

Some difficulty was encountered in applying the convergence criterion. First, some of the participants did not respond in every round. Second, the convergence criterion applies to individual categories rather than the survey as a whole. These problems were overcome by computing the average category stability and by taking the magnitude of the changes in the mean ratings into consideration. Table B.6 presents the round-to-round category stability and the computed average stability. As shown in this table, an average stability of 18% was achieved between rounds 2 and 3. Although larger than the desired 15%, the stability was considered satisfactory due to the fact that the mean category ratings were not changing significantly.

The data reduction, histogram plotting, and stability analyses were done with an HP-9825 minicomputer. The program used computes both weighted (confidence levels included) and unweighted (confidence levels excluded) mean ratings and histograms, but only the weighted results were used in the course of the survey.

Table B.6. Category Rating Survey Stability

Category	Total Percent Change			
	Rounds 1 to 2		Rounds 2 to 3	
	Airplane A	Airplane B	Airplane A	Airplane B
Ceiling	44.44	38.46	38.46	19.23
Crashworthiness	33.33	50.00	30.77	38.46
Cruise Speed	40.74	53.85	15.38	7.69
Direct Operating Cost	44.44	42.31	11.54	11.54
Emissions	40.74	42.31	26.92	38.46
Empty Weight	40.74	50.00	11.54	15.38
Exterior Noise	44.44	34.62	19.23	11.54
Fuel Efficiency	48.15	53.85	11.54	15.38
Interior Noise	48.15	42.31	19.23	7.69
Pilot Workload	51.85	38.46	23.08	19.23
Purchase Price	51.85	53.85	11.54	23.08
Range	55.56	42.31	11.54	23.08
Reliability	40.74	50.00	19.23	11.54
Ride Qualities	37.04	42.31	15.38	26.92
Safety	25.93	30.77	7.69	7.69
Static Comfort	29.63	42.31	19.23	19.23
Takeoff/Landing Performance	33.33	42.31	15.38	7.69
Averages	42.97%		17.99%	

The category weightings used in the evaluation technique are the weighted mean category ratings from Round 3 and are given in Chapter 4, Table 4.3.

B.3 CANDIDATE TECHNOLOGY IDENTIFICATION

This appendix discusses the literature search, the preliminary candidate technology selection, the final candidate technology selection, and the deleted candidate technologies.

(1) Literature Search - The literature search was conducted using the Lockheed DIALOG system. The on-line search resulted in 1655 abstracts from which 107 articles were ordered from the National Technical Information Service (NTIS). In conducting the search, nine search topics were used and are as follows:

(a) Aircraft Design
(b) Aircraft Propulsion
(c) Aircraft Structures
(d) Flight Controls
(e) Navigational Aids
(f) Avionics
(g) Canard Configurations
(h) NAVSTAR/GPS
(i) GASP (General Aviation Synthesis Program)

The actual transcripts of the search are given in Tables B.7 and B.8 for topics a, b, c, and d, e, f, g, h, respectively. Topic (i) yielded no new articles.

(2) Preliminary Candidate Technologies - The preliminary candidate technologies (137) were selected according to the criteria given in Chapter 4 and are presented in Table 4.6.

Table B.7. Search of Aircraft Design, Aircraft Propulsion, and Aircraft Structures.

```
Set Items Description
  1 52062 DESIGN?
  2  8333 SYNTHESI?
  3   153 SIZING
  4  9910 CONFIGURAT?
  5 67520  1-4/OR
  6 26161 AIRCRAFT
  7  2193 AIRPLANE?
  8    33 AEROPLANE?
  9 23605 FLIGHT
 10 44234  6-9/OR
 11  7830  5AND10
 12 11155 OPTIMIZ?
 13  5331 TRADE?
 14 16374  12+13
 15   449  14AND11
 16  1455 FIGHTER?
 17  3097 HEAVY
 18   558 TANKER?
 19 12598 SPACECRAFT
 20  5984 SUPERSONIC
 21  3192 HYPERSONIC
 22     0 YC14
 23     5 YC(W)14
 24    11 MILITARY(W)TRANSPORT
 25     2 MILITARY(W)TRANSPORTS
 26   312 VTOL?
 27    65 RPV?
 28   281 REMOTELY(W)PILOTED
 29     0 HIMAT
 30 11639 MISSIL?
 31   429 VERTICAL(W)TAKE(W)OFF
 32   628 VERTICAL(W)TAKEOFF
 33 37642  16-32/OR
 34   303  15-33
 35  3640 HELICOPTER?
 36    40 HOVERCRAFT
 37   575 SPACE(W)VEHICLE
 38   538 SPACE(W)VEHICLES
 39     4 GROUND(W)EFFECT(W)VEHICLE
 40     3 GROUND(W)EFFECT(W)VEHICLES
 41    16 SURFACE(W)EFFECT(W)VEHICLE
 42    58 SURFACE(W)EFFECT(W)VEHICLES
 43  4827  35-42/OR
 44   283  34-43
 45 16710 AIRCRAFT/DE
 46   145  45*44
 47   138  44-46
```

```
 48   161 TURBOPROP?
 49   396 RECIP?
 50   535 PISTON?
 51   926 TURBOFAN?
 52  1249 PROPELLER?
 53   135 PROPULSIVE
 54     1 PROPELLOR?
 55  3302  48-54/OR
 56 26161 AIRCRAFT
 57  2193 AIRPLANE?
 58    33 AEROPLANE?
 59 23605 FLIGHT
 60 44234  56-59/OR
 61135978 SYSTEM?
 62 97009 ENGINE?
 63  2765 POWER(W)PLANT
 64  8363 POWER(W)PLANTS
 65210253  61-64/OR
 66   955  55AND60AND65
 67 13425 SOLAR?
 68 51428 NUCLEAR?
 69   593 RAMJET
 70 12598 SPACECRAFT
 71   575 SPACE(W)VEHICLE
 72   538 SPACE(W)VEHICLES
 73  1097 TURBOJET?
 74    61 ION(W)ENGINE
 75   399 ION(W)ENGINES
 76   367 SCRAM?
 77     0 SCRAM(W)JET
 78 77841  67-77/OR
 79   788  66-78
 80 61124 MODEL?
 81 24628 SIMULAT?
 82   627  79-(80+81)
 83   506  82-33
 84    11 FUEL(W)PROPERTIES
 85    10  44*83
 86    84  (48+50)*83
 87   206  (48+50+52)*83
 88   122  87-86

Print 44/5/1-283
Print 87/5/1-206

Search Time:  0.140   Prints: 489
```

```
Set Items Description
  1  1885 AIRFRAME?
  2 49696 MATERIAL?
  3  2588 BONDING
  4 15251 COMPOSIT?
  5 60486  2-4/OR
  6 23605 FLIGHT
  7 26161 AIRCRAFT
  8 43598  6+7
  9 45145 STRUCTUR?
 10  1051 FRAME?
 11 45877  9+10
 12   697  11*8*5
 13 61124 MODEL?
 14 24628 SIMULAT?
 15     0 SYNTPH?
 16  8381 SYNTHES?
 17 83794  13-16/OR
 18   625  12-17
 19  5331 TRADE?
 20 13134 OPTIM?
 21    19  18*(19+20)
 22     0 LARGE(W)MILITARY
 23  5984 SUPERSONIC
 24  3192 HYPERSONIC
 25    17  21-(23+24)
 26   582  18-(23+24)
 27     9 LARGE(W)TRANSPORT
 28  3097 HEAVY
 29   579  26-(27+29)
 30 18680 AIRCRAFT/TI,DE
 31 16172 FLIGHT/TI,DE
 32   389  29*(30+31)

Print 32/5/1-275

Search Time:  0.378   Prints: 275
```

Table B.8. Search of Flight Controls, Navigational Aids, Avionics, Canard Configurations, and NAVSTAR/GPS.

```
Set Items Description
  1 26161 AIRCRAFT
  2 23605 FLIGHT
  3    68 STABILITY(W)AUGMENTATION
  4    14 ACTIVE(W)CONTROLS
  5    23 ACTIVE(W)CONTROL
  6 16640 STABILITY
  7  2020 CONTROL(W)SYSTEM
  8 14746 CONTROL(W)SYSTEMS
  9     1 AUTOMATIC(W)PILOT
 10   519 AUTOMATIC(W)PILOTS
 11     7 AUTO(W)PILOT
 12     0 AUTO(W)PILOTS
 13   100 AUTOPILOT?
 14 31673  6-13/OR
 15  6019  (1+2)*14
 16  6052  15+3+4+5
 17    65 RPV?
 18    53 TFR
 19    54 TERRAIN(W)FOLLOWING
 20    76 DATA(W)LINK
 21 12607 SPACECRAFT?
 22   575 SPACE(W)VEHICLE
 23   538 SPACE(W)VEHICLES
 24 13492  17-23/OR
 25  5651  16-24
 26 45145 STRUCTUR?
 27   871 FLUTTER?
 28    13 LOAD(W)ALLEVIATION
 29  5212  25-(26+27+28)
 30    29 V/STOL
 31   312 VTOL
 32  3640 HELICOPTER?
 33  7500 MISSILE
 34  3199 HYPERSONIC?
 35  5990 SUPERSONIC?
 36 19720  30-35/OR
 37  3868  29-36
 38 52062 DESIGN?
 39  8333 SYNTHESI?
 40  5331 TRADE?
 41 13134 OPTIM?
 42 75053  38-41/OR
 43   840  42*37
 44 61124 MODEL?
 45 24628 SIMULAT?
 46  1455 FIGHTER?
 47     2 MILITARY(W)TRANSPORTS
 48  3097 HEAVY
 49    40 HOVERCRAFT?
 50   173 SURFACE(W)EFFECT
 51    11 MILITARY(W)TRANSPORT
 52 79717  44-51/OR
 53   500  43-52
 54  4746 NAVIGATION
 55  4203 POSITION?
 56  7806 AID?
```

```
 57 20912 FACILIT?
 58   369  (1+2)*(54+55)*(56+57)
 59105234  24+36+52
 60   257  58-59
 61     9  53*60
 62  1508 AVIONICS
 63  7918 INSTRUMENTATION
 64  5702 DISPLAY?
 65  2781  (1+2)*(62+63+64)
 66  1482  65-59
 67  7997 WEATHER
 68 49696 MATERIAL?
 69  1330  66-(67+68)
 70     0 AIRCRACFT/DE
 71 14500 FLIGHT/DE
 72 16710 AIRCRAFT/DE
 73  1030  (71+72)*69
 74 76790 TEST?
 75 44699 MEASUR?
 76   669  73-(74+75)
 77     2  76*60*53
 78    43  76*53
 79   554 76-(38+39)
 80  1267  79+60+53
 81 15513 SATELLIT?
 82   165 CANARD
 83     7 CANARDS
 84    80  (82+83)*(1+2)
 85    22  42*84

Print 80/5/1-780
Print 85/5/1-22

Search Time:  0.967   Prints: 802
```

```
Set Items Description
  1     0 GLOBAL(W)POSITIONIG(W)SYSTEM
  2    34 GPS
  3    81 GLOBAL(W)POSITIONING(W)SYSTEM
  4    29 NAVSTAR
  5     9  2*3*4
  6    24  2*3
  7    44  4+6
  8    89  3+4

Print 8/5/1-89

Search Time:  0.112   Prints:  89
```

(3) Final Candidate Technologies - The final candidate technologies (56) were selected according to the criteria given in Chapter 4 and are presented in Table 4.7.

(4) Deleted Technology Discussion - The reasons for deleting technologies from the preliminary candidate technology list in generating the final candidate technology list are now discussed for each deleted technology by area.

I. AERODYNAMICS

- Variable Geometry Winglets
  Deleted because it appears to be more of an idea than a technology. Data are lacking.

- Supercritical airfoils
  Deleted because it is not applicable to the 6-passenger or commuter airplanes. It does appear very promising for high subsonic cruise applications and is currently used on a few airplanes.

II. AIRCRAFT SYSTEMS

- Microwave Anti-Icing
  Deleted because it appears to be an idea rather than a technology. Data are lacking.

- Lithium Hydroxide/Hydrogen Peroxide Batteries
  Research on advanced batteries is on-going, but data are somewhat limited. If the potential of these batteries is realized, they will certainly benefit general aviation airplanes. Unless an electric-powered airplane becomes feasible, impacts may be expected to be minimal.

- Air-Cycle Environmental Systems
  Deleted due to a lack of data. Also, improvements in most environmental systems can be expected to gain acceptance.

- Improved Lead-Acid Batteries
  Lead-acid batteries are an established technology. Improvements in this area can be expected to gain acceptance of their own accord.

- Variable Cycle Environmental Systems
  These systems do not appear to be well suited to general aviation airplanes.

·Accurate Fuel Monitoring and Management
This is a result of the application of various technologies. Improvements in this area do not appear to be cost-effective for most general aviation applications.

·High-Speed Brushless Alternator
This was combined with AC electrical systems due to technology level considerations.

·Single Unit Starter/Generator
Deleted due to technology level considerations. Also, viable developments in this area are expected to gain acceptance of their own accord. Although used on some turbine engines, gearing for reciprocating engines is expected to be heavy.

·Air Bearings
Deleted due to technology level considerations. However, this technology is considered to be the most important of several in order to develop improved turbochargers.

III. COMPUTATIONAL METHODS

This entire group was deleted for two reasons. First, all are second order technologies. Second, with the exception of CADCAM (which appears a long way off for general aviation), general aviation is increasingly using computational methods at present. Specific developments which must be realized are those codes with an ability to handle (1) canards where deformed wakes may be accounted for, (2) 3D analytical methods for advanced low-speed, medium-speed, and natural laminar flow wings, and (3) wing-spoiler-flap configurations.

IV. CRASHWORTHINESS

·Foam-Filled Fuel Tanks
Deleted primarily due to a lack of data.

·Anti-Misting Fuel Treatment.
Deleted primarily due to a lack of data.

·Frangible Fuel Fittings
Current systems are quite expensive. If the costs could be reduced, widespread use could be expected. Note that these fittings are used in the Burst/Tear Resistant Fuel Tanks which are discussed in Section 3.5.4.4.

V. FLIGHT CONTROL SYSTEMS

·Winglets for Lateral-Directional Control
This is an unlikely application of winglets except for canard configurations. Deleted primarily because winglets are included in the aerodynamics technology area.

·Force-Stick Controllers
Deleted due to technology level considerations, and is actually implied in the technologies of fly-by-wire and fly-by-light.

·Digital Automatic Flight Controls
Deleted because these technologies are already filtering into general aviation.

·Stick Shaker/Pusher and Stabilizer/Elevator Spoilers for Stall Prevention
These two technologies were combined into one and are evaluated (Active Stall Prevention).

IV. INFORMATION SYSTEMS

·Flush Antennas
This was deleted due to technology level considerations.

·Single-Function and Time Shared CRT Displays
These were combined into "CRT Displays" and are evaluated.

·Warning Annunciators and Airplane Health/Diagnostic Systems
These were combined into "Systems Status Displays" and are evaluated.

·Total Panel-Mounted Avionics
Deleted because the trend is already towards panel-mounted avionics.

·Active Outside Imaging
While this is possible, it will not be feasible for general aviation airplanes in the foreseeable future.

·Fluidic Shed Vortex Airspeed Sensors
Deleted due to technology level considerations.

·Fluidic Rate Sensors
Deleted due to technology level considerations.

·Multiplexing and ARINC-Type Broadcast Hierarchy
Both were deleted because they represent design philosophies more than technologies. Either is applicable to integrated avionics packages.

·Piezo-Resistive Pressure Transducers
Deleted due to technology level considerations.

- **Liquid Crystal Displays**
  Deleted due to technology level considerations and the fact that non-mechanical displays in the near future will probably be CRT's in most applications. See the discussion of displays in Section 4.5.6.2.

- **Flat Panel CRT Displays**
  Deleted because flat CRT's appear unlikely in general aviation applications in the foreseeable future. See the discussion of displays in Section 4.5.6.2.

- Touch Sensitive CRT
  Deleted due to technology level considerations. This could be a component of a number of advanced avionics systems, and was an integral part of PCAAS.

- Weather Radar and Radar Altimeter
  Deleted because they are already gaining acceptance in general aviation.

- Alternate Weather Detection
  Only one alternate weather detection device (aside from radar) was found and it is currently available (Ryan Stormscope).

- On-Board Computing Capability
  This was deleted because it is an integral part of many other advanced technologies such as integrated avionics and displays, systems management displays, etc.

- 3-Axis Magnetometer Acceleration Sensor
  Deleted due to technology level considerations. See related work discussed in Section 4.5.6.6 and Figure 4.21.

- Improved Stall Warning
  This is more of an idea than a specific technology. Active stall prevention is discussed in Section 4.5.5.14.

VII. MATERIALS/PROCESSES

- All Processes
  These were deleted because they are second order technologies.

- Metal/Metal Bonding
  This technology is already finding substantial acceptance.

- Corrosion Resistant Coatings
  Deleted due to technology level considerations.

- Honeycomb Core/Composite Skin Panels
  Considered as a possible use of all composite materials.

VIII. NAVIGATION CONCEPTS

·VOR/DME RNAV
This technology is already in use.

·Scanning VOR/DME RNAV
This extension of VOR/DME RNAV does not really change the fundamental technology of VOR navigation although it does represent an improvement in more efficient use and automation. Work done at Ames appears in Section 4.5.6.6.

·VLF NAVCOM
Deleted because it is currently available.

·Differential OMEGA
Deleted due to technology considerations. OMEGA is evaluated in Section 4.5.7.6.

·Inertial Smoothing
This concept is not really applicable to general aviation airplanes although inertial navigation is evaluated. Ames has done work in this area for VTOL aircraft.

IX. NOISE

·Noise Absorbing Materials
No breakthroughs were found in this area.

·Improved Mufflers
This is a concept rather than a technology. No specific examples were found.

·Variable Engine/Propeller Gearing
This is a concept rather than a technology. No specific examples were found.

X. PROPULSION

·Advanced Reciprocating Engine
This was divided into the two technologies described as an Advanced Stratified Charge Reciprocating Engine and an Advanced High Compression Ratio Lean Burn Engine. Both are assumed to have variable ignition timing and fuel injection.

·Auto Engine Conversions
This was deleted because it has limited application to general aviation although it is being examined for agricultural airplanes.

- Stratified Charge, Variable Timing, Electronic Ignition, Automatic Mixture Control, Lean Burn Combustion Chamber, Density Compensating Fuel Injection, and Total Microprocessor Engine Control.
  These technologies were either deleted due to technology level considerations or were considered to be included in one or more of the advanced technology engines.

- Cooled Turbine Blades
  This technology is already being pursued.

- Ceramic Turbines
  Deleted due to technology level considerations. Ceramic components are considered a part of certain advanced engines.

- Composite Propellers
  This is included in quiet, efficient propeller technology.

- Torsionally (aeroelastic) Tailored Propeller Blades
  This is more a concept than a technology.

- Single Lever Throttle/Mixture Control
  This has already been developed for general aviation.

- QCGAT Engine and Propfans
  Both of these technologies were deleted because they are not applicable to either the 6-passenger or commuter airplanes. However, both are very promising and are discussed in Section 4.6.

- Variable Bypass Turbofan and Variable Pitch Fan (turbofan)
  Neither one is applicable to the airplanes in question.

- Efficient Propeller Technology
  This was combined with Quiet Propeller Technology.

B.4 PESSIMISTIC, LIKELY, OPTIMISTIC, AND EXPECTED (PLOE) FIGURE OF MERIT STUDIES

The rationale and methodology of the PLOE studies are presented in Chapter 4. The purpose of this appendix is to supply basic documentation for the analysis.

Tables B.9 through B.11 present the actual technology evaluations for pessimistic, likely, and optimistic relative benefits respectively. Figures B.3 and B.4 illustrate the PLOE figures of merit for Airplanes A and B respectively.

When reviewing the evaluations presented here, the reader is reminded that they are used only to test the evaluation technique and do not (in general) correspond to the final technology evaluation as far as the overall ordering of the technologies is concerned. Also, Efficient Propeller Technology and Quiet Propeller Technology are treated separately in the PLOE studies but were combined into a single technology in the final technology evaluation.

Table B.9. Pessimistic Technology Evaluation

```
                                               AIRPLANE A


***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                                CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD      FIG OF
                           CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRK. PRCE RGE  BLTY QLTY SFTY CMFT PERF      MERIT
        CATEGORY WEIGHTS 5.43 6.82 7.92 7.91 1.61 4.34 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.62 6.24 6.87


GATE ENGINE                0.   0.   1.0  1.5  1.0  3.0  0.   2.0  0.   1.0 -1.0  1.0  2.0  1.0  2.0  0.   0.5   102.944
STRT CHG ROT COMB ENGINE   0.   0.   1.0  1.0  2.0  2.0  1.0  1.0  1.0  0.   0.   1.0  1.0  0.   0.5  1.0  0.     74.300
KEVLAR COMPOSITES          0.   0.   1.0  1.5  0.   2.0  0.   2.0  0.   0.  -1.0  2.0  0.   0.   0.   0.   0.     50.840
ADVANCED DIESEL ENGINE     0.   0.   0.   1.0  3.0  0.   1.0  1.0  1.0  0.  -1.0  2.0  0.5  0.   0.5  0.   0.     47.408
QUIET PROP TECHNOLOGY      0.   0.   0.   0.   0.   0.5  3.0  0.   3.0  0.   0.   0.   0.5  0.   0.5  0.   0.     45.280
GRAPHITE COMPOSITES        0.5  0.   1.0  1.5  0.   3.0  0.   2.0  0.   0.  -3.0  2.0  0.   0.   0.   0.   0.     40.865
STRAT CHG RECIP ENGINE     0.   0.   0.   1.0  3.0  0.5  0.   1.0  0.   0.   0.   1.0  0.5  0.   0.5  0.   0.     39.479
HCRLB RECIP ENGINE         0.   0.   0.   1.0  3.0  0.5  0.   1.0  0.   0.   0.   1.0  0.5  0.   0.5  0.   0.     39.479
EFFICIENT PROP TCHNLGY     0.   0.   0.5  0.5  0.   0.5  0.   0.5  0.   0.   0.   0.5  1.0  0.   0.5  0.   1.0    38.247
FIBERGLASS COMPOSITES      0.   0.   1.0  0.5  0.   0.5  0.   1.0  0.   0.   0.5  1.0  0.   0.   0.   0.   0.     33.749
SPOILERS                   0.5  0.   1.0  0.5  0.   0.   0.   0.5  0.   0.  -0.5  0.5  0.   1.0  0.   0.   0.     24.165
IMPROVED TURBOCHARGING     2.0  0.   0.   0.   0.   0.   0.   1.0  0.   0.  -1.5  1.0  0.   0.   0.   0.   1.0    20.406
SEPARATE SFC TECHNOLOGY    0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  0.   0.   0.   0.   1.0  0.   0.     16.771
LIQUID COOLING             0.   0.   0.5  0.   2.0 -1.5  1.0  1.0  1.0  0.  -0.5  0.  -0.5  0.   0.5  0.   0.     16.171
LOAD LIMITING SEATS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -1.0  0.     14.210
NAT LAM FLOW AIRFOILS      0.5  0.   0.5  0.5  0.   0.   0.   1.0  0.   0.  -1.0  0.5  0.   0.   0.   0.   0.     13.916
SYS STATUS DSP             0.   0.   0.  -0.5  0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   1.0  0.   0.     11.652
ACTIVE LAMINAR FLOW CTL    1.5  0.   1.5  1.0  0.  -2.5  0.   3.0  0.   0.  -3.0  3.0 -3.0  0.   0.   0.   0.     11.317
IMPROVED RESTRAINTS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -1.5  0.     11.088
INTEG AVIONICS AND DSPYS   0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -2.0  0.   0.   0.   1.0  0.   0.      7.090
LOW/MEDM SPEED AIRFOILS    0.   0.   0.   0.   0.   0.5  0.   0.5  0.   0.  -1.0  0.   0.   0.   0.   0.   1.0     6.608
```

Table B.9. Pessimistic Technology Evaluation (continued)

FOWLER FLAPS	0.	0.	0.	0.	0.	-0.5	0.	0.5	0.	0.	-0.5	0.	0.	0.5	0.	0.	0.5	4.143
ENERGY ABSORBING FLOOR	0.	0.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.409
SGL LEVER THRUST/DRAG CT	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-0.5	0.	0.	0.	0.	0.	0.	3.092
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.170
INTEG LOW-COST WG LVLER	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-1.5	0.	2.0	0.	0.	1.670
ANTI-ICING SFC COATINGS	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	0.	-1.5	0.	-0.5	0.	3.0	0.	0.	0.990
ACTIVE STALL PREVENTION	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	3.0	0.	0.	-0.345
DATA LINKS	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	1.0	0.	0.	-1.155
LOW-DRAG SFC COATINGS	0.	0.	0.5	0.	0.	-1.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-1.179
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.5	0.	0.	0.	0.	1.0	0.	0.	-1.602
IMPR STLL/SPN--AERO TLRG	0.	0.	-1.0	-0.5	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	1.5	0.	0.	-1.821
BRST/TEAR RESIS FUEL TKS	0.	1.5	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-2.628
LEADING EDGE DEVICES	0.5	0.	1.0	0.	0.	-0.5	0.	0.5	0.	0.	-1.5	0.5	-1.5	1.0	0.	0.	0.	-3.753
NAVSTAR/GPS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.5	-0.5	0.	0.	0.	0.	0.	0.	-4.536
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.5	0.	0.	0.	0.	0.	0.	-5.423
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-1.0	0.	0.	0.	1.0	-1.0	0.	-1.0	0.	0.5	0.	0.5	-6.212
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-8.515
ACT CTLS FOR RLX STBLTY	1.0	0.	1.0	0.	0.	2.0	0.	1.5	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	0.	-10.550
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-2.0	0.5	0.	0.	0.	0.	0.	-11.319
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-1.0	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-11.588
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.5	0.	0.	0.	0.	0.	0.	-12.773
INTEGRATED YAW DAMPER	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.5	0.	-1.5	3.0	0.	0.	0.	-12.842
DUCTED PROPULSORS	0.	0.	-2.0	-1.0	0.	-1.0	3.0	-2.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	1.5	-18.505
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	1.0	0.	-2.0	0.	0.	0.	0.	-21.439
LASER GYROS	0.	0.	0.	-3.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	2.0	0.	0.	0.	0.	-29.385
MICRO HUD	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	1.0	-2.0	0.	-2.0	0.	0.5	0.	0.	-30.584
FIBER OPTICS	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	0.	-31.533
ACT RIDE SM	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-2.0	3.0	0.	0.	0.	-37.169
HUD	0.	0.	0.	-1.5	0.	-1.5	0.	0.	0.	2.0	-3.0	0.	-2.0	0.	1.0	0.	0.	-37.502
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	-1.0	-1.0	0.	-1.0	0.	0.	0.	1.0	-38.247

Table B.9. Pessimistic Technology Evaluation (continued)

DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-2.0	0.	0.5	0.	0.	-51.345
INERTIAL NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-2.0	0.	0.5	0.	0.	-51.345
ACT GUST ALLV	0.	0.	0.	-1.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-2.5	1.0	0.	0.	0.	-53.429
ACT FLUTTER SUPRESSION	0.	0.	0.	-2.5	0.	1.0	0.	0.5	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-63.453
FLY-BY-LIGHT	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-72.259
FLY-BY-WIRE	0.	0.	0.	-2.5	0.	-1.5	0.	0.	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-78.382

Table B.9. Pessimistic Technology Evaluation (continued)

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                                       AIRPLANE B

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                                CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD     FIG OF
                           CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF      MERIT

          CATEGORY WEIGHTS 5.45 7.33 7.48 9.45 2.16 5.66 5.41 8.61 7.45 7.00 7.76 7.18 9.55 7.24 9.56 6.71 7.41


KEVLAR COMPOSITES          0.   0.   1.0  1.5  0.   2.0  0.   2.0  0.   0.   -1.0 2.0  0.   0.   0.   0.   0.       56.784
QUIET PROP TECHNOLOGY      0.   0.   0.   0.   0.   0.5  3.0  0.   3.0  0.   0.   0.   0.5  0.   0.5  0.   0.       50.969
GRAPHITE COMPOSITES        0.5  0.   1.0  1.5  0.   3.0  0.   2.0  0.   0.   -3.0 2.0  0.   0.   0.   0.   0.       49.642
GATE ENGINE                0.   0.   0.   1.0  0.   0.   0.   0.   0.   0.   2.0  0.   1.0  0.   1.0  0.   0.       44.064
EFFICIENT PROP TCHNLGY     0.   0.   0.5  0.5  0.   0.5  0.   0.5  0.   0.   0.   0.5  1.0  0.   0.5  0.   1.0      40.914
FIBERGLASS COMPOSITES      0.   0.   1.0  0.5  0.   0.5  0.   1.0  0.   0.   0.5  1.0  0.   0.   0.   0.   0.       34.702
SPOILERS                   0.5  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.   -0.5 0.5  0.   0.5  0.   0.   0.       18.821
SEPARATE SFC TECHNOLOGY    0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  0.   0.   0.   0.   1.0  0.   0.       16.542
LOW/MEDM SPEED AIRFOILS    0.   0.   0.   0.5  0.   0.5  0.   1.0  0.   0.   -1.0 0.   0.   0.   0.   0.   1.0      15.806
NAT LAM FLOW AIRFOILS      0.5  0.   0.5  0.5  0.   0.   0.   1.0  0.   0.   -1.0 0.5  0.   0.   0.   0.   0.       15.625
LOAD LIMITING SEATS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   -1.0 0.       15.292
IMPROVED RESTRAINTS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   -1.5 0.       11.939
ACTIVE LAMINAR FLOW CTL    1.5  0.   1.5  0.5  0.   -1.5 0.   3.0  0.   0.   -3.0 3.0  -3.0 0.   0.   0.   0.       11.068
SYS STATUS DSP             0.   0.   0.   -0.5 0.   0.   0.   0.   0.   2.0  -1.0 0.   0.   0.   1.0  0.   0.       11.053
INTEG AVIONICS AND DSPYS   0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0  -2.0 0.   0.   0.   1.0  0.   0.        8.018
ENERGY ABSORBING FLOOR     0.   1.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.        7.333
ANTI-ICING SFC COATINGS    0.   0.   0.   0.5  0.   1.0  0.   0.   0.   0.5  0.   0.   1.0  0.   -2.0 0.   0.        6.341
SGL LEVER THRUST/DRAG CT   0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  -0.5 0.   0.   0.   0.   0.   0.        3.117
AC ELECTRICAL SYSTEMS      0.   0.   0.   0.   0.   0.5  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.        2.829
ACTIVE STALL PREVENTION    0.   0.   0.   -1.0 0.   -0.5 0.   0.   0.   1.0  -1.5 0.   -1.0 0.   3.0  0.   0.        2.162
LEADING EDGE DEVICES       0.5  0.   1.0  0.   0.   -0.5 0.   0.5  0.   0.   -1.0 0.5  -1.5 1.0  0.   0.   0.        0.425
```

Table B.9. Pessimistic Technology Evaluation (concluded)

INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.5	0.	0.	0.	0.	1.0	0.	0.	-0.953
INTEG LOW-COST WG LVLER	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-1.5	0.	2.0	0.	0.	-1.277
LOW-DRAG SFC COATINGS	0.	0.	0.5	0.	0.	-1.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-1.785
IMPR STLL/SPN--AERO TLRG	0.	0.	-1.0	-0.5	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	1.5	0.	0.	-2.193
DATA LINKS	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	1.0	0.	0.	-3.219
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.5	0.	0.	0.	0.	0.	0.	-4.664
NAVSTAR/GPS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.5	-0.5	0.	0.	0.	0.	0.	0.	-5.107
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-1.0	0.	0.	0.	1.0	-1.0	0.	-1.0	0.	0.5	0.	0.5	-7.492
ACT CTLS FOR RLX STBLTY	1.0	0.	1.0	0.	0.	2.0	0.	1.5	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	0.	-7.593
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-7.761
BRST/TEAR RESIS FUEL TKS	0.	1.5	0.	0.	0.	-2.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-8.076
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-2.0	0.5	0.	0.	0.	0.	0.	-11.494
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.5	0.	0.	0.	0.	0.	0.	-11.641
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-1.0	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-12.787
DUCTED PROPULSORS	0.	0.	-2.0	-1.0	0.	-1.0	3.0	-2.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	1.5	-14.926
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	1.0	0.	-2.0	0.	0.	0.	0.	-26.441
LASER GYROS	0.	0.	0.	-3.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	2.0	0.	0.	0.	0.	-29.714
FIBER OPTICS	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	0.	-29.747
MICRO HUD	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	1.0	-2.0	0.	-2.0	0.	0.5	0.	0.	-32.297
ACT RIDE SM	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-2.0	3.0	0.	0.	0.	-35.771
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	-1.0	-1.0	0.	-1.0	0.	0.	0.	1.0	-40.613
HUD	0.	0.	0.	-1.5	0.	-1.5	0.	0.	0.	2.0	-3.0	0.	-2.0	0.	1.0	0.	0.	-41.699
ACT GUST ALLV	0.	0.	0.	-1.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-2.5	1.0	0.	0.	0.	-56.089
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-2.0	0.	0.5	0.	0.	-55.166
INERTIAL NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-2.0	0.	0.5	0.	0.	-55.166
ACT FLUTTER SUPRESSION	0.	0.	0.	-2.5	0.	1.0	0.	0.5	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-65.592
FLY-BY-LIGHT	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-75.483
FLY-BY-WIRE	0.	0.	0.	-2.5	0.	-1.5	0.	0.	0.	0.	-3.0	0.	-3.0	0.	0.	0.	0.	-84.037

Table B.10. Likely Technology Evaluation

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                                                        AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                                  CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD    FIG OF
                             CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  QLTY QLTY SFTY CHFT PERF     MERIT
        CATEGORY WEIGHTS     5.43 6.82 7.92 7.91 1.61 4.34 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87

GATE ENGINE                  0.5  0.   2.0  2.0  1.0  3.0  0.   2.0  0.   1.0  0.   1.0  2.0  1.0  2.0  0.   0.5   125.048
STRT CHG ROT COMB ENGINE     0.   0.   1.5  1.0  2.0  2.0  1.0  1.0  1.0  0.   0.   1.0  1.0  0.   0.5  1.0  0.5    81.698
KEVLAR COMPOSITES            0.5  0.   1.0  2.0  0.   2.0  0.   2.0  0.   0.   0.   2.0  0.   0.   0.   0.   0.     66.023
GRAPHITE COMPOSITES          1.0  0.   1.5  2.0  0.   3.0  0.   2.5  0.   0.  -2.0  2.0  0.   0.   0.   0.   0.     64.086
ADVANCED DIESEL ENGINE       0.   0.   0.   1.5  3.0  0.5  1.0  1.5  1.0  0.  -1.0  2.0  1.0  0.   0.5  0.   0.     62.037
SPOILERS                     1.0  0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.   0.   1.0  0.   2.0  0.   0.   0.     61.186
STRAT CHG RECIP ENGINE       0.   0.   0.5  1.5  3.0  0.5  0.   1.5  0.   0.   0.   1.0  1.0  0.   0.5  0.   0.     55.898
MCRLB RECIP ENGINE           0.   0.   0.5  1.5  3.0  0.5  0.   1.5  0.   0.   0.   1.0  1.0  0.   0.5  0.   0.     55.898
QUIET PROP TECHNOLOGY        0.   0.   0.   0.   0.   0.5  3.0  0.   3.0  0.   0.   0.   1.0  0.   0.5  0.   0.     49.707
EFFICIENT PROP TCHNLGY       0.   0.   0.5  0.5  0.   0.5  0.   1.0  0.   0.   0.   1.0  1.0  0.   0.5  0.   1.0    45.970
FIBERGLASS COMPOSITES        0.   0.   1.0  1.0  0.   1.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.     44.130
IMPROVED TURBOCHARGING       3.0  0.   1.0  0.5  0.   0.   0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   1.0    41.968
NAT LAM FLOW AIRFOILS        1.0  0.   1.0  1.5  0.   0.   0.   1.5  0.   0.  -0.5  1.0  0.   0.   0.   0.   0.     40.478
LIQUID COOLING               0.   0.   0.5  1.0  2.0 -1.0  1.0  1.0  1.0  0.   0.   0.5  0.   0.   0.5  0.   0.     38.576
LEADING EDGE DEVICES         1.0  0.   1.0  0.5  0.   0.   0.   1.0  0.   0.  -1.0  1.0 -1.0  1.5  0.5  0.   0.     29.258
LOW/MEDM SPEED AIRFOILS      0.   0.   0.   0.5  0.   1.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   2.0    28.973
FOWLER FLAPS                 0.   0.   0.5  0.5  0.   0.   0.   0.5  0.   0.   0.   0.5  0.   1.0  0.   0.   1.0    28.622
INTEG AVIONICS AND DSPYS     0.   0.   0.   0.5  0.   0.5  0.   0.   0.   2.0 -1.0  0.   0.   0.   1.5  0.   0.     25.439
ACTIVE LAMINAR FLOW CTL      2.0  0.   2.0  1.5  0.  -2.0  0.   3.0  0.   0.  -3.0  3.0 -3.0  0.   0.   0.   0.     24.115
LOAD LIMITING SEATS          0.   3.0  0.   0.   0.   0.5  0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.     19.502
WINGLETS                     1.0  0.   0.   1.0  0.  -1.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.5    17.364
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Table B.10. Likely Technology Evaluation (continued)

SEPARATE SFC TECHNOLOGY	0.	0.	0.	0.	0.	0.5	0.	0.	0.	1.0	0.	0.	0.	0.	1.0	0.	0.	18.941
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.5	-1.0	0.	1.0	0.	0.5	0.	0.	16.073
SYS STATUS DSP	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	0.	0.	1.0	0.	0.	15.605
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	14.210
LOW-DRAG SFC COATINGS	0.	0.	0.5	0.5	0.	-0.5	0.	1.0	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	13.288
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	12.060
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	12.060
INTEG LOW-COST WG LVLER	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	2.0	0.	0.	10.050
ANTI-ICING SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	9.201
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	0.	0.	0.	0.	8.598
DATA LINKS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	1.0	0.	0.	7.225
IMPR STLL/SPN--AERO TLRG	0.	0.	-0.5	-0.5	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	2.0	0.	0.	6.851
ENERGY ABSORBING FLOOR	0.	1.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	5.818
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	0.5	0.	-1.0	0.	0.	0.	0.	1.0	0.	0.	6.151
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	0.	1.0	0.	0.5	5.096
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0	0.	0.5	0.	1.0	-2.0	0.	-1.0	3.0	0.	0.	0.	3.874
ACTIVE STALL PREVENTION	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	3.0	0.	0.	3.608
ACT CTLS FOR RLX STBLTY	1.0	0.	1.0	1.0	0.	2.0	0.	2.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	0.	1.434
BRST/TEAR RESIS FUEL TKS	0.	2.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	0.781
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5	-0.5	0.	0.	0.	0.	0.	0.	-0.583
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5	-1.0	0.	0.	0.	0.	0.	0.	-4.840
LOW-LEVEL PRESSURIZATION	0.	0.	0.	0.	0.	-0.5	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-5.465
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	1.0	0.	-1.0	0.	0.	0.	0.	-6.462
DUCTED PROPULSORS	0.	0.	-2.0	-1.0	0.	-1.0	3.0	-1.5	3.0	0.	-1.0	-1.5	0.	0.	0.5	0.	2.0	-7.344
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.5	-2.0	0.	-1.0	0.	0.5	0.	0.	-14.102
LASER GYROS	0.	0.	0.	-2.0	0.	1.0	0.	0.	0.	0.	-3.0	0.	2.0	0.	0.5	0.	0.	-14.598
FIBER OPTICS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-2.0	0.	0.	0.	0.	0.	0.	-17.030
ACT RIDE SM	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-1.5	3.0	0.	0.	0.	-18.104
HUD	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-22.525
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	-0.5	-1.0	0.	-0.5	0.	0.	0.	1.0	-30.146

Table B.10. Likely Technology Evaluation (continued)

ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	-2.0	1.0	0.	0.	0.	-42.879
DOPPLER NAVIGATION	0.	0.	0	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.5	0.	0.5	0.	0.	-45.918
INERTIAL NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.5	0.	0.5	0.	0.	-45.918
ACT FLUTTER SUPPRESSION	0.	0.	0.	-2.0	0.	1.0	0.	1.0	0.	0.	-3.0	0.	-2.5	0.	0.	0.	0.	-50.995
FLY-BY-LIGHT	0.	0.	0.	-1.5	0.	-0.5	0.	0.	0.	0.	-3.0	0.	-2.0	0.	0.	0.	0.	-57.282
FLY-BY-WIRE	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-2.0	0.	0.	0.	0.	-63.405

Table B.10. Likely Technology Evaluation (continued)

AIRPLANE B

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:

	CEIL	CRSH WTHY	CRUS SPED	DOC	EMIS SION	EMTY WGHT	EXTR NOIS	FUEL EFFC	INTR NOIS	PILT WRKL	PRCH PRCE	RGE	RELI BLTY	RIDE QLTY	SFTY	STAT CMFT	TOLD PERF	FIG OF MERIT
CATEGORY WEIGHTS	5.45	7.33	7.48	9.45	2.16	5.66	5.41	8.61	7.45	7.00	7.76	7.18	9.55	7.24	9.54	6.71	7.41	
GRAPHITE COMPOSITES	1.0	0.	1.5	2.0	0.	3.0	0.	2.5	0.	0.	-2.0	2.0	0.	0.	0.	0.	0.	72.895
KEVLAR COMPOSITES	0.5	0.	1.0	2.0	0.	2.0	0.	2.0	0.	0.	0.	2.0	0.	0.	0.	0.	0.	71.996
QUIET PROP TECHNOLOGY	0.	0.	0.	0.	0.	0.5	3.0	0.	3.0	0.	0.	0.	1.0	0.	0.5	0.	0.	55.742
EFFICIENT PROP TCHNLGY	0.	0.	0.5	0.5	0.	0.5	0.	1.0	0.	0.	0.	1.0	1.0	0.	0.5	0.	1.0	48.807
SPOILERS	1.0	0.	1.0	1.0	0.	0.5	0.	1.0	0.	0.	0.	1.0	0.	1.0	0.	0.	0.	48.232
FIBERGLASS COMPOSITES	0.	0.	1.0	1.0	0.	1.0	0.	1.0	0.	0.	1.0	1.0	0.	0.	0.	0.	0.	46.136
GATE ENGINE	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	2.0	0.	1.0	0.	1.0	0.	0.	44.064
NAT LAM FLOW AIRFOILS	1.0	0.	1.0	1.5	0.	0.	0.	1.5	0.	0.	-0.5	1.0	0.	0.	0.	0.	0.	43.313
LOW/MEDM SPEED AIRFOILS	0.	0.	0.	1.0	0.	1.0	0.	1.5	0.	0.	-1.0	1.0	0.	0.	0.	0.	2.0	42.251
LEADING EDGE DEVICES	1.0	0.	1.0	0.5	0.	0.	0.	1.0	0.	0.	-0.5	1.0	-1.0	1.0	0.5	0.	0.	32.022
INTEG AVIONICS AND DSPYS	0.	0.	0.	0.5	0.	0.5	0.	0.	0.	2.0	-1.0	0.	0.	0.	1.5	0.	0.	28.105
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	1.0	0.	-1.0	0.	3.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	0.	25.085
ANTI-ICING SFC COATINGS	0.	0.	0.	0.5	0.	1.0	0.	0.	0.	0.5	0.5	0.	2.0	0.	-1.5	0.	0.	22.540
LOAD LIMITING SEATS	0.	3.0	0.	0.	0.	0.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	21.476
WINGLETS	1.0	0.	0.	1.0	0.	-1.0	0.	1.0	0.	0.	-1.0	1.0	0.	0.	0.	0.	0.5	20.971
SEPARATE SFC TECHNOLOGY	0.	0.	0.	0.	0.	0.5	0.	0.	0.	1.0	0.	0.	0.	0.	1.0	0.	0.	19.371
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.5	-1.0	0.	1.0	0.	0.5	0.	0.	17.055
SYS STATUS DSP	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	0.	0.	1.0	0.	0.	15.779
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	15.292
LOW-DRAG SFC COATINGS	0.	0.	0.5	0.5	0.	-0.5	0.	1.0	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	13.953
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	11.770

Figure B.10. Likely Technology Evaluation (concluded)

NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	11.770
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	1.0	0.	-1.0	0.	0.	0.	0.	1.0	0.	0.	11.152
ENERGY ABSORBING FLOOR	0.	1.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	11.000
ACTIVE STALL PREVENTION	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-1.0	0.	3.0	0.	0.	10.768
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.5	0.	0.	0.	0.	0.	0.	9.538
INTEG LOW-COST WG LVLER	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	2.0	0.	0.	8.222
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.5	0.	0.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	7.132
IMPR STLL/SPN--AERO TLRG	0.	0.	-0.5	-0.5	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	2.0	0.	0.	6.319
DATA LINKS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	1.0	0.	0.	6.280
ACT CTLS FOR RLX STBLTY	1.0	0.	1.0	1.0	0.	2.0	0.	2.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	0.	6.161
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	0.	1.0	0.	0.5	4.882
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5	-0.5	0.	0.	0.	0.	0.	0.	-0.382
BRST/TEAR RESIS FUEL TKS	0.	2.0	0.	0.	0.	-1.5	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-1.581
DUCTED PROPULSORS	0.	0.	-2.0	-1.0	0.	-1.0	3.0	-1.5	3.0	0.	-1.0	-1.5	0.	0.	0.5	0.	2.0	-3.329
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.5	-1.0	0.	0.	0.	0.	0.	0.	-4.262
LOW-LEVEL PRESSURIZATION	0.	0.	0.	0.	0.	-0.5	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-5.233
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	1.0	0.	-1.0	0.	0.	0.	0.	-9.340
LASER GYROS	0.	0.	0.	-2.0	0.	1.0	0.	0.	0.	0.	-3.0	0.	2.0	0.	0.5	0.	0.	-12.662
FIBER OPTICS	0.	0.	0.	0.	0.	0.5	0.	0.	0.	0.	-2.0	0.	0.	0.	0.	0.	0.	-12.693
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.5	-2.0	0.	-1.0	0.	0.5	0.	0.	-14.525
ACT RIDE SM	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-1.5	3.0	0.	0.	0.	-15.683
HUD	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-2.5	0.	-1.0	0.	1.0	0.	0.	-20.598
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	-0.5	-1.0	0.	-0.5	0.	0.	0.	1.0	-32.341
ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	-2.0	1.0	0.	0.	0.	-41.761
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.5	0.	0.5	0.	0.	-50.392
INERTIAL NAVIGATION	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.5	0.	0.5	0.	0.	-50.392
ACT FLUTTER SUPPRESSION	0.	0.	0.	-2.0	0.	1.0	0.	1.0	0.	0.	-3.0	0.	-2.5	0.	0.	0.	0.	-51.789
FLY-BY-LIGHT	0.	0.	0.	-1.5	0.	-0.5	0.	0.	0.	0.	-2.5	0.	-2.0	0.	0.	0.	0.	-55.502
FLY-BY-WIRE	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-2.5	0.	-2.0	0.	0.	0.	0.	-63.056

Table B.11. Optimistic Technology Evaluation

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                                  AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                               CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD      FIG OF
                          CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF       MERIT
       CATEGORY WEIGHTS   5.43 6.82 7.92 7.91 1.61 4.34 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87

GATE ENGINE               1.0  0.   2.0  2.0  1.0  3.0  0.   2.0  0.   1.0  1.0  1.0  2.0  1.0  2.0  0.   1.0   140.715
SPOILERS                  1.5  0.   2.0  2.0  0.   1.5  0.   2.0  0.   0.   1.0  1.5  0.   3.0  0.   0.   0.    100.404
STRT CMG ROT COMB ENGINE  0.   0.   1.5  2.0  2.0  2.0  1.0  1.0  1.0  0.   1.0  1.0  1.0  0.   0.5  1.0  0.5    98.119
KEVLAR COMPOSITES         0.5  0.   1.5  2.0  0.   2.0  0.   2.0  0.   0.   1.0  2.0  0.   0.   0.   0.   0.     78.498
ADVANCED DIESEL ENGINE    0.   0.   0.   2.0  3.0  1.0  1.0  2.0  1.0  0.  -1.0  2.0  1.5  0.   0.5  0.   0.     76.665
GRAPHITE COMPOSITES       1.5  0.   2.0  2.0  0.   3.0  0.   3.0  0.   0.  -2.0  2.0  0.   0.   0.   0.   0.     74.848
STRAT CMG RECIP ENGINE    0.   0.   1.0  1.5  3.0  1.0  0.   2.0  0.   0.   0.   1.0  1.5  0.   0.5  0.   0.     70.535
MCRLD RECIP ENGINE        0.   0.   1.0  1.5  3.0  1.0  0.   2.0  0.   0.   0.   1.0  1.5  0.   0.5  0.   0.     70.535
LIQUID COOLING            0.   0.   0.5  1.5  2.0  0.   1.0  1.0  1.0  0.   0.5  1.0  0.5  0.   0.5  0.   0.     59.199
NAT LAM FLOW AIRFOILS     1.5  0.   1.0  2.0  0.   0.   0.   2.0  0.   0.   0.   1.5  0.   0.   0.   0.   0.     59.127
LEADING EDGE DEVICES      1.5  0.   1.0  1.0  0.   0.5  0.   1.0  0.   0.  -0.5  1.5 -0.5  2.0  1.0  0.   0.     58.191
EFFICIENT PROP TCHNLGY    0.   0.   0.5  1.0  0.   0.5  0.   1.5  0.   0.   0.   1.5  1.0  0.   0.5  0.   1.0    57.647
QUIET PROP TECHNOLOGY     0.   0.   0.   0.   0.   1.0  3.0  0.   3.0  0.   0.   0.   1.5  0.   0.5  0.   0.     56.304
INTEG AVIONICS AND DSPYS  0.   0.   0.   1.0  0.   0.5  0.   0.   0.   3.0  0.   0.   0.5  0.   2.0  0.   0.     55.394
FIBERGLASS COMPOSITES     0.   0.   1.0  1.5  0.   1.5  0.   1.0  0.   0.   1.5  1.0  0.   0.   0.   0.   0.     54.518
IMPROVED TURBOCHARGING    3.0  0.   1.5  1.0  0.   0.   0.   1.0  0.   0.  -0.5  1.0  0.   0.   0.   0.   1.0    54.139
WINGLETS                  2.0  0.   0.   1.5  0.  -0.5  0.   2.0  0.   0.  -0.5  2.0  0.   0.   0.   0.   1.0    54.057
FOWLER FLAPS              0.5  0.   1.0  1.0  0.   0.5  0.   1.0  0.   0.   0.5  0.5  0.   1.0  0.   0.   1.0    49.756
LOW/MEDM SPEED AIRFOILS   0.   0.   0.   1.0  0.   1.0  0.   1.5  0.   0.   0.   1.0  0.   0.   0.   0.   2.0    45.519
ACTIVE LAMINAR FLOW CTL   2.5  0.   2.5  2.0  0.  -1.5  0.   3.0  0.   0.  -3.0  3.0 -3.0  0.   0.   0.   0.     36.913
LOW-DRAG SFC COATINGS     0.   0.   1.0  1.0  0.  -0.5  0.   1.5  0.   0.  -0.5  1.0  0.   0.   0.   0.   0.     28.926
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Table B.11. Optimistic Technology Evaluation (continued)

CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-0.5	0.	1.0	0.	1.0	0.	0.	28.717
LOAD LIMITING SEATS	0.	3.0	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	24.796
SYS STATUS DSP	0.	0.	0.	0.5	0.	0.	0.	0.	0.	2.0	-1.0	0.	0.5	0.	1.0	0.	0.	23.985
ACT CTLS FOR RLX STBLTY	1.0	0.	1.0	2.0	0.	2.0	0.	2.5	0.	0.	-3.0	1.0	-2.0	0.	0.	0.	0.	22.273
SEPARATE SFC TECHNOLOGY	0.	0.	0.	0.	0.	1.0	0.	0.	0.	1.0	0.	0.	0.	0.	1.0	0.	0.	21.111
NAVSTAR/GPS	0.	0.	0.	0.5	0.	0.	0.	0.	0.	1.0	0.5	0.	0.	0.	0.5	0.	0.	20.271
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	2.0	0.	0.	18.430
ANTI-ICING SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	3.0	0.	0.	17.885
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	17.332
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	1.0	0.	0.	16.771
INTEGRATED YAW DAMPER	0.	0.	0.	0.5	0.	0.	0.	0.5	0.	1.0	-1.5	0.	-0.5	3.0	0.	0.	0.	16.511
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	-0.5	0.	0.	0.	-0.5	0.	0.5	0.	0.	0.	0.	2.0	0.	0.	14.487
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	1.0	0.	-0.5	0.	0.	0.	0.	1.0	0.	0.	13.904
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	12.855
ACTIVE STALL PREVENTION	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-1.0	0.	3.0	0.	0.	12.123
DATA LINKS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	1.0	0.	0.	11.178
ENERGY ABSORBING FLOOR	0.	1.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	13.227
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	9.769
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.5	9.523
DUCTED PROPULSORS	0.	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-1.0	0.	0.	0.5	0.	2.0	8.301
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-0.5	0.	0.	0.	0.	0.	0.	3.092
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	0.	0.	0.	-1.166
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	1.0	0.	-0.5	0.	0.	0.	0.	-2.035
LOW-LEVEL PRESSURIZATION	0.	0.	0.	0.	0.	0.	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.295
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	1.0	0.	0.	-5.717
FIBER OPTICS	0.	0.	0.	0.5	0.	0.5	0.	0.	0.	0.	-2.0	0.	0.5	0.	0.	0.	0.	-6.480
LASER GYROS	0.	0.	0.	-2.0	0.	1.5	0.	0.	0.	0.	-3.0	0.	2.0	0.	1.0	0.	0.	-7.717
HUD	0.	0.	0.	-0.5	0.	-1.0	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	1.0	0.	0.	-10.057
ACT RIDE SM	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-1.0	3.0	0.	0.	0.	-13.677
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-1.0	0.	-0.5	0.	0.	0.	1.0	-26.471

Table B.11. Optimistic Technology Evaluation (continued)

ACT FLUTTER SUPPRESSION	0.	0.	0.	-1.0	0.	2.0	0.	1.5	0.	0.	-3.0	0.	-2.0	0.	0.	0.	0.	-30.243
ACT GUST ALLV	0.	0.	0.	-0.5	0.	1.0	0.	0.	0.	0.	-3.0	0.	-1.5	1.0	0.	0.	0.	-32.329
DOPPLER NAVIGATION	0.	0.	0.	-1.5	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.5	0.	0.	-38.538
INERTIAL NAVIGATION	0.	0.	0.	-1.5	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.5	0.	0.	-38.538
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-42.305
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-44.475

Table B.11. Optimistic Technology Evaluation (continued)

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                                                  AIRPLANE B

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                               CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT MRCH      RELI RIDE      STAT TOLD     FIG OF
                          CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF      MERIT
       CATEGORY WEIGHTS   5.45 7.33 7.48 9.45 2.16 5.66 5.41 8.61 7.45 7.00 7.76 7.18 9.55 7.24 9.54 6.71 7.61


GRAPHITE COMPOSITES       1.5  0.   2.0  2.0  0.   3.0  0.   3.0  0.   0.  -2.0  2.0  0.   0.   0.   0.   0.      83.652
KEVLAR COMPOSITES         0.5  0.   1.5  2.0  0.   2.0  0.   2.0  0.   0.   1.0  2.0  0.   0.   0.   0.   0.      83.495
SPOILERS                  1.5  0.   1.5  1.5  0.   1.0  0.   1.5  0.   0.   1.0  1.5  0.   1.5  0.   0.   0.      81.523
QUIET PROP TECHNOLOGY     0.   0.   0.   0.   0.   1.0  3.0  0.   3.0  0.   0.   0.   1.5  0.   0.5  0.   0.      63.344
NAT LAM FLOW AIRFOILS     1.5  0.   1.0  2.0  0.   0.   0.   2.0  0.   0.   0.   1.5  0.   0.   0.   0.   0.      62.536
EFFICIENT PROP TCHNLGY    0.   0.   0.5  1.0  0.   0.5  0.   1.5  0.   0.   0.   1.5  1.0  0.   0.5  0.   1.0     61.426
LEADING EDGE DEVICES      1.5  0.   1.0  1.0  0.   0.5  0.   1.0  0.   0.   0.   1.5 -0.5  1.0  1.0  0.   0.      59.316
LOW/MEDM SPEED AIRFOILS   0.   0.   0.   1.5  0.   1.0  0.   2.0  0.   0.   0.   1.0  0.   0.   0.   0.   2.0     59.041
FIBERGLASS COMPOSITES     0.   0.   1.0  1.5  0.   1.5  0.   1.0  0.   0.   1.5  1.0  0.   0.   0.   0.   0.      57.571
WINGLETS                  2.0  0.   0.   1.5  0.  -0.5  0.   2.0  0.   0.  -0.5  2.0  0.   0.   0.   0.   1.0     57.343
INTEG AVIONICS AND DSPYS  0.   0.   0.   1.0  0.   0.5  0.   0.   0.   3.0  0.   0.   0.5  0.   2.0  0.   0.      57.135
GATE ENGINE               0.   0.   0.   1.0  0.   0.   0.   0.   0.   0.   2.0  0.   1.0  0.   1.0  0.   0.      44.064
ACTIVF LAMINAR FLOW CTL   2.5  0.   2.5  1.5  0.  -0.5  0.   3.0  0.   0.  -3.0  3.0 -3.0  0.   0.   0.   0.      39.183
ANTI-ICING SFC COATINGS   0.   0.   0.   0.5  0.   1.0  0.   0.   0.   1.0  0.5  0.   2.0  0.  -1.0  0.   0.      30.811
LOW-DRAG SFC COATINGS     0.   0.   1.0  1.0  0.  -0.5  0.   1.5  0.   0.  -0.5  1.0  0.   0.   0.   0.   0.      30.312
ACT CTLS FOR RLX STBLTY   1.0  0.   1.0  2.0  0.   2.0  0.   2.5  0.   0.  -3.0  1.0 -2.0  0.   0.   0.   0.      29.462
CRT DISPLAYS              0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -0.5  0.   1.0  0.   1.0  0.   0.      29.206
LOAD LIMITING SEATS       0.   3.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.      27.656
SYS STATUS DSP            0.   0.   0.   0.5  0.   0.   0.   0.   0.   2.0 -1.0  0.   0.5  0.   1.0  0.   0.      25.278
SEPARATE SFC TECHNOLOGY   0.   0.   0.   0.   0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   1.0  0.   0.      22.199
NAVSTAR/GPS               0.   0.   0.   0.5  0.   0.   0.   0.   0.   1.0  0.5  0.   0.   0.   0.5  0.   0.      20.376
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Table B.11. Optimistic Technology Evaluation (concluded)

MICROWAVE LANDING SYSTEM	0.	0.	0.	0.	0.	0.	0.	1.5	0.	-0.5	0.	0.	0.	0.	1.0	0.	0.	18.854
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	18.646
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	2.0	0.	0.	17.721
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	.0	0.	0.	0.	0.	1.0	0.	0.	16.542
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	1.5	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	16.247
ENERGY ABSORBING FLOOR	0.	2.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	16.666
ACTIVE STALL PREVENTION	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	1.0	-0.5	0.	-1.0	0.	3.0	0.	0.	16.648
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	-0.5	0.	0.	0.	-0.5	0.	0.5	0.	0.	0.	0.	2.0	0.	0.	13.558
DUCTED PROPUL ORS	0.	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-1.0	0.	0.	0.5	0.	2.0	12.045
DATA LINKS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-0.5	0.	1.0	0.	0.	11.005
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	1.0	0.	0.5	0.	0.	0.	0.	0.	0.	0.	0.	0.	9.960
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.5	9.656
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	8.581
LORAN C	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-0.5	0.	0.	0.	0.	0.	0.	3.117
FIBER OPTICS	0.	0.	0.	0.5	0.	1.0	0.	0.	0.	0.	-2.0	0.	0.5	0.	0.	0.	0.	-0.366
OMEGA	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	0.	0.	0.	-0.763
LOW-LEVEL PRESSURIZATION	0.	0.	0.	0.	0.	0.	0.	0.	2.0	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-2.404
FLUIDIC AUTO FLT CTL SYS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	1.0	0.	-0.5	0.	0.	0.	0.	-4.567
LASER GYROS	0.	0.	0.	-2.0	0.	1.5	0.	0.	0.	0.	-3.0	0.	2.0	0.	1.0	0.	0.	-5.061
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	1.0	0.	0.	-6.255
ACT RIDE SM	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-1.0	3.0	0.	0.	0.	-10.909
HUD	0.	0.	0.	-0.5	0.	-1.0	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	1.0	0.	0.	-11.912
ACT FLUTTER SUPPRESSION	0.	0.	0.	-1.0	0.	2.0	0.	1.5	0.	0.	-3.0	0.	-2.0	0.	0.	0.	0.	-27.605
DIRECT SIDE FORCE CTL	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-1.0	0.	-0.5	0.	0.	0.	1.0	-28.842
ACT GUST ALLV	0.	0.	0.	-0.5	0.	1.0	0.	0.	0.	0.	-3.0	0.	-1.5	1.0	0.	0.	0.	-29.434
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-34.520
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-0.5	0.	0.	0.	0.	-2.0	0.	-1.0	0.	0.	0.	0.	-37.369
DOPPLER NAVIGATION	0.	0.	0.	-1.5	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.5	0.	0.	-40.894
INERTIAL NAVIGATION	0.	0.	0.	-1.5	0.	-1.0	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.5	0.	0.	-40.894

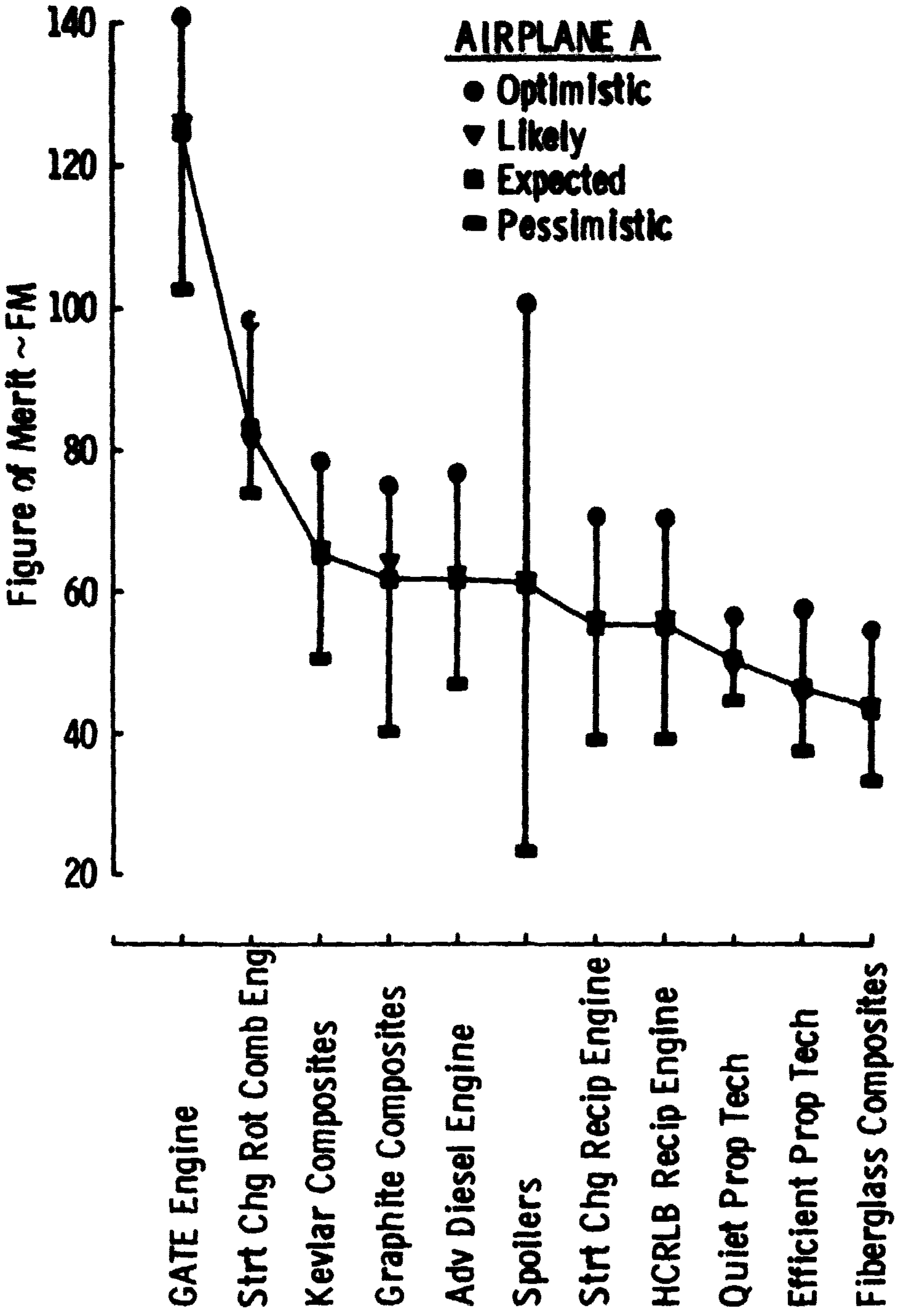

Fig. B.3. Airplane A PLOE Figure of Merit Comparisons

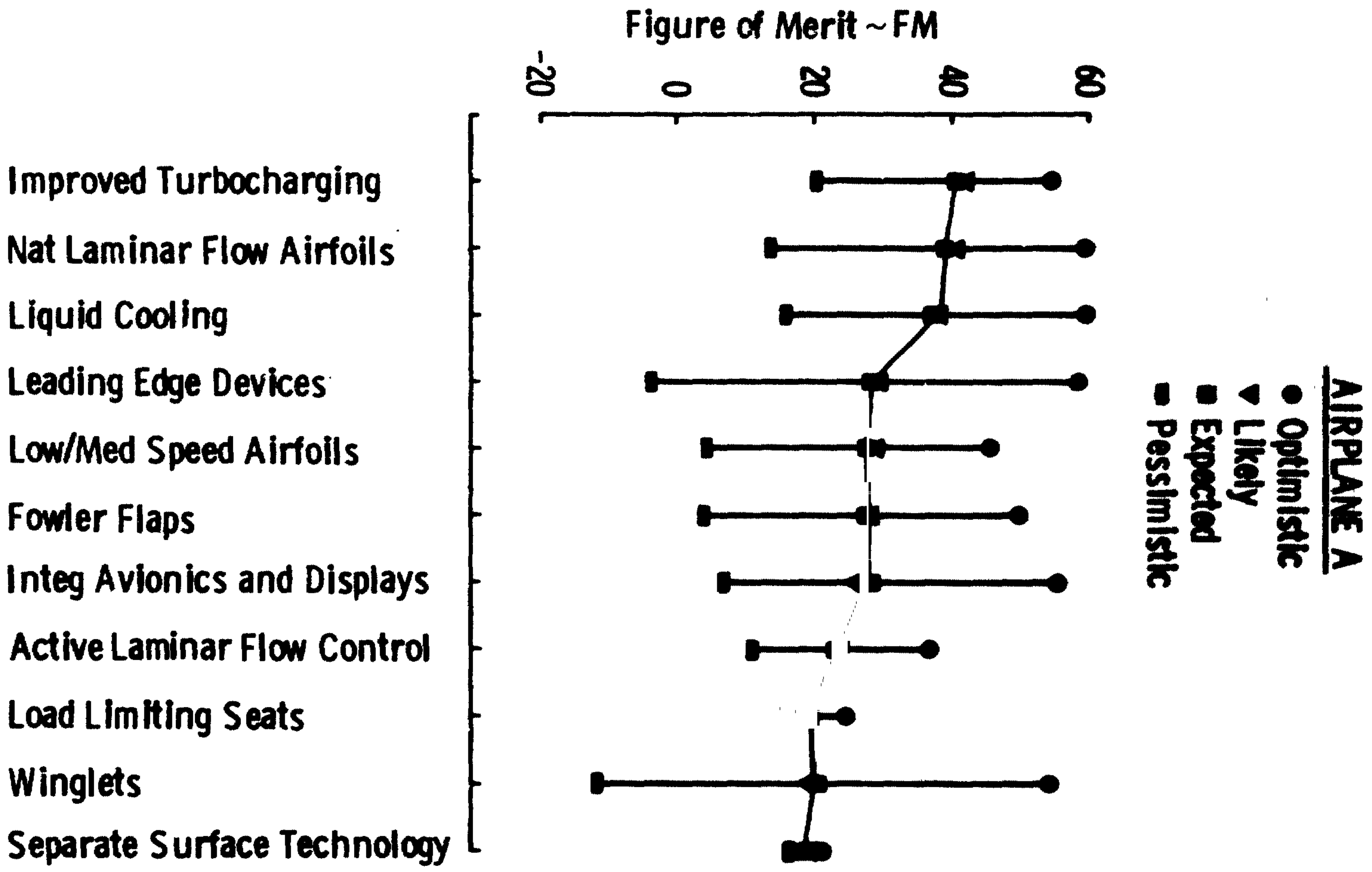

Fig. B.3. Airplane A PLOE Figure of Merit Comparisons (continued)

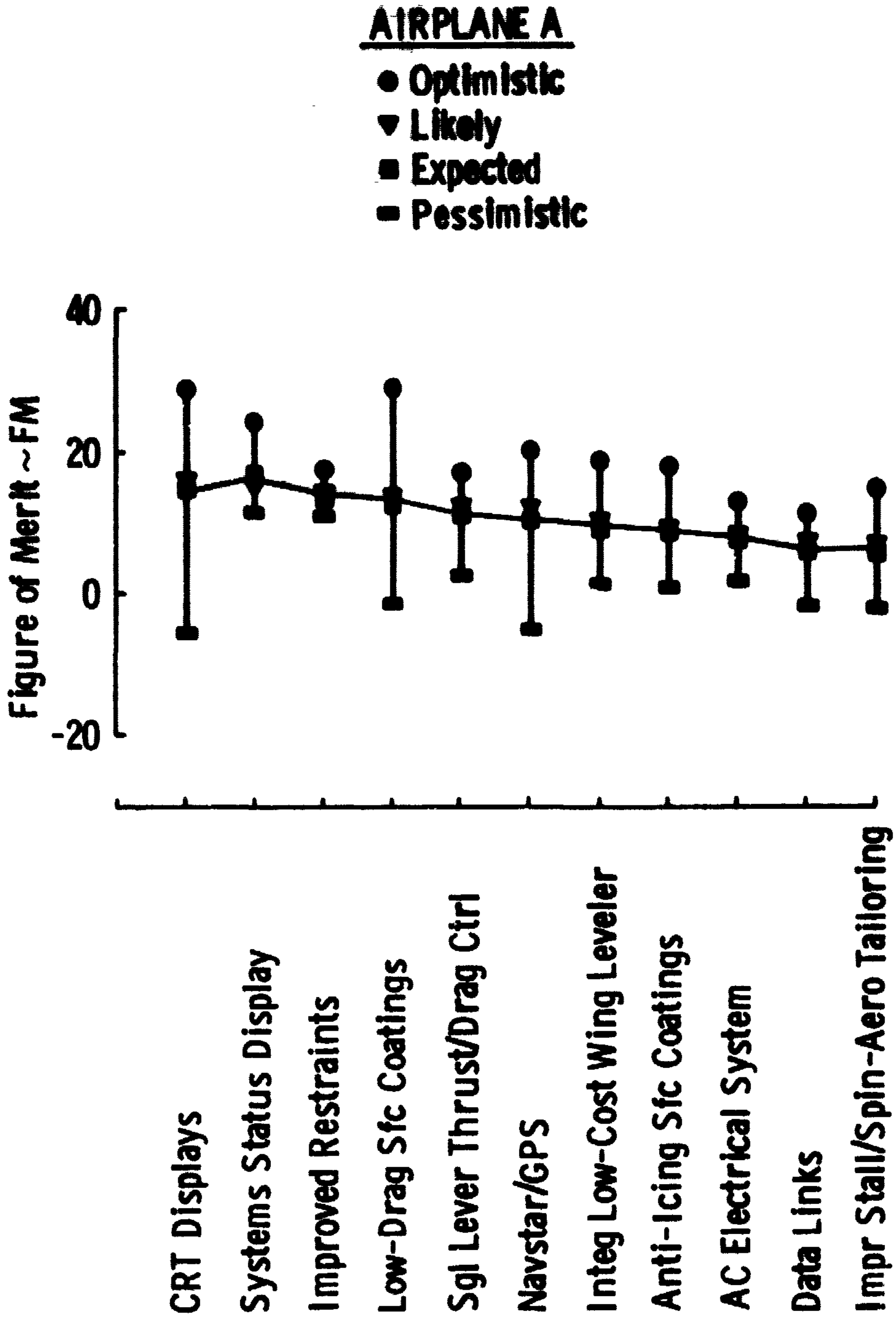

Fig. B.3. Airplane A PLOE Figure of Merit Comparisons (continued)

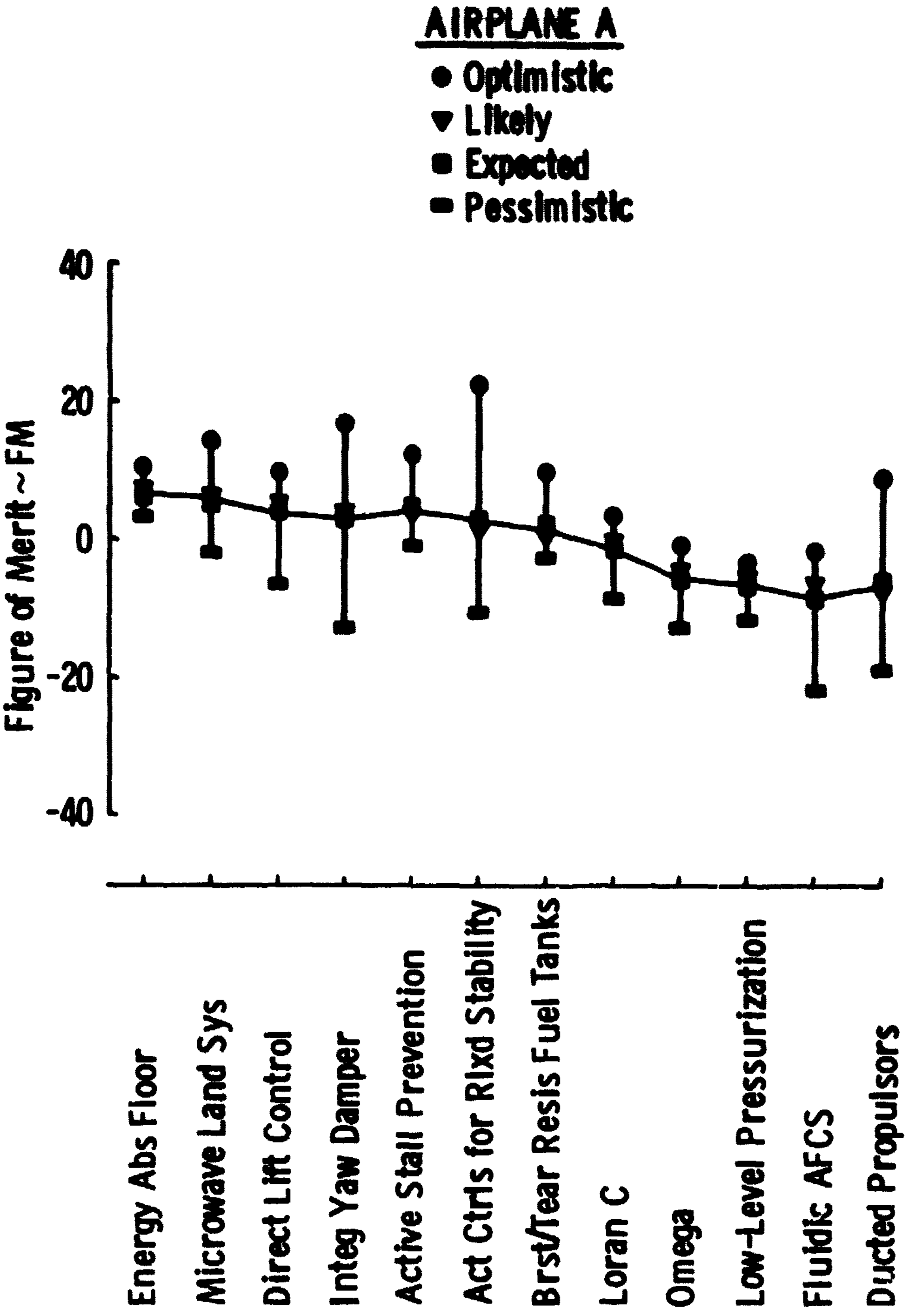

Fig. B.3. Airplane A PLOE Figure of Merit Comparisons (continued)

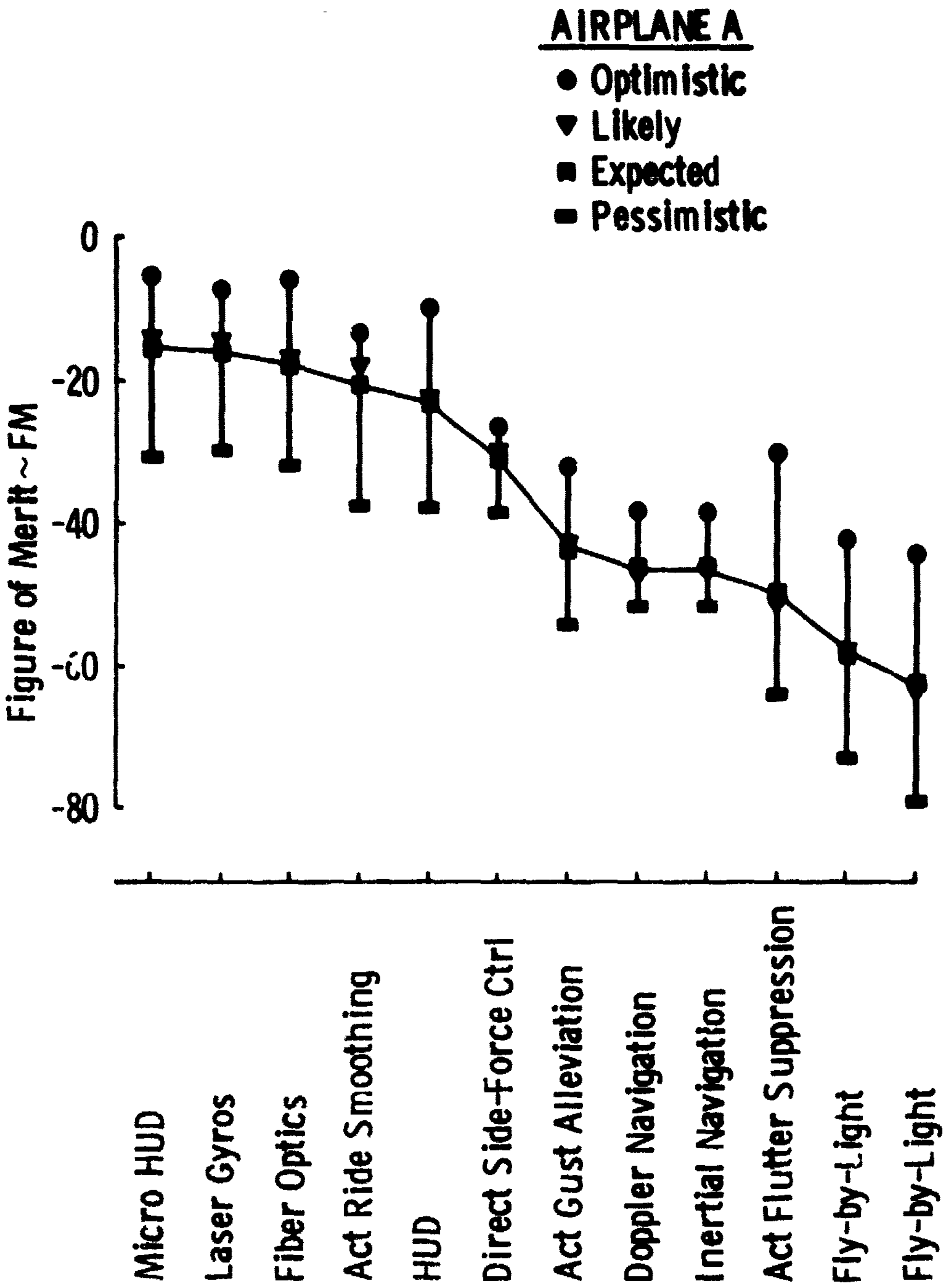

Fig. B.3. Airplane A PLOE Figure of Merit Comparisons (concluded)

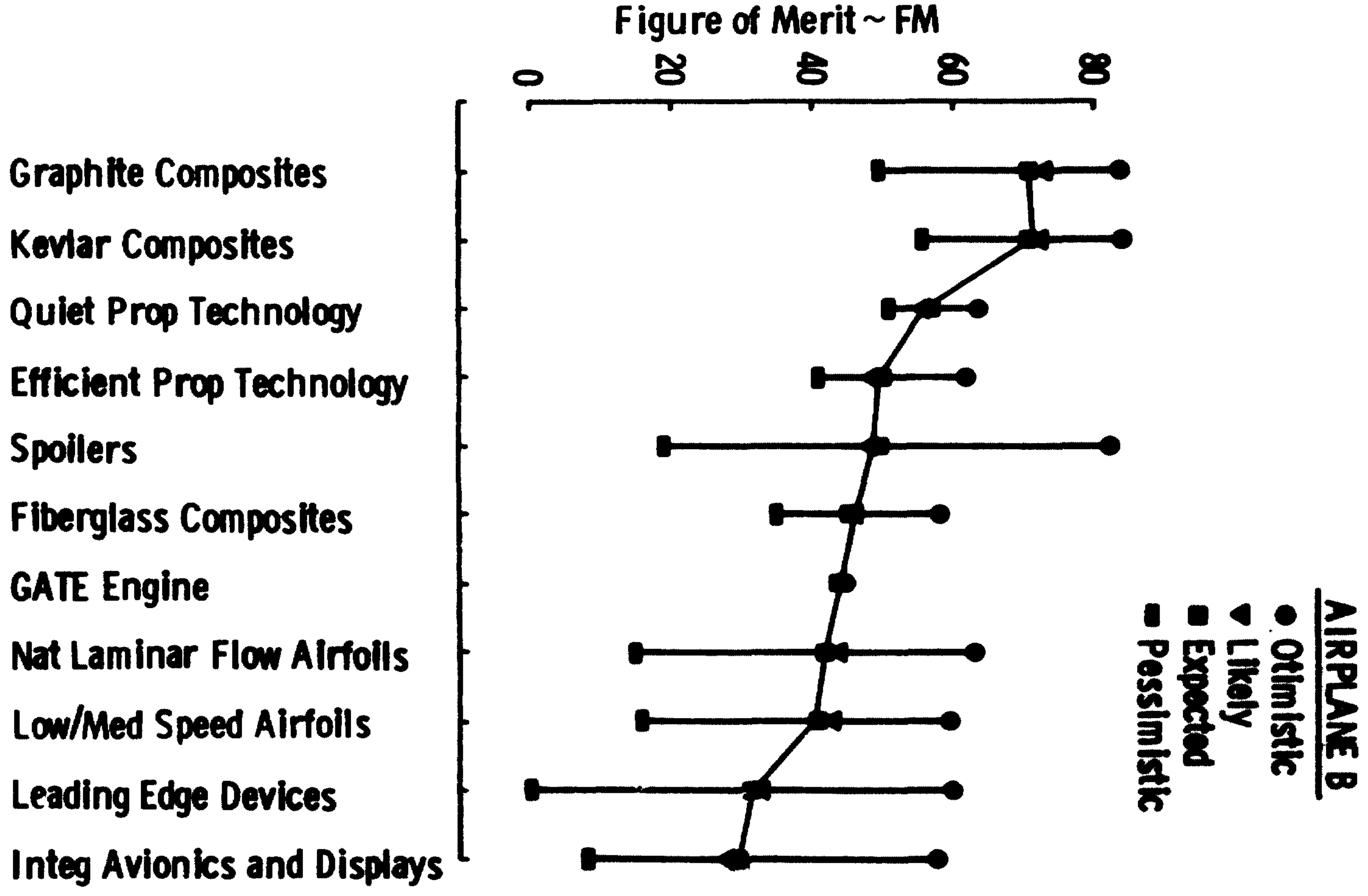

Fig. B.4. Airplane B PLOE Figure of Merit Comparisons

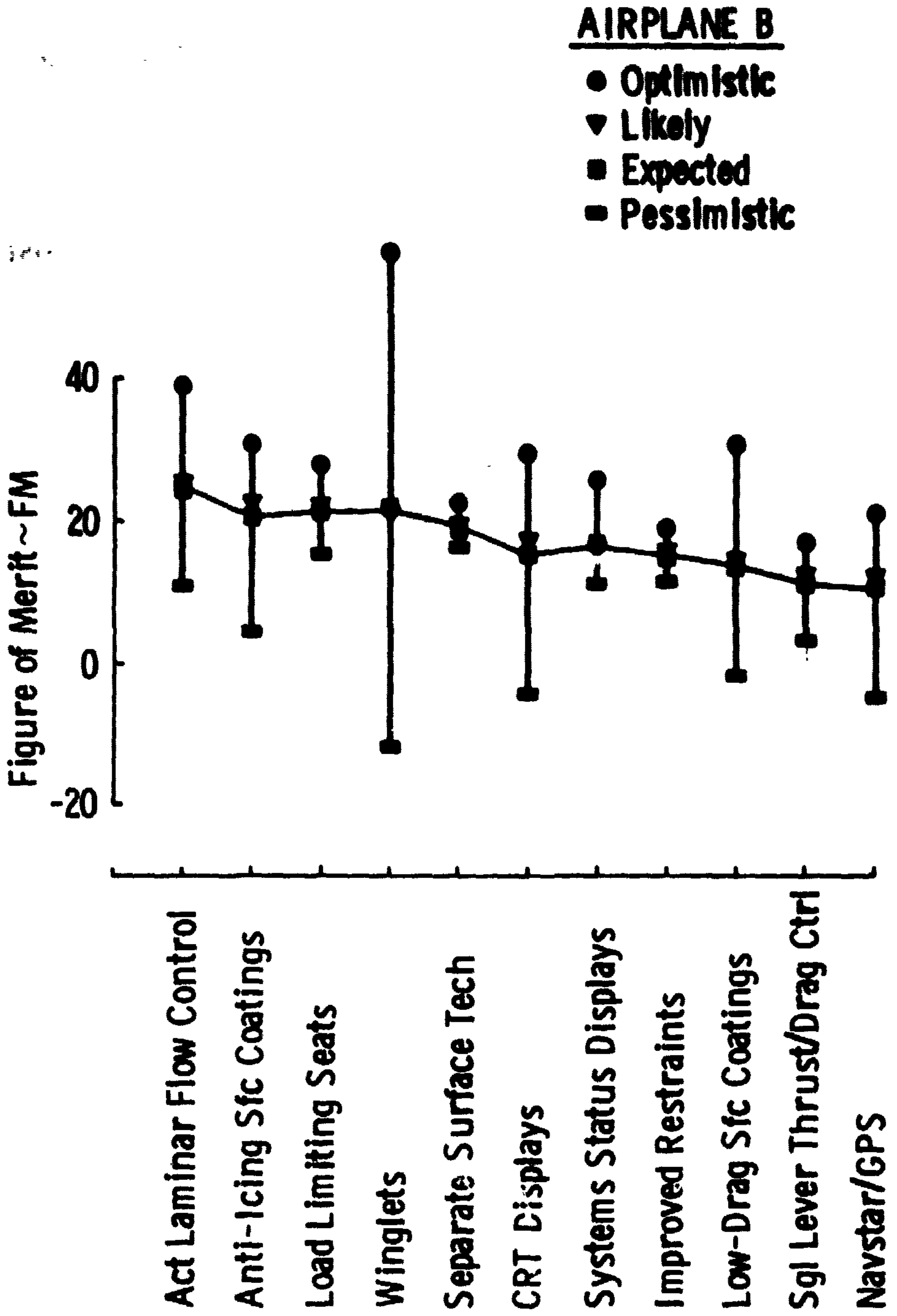

Fig. B.4. Airplane B PLOE Figure of Merit Comparisons (continued)

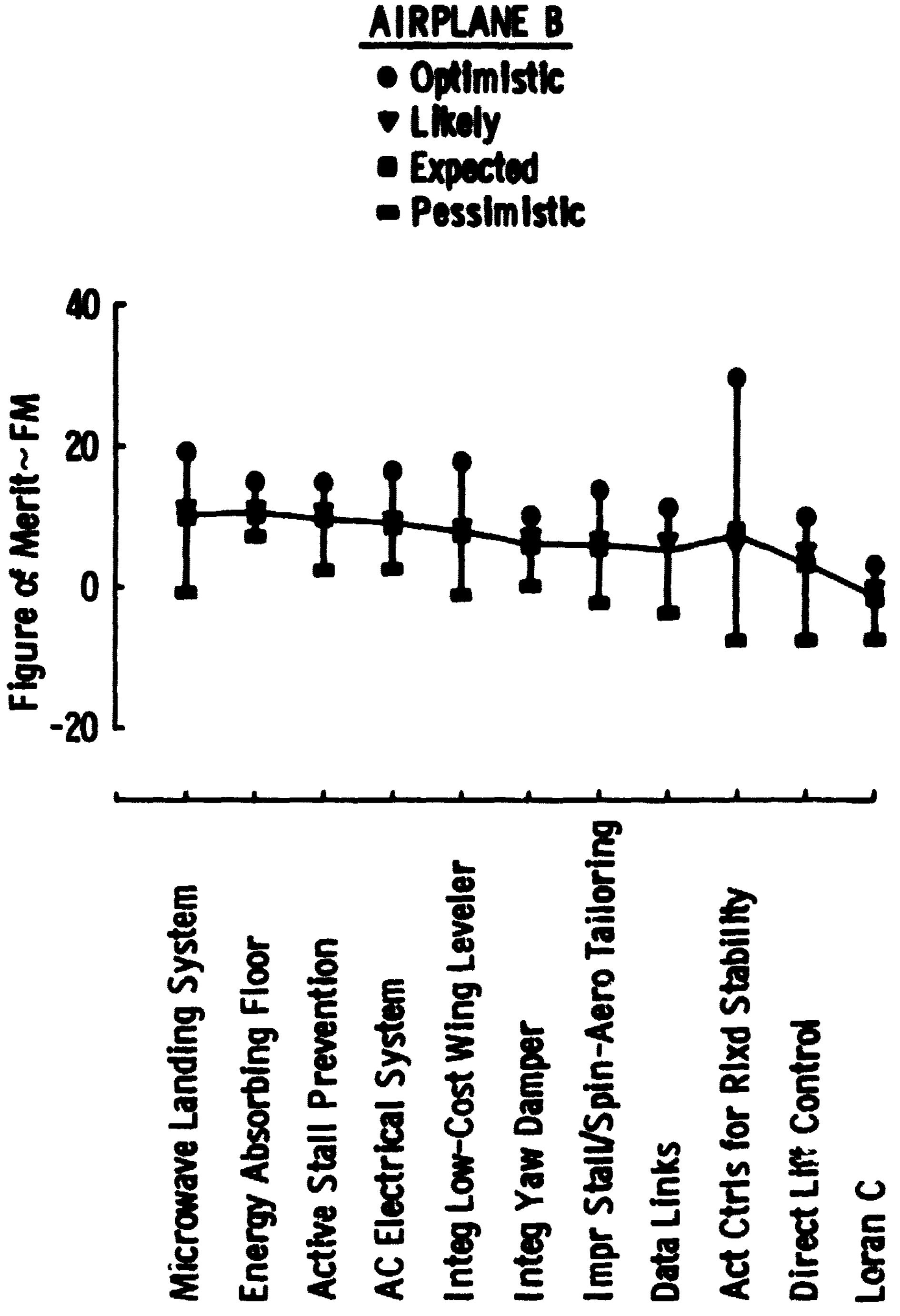

Fig. B.4. Airplane B PLOE Figure of Merit Comparisons (continued)

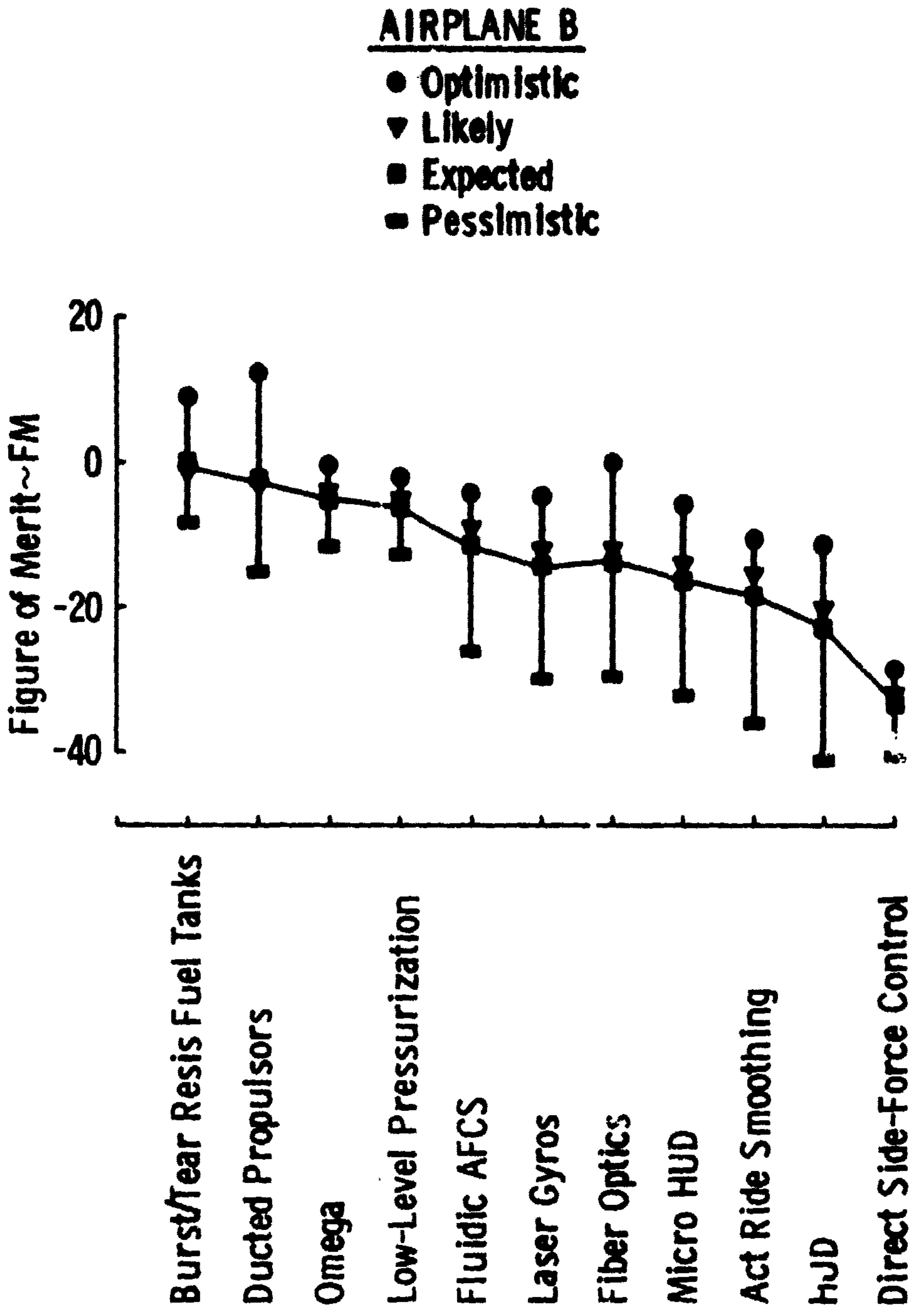

Fig. B.4. Airplane B PLOE Figure of Merit Comparisons (continued)

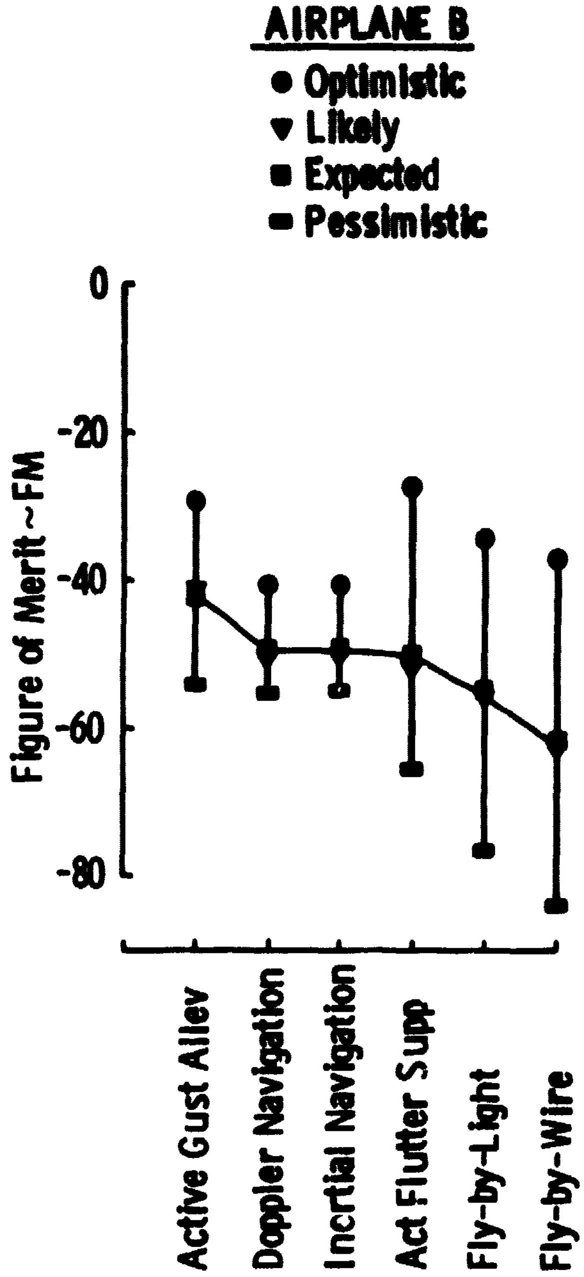

Fig. B.4. Airplane B PLOE Figure of Merit Comparisons (concluded)

B.5 TABULAR RESULTS OF THE TECHNOLOGY EVALUATION WITH AN EXAMINATION OF THE EFFECT OF EMPTY WEIGHT

This section contains computer output from Program TCHLST and represents three different sets of category rating data for Airplane A and Airplane B. In all cases, the matrix of relative benefits for both airplanes was kept constant.

These data examine the effects of perturbations to the Empty Weight category because this category was awarded unusually low weightings by the respondents to Survey 2. This was cause for concern to the present research effort because empty weight is directly related to payload and, for a given takeoff gross weight, technologies which reduce empty weight will ultimately increase payload if fuel capacity is maintained. As a result, Payload was specifically eliminated as a category during Survey 1 because it overlapped almost completely with Empty Weight. At the conclusion of Survey 2, however, Empty Weight had an average weighting of 4.340 for Airplane A and was ranked 15th of 17 categories. Airplane B likewise had an average weighting of 5.657 and here the category was ranked 14th of 17 categories. Evaluation ratings varied from 0.0 to 9.5 for both airplanes. However, although the category showed some convergence to its mean for Airplane A, there was no apparent agreement on the weighting for Airplane B, and scores appeared to be distributed uniformly as shown in the histograms of Appendix B.2. Consequently, results from average category weightings as well as those resulting when Empty Weight was rated 9.5 and 0.0 are included.

B.5.1 Average Category Weights

Four tables are presented where the average category weights as generated by Survey 2 are utilized. Table B.12 shows relative benefits and technology rankings by figures of merit within technology groups for Airplane A. These figures of merit are those shown in the tables of Section 4.5. Table B.13 is a duplicate of Table 4.10 for Airplane A and shows overall technology rankings for this airplane. Table B.14 shows relative benefits and technology rankings by figures of merit within technology groups for Airplane B. These data were also reflected in the tables of Section 4.5 Finally, Table B.15 is a duplicate of Table 4.11 for Airplane B and shows the overall technology rankings. These four figures are included here to illustrate data output by technology group with relative benefits shown (Tables B.12 and B.14) and to form a baseline against which to compare the overall technology rankings of the next two sections.

B.5.2 Maximum Category Weight For Empty Weight

Here, the maximum Empty Weight rating (9.5) is used for both airplanes as shown in Tables B.16 and B.17. When Table B.16 is compared with B.13 for Airplane A, it can be seen that the effect of increasing the significance of Empty Weight is to increase the range of figures of merit, while the relative rankings remain almost constant. Likewise, the same trend is noted for Airplane B when Tables B.17 and B.15 are compared. The significant points to be noted in these comparisons are that:

(1) those technologies which improve empty weight also improve several other measurements when integrated into an airplane and hence are already ranked at the top of the overall technology list for both airplanes (first 8 for Airplane A and first 3 for Airplane B).

(2) the effect of increasing the Empty Weight rating serves to make these technologies even more attractive when compared to other technologies.

(3) those technologies which are ranked low do not impact Empty Weight significantly and consequently retain their relative unattractiveness with respect to a figure of merit of zero.

B.5.3 Minimum Category Weight For Empty Weight

Here, the minimum Empty Weight rating (0.0) is used for both airplanes as shown in Tables B.18 and B.19. When these tables are compared with Tables B.13 and B.15, results inferred from the previous section are noted.

(1) Relative technology rankings exhibit insignificant changes for both airplanes.

(2) Those technologies which are ranked high retain their relative dominance over other technologies but do not display advantages as distinct as originally reflected.

(3) Unattractive technologies remain so and do not reflect changes in figures of merit with respect to zero.

Table B.12. Technology Ranking By Technology Group For Airplane A

AIRPLANE A

***TABULAR RESULTS BY CATEGORY FOLLOW:

	CEIL	CRSH WTHY	CRUS SPED	DOC	EMIS SION	EMTY WGHT	EXTR NOIS	FUEL EFFC	INTR NOIS	PILT WRKL	PRCH PRCE	RGE	RELI BLTY	RIDE QLTY	SFTY	STAT CMFT	TOLD PERF	FIG OF MERIT
CATEGORY WEIGHTS	5.43	6.82	7.92	7.91	1.61	4.34	4.29	8.16	7.04	7.35	8.51	7.29	8.85	6.11	9.42	6.24	6.87	
**AERODYNAMICS:																		
NAT LAM FLOW AIRFOILS	1.0	0.	2.0	2.0	0.	1.0	0.	1.0	0.	0.	-0.5	2.0	-1.0	0.	0.	0.	1.0	57.926
SPOILERS	-0.5	0.	2.0	1.0	0.	1.0	0.	1.0	0.	0.5	0.	1.0	0.	2.0	0.	0.	0.	56.717
FOWLER FLAPS	-0.5	0.	2.0	1.0	0.	1.0	0.	1.0	0.	0.	-0.5	1.0	0.	2.0	0.	0.	0.	48.785
LOW/MEDM SPEED AIRFOILS	0.	0.	1.0	0.5	0.	0.5	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.5	0.	1.0	29.096
LEADING EDGE DEVICES	1.0	0.	0.5	0.5	0.	0.	0.	0.5	0.	0.	-1.0	0.5	0.	1.0	0.	0.	1.0	25.536
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	3.0	0.	0.	24.008
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	-2.0	0.	0.	0.	2.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	1.0	3.841
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-2.804
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.5	0.	0.	-1.0	0.	0.	0.	0.	0.	-0.5	-13.997
**AIRCRAFT SYSTEMS:																		
ICEPHOBIC SFC COATINGS	-0.5	0.	0.	-0.5	0.	-1.0	0.	0.	0.	0.	-1.0	-0.5	0.	0.	3.0	0.	0.	5.098
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
**CRASHWORTHINESS:																		
LOAD LIMITING SEATS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	17.326
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	16.191
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	14.020
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	7.593
**FLIGHT CONTROL SYSTEMS:																		
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	3.0	-0.5	0.	-0.5	0.	3.0	0.	0.	39.458
SEPARATE SFC TECHNOLOGY	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	3.0	-2.0	0.	-0.5	3.0	1.0	0.	0.	22.219

Table B.12. Technology Ranking By Technology Group For Airplane A (continued)

ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	13.154
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	11.206
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	2.539
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	-3.030
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-2.671
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	-0.5	0.	-0.5	0.	0.	-1.0	-0.5	1.0	0.	0.	0.	0.	-12.269
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-14.090
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-14.090
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-38.352
ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-42.305
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
**INFORMATION SYSTEMS:																		
DIGITAL DATA LINKS	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.0	-2.0	0.	0.	0.	3.0	0.	0.	33.283
INTEG AVIONICS AND DSPYS	0.	0.	0.	1.0	0.	0.	0.	0.	0.	3.0	-2.0	0.	0.	0.	2.0	0.	0.	31.767
SYS STATUS DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	0.	0.	2.0	0.	0.	25.027
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-2.0	0.	1.0	0.	0.5	0.	0.	11.233
MICRO HUD	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	1.535
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-15.933
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-22.525
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-25.545
**NAVIGATION CONCEPTS:																		
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.5	0.	0.	1.0	0.	0.	0.	-1.0	0.	0.	0.	1.0	0.	0.	9.147
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.256
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-0.5	0.	0.	-25.776
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-0.5	0.	0.	-26.033
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-36.517
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-52.938

Table B.12. Technology Ranking By Technology Group For Airplane A (concluded)

**NOISE:																		
QUIET EFFICIENT PROPS	0.	0.	0.	0.5	0.	0.5	2.0	0.	2.0	0.	-1.0	0.5	0.	0.	0.	0.	0.	23.901
DUCTED PROPULSORS	-0.5	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	2.0	-1.703
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.141
**PROPULSION:																		
GATE ENGINE	2.0	0.	1.0	1.0	1.0	3.0	0.	2.0	1.0	1.0	-3.0	1.0	1.0	1.0	1.0	0.	1.0	85.017
STRT CHG ROT COMB ENGINE	1.0	0.	1.0	2.0	2.0	1.0	0.5	2.0	1.0	1.0	-2.0	1.0	1.0	1.0	1.0	0.	0.	84.205
2 STR ADV DIESEL ENGINE	0.	0.	0.	2.0	0.	0.	0.5	3.0	0.5	0.	-2.0	1.0	0.	0.	0.	0.	0.	36.205
IMPROVED TURBOCHARGING	1.0	0.	1.0	0.5	0.	0.	0.	1.0	0.	0.	-1.0	1.0	0.	0.	0.	0.	1.0	31.110
LIQUID COOLING	0.	0.	0.	2.0	0.	-1.0	1.0	1.0	1.0	0.	0.	0.	-1.0	0.	-1.0	0.	0.	12.677
STRAT CHG RECIP ENGINE	0.	0.	0.	1.0	2.0	-0.5	0.	1.0	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	12.235
HCRLB RECIP ENGINE	0.	0.	0.	0.5	2.0	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	10.631
**STRUCTURAL MATERIALS:																		
FIBERGLASS COMPOSITES	2.0	0.	1.0	0.5	0.	2.0	0.	1.0	0.	0.	1.0	1.0	0.	0.	0.	0.	0.	55.375
KEVLAR COMPOSITES	2.0	0.	1.0	0.5	0.	3.0	0.	1.0	0.	0.	0.	1.0	0.	0.	0.	0.	0.	51.230
GRAPHITE COMPOSITES	2.0	0.	1.0	0.5	0.	3.0	0.	1.0	0.	0.	-1.0	1.0	0.	0.	0.	0.	0.	62.685

Table B.13. Overall Technology Ranking For Airplane A

```
                                           AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                              CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD         FIG OF
                         CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF          MERIT
       CATEGORY WEIGHTS  5.43 6.82 7.92 7.91 1.61 4.34 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87

GATE ENGINE               2.0  0.   1.0  1.0  1.0  3.0  0.   2.0  1.0  1.0 -3.0  1.0  1.0  1.0  1.0  0.   1.0          85.017
STRT CHG ROT COMB ENGINE  1.0  0.   1.0  2.0  2.0  1.0  0.5  2.0  1.0  1.0 -2.0  1.0  1.0  1.0  1.0  0.   0.           84.205
NAT LAM FLOW AIRFOILS     1.0  0.   2.0  2.0  0.   1.0  0.   1.0  0.   0.  -0.5  2.0 -1.0  0.   0.   0.   1.0          57.924
SPOILERS                 -0.5  0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.5  0.   1.0  0.   2.0  0.   0.   0.           56.717
FIBERGLASS COMPOSITES     2.0  0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.           55.375
KEVLAR COMPOSITES         2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.           51.200
FOWLER FLAPS             -0.5  0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0  0.   2.0  0.   0.   0.           48.785
GRAPHITE COMPOSITES       2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.           42.685
INTEG LOW-COST WC LVLER   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   3.0 -0.5  0.  -0.5  0.   3.0  0.   0.           39.458
2 STR ADV DIESEL ENGINE   0.   0.   0.   2.0  0.   0.   0.5  3.0  0.5  0.  -2.0  1.0  0.   0.   0.   0.   0.           36.205
DIGITAL DATA LINKS        0.   0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.           33.283
INTEG AVIONICS AND DSPYS  0.   0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   2.0  0.   0.           31.767
IMPROVED TURBOCHARGING    1.0  0.   1.0  0.5  0.   0.   0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   1.0          31.110
LOW/MEDM SPEED AIRFOILS   0.   0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0          29.096
LEADING EDGE DEVICES      1.0  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -1.0  0.5  0.   1.0  0.   0.   1.0          25.536
SYS STATUS DISPLAYS       0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.           25.027
IMPR STLL/SPN--AERO TLRG  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   3.0  0.   0.           24.008
QUIET EFFICIENT PROPS     0.   0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.           23.901
SEPARATE SFC TECHNOLOGY   0.   0.   0.  -0.5  0.  -0.5  0.   0.   0.   3.0 -2.0  0.  -0.5  3.0  1.0  0.   0.           22.219
LOAD LIMITING SEATS       0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.           17.326
IMPROVED RESTRAINTS       0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.           16.191
ENERGY ABSORBING FLOOR    0.   3.0  0.   0.   0.  -0.5  0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.           14.020
ACTIVE STALL PREVENTION   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.  -1.0  0.  -0.5  0.   3.0  0.   0.           13.154
LIQUID COOLING            0.   0.   0.   2.0  0.  -1.0  1.0  1.0  1.0  0.   0.   0.  -1.0  0.  -1.0  0.   0.           12.677
```

Table B.13. Overall Technology Ranking For Airplane A (concluded)

STRAT CNG RECIP ENGINE	0.	0.	0.	1.0	2.0	-0.5	0.	1.0	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	12.235
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-2.0	0.	1.0	0.	0.5	0.	0.	11.233
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	11.206
HCRLP RECIP ENGINE	0.	0.	0.	0.5	2.0	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	10.631
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.5	0.	0.	1.0	0.	0.	0.	-1.0	0.	0.	0.	1.0	0.	0.	9.147
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.256
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	7.593
ICEPHOBIC SFC COATINGS	-0.5	0.	0.	-0.5	0.	-1.0	0.	0.	0.	0.	-1.0	-0.5	0.	0.	3.0	0.	0.	5.098
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	-2.0	0.	0.	0.	2.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	1.0	3.841
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	2.539
MICRO HUD	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	1.535
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	-0.030
DUCTED PROPULSORS	-0.5	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	2.0	-1.703
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-2.671
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-2.804
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	-0.5	0.	-0.5	0.	0.	-1.0	-0.5	1.0	0.	0.	0.	0.	-12.269
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.5	0.	0.	-1.0	0.	0.	0.	0.	0.	-0.5	-13.997
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-14.090
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-14.090
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-15.933
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.141
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-22.525
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-0.5	0.	0.	-23.776
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-25.545
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-0.5	0.	0.	-26.033
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-36.517
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-38.352
ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-42.305
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-46.645
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-52.938

Table B.14. Technology Ranking By Technology Group For Airplane B

AIRPLANE B

***TABULAR RESULTS BY CATEGORY FOLLOW:

	CEIL	CRSH WTHY	CRUS SPED	DOC	EMIS SION	EMTY WGHT	EXTR NOIS	FUEL EFFC	INTR NOIS	PILT WRKL	PRCH PRCE	RGE	RELI BLTY	RIDE QLTY	SFTY	STAT CMFT	TOLD PERF	FIG OF MERIT
CATEGORY WEIGHTS	5.45	7.33	7.48	9.45	2.16	5.66	5.41	8.61	7.45	7.00	7.76	7.18	9.55	7.24	9.54	6.71	7.41	
**AERODYNAMICS:																		
SPOILERS	0.	0.	1.0	1.0	0.	0.5	0.	0.5	0.	0.5	0.	0.5	0.	1.0	0.	0.	0.	38.390
LOW/MEDM SPEED AIRFOILS	0.	0.	1.0	0.5	0.	0.5	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.5	0.	1.0	31.226
LEADING EDGE DEVICES	1.0	0.	0.5	0.5	0.	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.5	0.	0.	1.0	28.952
NAT LAM FLOW AIRFOILS	0.5	0.	1.0	1.0	0.	1.0	0.	1.0	0.	0.	-0.5	1.0	-2.0	0.	0.	0.	1.0	25.531
FOWLER FLAPS	0.	0.	0.5	0.5	0.	0.	0.	0.5	0.	0.	0.	0.5	0.	1.0	0.	0.	0.	23.597
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	0.	0.	15.207
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-3.733
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	-0.5	-15.138
ACTIVE LAMINAR FLOW CTL	2.0	0.	0.	-3.0	0.	0.	0.	1.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	1.0	-45.189
**AIRCRAFT SYSTEMS:																		
ICEPHOBIC SFC COATINGS	1.0	0.	0.	0.	0.	1.0	0.	0.5	0.	0.	1.0	0.	0.5	0.	0.5	0.	0.	32.714
AC ELECTRICAL SYSTEMS	0.5	0.	0.	0.	0.	0.5	0.	0.	0.	0.	1.0	0.5	0.	0.	0.	0.	0.	16.904
**CRASHWORTHINESS:																		
LOAD LIMITING SEATS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	18.646
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	18.118
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	15.290
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	8.581

Table B.14. Technology Ranking By Technology Group For Airplane B (continued)

**FLIGHT CONTROL SYSTEMS:																	
SEPARATE SFC TECHNOLOGY	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	1.0	1.0	0.	0.	23.780
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	16.097
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	12.120
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	7.761
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	5.952
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	4.529
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.0	0.	-0.5	3.0	0.	0.	0.	3.691
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	-0.5	1.0	0.	0.	0.	0.	-1.070
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-3.312
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.066
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-29.905
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
ACT GUST ALLEVIATION	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	1.0	0.	0.	0.	-35.043
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-37.556
**INFORMATION SYSTEMS:																	
INTEG AVIONICS AND DSPYS	0.	0.	0.	1.0	0.	0.	0.	0.	0.	3.0	-1.0	0.	0.	0.	2.0	0.	0.	41.772
DIGITAL DATA LINKS	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.0	-2.0	0.	0.	0.	3.0	0.	0.	34.104
SYS STATUS DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	0.	0.	2.0	0.	0.	25.323
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	1.0	0.	0.5	0.	0.	20.554
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.289
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-13.689
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-23.283
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-26.398
**NAVIGATION CONCEPTS:																	
MICROWAVE LANDING SYSTEM	0.	0.	0.	1.0	0.	0.	1.0	0.	0.	0.	-0.5	0.	0.	0.	1.0	0.	0.	20.527
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.781
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-1.0	0.	0.	-29.632

Table B.14. Technology Ranking By Technology Group For Airplane B (concluded)

OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-31.577
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-39.802
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-57.013
**NOISE:																		
QUIET EFFICIENT PROPS	0.	0.	0.	0.5	0.	0.5	2.0	0.	2.0	0.	-1.0	0.5	0.	0.	0.	0.	0.	29.114
DUCTED PROPULSORS	-0.5	0.	-1.0	-0.5	0.	-1.0	3.0	-0.5	3.0	0.	-1.0	-1.0	0.	0.	0.5	0.	2.0	18.350
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.652
**PROPULSION:																		
GATE ENGINE	0.	0.	0.	1.0	0.	0.	0.	1.0	0.	0.	0.	2.0	0.	0.	0.	0.	0.	32.419
STRT CHG RCT COMB ENGINE	0.	0.	0.	1.0	1.0	-1.0	0.	0.	0.	0.	1.0	1.0	0.	0.	0.	0.	0.	20.893
**STRUCTURAL MATERIALS:																		
FIBERGLASS COMPOSITES	2.0	0.	1.0	0.5	0.	2.0	0.	1.0	0.	0.	1.0	1.0	0.	0.	0.	0.	0.	57.962
KEVLAR COMPOSITES	2.0	0.	1.0	0.5	0.	3.0	0.	1.0	0.	0.	0.	1.0	0.	0.	0.	0.	0.	55.858
GRAPHITE COMPOSITES	2.0	0.	1.0	0.5	0.	3.0	0.	1.0	0.	0.	-1.0	1.0	0.	0.	0.	0.	0.	48.097

Table B.15. Overall Technology Ranking For Airplane B

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                                        AIRPLANE B

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                               CRSH  CRUS              EMIS  ENTY  EXTR  FUEL  INTR  PILT  PRCH        RELI  RIDE        STAT  TOLD     FIG OF
                         CEIL  WTHY  SPED  DOC         SION  WGHT  NOIS  EFFC  NOIS  WRKL  PRCE  RGE   BLTY  QLTY  SFTY  CRFT  PERF      MERIT
        CATEGORY WEIGHTS 5.45  7.33  7.48  9.45        2.16  5.66  5.41  8.61  7.45  7.00  7.76  7.18  9.55  7.24  9.54  6.71  7.41

FIBERGLASS COMPOSITES    2.0   0.    1.0   0.5   0.    2.0   0.    1.0   0.    0.    1.0   1.0   0.    0.    0.    0.    0.        57.962
KEVLAR COMPOSITES        2.0   0.    1.0   0.5   0.    3.0   0.    1.0   0.    0.    0.    1.0   0.    0.    0.    0.    0.        55.858
GRAPHITE COMPOSITES      2.0   0.    1.0   0.5   0.    3.0   0.    1.0   0.    0.   -1.0   1.0   0.    0.    0.    0.    0.        48.097
INTEG AVIONICS AND DSPYS 0.    0.    0.    1.0   0.    0.    0.    0.    0.    3.0  -1.0   0.    0.    0.    2.0   0.    0.        41.772
SPOILERS                 0.    0.    1.0   1.0   0.    0.5   0.    0.5   0.    0.5   0.    0.5   0.    1.0   0.    0.    0.        38.390
DIGITAL DATA LINKS       0.    0.    0.    0.    0.    0.    0.    0.    0.    3.0  -2.0   0.    0.    0.    3.0   0.    0.        34.104
ICEPHOBIC SFC COATINGS   1.0   0.    0.    0.    0.    1.0   0.    0.5   0.    0.    1.0   0.    0.5   0.    0.5   0.    0.        32.714
GATE ENGINE              0.    0.    0.    1.0   0.    0.    0.    1.0   0.    0.    0.    2.0   0.    0.    0.    0.    0.        32.419
LOW/MEDM SPEED AIRFOILS  0.    0.    1.0   0.5   0.    0.5   0.    0.5   0.    0.   -0.5   0.5   0.    0.    0.5   0.    1.0       31.226
QUIET EFFICIENT PROPS    0.    0.    0.    0.5   0.    0.5   2.0   0.    2.0   0.   -1.0   0.5   0.    0.    0.    0.    0.        29.114
LEADING EDGE DEVICES     1.0   0.    0.5   0.5   0.    0.    0.    0.5   0.    0.   -0.5   0.5   0.    0.5   0.    0.    1.0       28.952
NAT LAM FLOW AIRFOILS    0.5   0.    1.0   1.0   0.    1.0   0.    1.0   0.    0.   -0.5   1.0  -2.0   0.    0.    0.    1.0       25.531
SYS STATUS DISPLAYS      0.    0.    0.    0.    0.    0.    0.    0.    0.    2.0  -1.0   0.    0.    0.    2.0   0.    0.        25.323
SEPARATE SFC TECHNOLOGY  0.    0.    0.    0.    0.    0.    0.    0.    0.    1.0   0.    0.    0.    1.0   1.0   0.    0.        23.780
FOWLER FLAPS             0.    0.    0.5   0.5   0.    0.    0.    0.5   0.    0.    0.    0.5   0.    1.0   0.    0.    0.        23.597
STRT CNG ROT COMB ENGINE 0.    0.    0.    1.0   1.0  -1.0   0.    0.    0.    0.    1.0   1.0   0.    0.    0.    0.    0.        20.893
CRT DISPLAYS             0.    0.    0.    0.    0.    0.    0.    0.    0.    2.0  -1.0   0.    1.0   0.    0.5   0.    0.        20.554
MICROWAVE LANDING SYSTEM 0.    0.    0.    1.0   0.    0.    1.0   0.    0.    0.   -0.5   0.    0.    0.    1.0   0.    0.        20.527
LOAD LIMITING SEATS      0.    3.0   0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.   -0.5   0.        18.646
DUCTED PROPULSORS       -0.5   0.   -1.0  -0.5   0.   -1.0   3.0  -0.5   3.0   0.   -1.0  -1.0   0.    0.    0.5   0.    2.0       18.350
IMPROVED RESTRAINTS      0.    3.0   0.    0.    0.    0.    0.    0.    0.    0.   -0.5   0.    0.    0.    0.    0.    0.        18.118
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Table B.15. Overall Technology Ranking For Airplane B (concluded)

AC ELECTRICAL SYSTEMS	0.5	0.	0.	0.	0.	0.5	0.	0.	0.	0.	1.0	0.5	0.	0.	0.	0.	0.	16.904
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	16.097
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	15.290
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	0.	0.	15.207
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	12.120
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.781
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	8.581
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	7.761
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	5.952
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	4.529
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.0	0.	-0.5	3.0	0.	0.	0.	3.691
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.289
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	-0.5	1.0	0.	0.	0.	0.	-1.070
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-3.312
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-3.733
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.068
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-13.689
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	-0.5	-15.138
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-17.852
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-23.283
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-26.398
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-1.0	0.	0.	-29.632
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-29.905
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-31.577
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
ACT GUST ALLEVIATION	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	1.0	0.	0.	0.	-35.043
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-37.556
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-39.802
ACTIVE LAMINAR FLOW CTL	2.0	0.	0.	-3.0	0.	0.	0.	1.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	1.0	-45.189
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-57.013

Table B.16. Overall Technology Ranking With Empty Weight = 9.5 For Airplane A

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                                                         AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                                CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD    FIG OF
                           CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  QLTY QLTY SFTY CNFT PERF     MERIT
          CATEGORY WEIGHTS 5.43 6.82 7.92 7.91 1.61 9.50 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87

GATE ENGINE                2.0  0.   1.0  1.0  1.0  3.0  0.   2.0  1.0  1.0 -3.0  1.0  1.0  1.0  1.0  0.   1.0   100.497
STRT CNG ROT COMB ENGINE   1.0  0.   1.0  2.0  2.0  1.0  0.5  2.0  1.0  1.0 -2.0  1.0  1.0  1.0  1.0  0.   0.     89.365
KEVLAR COMPOSITES          2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.     66.680
FIBERGLASS COMPOSITES      2.0  0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.     65.695
NAT LAM FLOW AIRFOILS      1.0  0.   2.0  2.0  0.   1.0  0.   1.0  0.   0.  -0.5  2.0 -1.0  0.   0.   0.   1.0    63.085
SPOILERS                  -0.5  0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.5  0.   1.0  0.   2.0  0.   0.   0.     61.877
GRAPHITE COMPOSITES        2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.     58.165
FOWLER FLAPS              -0.5  0.   2.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0  0.   2.0  0.   0.   0.     53.945
INTEG LOW-COST WG LVLER    0.   0.   0.   0.   0.  -0.5  0.   0.   0.   3.0 -0.5  0.  -0.5  0.   3.0  0.   0.     36.878
2 STR ADV DIESEL ENGINE    0.   0.   0.   2.0  0.   0.   0.5  3.0  0.5  0.  -2.0  1.0  0.   0.   0.   0.   0.     36.205
DIGITAL DATA LINKS         0.   0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.     35.283
INTEG AVIONICS AND DSPYS   0.   0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   2.0  0.   0.     31.767
LOW/MEDM SPEED AIRFOILS    0.   0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0    31.676
IMPROVED TURBOCHARGING     1.0  0.   1.0  0.5  0.   0.   0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   1.0    31.110
QUIET EFFICIENT PROPS      0.   0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.     26.481
LEADING EDGE DEVICES       1.0  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -1.0  0.5  0.   1.0  0.   0.   1.0    25.536
SYS STATUS DISPLAYS        0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.     25.027
IMPR STLL/SPN--AERO TLRG   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   3.0  0.   0.     24.008
SEPARATE SFC TECHNOLOGY    0.   0.   0.  -0.5  0.  -0.5  0.   0.   0.   3.0 -2.0  0.  -0.5  3.0  1.0  0.   0.     19.639
LOAD LIMITING SEATS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.     17.326
IMPROVED RESTRAINTS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.     16.191
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Table B.16. *Overall Technology Ranking With Empty Weight = 9.5 For Airplane A (continued)*

ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	11.441
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-2.0	0.	1.0	0.	0.5	0.	0.	11.233
MCRLB RECIP ENGINE	0.	0.	0.	0.5	2.0	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	13.631
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	10.574
STRAT CHG RECIP ENGINE	0.	0.	0.	1.0	2.0	-0.5	0.	1.0	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	9.655
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.5	0.	0.	1.0	0.	0.	0.	-1.0	0.	0.	0.	1.0	0.	0.	9.147
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	8.626
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.256
LIQUID COOLING	0.	0.	0.	2.0	0.	-1.0	1.0	1.0	1.0	0.	0.	0.	-1.0	0.	-1.0	0.	0.	7.517
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	5.130
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	-2.0	0.	0.	0.	2.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	1.0	3.841
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	2.539
BRST/T [illegible] RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	2.433
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
ICEPHOBIC SFC COATINGS	-0.5	0.	0.	-0.5	0.	-1.0	0.	0.	0.	0.	-1.0	-0.5	0.	0.	3.0	0.	0.	-0.062
MICRO HUD	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	-1.065
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-2.671
DUCTED PROPULSORS	-0.5	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	2.0	-6.863
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-13.126
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	-0.5	0.	-0.5	0.	0.	-1.0	-0.5	1.0	0.	0.	0.	0.	-14.849
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-15.933
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.5	0.	0.	-1.0	0.	0.	0.	0.	0.	-0.5	-16.576
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-16.670
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-16.670
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-19.721
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-25.545
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-0.5	0.	0.	-26.033
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-0.5	0.	0.	-26.356
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-27.685
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-38.352

Table B.16. Overall Technology Ranking With Empty Weight = 9.5 For Airplane A (concluded)

DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-39.097
ACT GUST ALLV	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-42.305
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-51.805
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-51.805
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-55.518

Table B.17. Overall Technology Ranking With Empty Weight = 9.5 For Airplane B

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                                            AIRPLANE B

***TABULAR RESULTS FOR ALL TECKNOLOGIES FOLLOW:
                                  CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD       FIG OF
                             CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  BLTY QLTY SFTY CMFT PERF       MERIT
        CATEGORY WEIGHTS     5.45 7.33 7.48 9.45 2.16 9.56 5.41 8.61 7.45 7.00 7.76 7.18 9.55 7.24 9.56 6.71 7.41


KEVLAR COMPOSITES             2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.        67.387
FIBERGLASS COMPOSITES         2.0  0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.        65.648
GRAPHITE COMPOSITES           2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.        59.626
INTEG AVIONICS AND DSPYS      0.   0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -1.0  0.   0.   0.   2.0  0.   0.        41.772
SPOILERS                      0.   0.   1.0  1.0  0.   0.5  0.   0.5  0.   0.5  0.   0.5  0.   1.0  0.   0.   0.        40.312
ICEPHOBIC SFC COATINGS        1.0  0.   0.   0.   0.   1.0  0.   0.5  0.   0.   1.0  0.   0.5  0.   0.5  0.   0.        36.556
DIGITAL DATA LINKS            0.   0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.        34.104
LOW/MEDM SPEED AIRFOILS       0.   0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0       33.148
GATE ENGINE                   0.   0.   0.   1.0  0.   0.   0.   1.0  0.   0.   0.   2.0  0.   0.   0.   0.   0.        32.419
QUIET EFFICIENT PROPS         0.   0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.        31.035
NAT LAM FLOW AIRFOILS         0.5  0.   1.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0 -2.0  0.   0.   0.   1.0       29.374
LEADING EDGE DEVICES          1.0  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -0.5  0.5  0.   0.5  0.   0.   1.0       28.952
SYS STATUS DISPLAYS           0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.        25.323
SEPARATE SFC TECHNOLOGY       0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  0.   0.   0.   1.0  1.0  0.   0.        23.780
FOWLER FLAPS                  0.   0.   0.5  0.5  0.   0.   0.   0.5  0.   0.   0.   0.5  0.   1.0  0.   0.   0.        23.597
CRT DISPLAYS                  0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   1.0  0.   0.5  0.   0.        20.554
MICROWAVE LANDING SYSTEM      0.   0.   0.   1.0  0.   0.   1.0  0.   0.   0.  -0.5  0.   0.   0.   1.0  0.   0.        20.527
AC ELECTRICAL SYSTEMS         0.5  0.   0.   0.   0.   0.5  0.   0.   0.   0.   1.0  0.5  0.   0.   0.   0.   0.        18.825
LOAD LIMITING SEATS           0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.        18.646
IMPROVED RESTRAINTS           0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.        18.118
STRT CHG ROT COMB ENGINE      0.   0.   0.   1.0  1.0 -1.0  0.   0.   0.   0.   1.0  1.0  0.   0.   0.   0.   0.        17.050
```

Table B.17. Overall Technology Ranking With Empty Weight = 9.5 For Airplane B (concluded)

ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	16.097
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	0.	0.	15.207
DUCTED PROPULSORS	-0.5	0.	-1.0	-0.5	0.	-1.0	3.0	-0.5	3.0	0.	-1.0	-1.0	0.	0.	0.5	0.	2.0	14.507
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	13.369
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	10.199
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.781
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	8.372
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	7.761
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	5.952
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	4.738
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.0	0.	-0.5	3.0	0.	0.	0.	3.691
MICRO HUB	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.289
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	-0.5	1.0	0.	0.	0.	0.	-1.070
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-3.312
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.068
WINGLETS	0.5	0.	0.	-0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	-11.418
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-13.689
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	-0.5	-17.059
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-19.773
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-23.283
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	3.	-27.984
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-28.261
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-1.0	0.	0.	-31.554
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-31.577
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
ACT GUST ALLEVIATION	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	1.0	0.	0.	0.	-35.043
ACT FLUTTER SUPPRESSION	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	0.	0.	0.	0.	-37.556
DOPPLER NAVIGATION	0.	0.	0.	-2.0	0.	-0.5	0.	0.	0.	1.0	-2.0	0.	-1.0	0.	0.	0.	0.	-41.723
ACTIVE LAMINAR FLOW CTL	2.0	0.	0.	-3.0	0.	0.	0.	1.0	0.	0.	-3.0	1.0	-3.0	0.	0.	0.	1.0	-45.189
INERTIAL NAVIGATION	0.	0.	0.	-3.0	0.	-0.5	0.	0.	0.	1.0	-3.0	0.	-1.0	0.	0.	0.	0.	-58.935

Table B.18. Overall Technology Ranking With Empty Weight = 0.0 For Airplane A

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                                              AIRPLANE A

***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                               CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD    FIG OF
                          CEIL WTHY SPED  DOC SION WGHT NOIS EFFC NOIS WRKL PRCE  RGE QLTY QLTY SFTY CMFT PERF     MERIT

          CATEGORY WEIGHTS 5.43 6.82 7.92 7.91 1.61 9.50 4.29 8.16 7.04 7.35 8.51 7.29 8.85 6.11 9.42 6.24 6.87
    **SEE 'NOTES' BELOW:                                   (1)

STRT CHG ROT COMB ENGINE   1.0   0.  1.0  2.0  2.0  1.0  0.5  2.0  1.0  1.0 -2.0  1.0  1.0  1.0  1.0   0.   0.    79.865
SAVE ENGINE                2.0   0.  1.0  1.0  1.0  3.0   0.  2.0  1.0  1.0 -3.0  1.0  1.0  1.0  1.0   0.  1.0    71.997
NAT LAM FLOW AIRFOILS      1.0   0.  2.0  2.0   0.  1.0   0.  1.0   0.   0. -0.5  2.0 -1.0   0.   0.   0.  1.0    53.584
SPOILERS                  -0.5   0.  2.0  1.0   0.  1.0   0.  1.0   0.  0.5   0.  1.0   0.  2.0   0.   0.   0.    52.377
FIBERGLASS COMPOSITES      2.0   0.  1.0  0.5   0.  2.0   0.  1.0   0.   0.  1.0  1.0   0.   0.   0.   0.   0.    46.695
FOWLER FLAPS              -0.5   0.  2.0  1.0   0.  1.0   0.  1.0   0.   0. -0.5  1.0   0.  2.0   0.   0.   0.    44.445
INTEG LOW-COST WG LVLER     0.   0.   0.   0.   0. -0.5   0.   0.   0.  3.0 -0.5   0. -0.5   0.  3.0   0.   0.    41.628
KEVLAR COMPOSITES          2.0   0.  1.0  0.5   0.  3.0   0.  1.0   0.   0.   0.  1.0   0.   0.   0.   0.   0.    38.780
2 STR ADV DIESEL ENGINE     0.   0.   0.  2.0   0.   0.  0.5  3.0  0.5   0. -2.0  1.0   0.   0.   0.   0.   0.    36.205
DIGITAL DATA LINKS          0.   0.   0.   0.   0.   0.   0.   0.   0.  3.0 -2.0   0.   0.   0.  3.0   0.   0.    33.283
INTEG AVIONICS AND DSPYS    0.   0.   0.  1.0   0.   0.   0.   0.   0.  3.0 -2.0   0.   0.   0.  2.0   0.   0.    31.767
IMPROVED TURBOCHARGING     1.0   0.  1.0  0.5   0.   0.   0.  1.0   0.   0. -1.0  1.0   0.   0.   0.   0.  1.0    31.110
GRAPHITE COMPOSITES        2.0   0.  1.0  0.5   0.  3.0   0.  1.0   0.   0. -1.0  1.0   0.   0.   0.   0.   0.    29.665
LOW/MEDM SPEED AIRFOILS     0.   0.  1.0  0.5   0.  0.5   0.  0.5   0.   0. -0.5  0.5   0.   0.  0.5   0.  1.0    26.926
LEADING EDGE DEVICES       1.0   0.  0.5  0.5   0.   0.   0.  0.5   0.   0. -1.0  0.5   0.  1.0   0.   0.  1.0    25.536
SYS STATUS DISPLAYS         0.   0.   0.   0.   0.   0.   0.   0.   0.  2.0 -1.0   0.   0.   0.  2.0   0.   0.    25.027
SEPARATE SFC TECHNOLOGY     0.   0.   0. -0.5   0. -0.5   0.   0.   0.  3.0 -2.0   0. -0.5  3.0  1.0   0.   0.    24.389
IMPR STLL/SPN--AERO TLRG    0.   0.   0.   0.   0.   0.   0.   0.   0.   0. -0.5   0.   0.   0.  3.0   0.   0.    26.809
QUIET EFFICIENT PROPS       0.   0.   0.  0.5   0.  0.5  2.0   0.  2.0   0. -1.0  0.5   0.   0.   0.   0.   0.    21.731
LOAD LIMITING SEATS         0.  3.0   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0. -0.5   0.    17.326
```

Table B.18. Overall Technology Ranking With Empty Weight = 0.0 For Airplane A (continued)

LIQUID COOLING	0.	0.	0.	2.0	0.	-1.0	1.0	1.0	1.0	0.	0.	0.	-1.0	0.	-1.0	0.	0.	17.017
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	16.191
ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	16.191
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	15.324
STRAT CHG RECIP ENGINE	0.	0.	0.	1.0	2.0	-0.5	0.	1.0	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	16.405
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	15.376
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	11.933
CRT DISPLAYS	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-2.0	0.	1.0	0.	0.5	0.	0.	11.235
HCRLB RECIP ENGINE	0.	0.	0.	0.5	2.0	0.	0.	0.5	0.	0.	-0.5	0.5	0.	0.	0.	0.	0.	10.631
ICEPHOBIC SFC COATINGS	-0.5	0.	0.	-0.5	0.	-1.0	0.	0.	0.	0.	-1.0	-0.5	0.	0.	3.0	0.	0.	9.438
MICROWAVE LANDING SYSTEM	0.	0.	0.	0.5	0.	0.	1.0	0.	0.	0.	-1.0	0.	0.	0.	1.0	0.	0.	9.147
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.256
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	5.876
ACTIVE LAMINAR FLOW CTL	2.0	0.	2.0	-2.0	0.	0.	0.	2.0	0.	0.	-3.0	3.0	-3.0	0.	0.	0.	1.0	3.841
MICRO HUD	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.705
DUCTED PROPULSORS	-0.5	0.	-1.0	-1.0	0.	-1.0	3.0	-1.0	3.0	0.	-1.0	-2.0	0.	0.	0.5	0.	2.0	2.637
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	2.539
AC ELECTRICAL SYSTEMS	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-2.671
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	-6.370
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	-0.5	0.	-0.5	0.	0.	-1.0	-0.5	1.0	0.	0.	0.	0.	-10.099
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.5	0.	0.	-1.0	0.	0.	0.	0.	0.	-0.5	-11.827
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.920
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.5	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.920
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-14.971
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-15.933
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-18.185
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-0.5	0.	0.	-21.606
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-25.545
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-0.5	0.	0.	-26.033

Table B.18. Overall Technology Ranking With Empty Weight = 0.0 For Airplane A (concluded)

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DOPPLER NAVIGATION          0.   0.   0.  -2.0  0.  -0.5  0.   0.   0.   1.0 -2.0  0.  -1.0  0.   0.   0.   0.   -34.347
ACT FLUTTER SUPPRESSION     0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.  -3.0  0.  -1.0  0.   0.   0.   0.   -38.352
FLY-BY-LIGHT                0.   0.   0.  -1.0  0.  -1.0  0.   0.   0.   0.  -3.0  0.  -1.0  0.   0.   0.   0.   -42.305
ACT GUST ALLV               0.   0.   0.  -1.0  0.   0.   0.   0.   0.   0.  -3.0  0.  -1.0  0.   0.   0.   0.   -42.305
FLY-BY-WIRE                 0.   0.   0.  -1.0  0.  -1.0  0.   0.   0.   0.  -3.0  0.  -1.0  0.   0.   0.   0.   -42.305
INERTIAL NAVIGATION         0.   0.   0.  -3.0  0.  -0.5  0.   0.   0.   1.0 -3.0  0.  -1.0  0.   0.   0.   0.   -50.768
  **NOTES:
   ( 1) EMPTY WEIGHT IS OMITTED.
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Table B.19. Overall Technology Ranking With Empty Weight = 0.0 For Airplane B

```
                                               AIRPLANE B


***TABULAR RESULTS FOR ALL TECHNOLOGIES FOLLOW:
                               CRSH CRUS      EMIS EMTY EXTR FUEL INTR PILT PRCH      RELI RIDE      STAT TOLD      FIG OF
                          CEIL WTHY SPED DOC  SION WGHT NOIS EFFC NOIS WRKL PRCE RGE  QLTY QLTY SFTY CRFT PERF       MERIT

     CATEGORY WEIGHTS 5.45 7.33 7.48 9.45 2.16 9.50 5.41 8.61 7.45 7.00 7.76 7.18 9.55 7.24 9.54 6.71 7.41
   **SEE 'NOTES' BELOW:                        (1)


FIBERGLASS COMPOSITES      2.0  0.   1.0  0.5  0.   2.0  0.   1.0  0.   0.   1.0  1.0  0.   0.   0.   0.   0.        46.648
INTEG AVIONICS AND DSPYS   0.   0.   0.   1.0  0.   0.   0.   0.   0.   3.0 -1.0  0.   0.   0.   2.0  0.   0.        41.772
KEVLAR COMPOSITES          2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.   0.   1.0  0.   0.   0.   0.   0.        38.887
SPOILERS                   0.   0.   1.0  1.0  0.   0.5  0.   0.5  0.   0.5  0.   0.5  0.   1.0  0.   0.   0.        35.562
DIGITAL DATA LINKS         0.   0.   0.   0.   0.   0.   0.   0.   0.   3.0 -2.0  0.   0.   0.   3.0  0.   0.        34.104
GATE ENGINE                0.   0.   0.   1.0  0.   0.   0.   1.0  0.   0.   0.   2.0  0.   0.   0.   0.   0.        32.419
GRAPHITE COMPOSITES        2.0  0.   1.0  0.5  0.   3.0  0.   1.0  0.   0.  -1.0  1.0  0.   0.   0.   0.   0.        31.126
LEADING EDGE DEVICES       1.0  0.   0.5  0.5  0.   0.   0.   0.5  0.   0.  -0.5  0.5  0.   0.5  0.   0.   1.0       28.952
LOW/MEDM SPEED AIRFOILS    0.   0.   1.0  0.5  0.   0.5  0.   0.5  0.   0.  -0.5  0.5  0.   0.   0.5  0.   1.0       28.398
ICEPHOBIC SFC COATINGS     1.0  0.   0.   0.   0.   1.0  0.   0.5  0.   0.   1.0  0.   0.5  0.   0.5  0.   0.        27.057
STRT CHG ROT COMB ENGINE   0.   0.   0.   1.0  1.0 -1.0  0.   0.   0.   0.   1.0  1.0  0.   0.   0.   0.   0.        26.550
QUIET EFFICIENT PROPS      0.   0.   0.   0.5  0.   0.5  2.0  0.   2.0  0.  -1.0  0.5  0.   0.   0.   0.   0.        26.285
SYS STATUS DISPLAYS        0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   0.   0.   2.0  0.   0.        25.323
DUCTED PROPULSORS         -0.5  0.  -1.0 -0.5  0.  -1.0  3.0 -0.5  3.0  0.  -1.0 -1.0  0.   0.   0.5  0.   2.0       24.007
SEPARATE SFC TECHNOLOGY    0.   0.   0.   0.   0.   0.   0.   0.   0.   1.0  0.   0.   0.   1.0  1.0  0.   0.        23.788
FOWLER FLAPS               0.   0.   0.5  0.5  0.   0.   0.   0.5  0.   0.   0.   0.5  0.   1.0  0.   0.   0.        23.597
CRT DISPLAYS               0.   0.   0.   0.   0.   0.   0.   0.   0.   2.0 -1.0  0.   1.0  0.   0.5  0.   0.        20.556
MICROWAVE LANDING SYSTEM   0.   0.   0.   1.0  0.   0.   1.0  0.   0.   0.  -0.5  0.   0.   0.   1.0  0.   0.        20.527
NAT LAM FLOW AIRFOILS      0.5  0.   1.0  1.0  0.   1.0  0.   1.0  0.   0.  -0.5  1.0 -2.0  0.   0.   0.   1.0       19.874
LOAD LIMITING SEATS        0.   3.0  0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.  -0.5  0.        18.646
```

Table B.19. Overall Technology Ranking With Empty Weight = 0.0 For Airplane B (continued)

ENERGY ABSORBING FLOOR	0.	3.0	0.	0.	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	18.118
IMPROVED RESTRAINTS	0.	3.0	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	18.118
ACTIVE STALL PREVENTION	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-1.0	0.	-0.5	0.	3.0	0.	0.	16.097
IMPR STLL/SPN--AERO TLRG	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	2.0	0.	0.	15.207
DIRECT LIFT CONTROL	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	1.0	-1.0	0.	-0.5	1.0	1.0	0.	0.5	14.949
BRST/TEAR RESIS FUEL TKS	0.	3.0	0.	0.	0.	-1.0	0.	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	14.238
AC ELECTRICAL SYSTEMS	0.5	0.	0.	0.	0.	0.5	0.	0.	0.	0.	1.0	0.5	0.	0.	0.	0.	0.	14.075
NAVSTAR/GPS	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-1.0	0.	0.	0.	1.0	0.	0.	8.781
INTEG LOW-COST WG LVLER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	0.	0.	0.	0.	0.	0.	7.761
WINGLETS	0.5	0.	0.	0.5	0.	-2.0	0.	0.5	0.	0.	-1.0	0.5	0.	0.	0.	0.	0.	7.582
INTEGRATED YAW DAMPER	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.0	-2.0	0.	0.	2.0	0.	0.	0.	5.952
ACT RIDE SMOOTHING	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	1.0	-2.0	0.	-0.5	3.0	0.	0.	0.	3.691
MICRO HUD	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	2.0	-2.0	0.	-1.0	0.	2.0	0.	0.	3.289
FLUIDIC AUTO FLT CTL SYS	-0.5	0.	0.	0.	0.	0.	0.	-0.5	0.	0.	0.	-0.5	1.0	0.	0.	0.	0.	-1.070
ACT CTLS FOR RLX STBLTY	0.5	0.	0.5	1.0	0.	1.0	0.	1.0	0.	0.	-3.0	1.0	-1.0	0.	0.	0.	0.	-1.128
SGL LEVER THRUST/DRG CTL	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.0	-1.0	0.	-1.0	0.	0.	0.	0.	-3.312
DIRECT SIDE FORCE CTL	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	-0.5	3.0	0.	0.	0.	-11.068
LOW-DRAG SFC COATINGS	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	-0.5	-12.309
LASER GYROS	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-3.0	0.	1.0	0.	0.5	0.	0.	-13.689
LOW-LEVEL PRESSURIZATION	0.	0.	0.	-0.5	0.	-0.5	0.	-0.5	2.0	0.	-1.0	-0.5	-1.0	0.	0.	0.	0.	-15.023
HEADS-UP DISPLAY	0.	0.	0.	-1.0	0.	-1.0	0.	0.	0.	2.0	-3.0	0.	-1.0	0.	1.0	0.	0.	-18.741
FIBER OPTICS (DATA TRNS)	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-23.283
LORAN C	0.	0.	0.	-0.5	0.	-0.5	0.	0.	0.	0.	-1.0	0.	-0.5	0.	-1.0	0.	0.	-26.804
OMEGA	0.	0.	0.	-0.5	0.	0.	0.	0.	0.	0.	-1.0	0.	-1.0	0.	-1.0	0.	0.	-31.577
FLY-BY-LIGHT	0.	0.	0.	-1.0	0.	0.5	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
FLY-BY-WIRE	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	0.	0.	0.	0.	0.	-32.734
ACT GUST ALLEVIATION	0.	0.	0.	-1.0	0.	0.	0.	0.	0.	0.	-3.0	0.	-1.0	1.0	0.	0.	0.	-35.043

Table B.19. Overall Technology Ranking With Empty Weight = 0.0 For Airplane B (concluded)

```
DOPPLER NAVIGATION          0.   0.   0.  -2.0  0.  -0.5  0.   0.   0.   1.0 -2.0  0.  -1.0  0.   0.   0.   0.   -36.973
ACT FLUTTER SUPPRESSION     0.   0.   0.  -0.5  0.   0.   0.   0.   0.   0.  -3.0  0.  -1.0  0.   0.   0.   0.   -37.556
ACTIVE LAMINAR FLOW CTL     2.0  0.   0.  -3.0  0.   0.   0.   1.0  0.   0.  -3.0  1.0 -3.0  0.   0.   0.   1.0  -46.189
INERTIAL NAVIGATION         0.   0.   0.  -3.0  0.  -0.5  0.   0.   0.   1.0 -3.0  0.  -1.0  0.   0.   0.   0.   -56.185
  **NOTES:
   ( 1) EMPTY WEIGHT IS OMITTED.
```

APPENDIX C

6-PASSENGER AND COMMUTER DESIGN STUDIES

This appendix details basic equations used in the configuration trades for both the 6-passenger and commuter aircraft. Weight and drag breakdowns are shown for both baseline and advanced conventional configurations for both airplanes. Also, the Range Factor derivation is shown.

C.1 6-PASSENGER DESIGNS

Three airplanes were designed: a current technology airplane, an advanced technology conventionally configured airplane, and an advanced technology canard configured airplane. Specifications and technologies incorporated are detailed in Chapter 5 as is the cabin layout which is common to all three designs.

The following paragraphs discuss, in order, the parametric trade studies, the current technology airplane, the conventional configuration advanced technology airplane, and the canard configuration advanced technology airplane.

C.1.1 Trade Studies

Three trade studies were done covering cruise, takeoff, and landing performance. Derivations are as follows (the resulting graphs may be found in Chapter 5).

Cruise trades were formulated to show effective power loading required to cruise at 250 kt. The relationship is given in Equation C.1.

$$(\eta_p\ P/W) = \frac{\rho V^3}{4882}\left\{\frac{23.95\ C_{D_o}}{(W/s)} + \frac{(W/s)}{\pi(Ae)\rho^2\ V^4}\right\} \qquad \text{(C.1)}$$

for ρ in kg sec^2/m^4 — W/S in N/m^2

V in m/s — $(\eta_p\ P/W)$ in kw/N

Note: $(\eta_p\ P/W)$ is that required at cruise and is not the sea level maximum.

L/D can also be included in the plots because it is related to the effective power loading as given by Equation C.2.

$$L/D = (\eta_p\ P/W)^{-1}\ (V/\quad) \qquad \text{(C.2)}$$

for V in m/s

$(\eta_p\ P/W)$ in kw/N

The takeoff trade study was formulated to show wing loading required for a 2000 ft takeoff over a 50 ft obstacle. The approximations of Reference 214 were used to model the takeoff maneuver. Equation C.3 presents the resulting expression.

$$\frac{W}{S} = \frac{\left\{610 - \dfrac{15.7\sqrt{A}}{16.505\ (\frac{P}{W})\ \sqrt{A} - .3}\right\}}{\left[\dfrac{.1198}{18.332(P/W)C_{L_{max_{TO}}} - .02\ C_{L_{max_{TO}}} - .72\ C_{D_o}} + \dfrac{.1694}{C_{L_{max_{TO}}}}\right]} \qquad \text{(C.3)}$$

for W/S in N/m^2 sea level (ISA)

P/W in kw/kg concrete runway ($\mu = .02$)

Computations showed that the required W/S was a very weak function of C_{D_o} and A so the plots were generated with $W/S = f(P/W, C_{L_{max_{TO}}})$ only.

The landing trade study was formulated to show W/S and $C_{L_{max_{LDG}}}$ required to land in 610 over a 15.2 m obstacle. The approximations of Reference 214 were used to model the landing maneuver. The relation proved to be linear as shown in Equation C.4.

$$C_{L_{max_{LDG}}} = .0011\ (W/S) \tag{C.4}$$

for W/S in N/m^2

$V_{approach} = 1.3\ V_{stall}$

sea level (ISA)

C.1.2 Current Technology Design - 6PAXBL

Preliminary sizing of the 6PAXBL was accomplished using a standard weight breakdown and the Breguet range equation as given by Equations C.5 and C.6.

$$W_G = W_E + W_p + W_f \tag{C.5}$$

where W_G = gross weight W_p = payload weight

W_E = empty weight W_f = fuel weight

$$R = 198.13 \, (\eta_p \, / \, sfc) \, (L/D) \, \ln \, (W_G/(W_G - W_f)) \qquad \text{(C.6)}$$

for R in nm sfc in kg/kw/hr

Use of Equations C.5 and C.6 resulted in the following preliminary weight breakdowns:

W_E = 1086 kg W_p = 545 kg

W_f = 213 kg W_G = 1844 kg

Next, the wing was sized for W/S = 1053 N/m^2 and the vertical and horizontal tails were sized with volume coefficients. With initial sizing completed, detailed component weight estimations were done primarily using the methods of References 214 and 154. Wing location and horizontal tail area were then determined from static margin and takeoff rotation requirements using a program which is briefly described following the design discussions in Section C.1.5. The final step in the manual conceptual design process was the calculation of the zero lift drag for which the methods of References 179, 214, 90, and 137 were used.

The final sizing began by calibrating the GASP weight and drag routines against the previous hand calculations by varying already-provided inputs. GASP then sized the engine and airframe to meet the required specifications. Table C.1 presents the final weight breakdown and Table C.2 presents the final drag breakdown for 6PAXBL.

Table C.1. 6PAXBL Weight Breakdown

Group	Item	Weight (kg)/(lb)
Propulsion	Engine (dry)	281.7 / 621
	Engine Installation	31.8 / 70
	Fuel System	10.4 / 23
	Propeller	33.6 / 74
Structures & Miscellaneous	Wing	177.4 / 391
	Horizontal Tail	27.7 / 61
	Vertical Tail	11.3 / 25
	Fuselage	219.1 / 483
	Landing Gear	62.1 / 137
	Fuel Tanks	18.1 / 40
	Battery & Wiring	22.7 / 50
Flight Controls & Fixed Equipment	Surface Controls	50.8 / 112
	Avionics & Instrumentation	33.1 / 73
	Seats & Furnishings	71.7 / 158

Empty Weight = 1051.4 kg (2318 lb)
Payload Weight = 544.3 kg (1200 lb)
Fuel Weight = 264.0 kg (582 lb)
Gross Weight = 1859.8 kg (4100 lb)

Table C.2. 6PAXBL Drag Breakdown

Item	Flatplate Area (m^2)	C_{D_o}	Wetted Area (m^2)
Wing	.1315	.00759	28.938
Fuselage	.0854	.00493	29.381
Vert. Tail	.0123	.00071	3.185
Horiz. Tail	.0277	.00160	6.202
Increment*	.0710	.00410	0.
Totals	.3279	.01894	67.706

*Accounts for roughness, protuberances, and cooling drag.

Breakdown is for cruise, gear and flaps up.

Altitude = 7620 m, Speed = 250 kt, Mach = .415

Reynolds number per meter = 4.59×10^6.

Cruise Drag Polar : $C_D = .0189 + .0511\,C_L^{\,2}$

C.1.3 Advanced Technology Conventional Design - 6PAXAD

Preliminary sizing is analogous to that of 6PAXBL (see Eq. C.5 and C.6). The methods of Reference 134 were used to account for composite structures as outlined below:

(1) For preliminary sizing, assume that composites result in a 16% empty weight reduction.

(2) For component weight estimation, fuselage, wing, and empennage weights are reduced by 25% through use of composite materials.

Applying (1) above and Equations C.5 and C.6 resulted in the following preliminary weight breakdown:

$W_E = 648$ kg	$W_P = 545$ kg
$W_f = 101$ kg	$W_G = 1294$ kg

GASP was used for final sizing as discussed previously for 6PAXBL. Tables C.3 and C.4 present the final weight and drag breakdowns for 6PAXAD.

C.1.4 Advanced Technology Canard Design - 6PAXC

Due to problems discussed in Chapter 5, the design of 6PAXC did not proceed beyond the preliminary sizing stage. Based on limited analysis, the following conclusions were made:

(1) Wetted area appears to be less than that of 6PAXAD. Hence, C_{D_o} may be expected to be slightly smaller.

(2) Structural weights are expected to be similar or slightly less than those of 6PAXAD.

(3) Feasibility (from a trim standpoint) of full span flaps on the main wing is unknown.

(4) In view of items 1 and 2, and assuming full span flaps are feasible, the performance and efficiency characteristics of 6PAXC are expected to be similar to or better than those of 6PAXAD.

C.1.5 Tail Sizing Computer Program

A short program was written to aid in horizontal tail sizing. The program requires aerodynamic, geometric, and weight inputs to compute horizontal tail area and weight (for conventional or

Table C.3. 6PAXAD Weight Breakdown

Group	Item	Weight (kg) / (lb)
Propulsion	Engine (dry)	92.1 / 203
	Engine Installation	25.9 / 57
	Fuel System	7.7 / 17
	Propeller	26.3 / 58
Structures & Miscellaneous	Wing	62.1 / 137
	Horizontal Tail	12.7 / 28
	Vertical Tail	6.8 / 15
	Fuselage	127.0 / 280
	Landing Gear	43.5 / 96
	Battery & Wiring	22.7 / 50
Flight Controls & Fixed Equipment	Surface Controls	50.8 / 112
	Avionics & Instrumentation	33.1 / 73
	Seats & Furnishings	71.7 / 158

Empty Weight = 582.0 kg (1283 lb)

Payload Weight = 544.3 kg (1200 lb)

Fuel Weight = 132.5 kg (292 lb)

Gross Weight = 1258.7 kg (2775 lb)

Table C.4. 6PAXAD Drag Breakdown

Item	Flatplate Area (m^2)	C_{D_o}	Wetted Area (m^2)
Wing	.0494	.00862	8.883
Fuselage	.0801	.01397	25.842
Vert. Tail	.0099	.00173	3.347
Horiz. Tail	.0156	.00273	3.223
Increment*	.0086	.00150	0.
Totals	.1636	.02856	40.367

*Accounts for roughness and protuberances. Cooling Drag is assumed negligible for liquid cooled engine.

Breakdown is for cruise, gear and flaps up.

Altitude = 9140 m Speed = 250 kt, Mach = .424

Reynolds number per meter = 3.94×10^6

Cruise Drag Polar: $C_D = .0286 + .0408\, C_L^{\,2}$

composite materials) to meet static margin and/or rotation requirements.

Static margin and rotation requirements are based on the methods of References 174 and 180.

In running the program, the operator has the following options:

(1) Fix main gear location or locate main gear 15° (from the vertical) aft of the computed center of gravity.

(2) **No tail sizing; compute input characteristics.**

(3) **Size tail for static margin requirement only.**

(4) **Size tail for rotation requirement only.**

(5) **Size tail for the critical requirement.**

Generally, a static margin of at least .10 ($dC_m/dC_L \leq -.10$) and rotation at or below 120% of the stall speed ($V_R \leq 1.2\ V_s$) were required.

C.2 COMMUTER DESIGN

Two aircraft were designed: an advanced technology conventional configuration and an advanced technology canard configuration. Specifications, technologies incorporated into the aircraft, and cabin layout (common to both aircraft) are detailed in Chapter 5. In addition, a baseline, current technology aircraft was analyzed for comparison with the advanced technology aircraft.

The following paragraphs discuss the parametric trade studies and the three commuter aircraft that were synthesized and/or analyzed.

C.2.1 Trade Studies

Two trade studies were performed covering cruise and balanced field length performance. The cruise trade studies are not covered in this section and the reader is referred to Section C.1 for their derivation.

The Balanced Field Length (BFL) trades were developed to illustrate the effects of effective power loading (η_p P/W), maximum lift in takeoff configuration ($C_{L_{max_{TO}}}$), zero lift drag coefficient (C_{D_o}), effective aspect ratio (Ae), and wing loading (W/S) on BFL. The relationship for these factors is presented in Equation C.7 and was derived from the approximations of Reference 214.

$$BF = \left\{ \frac{.863}{1 + 13.69\left\{ \frac{\eta_p P}{W} \times \frac{109.3}{\left(\frac{W}{S} \times \frac{1}{C_{L_{max_{TO}}}}\right)^{\frac{1}{2}}} - .242\left\{ \frac{C_{D_o}}{C_{L_{max_{TO}}}} \right\} - .1166\,\frac{C_{L_{max_{TO}}}}{\pi Ae} \right\}} \right\}$$

$$\times \left\{ \left(\frac{W}{S}\right) \left\{ \frac{.120}{C_{L_{max_{TO}}}} \right\} + 10.7 \right\}$$

$$\times \left\{ 2.7 + \left(\frac{1}{\frac{\eta_p P}{W} - \frac{459.9}{\left(\frac{W}{S} \times \frac{1}{C_{L_{max_{TO}}}}\right)^{\frac{1}{2}}} - \left(.02 + .72\,\frac{C_{D_o}}{C_{L_{max_{TO}}}}\right)} \right) \right\}$$

$$+ \quad 199.6 \qquad \text{(C.7)}$$

for sea level standard conditions (ISA)

concrete runway (μ = .02)

W/S in N/m^2.

η_p P/W in kw/kg.

BFL in m.

Calculations indicated that variations in Ae and C_{D_o} had little effect on BFL. The final plots were constructed with Ae and C_{D_o} held constant.

C.2.2 Current Technology Configuration - COMBL

The drag and weight routines of GASP were calibrated to known or predicted characteristics of COMBL, an existing commuter aircraft. This was done by iterating over a set of input values until the desired outcome was obtained. The existing propulsion characteristics of the aircraft were also input into the program. Table C.5 presents the final weight breakdown for COMBL, while Table C.6 presents the final drag breakdown for the aircraft.

C.2.3 Advanced Technology Conventional Configuration - ADCOM

Development of ADCOM proceeded as outlined for 6PAXAD in Section C.1.3, with the exception that only engine sizing was allowed in the GASP analysis. The final weight breakdown and the final drag breakdown appear in Tables C.7 and C.8 respectively.

C.2.4 Advanced Technology Canard Configuration - ADCOMCN

Because of the canard analysis problems discussed in Chapter 5, developmental work on ADCOMCN was halted after preliminary sizing. The following conclusions can be made based on limited

Table C.5. COMBL Weight Breakdown

Group	Item	Weight (kg) / (lb)
Propulsion	Engine (dry)	325 / 716
	Engine Installation	116 / 256
	Fuel System	24 / 53
	Propellers	137 / 303
Structures & Miscellaneous	Wing	620 /1367
	Horizontal Tail	89 / 196
	Vertical Tail	70 / 154
	Fuselage	685 /1443
	Landing Gear	283 / 623
	Engine Section	186 / 411
Flight Controls & Fixed Equipment	Cockpit Controls	14 / 31
	Fixed Wing Controls	65 / 144
	Fixed Equipment	796 /1753

Empty Weight = 3363 kg (7450 lb)

Operational Items (includes crew) = 311 kg (686 lb)

Max Payload Weight = 1994 kg (4395 lb)

Max Fuel Weight = 1970 kg (4342 lb)

Gross Weight (Design) = 5670 kg (12500 lb)

Gross Weight (multi-mission) = 6350 kg (14000 lb)

Table C.6. COMBL Drag Breakdown

Item	Flatplate Area (m^2)	C_{D_o}	Wetted Area (m^2)
Wing	.1971	.00764	43.114
Fuselage	.2539	.00985	80.530
Vert. Tail	.0325	.00126	10.025
Horiz. Tail	.0465	.00181	12.843
Engine Nacelles	.0768	.00298	18.729
Increment*	.0410	.00159	0.
Totals	.6478	.02513	165.241

*Accounts for roughness and protuberances.

Breakdown is for cruise, gear and flaps up.

Altitude = 3050 m, Speed = 250 kt, Mach = .4

Reynolds number per meter = 7.034×10^6

Cruise Drag Polar: $C_D = .0251 + .0511\, C_L^2$

preliminary analysis of the configuration:

(1) Wetted area is approximately the same as ADCOM, and therefore the drag characteristics are anticipated to be approximately the same.

(2) Both configurations are characterized by essentially identical weights. Wing sweep and landing gear location cause the basic structural weight differences.

Table C.7. ADCOM Weight Breakdown

Group	Item	Weight (kg) / (lb)
Propulsion	Engines (dry)	278 / 613
	Engine Installations[1]	63 / 139
	Fuel System	143 / 315
	Propellers	189 / 417
Structures & Miscellaneous	Wing	284 / 627
	Horizontal Tail	36 / 80
	Vertical Tail	16 / 35
	Fuselage	854 / 1883
	Landing Gear	308 / 679
	Systems[2]	210 / 463
Flight Controls & Fixed Equipment	Flight Controls	135 / 298
	Cockpit Accomodations	136 / 300
	Fixed Equipment[3]	405 / 893

Empty Weight = 3058 kg (6742 lb)

Operational Items (includes crew) = 273 kg (601 lb)

Max Payload Weight = 1723 kg (3800 lb)

Max Fuel Weight = 908 kg (2002 lb)

Gross Weight = 5706 kg (12580 lb)

1. includes engine mount and accessories.
2. includes hydraulic, electrical, and airconditioning systems.
3. includes cabin furnishings and emergency equipment.

Table C.8. ADCOM Drag Breakdown

Item	Flatplate Area (m^2)	C_{D_o}	Wetted Area (m^2)
Wing	.1525	.00887	28.726
Fuselage	.2075	.01207	91.856
Vert. Tail	.0314	.00183	9.415
Horiz. Tail	.0172	.00154	6.488
Increment*	.0431	.00251	0.
Total	.4610	.02682	136.485

*Accounts for roughness and protuberances.

Breakdown is for cruise, gear and flaps up.

Altitude = 3050 m, Speed = 250 kt, Mach = .4

Reynolds number per meter = 7.034×10^6.

Cruise Drag Polar: $C_D = .0268 + .0376\ C_L^2$

(3) Trim problems with full span flap deflection may exist. This is an area that merits more research.

C.3 RANGE FACTOR PARAMETRIC ANALYSIS

The Range Factor (RF) gives a useful measure of an airplane's cruise efficiency and utility in terms of kilogram (payload) kilometers per liter.

Equations C.5 and C.6 from Section C.1 can be combined to give an expression for fuel weight required as given by Equation C.8.

$$W_f = W_p \left\{ \frac{e^x - 1}{1 - (\frac{W_E}{W_G})\, e^x} \right\} \tag{C.8}$$

$$\text{where } x = \left\{ \frac{R\ (\frac{sfc}{\eta_p})}{198.10\ (\frac{L}{D})} \right\}$$

for R in nm

W_p in kg

sfc in kg/kw/hr

W_f in kg

Next, an expression for L/D is obtained as given by Equation C.9:

$$\frac{L}{D} = \frac{.0085\ \pi\ \rho\ V^2\ (Ae)\ (\frac{W}{S})}{.0418\ \pi\ \rho^2\ V^4\ (Ae) C_{D_o} + .0017\ (\frac{W}{S})^2} \tag{C.9}$$

for ρ in kg sec^2/m^4

V in m/s

W/S in N/m^2

RF is defined by Equation C.10 and is expressed in terms of airplane and mission parameters by combining Equations C.8 and C.9 as given by Equation C.11.

$$RF = W_p \, R \left(\frac{.705}{W_f}\right) \qquad \text{(C.10)}$$

for RF in kg-nm/liter

R in nm

W_p in kg

W_f in kg

$$RF = .705 \; R \left\{ \frac{1 - \left(\frac{W_E}{W_G}\right) e^x}{e^x - 1} \right\} \qquad \text{(C.11)}$$

$$\text{where} \quad x = \frac{\frac{sfc}{\eta_p} \; .0418 \left\{ \pi \rho^2 V^4 (Ae) \, C_{D_o} + .0017 \left(\frac{W}{S}\right)^2 \right\} R}{1.6934 \; \pi \rho V^2 (Ae) \left(\frac{W}{S}\right)}$$

for RF in kg-nm/liter

V in m/s

R in nm

W/S in N/m^2

ρ in kg sec^2/m^4

sfc in kg/kw/hr

Note: (1) valid for cruise flight only

(2) R is usually expressed as a fixed range (R_f) plus 45 minutes reserve: $R = R_f + .75 V$