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Systems Study of Transport Aircraft Incorporating Advanced Aluminum Alloys — Final Report

I. Frank Sakata

LOCKHEED-CALIFORNIA COMPANY
BURBANK, CALIFORNIA

CONTRACT NAS1-16434
January 1982

National Aeronautics and
Space Administration

Langley Research Center
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FOREWORD

This is the final report of the program completed by the Lockheed-California Company, "Systems Study of Transport Aircraft Incorporating Advanced Aluminum Alloys," which was conducted from October 1980 through September 1981.

The study was performed under the direction of the Structures Division of the Lockheed-California Company for the NASA-Langley Research Center, Hampton, Virginia. The study was coordinated with and supported by Lockheed's Advanced Technology Aircraft Program.

The engineering project leader for Lockheed was I. Frank Sakata. Other major contributors were:

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A.P. Hays	ATX-350I Aircraft
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G.G. Wald	Materials and Processes
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R.L. Caruthers	Advanced Structures
R.N. Levin	Advanced Structures
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E.C. Olson	Cessna Aircraft Company

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SYSTEMS STUDY OF TRANSPORT AIRCRAFT INCORPORATING ADVANCED ALUMINUM ALLOYS

I. Frank Sakata

Lockheed-California Company

SUMMARY

This report describes the findings of a study conducted by the Lockheed-California Company for the National Aeronautics and Space Administration (NASA), Langley Research Center under Contract NAS1-16434. The study program reported herein identified weight and economic benefits that might result from the incorporation of advanced aluminum alloys in future commercial aircraft. The study utilized aircraft configured considering fuel-efficient technologies that could reasonably be available in new aircraft with a 1990 in-service date. A long-range advanced trijet, a short-medium range advanced twinjet, and a short-haul supercommuter aircraft were used for the investigation. Structural weight savings of 16 percent and an annual operational cost savings in excess of one-million dollars per aircraft were shown for the long-range aircraft using a fuel price of $\$264/m^3$ (\$1.00/gal). Fuel prices of $\$528/m^3$ (\$2.00/gal) and $\$792/m^3$ (\$3.00/gal) were also considered in the economic analyses. Comparable savings were also realized for the short-medium range and short-haul supercommuter aircraft.

An estimate of the demand for the new powder metallurgy (PM) and ingot metallurgy (IM) aluminum alloy products was made. The estimate was based on projected market factors for various classes of commercial transport aircraft, general aviation aircraft, military aircraft and air/intermodal container applications. The estimated demand for PM billet amounted to nearly 20 Gg (44×10^6 lb) per year. The market demand for ingot alloys was approximately 50 percent of the PM billet demands. Capital investment in PM billet production facilities and atomizing facilities is required to meet the market demands. Substantial capital investment in ingot casting facilities and casting technology development are also anticipated. However, it is felt that the advanced IM aluminum-lithium alloys will be developed by the aluminum industry without government funding.

A material and structural technology development program was defined to guide a systematic development of new alloys to a viable production capability. The estimated cost to develop two advanced PM alloys over a five-year time span is 150 equivalent man-years.

Early initiation of critical and long lead time development efforts are recommended, including: (1) an improved toughness PM alloy for damage tolerant design, (2) large PM compacts and (3) sheet and plate PM product forms for fuselage and lower skin applications.

INTRODUCTION

For several decades high strength wrought aluminum alloys have been widely used by the air transport industry in airframe structures applications. Significant advances have been made in materials and temper conditions with high resistance to corrosion; i.e., high-strength clad plate for wing skins, precision forgings with desirable grain flow, and exfoliation and stress corrosion resistant 7075-T76 and T73 products. Lockheed pioneered the development of the latter optimized overaged tempers which offered improved stress corrosion and exfoliation resistance. The use of these alloys, however, has resulted in some weight penalties because of reductions in strength properties. The projected fuel costs and fuel availability require the incorporation of energy-efficient technologies into the next generation transport aircraft. This demand necessitates improved performance and better structural reliability in advanced aircraft structures. There is a need for alloys that combine high strength, low density, and high modulus of elasticity with improved toughness, corrosion, and fatigue properties.

A number of alloy development programs have been and are being conducted to study the feasibility of improving aluminum alloys for aerospace applications. Ingot metallurgy (IM), with appropriate thermomechanical processing, and powder metallurgy (PM) techniques, using selected consolidation and processing conditions, are being investigated.

The study program reported herein was conducted to quantify the potential benefits of utilizing advanced aluminum alloys in commercial transport aircraft and to define the effort necessary to fully develop the alloys to a viable commercial production capability. The comprehensive investigation: (1) established realistic advanced aluminum alloy material property goals, in coordination with the Aluminum Company of America (Alcoa), to maximize aircraft system effectiveness; (2) identified performance and economic benefits of incorporating the advanced alloys in future commercial aircraft; (3) provided a plan for the development and integration of the alloys into commercial aircraft production; (4) provided an indication of the timing and investment required by the metal producing industry to support the projected markets; and (5) evaluated application of advanced aluminum alloys to other aerospace and transit systems. The results of the investigation provide a roadmap and identifies key issues requiring attention in an advanced aluminum alloy and applications technology development program.

The benefits resulting from the incorporation of advanced aluminum alloys were determined for selected reference aircraft. These aircraft were configured considering fuel-efficient technologies that could be reasonably expected to be available in new aircraft with a 1990 in-service date. A long-range advanced trijet, a short-medium range advanced twinjet, and a modern energy-efficient supercommuter aircraft were used for the investigation. The weight and economic benefits for these aircraft were determined, with and without incorporation of the advanced aluminum alloys. The application of the advanced aluminum alloys to the airframe, based on appropriate component design criteria, resulted in a structural weight savings of 16, 15, and 10 percent for the long-range, short-medium range and supercommuter aircraft, respectively.

The development and production costs remained invariant because of the compensating effect between weight saved and material cost increases; however, the block fuel usage varied from 8 to 3 percent, depending on the aircraft size. Significant reduction in operational costs was noted. The annual savings from the application of the new materials to one long-range aircraft is in excess of one-million dollars. An airline operator with 23 of these long-range transport aircraft can save $24.5 million dollars annually. This annual cost savings was based on a fuel price of $264/m^3 ($1.00/gal) and an average stage length of 4630 km (2500 n.mi). Comparable savings in operational costs were realized for the short-medium range of supercommuter aircraft. Alternate fuel prices were also considered.

An estimate of PM products was made. The manufactured weight of PM products by the producer to meet the purchased weight required by the airframe manufacturer was determined. The yearly PM production capacity was obtained assuming a 50 percent recovery from billet and that the total volume is distributed evenly over 15 years from 1990-2005. The estimated yearly capacity of PM billet amounted to 20 Gg (44 x 10^6 lb) per year. Existing plans for PM billet capacity are based on smaller numbers. The primary limitation posed by the estimates are billet volume. Capital investment in billet production facilities and possibly atomizing facilities will be required to meet such production. Due to the uncertainty of the estimated volume, the exact size of such capital investment is not yet determined. The largest required volume of product form occurs in plate and sheet. The plate and sheet capacity will require development of a PM billet of at least 2700 - 3600 kg (6000 - 8000 lb). Plate and sheet availability is targeted by Alcoa for a 1985-86 time period.

In addition, two ingot alloys are considered on the basis of cost and properties. The market for these alloys, designated as IM Advanced 2020-T6 and IM Al-Li-X, are 7 Gg (15 x 10^6 lb) and 2 Gg (3 x 10^6 lb), respectively. Alcoa envisages a need for substantial capital investment in ingot casting facilities and casting technology development. It is also Alcoa's opinion that such capital investment would be made by the aluminum industry without government funding.

A multiyear material and structural technology development program was defined. The program spans a five-year period and encompasses: (1) alloy and product development; (2) mill and fabrication process development; (3) material design data development; and (4) structural design development. The estimate cost for the technology development is 150 equivalent man-years. In order to introduce a new aircraft into service in 1990, the production program must be initiated in the mid-1980s. The advanced aluminum alloy applications development must be systematically carried out prior to the production commitment date. Therefore, the necessary material property data must be available in a timely manner so that the new materials and processes can be incorporated with confidence into the next generation's economically viable transport aircraft.

Use of commercial products or names of Manufacturers in this report does not constitute official endorsement of such products or Manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

1. MATERIAL PROPERTIES

Aluminum alloy products are a substantial portion of the commercial transport aircraft airframe weight, and the airframe manufacturers have years of aluminum experience and are completely tooled to effectively produce aluminum structures. Therefore, continuing research for advancing the aluminum alloy performance characteristics is of prime concern to airframe manufacturers. The current aluminum alloys represent the continued development of ingot metallurgy (IM) and processing techniques to provide specific property needs. However, the overall combination of properties associated with a particular alloy/product/temper are generally not optimum. For example, the high strength alloy conditions are associated with low toughness and poor stress corrosion properties. To improve stress-corrosion behavior or to increase toughness, an overaged condition is often used. This overaged condition reduces the strength of the material thereby requiring additional material and resulting in increased structural weight. When current alloys are tailored to provide durability and damage-tol~~rant~~erant designs, then compromises must be made to satisfy crack growth and toughness requirements which, in turn, penalizes the overall design with a weight increase. Similarly, the density and stiffness of aluminum alloys have limited their competitiveness in stiffness-critical and minimum-gage designs.

During the past several decades, the improvements on the 2000 and 7000 series aluminum alloy systems have provided a technology base in the areas of stress corrosion cracking resistance, toughness, fatigue, and fatigue-crack growth. Through alloy modifications, along with development of high purity alloys and thermomechanical processing, improvements have been made providing a better combination of strength, corrosion resistance, toughness and fatigue properties.

Development activity on Al-Li-Mg alloy systems by Aluminum Company of America (Alcoa) (References 1, 2) and the British Aluminium Company has resulted in development of production ingot casting procedures and alloy compositions for lower density aluminum alloys with usable strength/weight/stiffness properties. Research by DARPA/Air Force on rapid solidification rate (RSR) powder metallurgy (PM) Al-Li-Cu and Al-Li-Cu-Mg alloy systems and research by three United Kingdom Universities, i.e., British Fulmer Institute, University of Cambridge, and University of Nottingham have demonstrated the potential for development of low density alloy systems with superior strength, modulus, toughness, and corrosion resistance properties. Although the current emphasis is on RSR PM alloys, the nature of the alloy systems suggest that IM technology could be applied and research along these lines could be initiated with a high probability of success.

Another major development area has been the powder metallurgy (PM) approach combined with air and inert gas atomization, rapid solidification rate (RSR) technology and high energy mechanical alloying systems. These PM studies have encompassed both intensive alloy/process development activity under Frankford Arsenal, Philadelphia, Pennsylvania, sponsorship, and scale up from 23 to 68 to 1360 kg (50 to 150 to 3000 lb) billets with production of plate, extruded, and forged products. A major finding of this program included process development permitting significant improvements in strength-toughness, strength-corrosion resistance and fatigue properties.

As evidence of these new developments (reference 3) the following is presented:

- The repeatability of producing the PM aluminum alloys has been demonstrated by the commercialization of CT-91, now designated as alloy X7091.
- The commercial PM alloy X7091, when compared to 7XXX series ingot material, has improved properties and characteristics.
- X7091 has a 69 to 103 MPa (10 to 15 ksi) higher yield strength than 7XXX series aluminum alloys.
- Notched axial fatigue strength of X7091 exhibits higher maximum allowable stress than 7050, 7075, and 2024 aluminum alloys at 10^6 and greater cycles.
- Improved strength-toughness relationship for X7091 versus several of the 7XXX series IM alloys is illustrated in figure 1. Typical fracture toughness versus yield strength of high strength aluminum alloy extruded shapes 6.4 mm to 38.1 mm (0.25 in. to 1.50 in.) thickness.
- X7091 alloy is available in billets up to 160 kg (350 lb) for fabrication into extrusion and forgings. The material is not available from Alcoa as rolled plate or sheet.

In recent years, as noted above, advances in aluminum technology have offered a variety of approaches for resolving some of these classic problems, including compositional controls, thermomechanical processing, powder metallurgy, and new alloys systems. Increased strength capability of PM alloys with high resistance to exfolitation, as compared to IM alloys, has been demonstrated by Alcoa (reference 3) as shown in figure 2.

These advancements in aluminum making technology provide a sound basis for development of a family of aluminum alloys with superior combinations of strength, stiffness, toughness, fatigue, and corrosion resistance characteristics along with low density so as to provide tailored metals displaying best cost/weight payoffs for specific design applications. This program defines property goals for such a family of alloys for integration into production application on advanced commercial transport aircraft entering service in 1990.

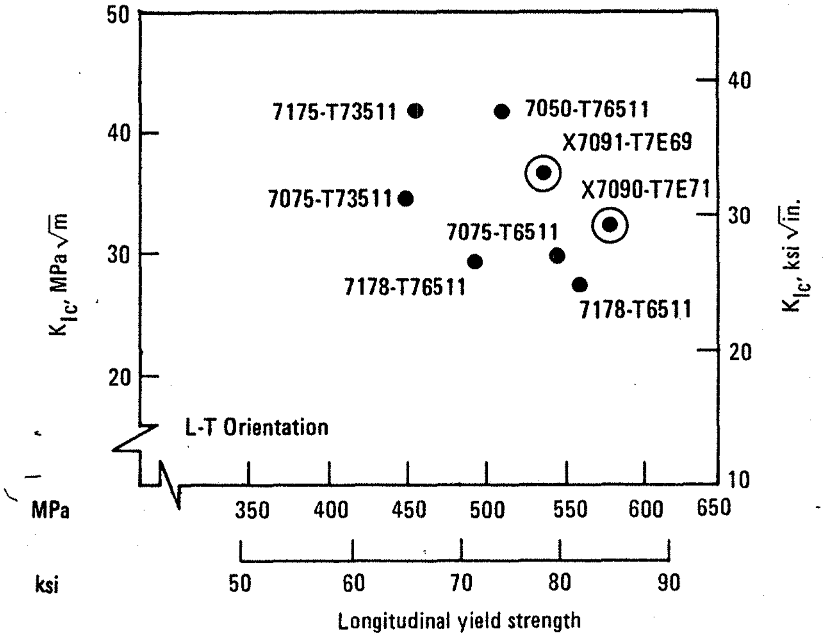


Figure 1. - Typical fracture toughness vs yield strength for high strength aluminum alloy extruded shapes, 6.4 mm (0.25 in.) to 38.1 mm (1.50 in.) thickness.

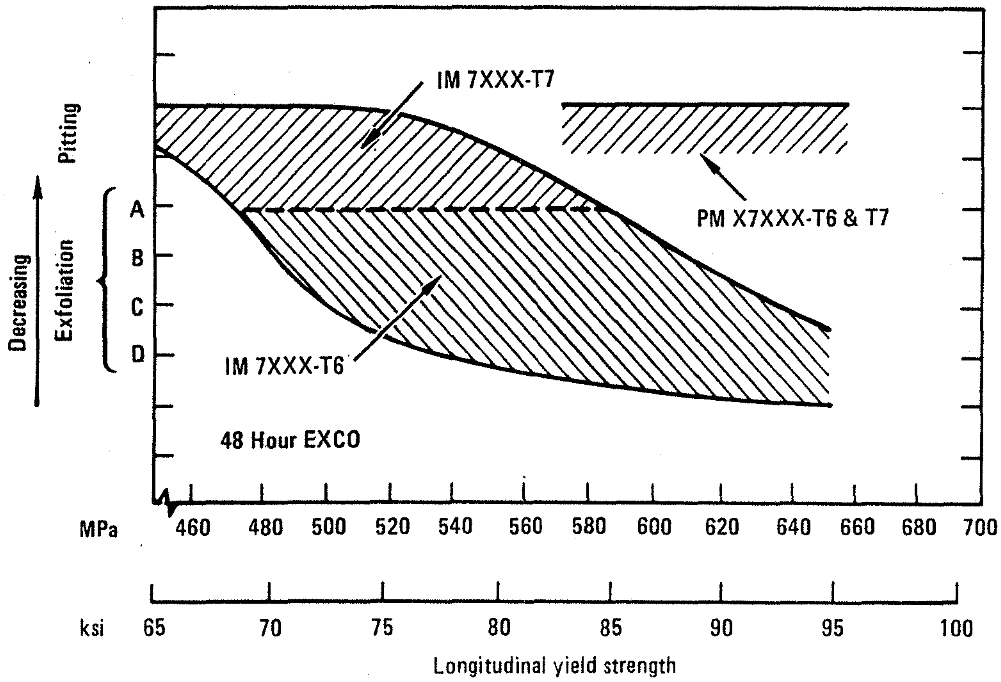


Figure 2. - Strength - exfoliation IM vs PM 7XXX extrusions.

1.1 Component Design Criteria

Major benefits for new commercial transport aircraft structures in terms of weight savings, performance, and direct operating cost reductions are anticipated from the implementation of advanced aluminum alloys. To obtain the maximum benefit of weight savings from these potentially available new materials, it is essential that the design criteria (both primary and secondary failure modes) for the specific airframe components be known. The design requirements and major applications of various product forms to commercial transport aircraft are shown in table 1 reflecting weight and cost considerations. Methodology for predicting weight savings resulting from material property substitution for specific airframe components has been developed considering primary and secondary failure modes (reference 4). Methodology for the assessment of aeroelastic effects of high aspect ratio wing configuration designs needs further development.

The wing, body, and tail comprise the major airframe components which utilize significant amounts of aluminum alloy in their construction. Some of the aluminum alloys used on commercial transport aircraft are shown in table 2. Aluminum alloys 2024 and 7075 are used for the majority of components. Alloy 2024 is used in the T3 and T4 conditions for applications which are not strength critical or require damage tolerance such as fuselage skins. Alloy 7075 is used in the T6 condition for strength critical applications where poor corrosion resistance can be tolerated and controlled. For increased corrosion resistance, 7075 is used in the T76 and T73 stabilized tempers at a

TABLE 1. - ALUMINUM ALLOY APPLICATIONS AND REQUIREMENTS FOR TRANSPORT AIRCRAFT

Product Form	Application	Design Requirements
Sheet, plate	Upper wing skin	Compressive strength, stiffness, exfoliation and stress corrosion resistance
Sheet, plate	Lower wing skin Fuselage skin	Strength, stiffness, exfoliation and stress corrosion resistance, fatigue strength, fatigue crack propagation resistance, fracture toughness
Sheet, plate, extrusions, forgings	Stringers, frames, spars, spar caps and webs	Strength, stiffness, stress corrosion resistance; fatigue strength (except webs); fatigue crack propagation resistance (stringers, frames)
Plate, extrusions, precision forgings	Rib and rib caps	Strength, stiffness, stress corrosion resistance
Plate, precision forgings and heavy forgings	Bulkheads, fittings, landing gear components (forgings)	Strength, stiffness, fatigue strength, stress corrosion resistance; fatigue crack propagation resistance, fracture toughness (bulkheads)

TABLE 2. - ALUMINUM ALLOY USAGE IN COMMERCIAL TRANSPORT AIRCRAFT

Aircraft	Fuselage		Wing			Tail	
	Skin (1)	Stringer (1)	Location	Skin	Stringer	Vertical Skin (1)	Horizontal Skin
L-1011	2024-T3	7075-T6	Upper Lower	7075-T76 (2) 7075-T76(2)	7075-T6 7075-T6	7075-T6	7075-T76
DC-9-80	2024-T3	7075-T6	Upper Lower	7075-T6 2024-T3	7075-T6 2024-T3	7075-T6	7075-T73
DC-10	2024-T3	7075-T6	Upper Lower	7075-T6 2024-T3	7075-T6 7075-T6	7075-T6	7075-T6
B-737	2024-T3	7075-T6	Upper Lower	7178-T6 2024-T3	7178-T6 2024-T3	7075-T6	7075-T6
B-727	2024-T3	7075-T6	Upper Lower	7075-T6 2024-T3	7075-T6 2024-T3	7075-T6	7075-T6
B-747	2024-T3	7075-T6	Upper Lower	7075-T6 2024-T3	7075-T6 2024-T3	7075-T6	7075-T6
B-757	2024-T3	7075-T6	Upper Lower	7150-T6 2324-T39	7150-T6 2224-T3	7075-T76	2024-T3(U) 7075-T6(L)
B-767	2024-T3	7075-T6	Upper Lower	7150-T6 2324-T39	7150-T6 2224-T3 and 2324-T39	7075-T6	7075-T6
A300	2024-T3	7075-T6	Upper Lower	7075-T6 2024-T3	7075-T6 2024-T3	2024-T3	7075-T6

Notes: (1) Clad (U) Upper
(2) High Strength Clad (L) Lower

sacrifice in tensile strength. However, while both 2024 and 7075 have been used for years on commercial aircraft, the trend for new design is to develop and use alloys with improved properties. The new generation Boeing aircraft are using 7150-T6, 2324-T39 and 2224-T3 ingot alloys which have improved strength and fracture toughness than comparable 7075 and 2024 alloys. The next step is to exploit the advantages of powder metallurgy materials and advanced technology ingot alloys.

The L-1011 transport, which represents a conventional technology wide-body aircraft, was used in this study to guide the selection of target properties for the various alloys and product forms required for future transport aircraft airframe construction. Aluminum alloy applications to this aircraft are highlighted in figure 3 as a benchmark for consideration of anticipated aluminum improvements. The basic materials and applications are presented in table 3 in terms of alloy and product form. Clad 2024-T3 aluminum alloy is

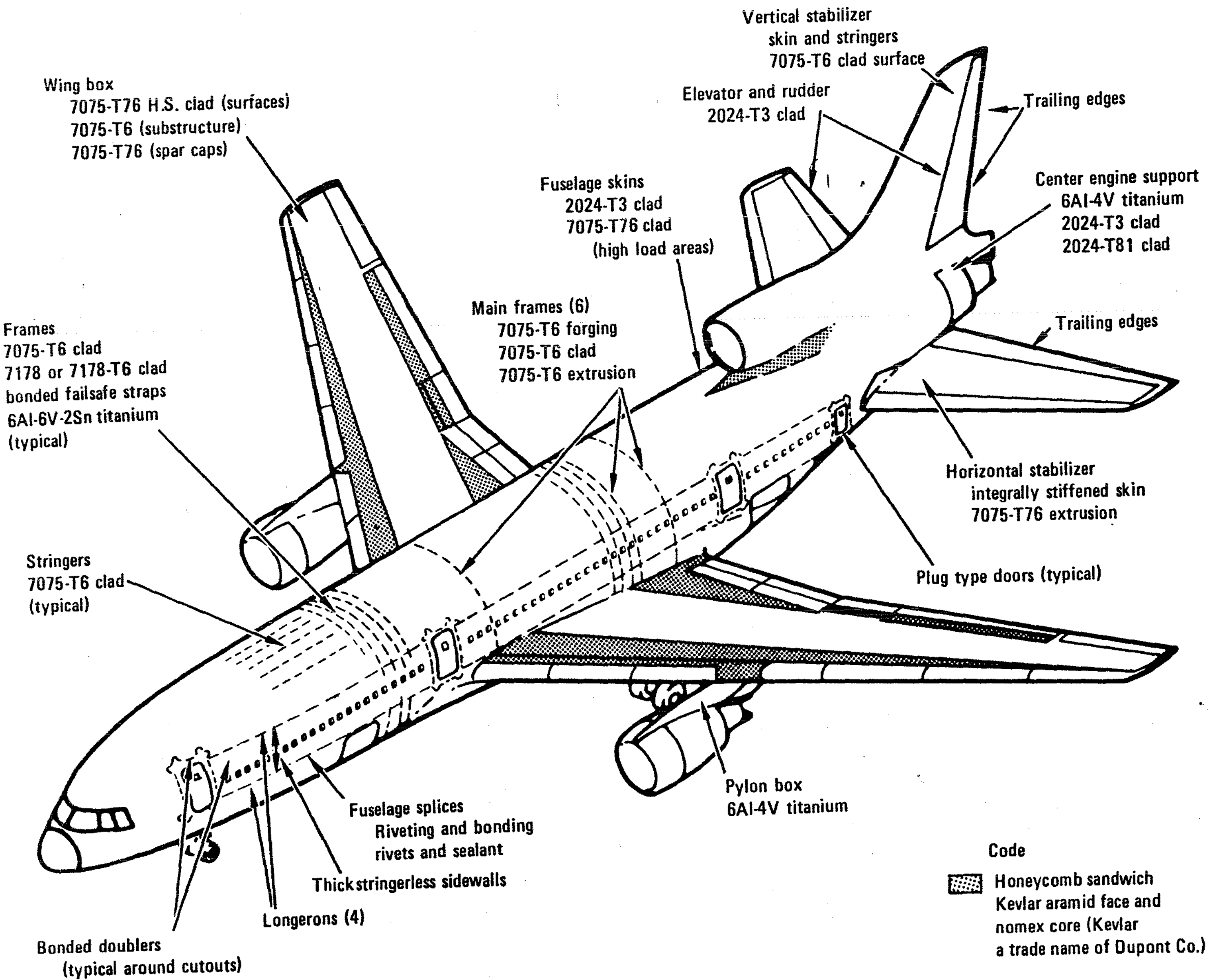


Figure 3. - Basic materials and design features of commercial transport aircraft.

TABLE 3. - BASIC MATERIALS AND APPLICATIONS

MATERIAL		CHARACTERISTICS	TYPICAL APPLICATIONS
7075-T6	Plate	Highest strength with acceptable toughness.	Used in highly loaded structure; where corrosive environment is not extreme in the case of bare material.
	Extrusions		
	Clad Sheet		
7075-T76	Extrusions	High strength (close to 7075-T6). Good toughness properties combined with high resistance to exfoliation and stress corrosion.	Plate with high strength clad used for wing skins. Used in applications where high strength is required as well as resistance to exfoliation and stress corrosion.
	Clad Sheet		
	Plate with High Strength Clad		
7075-T73	Forgings	High resistance to exfoliation and stress corrosion. Good fracture toughness.	Used for parts where residual stresses could possibly be present.
2024-T3	Clad Sheet	Good strength and excellent toughness properties.	Minimum gauge skins in pressurized fuselage. Lightly loaded skins such as those on control surfaces.

used predominately for the lighter gage fuselage skin, 7075-T6 clad for the highly loaded skin areas, and 7075-T6 clad for stringers. Alloy 7075-T76 aluminum plate is used for wing skins because of the good fatigue qualities and its resistance to exfoliation and stress corrosion cracking. High strength cladding, 7008 aluminum alloy material, is also used to provide additional corrosion protection.

The aluminum product form, alloy type and design criteria for the L-1011 airframe, i.e. wing, body, tail, are presented in figure 4 and table 4 in terms of percent airframe weight:

- The product form usage with respect to the total airframe weight, i.e., wing, body, tail, is distributed as follows: (1) 33 percent sheet; (2) 17 percent plate; (3) 30 percent extrusion; and (4) 5 percent forging.

- The sheet and extruded product forms make up approximately 63 percent of the airframe weight.

- The major application of the sheet product form is on the fuselage with approximately two-thirds 7075 clad and one-third 2024 clad material.

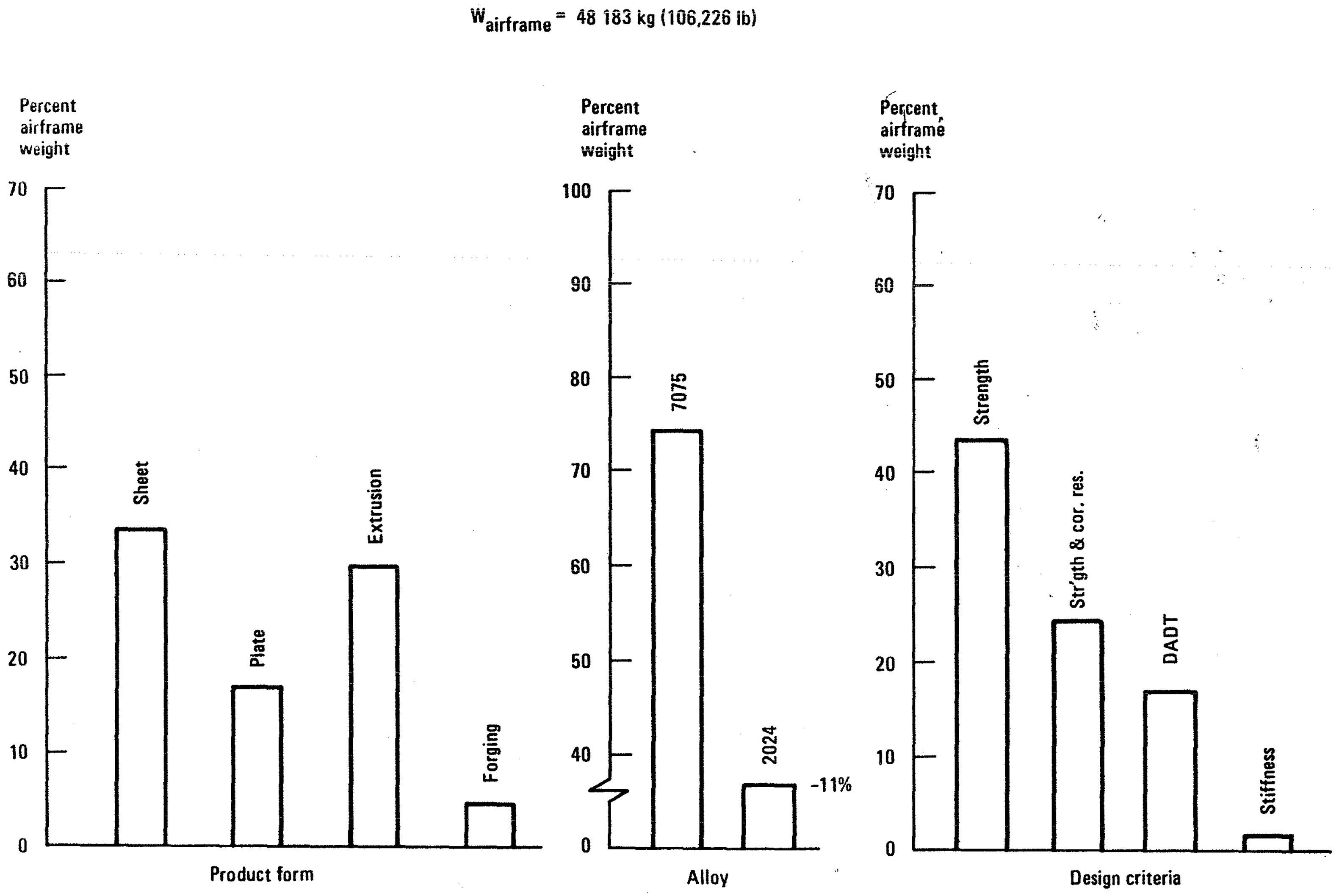


Figure 4. - Airframe product form-alloy-design criteria for transport aircraft.

TABLE 4. - BASELINE ALUMINUM ALLOYS

Requirement	Product Form	Percent Usage		Alloy-Temper
Strength	Sheet	23	43	7075-T6 Clad
	Extrusion	20		7075-T6
Strength and Corrosion Resistance	Plate	9	24	7075-T76 (HS Clad)
	Extrusion	10		7075-T76
	Forging	5		7075-T73
Durability and Damage Tolerance	Sheet	9	17	2024-T3 Clad
	Plate	8		7075-T76 (HS Clad)
Stiffness	Sheet	1	1	2024-T3 Clad
Total			85	

- The extruded product form is distributed, 12 percent to the fuselage and 14 percent to the wing.

- The 7075 alloy constitutes 74 percent and 2024 alloy is 11 percent of the airframe weight.

- The dominant design criteria for the airframe are strength, 43 percent; strength and corrosion resistance, 24 percent; and, durability and damage tolerance, 17 percent.

Sheet, plate, extruded, and forged product forms were identified for application to specific airframe components. Component design criteria, alloy types and product forms information for a representative transport aircraft were used to guide the selection of hypothetical alloys and corresponding target properties. The baseline alloys from which improvements are measured are alloys/tempers currently used on the L-1011 aircraft.

1.2 Preliminary Property Improvement Goals

The preliminary property improvement goals for the advanced aluminum alloys were developed by a survey of both alloy and process development programs, as well as programs providing insight into the interrelation of properties to microstructure to identify alloy systems and manufacturing processes of interest. A compilation of aluminum powder metallurgy development programs reviewed is given in table 5. The survey included both advanced ingot

TABLE 5. - STRUCTURAL ALUMINUM POWDER METALLURGY DEVELOPMENT

Current Program	Contract	Participants
1. Microstructure/Processing Control for Aluminum PM Wrought Products	DAAK10-79-C-0193 (Army/Alcoa)	ARRADCOM/Alcoa
2. Precision Aluminum Alloy Powder Metallurgy Structural Components	F33615-77-C-5129 (Air Force/Army/Alcoa)	Alcoa/General Dynamics, Lockheed
3. P-3 Wing Spar Cap Extrusions – Comparison of CT-91, 7075, and 7050	NADC-78185-60 (Lockheed/Navy)	Navy/Lockheed
4. Fatigue Crack Initiation and Propagation in MA87 and Related Alloys	AFOSR Grant	AFOSR/Northwestern Northwestern University
5. Fatigue Properties of CT-91 Forgings	AFOSR Grant #77-3247	AFOSR/Drexel University
6. Microstructure and Fatigue Resistance of 7XXX P/M Aluminum Alloys	–	AFML/Alcoa
7. Investigation of High Strength Alloys	Air Force	AFML
8. In-house Studies at ARRACOM	ARRACOM	Army
9. Effects of Processing and TMT on Properties of CT-91	ARRACOM	Army/Georgia Tech
10. Fatigue Properties of CT-91 Effects of Defects	Air Force/In Procurement	AFML
11. Cobalt-Free Alloys	Air Force/In Procurement	AFML
12. Low Cost Manufacturing Methods for High Strength Aluminum P/M Wrought Products	F33615-79-C-5053 (Air Force/Alcoa)	AFML/Alcoa
13. Manufacturing Technology for Mill Products	(Air Force/NOVAMET)	AFML/NOVAMET
14. Manufacturing Technology for High Strength, Aluminum, PM Mill Products	(Air Force/Reynolds)	AFML/Reynolds
15. High Strength PM Aluminum Mill Products	Air Force/In Procurement	AFML/LTM
16. Direct Rolling Powder Into a Strip	Air Force/In Procurement	AFML
17. Forming and Joining of IN-9051	(Air Force/Lockheed)	Air Force/Lockheed-Georgia
18. A Feasibility Study for Development of Structural Aluminum Alloys From Rapidly Solidified Powders for Aerospace Structural Applications	F33615-77-C-5186 (DARPA/Air Force/Lockheed)	DARPA/AFML/Lockheed Missiles and Space Co., Lockheed-California
19. Advanced Aluminum Alloys From Rapidly Solified Powders	F33615-78-C-5203 (DARPA/Air Force/Lockheed)	DARPA/Lockheed Missiles & Space, Lockheed-California
20. Microstructure and Properties of Powder-Processed Aluminum-Lithium Alloys	F49620-79-C-0039 (Air Force OSR/McDonnell Douglas)	AFOSR/McDonnell Douglass Research Laboratories
21. High Temperature Alloy Development – SCR	NAS1-14625 Mod 5 & 6 (NASA/Lockheed)	NASA Langley Research Center/Lockheed California
22. Elevated Temperature Aluminum Alloy Development	F33615-77-C-5086 (Air Force/Alcoa)	AFML/Alcoa
23. Mechanically Alloyed High Temperature Alloys	(Air Force/INCO)	AFML/INCO
24. Mechanically Alloyed Aluminum Alloy for 450-650°F Service	UC-AF-5227 (Air Force/UC)	AFML/LLS-UC
25. RSR High Temperature Alloys	DARPA/Air Force/Pratt & Whitney	DARPA/Pratt & Whitney
26. Recrystallization and Grain Growth in Aluminum P/M Alloys	DARPA/Air Force/Pratt & Whitney	AFML
27. Fundamentals of Compaction Processes for Rapidly Quenched Pre-alloyed Metal Powders	F33615-79-C-5037 (Air Force/Alcoa)	AFML/Alcoa

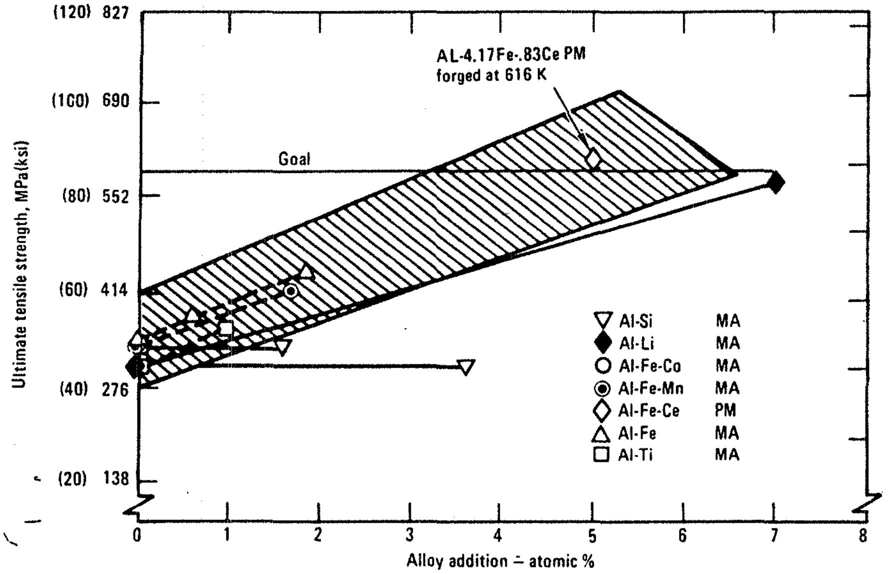
and powder metallurgy alloys (table 6). The latter PM alloys are derived using rapid solidification rate powders, powders from atomization, and mechanically alloyed powders. Both precipitation-hardened and dispersion-hardened systems were evaluated.

During the survey, property data were also reviewed to provide a data base from which to establish preliminary property improvement goals in accordance with the following:

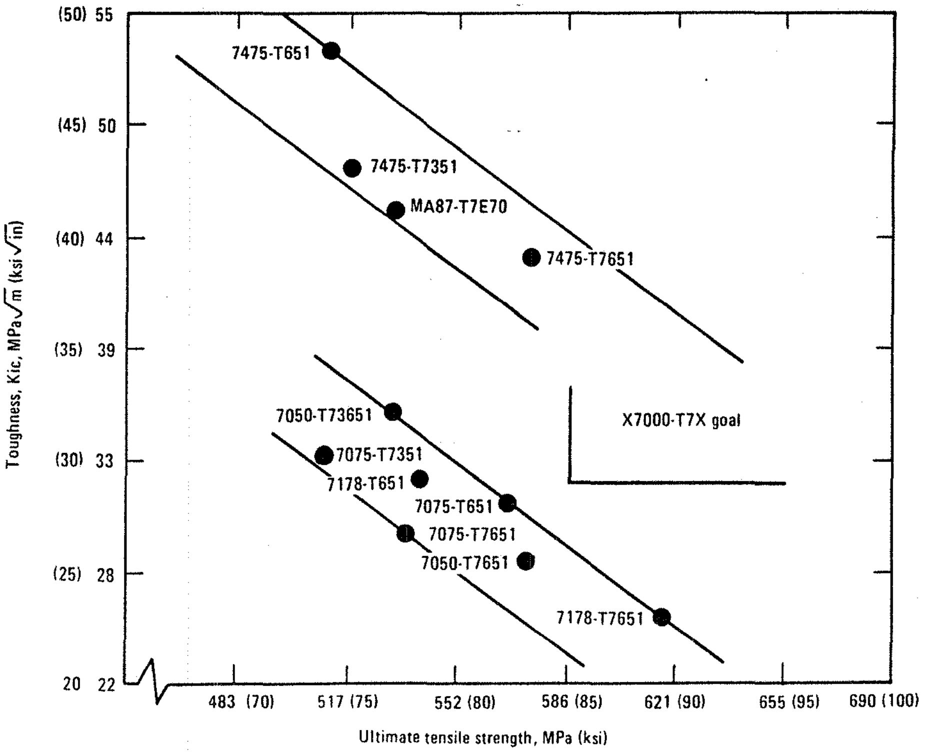
- Strength critical design. - Maximum strength attainable using PM and lithium technology consistent with corrosion and toughness requirements (see figure 5 for typical property improvement trends).
- Durability and damage tolerant design.- Maximum toughness using both IM and PM technology with control of purity, composition, microstructure, and heat treat was reviewed. The importance of mill process control is shown in figure 6. Maximum fatigue crack growth resistance (FCGR) obtained not only by control of composition and microstructure but also by use of heat treatments, optimized for FCGR rather than for

TABLE 6. - EXAMPLES OF CANDIDATE ALUMINUM ALLOYS

NEW AND IMPROVED IM COMMERCIAL ALLOYS	NEW PM ALLOYS	ADVANCED DEVELOPMENT – PM AND RSR			
		AFML/ ALCOA	NASA/ LOCKHEED-CALIFORNIA CO.	DARPA/ LOCKHEED LMSC	LOCKHEED-CALIFORNIA CO.
2114	X7090	Al-3Mn-7Co	Alcoa	LMSC	Al-Cu-Li-Zr (3 Alloys)
2124	X7091	Al-8Mn-2Co	2024	Al-3Li-4Cu + Zr	Al-Cu-Li-Mg-Zr (2 Alloys)
2224	IN9021	Al-6Mn-6Co	2024-1.5Mn	Al-3Li-2Cu + Zr	Al-Li-Mg-Zr
2324	IN9052	Al-3Fe-7Co	2618-1.5Fe - 1.5Ni	Al-3Li-4Cu + Zr or Mn	Al-Li-Zr
2048	MR61	Al-8Fe-2Co	Al-7Mn-5Cu + Cd	Al-3Li-1Zr	Al-Cu-Li-Cd-Mn
7010		Al-4Fe-4Co	Al-2.5Mn-9Cu	Al-3Li + Fe + Ni	
7175		Al-3Mn-7Ni	Inco	Al-3Li + Fe + Co	
7475		Al-8Mn-2Ni	Al-1.9Li	Alcoa	
7050		Al-4Mn-4Ni	Al-3.4Li	Al-3Fe-3Ni-3Co	
7150		Al-8Fe-4Co	Al-2Fe-1.5Mn	Al-3Fe-2Ni-4.5Co	
Al-Li		Al-8Fe - 1.5Cr	Al-3.6Fe	Al-3Fe-4.5Ni-2Co	
			Al-1.7Fe-1.8Co	Al-Fe-Ni-Co	
			Al-6Si	Al-9Mn	
			Al-1.6Si	Al-8Mn-2Si	
			Al-3.8Si	Al-5Mn-5Si	
				Al-14Mn	



(a) Effect of alloy content on strength of high strength aluminum alloys
Mechanical alloyed extrusions



(b) Fracture toughness of high strength alloys

Figure 5. - Examples of improvement in tensile strength of advanced aluminum alloys.

strength and corrosion. Maximum fatigue strength from use of PM technology as indicated by the typical property improvement trend in figure 7.

- Stiffness critical and minimum gage design. - Minimum density and maximum stiffness possible consistent with adequate strength, ductility, and toughness, were considered.

The remaining property goals were selected to be consistent with structural and environmental requirements and in accordance with the following guidelines and considerations:

- Material application to aircraft with an initial in-service date of 1990.
  - Laboratory fabrication: 1982-83 time period
  - Plant fabrication: 1984-85 time period
  - Production capability: 1985-86 time period.

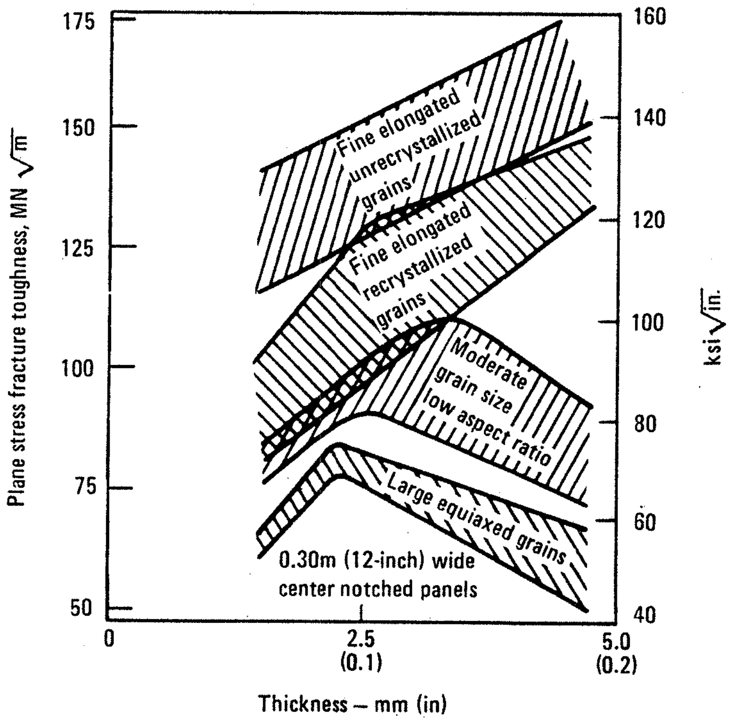
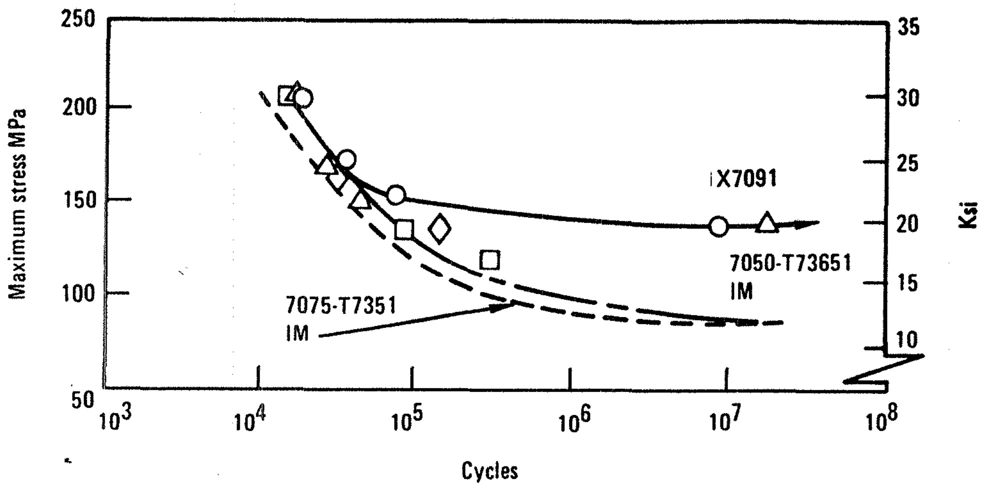
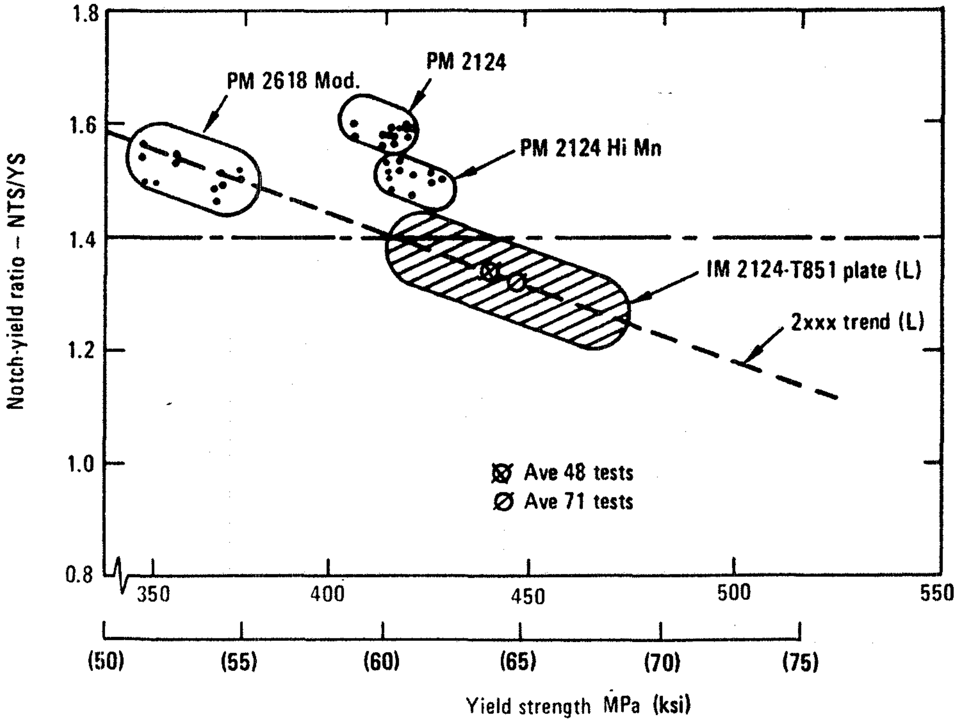


Figure 6. - Effect of mill processing on fracture toughness of 7075 sheet.



(a) Notched specimens fatigue performance of PM X7091
5-cm (2 in.) - thick plate, $K_T = 3$, $R = 0.0$, axial stress tests



(b) Notch toughness comparison of damage-tolerant aluminum alloys

Figure 7. - Examples of improvements in damage tolerant properties of advanced aluminum alloys.

TABLE 7. - PRELIMINARY MATERIAL PROPERTY GOALS

CLASSIFICATION ALLOY REQUIREMENT	ALLOY CODE	BASELINE ALLOY – PRODUCT FORM				TARGET GOALS PERCENT IMPROVEMENT
		SHEET	PLATE	EXTRUSION	FORGING	
Strength	A	7075-T6 clad	–	7075-T6	–	20-25% strength (F_{tu}, F_{ty}, F_{cy}) 20% fatigue ($K_t = 3$@ 10^5; R = 0.1). Toughness equiv. to baseline alloy
Strength and corrosion resistance	B	–	7075-T76	7075-T76	7075-T73	20-30% strength (F_{tu}, F_{ty}, F_{cy}) 20% fatigue ($K_t = 3$ @ 10^5, R = 0.1). Corrosion resistance and toughness comparable to baseline alloy
Strength, stiffness and corrosion resistance	C	–	7075-T76	7075-T76	–	10-20% strength (F_{tu}, F_{ty}, F_{cy}) 10% fatigue ($K_t = 3$ @ 10^5; R = 0.1). 8% stiffness. Corrosion resistance and toughness comparable to baseline alloy
Durability and damage tolerance	D	2024-T3 clad	2024-T3	–	–	20% fatigue ($K_t = 3$ @ 10^5, R = 0.1). 25% toughness. Corrosion resistance comparable to 7075-T76
Low density/ high stiffness	E	2024-T3 clad	–	–	–	10% fatigue ($K_t = 3$ @ 10^5, R = 0.1). 10% density (reduction). Strength comparable to baseline alloy

- Meets International Air Transport Association (IATA) corrosion objectives (reference 5)
- Meets anticipated more stringent 1990 durability and damage tolerant requirements.
- Considers impact of 1990 advanced systems technology and operational environment on relative importance of critical structural criteria
- Meets reasonable risk and cost criteria

The results of the preliminary material property assessment are summarized in table 7. The improvements are compared with baseline alloys determined from the component design criteria review of commercial transport aircraft. Five hypothetical alloys were identified to meet the requirements for future airframe design, alloys A, B, C, D, and E. The material-product form matrix for target property development of these alloys is presented in table 8.

Alloy A: The strength requirements are peculiar to sheet and extruded products. Currently, high strength 7075-T6 clad sheet and 7075-T6 extrusions make up a significant part of the airframe weight. In many instances, however, the alloy and temper are used for general applications, particularly for secondary structure because of material availability and cost. Decrease in usage will follow with the development and availability of a low density alloy system (alloy E).

Alloy B: Strength and corrosion resistance requirements are evidenced in the use of plate, extruded, and forged products. The plate application is primarily for upper wing covers. In addition to strength and corrosion resistance, the alloy system must have good toughness and high resistance to stress corrosion and exfoliation corrosion. For the upper wing skin the plate may require a compatible high strength cladding and be amenable to certain manufacturing processes (shot peen forming). Extrusions for wing beam caps or similar use where residual stresses may be induced during the manufacturing process require high strength alloys as well as resistance to stress corrosion. Forged products where residual stresses could possibly be present require good fracture toughness, high strength, and high resistance to stress and exfoliation corrosion.

TABLE 8. - MATERIAL-PRODUCT FORM MATRIX

CLASSIFICATION		PRODUCT-FORM			
ALLOY	REQUIREMENT	SHEET	PLATE	EXTRUSION	FORGING
A	Strength	X	–	X	X
B	Strength and corrosion resistance	–	X	X	X
C	Strength, stiffness and corrosion resistance	–	X	X	–
D	Durability and damage tolerance	X	X	–	–
E	Low density	X	–	–	–

Alloy C: Future needs of strength, stiffness, and corrosion resistance are indicated for advanced technology high aspect ratio wing configurations. The alloy, designated Alloy C, must be consistent with the demands of Alloy B. Plate and extruded product are identified to ensure compatibility between the cover, stringer and beam cap material. The benefit study will identify the weight benefits of Alloy B versus Alloy C.

Alloy D: Durability and damage tolerance (DADT) requirements are identified with fuselage skins (2024-T3 clad) and wing lower covers (7075-T76). The fuselage shell is designed to withstand the pressurization cycle repeatedly applied during the life of the aircraft. Low operating stresses, e.g., 100 MPa (14.5 ksi), are maintained to ensure long crack-free life. The wing lower skin is also designed to reduced values of stress to ensure adequate life. Good toughness properties, particularly at 218 K (-67°F), are essential as well as those attributes of Alloy B in terms of exfoliation and stress corrosion resistance.

Alloy E: Current aluminum alloys, regardless of the requirements noted above for specific applications, have one value for density $\rho = 0.277$ kg/cm^3 x 10^6 (0.10 lb/in^3.) The alloy has, therefore, not been competitive for certain applications. The potential availability of a low density alloy (Alloy E) with moderate strength properties, acceptable toughness, and which is fabricable, may find extensive application to secondary and small primary structures of future transport aircraft.

The detailed properties for the advanced aluminum alloys are presented for sheet, plate, extrusion and forging products in tables 9 through 12. The data are used to quantify the benefits obtained from the application of the hypothetical alloys to three future transport aircraft designs.

1.3 Final Property Goals

A set of firm property goals were defined for several selected alloys and product forms. The goals were selected for alloys exhibiting individual or combined properties that gave indications for achieving maximum systems benefits in terms of fuel efficiency and operational cost. Achieving the desired goals and priorities were estimated in coordination with Alcoa. The Alcoa research and planning inputs indicated that:

- The magnitude of expected improvement in extrusions is most probable in all categories. PM or IM methods may prove useful. In the high strength category, a low density alloy may be usable if specific strength is equally important.

- The improvements in plate products desired in Alloy B, high strength and corrosion resistance; and Alloy D, DADT; are difficult challenges due to the nature of plate fabricating and the lack of commercial availability of PM plate technology.

TABLE 9. - PRELIMINARY PROPERTY IMPROVEMENT GOALS - SHEET PRODUCT
(a) S.I. Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY D – DADT			ALLOY E – LOW DENSITY		
PROPERTY	7075–T6 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	503	25	627	428	–	428	428	–	428
F_{ty} (MPa)	448	25	559	310	–	310	310	–	310
F_{cy} (MPa)	441	25	552	255	–	255	255	22	310
E (GPa)	71	–	71	72	–	72	72	11	80
Elong. (%)	8	–	8	15	–	15	15	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (MPa)	124	–	124	124	22	152	124	–	124
ΔK @ da/dN *; R = 0.1 (MPa$\sqrt{m}$)	10	–	10	13	–	13	13	–	13
$K_{app.}$ (MPa$\sqrt{m}$)	66	–	66	88	25	110	88	–	66
Exfoliation corrosion	D	–	D	–	–	B	–	–	–
Stress LT (MPa)	–	–	–	–	–	–	–	–	–
Corrosion TL (MPa)	–	–	–	–	–	–	–	–	–
ST (MPa)	–	–	–	–	–	–	–	–	–
Density, (kg/cm^3 x 10^6)	0.279	–	0.279	0.277	–	0.277	0.277	10	0.249

*2.5 x 10^{-7} m/cycle

TABLE 9. - CONCLUDED
(b) Customary Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY D – DADT			ALLOY E – LOW DENSITY		
PROPERTY	7075-T6 CLAD BASELINE	% IMPROV.	TARGET	2024-T3 CLAD BASELINE	% IMPROV.	TARGET	2024-T3 CLAD BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	73	25	91	62	–	62	62	–	62
F_{ty} (ksi)	65	25	81	45	–	45	45	–	45
F_{cy} (ksi)	64	25	80	37	–	37	37	22	45
E (msi)	10.3	–	10.3	10.5	–	10.5	10.5	11	11.6
Elong. (%)	8	–	8	15	–	15	15	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	18	–	18	18	22	22	18	–	18
ΔK @ da/dN 10^{-5} in./cycle; R = 0.1 (ksi $\sqrt{in}$)	9	–	9	12	–	12	12	–	12
$K_{app.}$ (ksi $\sqrt{in}$)	60	–	60	80	25	100	80	–	60
Exfoliation Corrosion	D	–	D	–	–	B	–	–	–
Stress Corrosion LT TL ST	–	–	–	–	–	–	–	–	–
Density, ρ (pci)	0.101	–	0.101	0.100	–	0.100	0.100	10	0.090

TABLE 10. - PRELIMINARY PROPERTY IMPROVEMENT GOALS - PLATE PRODUCT
(a) S.I. Units

CLASSIFICATION	ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR			ALLOY D – DADT		
PROPERTY	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	490	28	627	490	20	588	490	–	490
F_{ty} (MPa)	414	40	579	414	31	538	414	–	414
F_{cy} (MPa)	407	40	572	407	31	538	407	–	407
E (GPa)	71	–	71	71	8	77	71	–	71
Elong. (%)	6	–	6	6	–	6	6	–	6
Fatigue: $K_t = 3.0$ @ 10^5; $R = 0.1$ (MPa)	152	10	165	152	10	165	152	18	179
ΔK @ da/dN *; $R = 0.1$ $(\text{MPa}\sqrt{\text{m}})$	11	–	11	11	–	11	11	20	13
K_{Ic} (L-T) $(\text{MPa}\sqrt{\text{m}})$	30	–	26	30	–	26	30	70	51
$K_{app.}$ (L-T)	–	–	–	–	–	–	–	–	–
Exfoliation corrosion	B	–	B	B	–	B	B	–	B
Stress Corrosion LT (MPa)	338	–	338	338	–	338	338	–	338
TL (MPa)	338	–	338	338	–	338	338	–	338
ST (MPa)	172	–	172	172	–	172	172	–	172
Density, $(\text{kg/cm}^3 \times 10^6)$	0.279	–	0.279	0.279	7	0.260	0.279	–	0.279

$*2.5 \times 10^{-7}$ m/cycle

TABLE 10. - CONCLUDED
(b) Customary Units

CLASSIFICATION	ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR			ALLOY D – DADT		
PROPERTY	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	71	28	90	71	20	85	71	–	71
F_{ty} (ksi)	60	40	84	60	31	78	60	–	60
F_{cy} (ksi)	59	40	83	59	31	78	59	–	59
E (msi)	10.3	–	10.3	10.3	8	11.2	10.3	–	10.3
Elong. (%)	6	–	6	6	–	6	6	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	22	10	24	22	10	24	22	18	26
ΔK @ da/dN 10^{-5} in./cycle; R = 0.1 (ksi$\sqrt{in}$)	10	–	10	10	–	10	10	20	12
K_{Ic} (L-T) (ksi$\sqrt{in}$)	27	–	24	27	–	24	27	70	46
Exfoliation Corrosion	B	–	B	B	–	B	B	–	B
Stress Corrosion LT	49	–	49	49	–	49	49	–	49
TL	49	–	49	49	–	49	49	–	49
ST (ksi)	25	–	25	25	–	25	25	–	25
Density, ρ (pci)	0.101	–	0.101	0.101	7	0.094	0.101	–	0.101

TABLE 11. - PRELIMINARY PROPERTY IMPROVEMENT GOALS - EXTRUSIONS
(a) S.I. Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR		
PROPERTY	7075-T6 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	558	20	669	517	20	621	517	13	586
F_{ty} (MPa)	496	25	621	448	30	586	448	20	538
F_{cy} (MPa)	496	25	621	448	30	586	448	20	538
E (GPa)	72	–	72	72	–	72	72	8	77
Elong. (%)	7	–	6	7	–	6	7	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (MPa)	152	10	165	152	10	165	152	10	165
ΔK @ da/dN *; R = 0.1 (MPa $\sqrt{m}$)	10	–	10	11	–	11	11	–	11
K_{Ic} (MPa $\sqrt{m}$)	31	–	26	33	–	26	33	–	26
$K_{app.}$ L-T	–	–	–	–	–	–	–	–	–
Exfoliation corrosion	D	–	D	B	–	B	B	–	B
Stress Corrosion LT (MPa)	310	–	310	345	–	345	345	–	345
TL (MPa)	276	–	276	345	–	345	345	–	345
ST (MPa)	55	–	55	172	–	172	172	–	172
Density, ρ (kg/cm^3 x 10^6)	0.279	–	0.279	0.279	–	0.279	0.279	7	0.260

*2.5 x 10^{-7} m/cycle

TABLE 11. - CONCLUDED
(b) Customary Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR		
PROPERTY	7075-T6 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	81	20	97	75	20	90	75	13	85
F_{ty} (ksi)	72	25	90	65	30	85	65	20	78
F_{cy} (ksi)	72	25	90	65	30	85	65	20	78
E (msi)	10.4	–	10.4	10.4	–	10.4	10.4	8	11.2
Elong. (%)	7	–	6	7	–	6	7	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	22	10	24	22	10	24	22	10	24
Δ K @ da/dN 10^{-5}in./cycle; R = 0.1 (ksi $\sqrt{in}$)	9	–	9	10	–	10	10	–	10
K_{Ic} (ksi $\sqrt{in}$)	28	–	24	30	–	24	30	–	24
Exfoliation Corrosion	D		D	B	–	B	B	–	B
Stress Corrosion LT	45	–	45	50	–	50	50	–	50
TL	40	–	40	50	–	50	50	–	50
ST (ksi)	8	–	8	25	–	25	25	–	25
Density, ρ (pci)	0.101	–	0.101	0.101	–	0.101	0.101	7	0.094

TABLE 12. - PRELIMINARY PROPERTY IMPROVEMENT GOALS - FORGINGS
(a) S.I. Units

Classification	Alloy A – Strength			Alloy B – Strength & CR		
Property	7075-T6 Baseline	% Improv.	Target	7075-T73 Baseline	% Improv.	Target
F_{tu} (MPa)	517	20	627	455	30	586
F_{ty} (MPa)	441	33	586	386	43	552
F_{cy} (MPa)	462	27	586	400	38	552
E (GPa)	69	4	72	69	4	72
Elong. (%)	7	–	7	7	–	7
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (MPa)	152	10	165	138	20	165
ΔK @ da/dN *; R = 0.1 (MPa $\sqrt{m}$)	10	–	10	11	–	11
K_{Ic} (MPa $\sqrt{m}$)	26	–	26	27	7	29
$K_{app.}$ LT	–	–	–	–	–	–
Exfoliation corrosion	D		D	B		B
Stress Corrosion LT (MPa)	241	–	241	345	–	345
TL (MPa)	172	–	172	345	–	345
ST (MPa)	48	–	48	290	–	241
Density, ρ (kg/cm^3 x 10^6)	0.279	–	0.279	0.279	–	0.279

*2.5 x 10^{-7} m/cycle

TABLE 12. - CONCLUDED
(b) Customary Units

Classification	Alloy A – Strength			Alloy B – Strength & CR		
Property	7075-T6 Baseline	% Improv.	Target	7075-T73 Baseline	% Improv.	Target
F_{tu} (ksi)	75	20	91	66	30	85
F_{ty} (ksi)	64	33	85	56	43	80
F_{cy} (ksi)	67	27	85	58	38	80
E (msi)	10.0	4	10.4	10.0	4	10.4
Elong. (%)	7	–	7	7	–	7
Fatigue: $K_t = 3.0$ @ 10^5; $R = 0.1$ (ksi)	22	10	24	20	20	24
ΔK @ da/dN *; $R = 0.1$ (ksi$\sqrt{in}$)	9	–	9	10	–	10
K_{Ic} (ksi$\sqrt{in}$)	24	–	24	25	7	26
Exfoliation corrosion	D	–	D	B	–	B
Stress Corrosion LT (ksi)	35	–	35	50	–	50
TL (ksi)	25	–	25	50	–	50
ST (ksi)	7	–	7	42	–	35
Density, ρ (pci)	0.101	–	0.101	0.101	–	0.101

*10^{-5} in./cycle

A re-assessment of the preliminary target properties was made taking into consideration the Alcoa inputs, as highlighted below:

1.3.1 High strength, alloy A; and strength and corrosion resistance, alloy B.- The high strength property targets are desired in the product forms of sheet, plate and extrusion. When these property goals are compared with the new PM alloys, X7090 and X7091, it is clear that the anticipated development improvements are realistically defined but still represent a challenge for alloy development. The ability to accommodate poor exfoliation and stress-corrosion performance in the high strength category improves the chances of success. The overaged precipitation hardening treatments may be used to achieve the higher corrosion resistance in the same alloy.

It is noted the combination of strength, fatigue (S-N) resistance, and toughness may be suited to a powder metallurgy approach. These alloys will be usable only in extrusions or forgings for several years as the technology for production of plate and sheet is not yet commercially available for PM products.

These two categories may be accessible using a low density alloy if the strength levels can be considered relative to alloy density. A lower density (Ingot Metallurgy) alloy may be available in plate and sheet much more rapidly than any PM alloy.

These property levels are most easily achievable in extrusions, and least probable in plate due to the nature of the metalworking processes and its influence on properties. A lithium-containing alloy with low density may also offer improved crack propagation resistance.

1.3.2 Strength, stiffness and corrosion resistance, alloy C.- This combination of properties appears realistic in extrusions considering the properties produced in PM alloys under government contracts. Again, these levels of improvements in mechanical properties of plate are very high and may not represent attainable minimum properties.

1.3.3 Durability and damage tolerance, alloy D.- This category anticipates a 22 percent improvement in fatigue strength relative to 2024-T3 clad sheet, while a substantial improvement in fatigue strength, crack growth resistance, and fracture toughness is desired in plate. These are the most difficult combinations of properties to optimize in a powder metallurgy product as the small microstructural size of the PM product leads to improved toughness and fatigue crack initiation resistance on the order desired, but also leads to no improvement, or to deterioration in fatigue crack propagation resistance. A well designed alloy development program using both IM and PM approaches would be indicated to define the accessible level of improvement. Again, such levels of improvement in fatigue strength and toughness have been obtained in PM alloys but the product of plate is not available on a commercial scale at this time. Products of these average properties in plate product may prove difficult using IM or PM technology. A lithium-containing alloy (IM) may provide improvement in crack growth resistance.

1.3.4 Low density, alloy E.- This target appears readily attainable in sheet products using ingot metallurgy methods.

1.3.5 Modified Goals.- A re-assessment of the preliminary property goals was made in light of Alcoa inputs, current literature of on-going aluminum alloy development and appropriate component design criteria. This review resulted in a reduction of plate tensile property goals for alloy B and C reflecting the ratio of plate-to-clad sheet-to extrusion tensile properties as displayed for current ingot alloys. Similarly, the alloy D clad sheet properties were increased to reflect the plate-to-clad sheet tensile property ratio of current ingot alloys. The Alcoa comments in reference to the fracture characteristics of alloy D are worthy of consideration, however, the original fracture toughness goals are retained as reasonable. The property improvements goals for sheet, plate, extrusion, and forgings are presented in tables 13, 14, 15, and 16. These property improvements goals are alloy development targets which will be modified on the basis of experimental results in subsequent programs.

The review also indicated that an accelerated effort is needed to develop sheet and plate products from powder metallurgy alloys. The lack of sheet and plate PM alloy products is readily visible in the current literature. Due to a lack of a data base for these products, the anticipated goals were influenced by the relationship of various ingot metallurgy product properties; i.e., clad sheet versus extrusion, etc.

TABLE 13. - FINAL PROPERTY IMPROVEMENT GOALS - SHEET PRODUCT
(a) S.I. Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY D – DADT			ALLOY E – LOW DENSITY		
PROPERTY	7075–T6 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	503	25	627	428	5	448	428	–	428
F_{ty} (MPa)	448	25	559	310	11	345	310	–	310
F_{cy} (MPa)	441	25	552	255	14	290	255	22	310
E (GPa)	71	–	71	72	–	72	72	11	80
Elong. (%)	8	–	8	15	–	8	15	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (MPa)	124	–	124	124	22	152	124	–	124
ΔK @ da/dN *; R = 0.1 (MPa$\sqrt{m}$)	10	–	10	13	–	13	13	–	13
$K_{app.}$ (MPa$\sqrt{m}$)	66	–	66	88	25	110	88	–	66
Exfoliation corrosion	D	–	D	–	–	B	–	–	–
Density, ρ (kg/cm^3 x 10^6)	0.279	–	0.279	0.277	–	0.277	0.277	10	0.249

*2.5 x 10^{-7} m/cycle

TABLE 13. - CONCLUDED

(b) Customary Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY D – DADT			ALLOY E – LOW DENSITY		
PROPERTY	7075–T6 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET	2024–T3 CLAD BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	73	25	91	62	5	65	62	–	62
F_{ty} (ksi)	65	25	81	45	11	50	45	–	45
F_{cy} (ksi)	64	25	80	37	14	42	37	22	45
E (msi)	10.3	–	10.3	10.5	–	10.5	10.5	11	11.6
Elong. (%)	8	–	8	15	–	8	15	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	18	–	18	18	22	22	18	–	18
ΔK @ da/dN *; R = 0.1 (ksi $\sqrt{in}$)	9	–	9	12	–	12	12	–	12
$K_{app.}$ (ksi $\sqrt{in}$)	60	–	60	80	25	100	80	–	60
Exfoliation corrosion	D	–	D	–	–	B	–	–	–
Density, ρ (pci)	0.101	–	0.101	0.100	–	0.100	0.100	10	0.090

10^{-5} in./cycle *

TABLE 14. - FINAL PROPERTY IMPROVEMENT GOALS - PLATE PRODUCT
(a) S.I. Units

CLASSIFICATION	ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR			ALLOY D – DADT		
PROPERTY	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	490	20	586	490	14	559	490	–	490
F_{ty} (MPa)	414	33	552	414	23	510	414	–	414
F_{cy} (MPa)	407	35	552	407	25	510	407	–	407
E (GPa)	71	–	71	71	8	77	71	–	71
Elong. (%)	6	–	6	6	–	6	6	–	6
Fatigue. K = 3.0 @ 10^5, R = 0.1 (MPa)	152	10	165	152	10	165	152	18	179
ΔK @ da/dN *; R = 0.1 (MPa $\sqrt{m}$)	11	–	11	11	–	11	11	20	13
K_{Ic} (L-T) (MPa $\sqrt{m}$)	30	–	29	30	–	26	30	70	51
Exfoliation corrosion	B	–	B	B	–	B	B	–	B
Stress LT (MPa)	338	–	338	338	–	338	338	–	338
Corrosion TL (MPa)	338	–	338	338	–	338	338	–	338
ST (MPa)	172	–	172	172	–	172	172	–	172
Density, ρ (kg/cm^3 x 10^6)	0.279	–	0.279	0.279	7	0.260	0.279	–	0.279

*2.5 x 10^{-7} m/cycle;

TABLE 14. - CONCLUDED
(b) Customary Units

CLASSIFICATION	ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR			ALLOY D – DADT		
PROPERTY	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	71	20	85	71	14	81	71	–	71
F_{ty} (ksi)	60	33	80	60	23	74	60	–	60
F_{cy} (ksi)	59	35	80	59	25	74	59	–	59
E (msi)	10.3	–	10.3	10.3	8	11.2	10.3	–	10.3
Elong. (%)	6	–	6	6	–	6	6	–	6
Fatigue. K = 3.0 @ 10^5; R = 0.1 (ksi)	22	10	24	22	10	24	22	18	26
ΔK @ da/dN*; R = 0.1 (ksi $\sqrt{in}$)	10	–	10	10	–	10	10	20	12
K_{Ic} (L-T) Ksi $\sqrt{in}$	27	–	26	27	–	24	27	70	46
Exfoliation corrosion	B	–	B	B	–	B	B	–	B
Stress Corrosion LT (Ksi)	49	–	49	49	–	49	49	–	49
TL (Ksi)	49	–	49	49	–	49	49	–	49
ST (Ksi)	25	–	25	25	–	25	25	–	25
Density, ρ (pci)	0.101	–	0.101	0.101	7	0.094	0.101	–	0.101

*10^{-5} in./cycle

TABLE 15. - FINAL PROPERTY IMPROVEMENT GOALS - EXTRUSIONS
(a) S.I. Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR		
PROPERTY	7075-T6 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (MPa)	558	20	669	517	20	621	517	13	586
F_{ty} (MPa)	496	25	621	448	30	586	448	20	538
F_{cy} (MPa)	496	25	621	448	30	586	448	20	538
E (GPa)	72	–	72	72	–	72	72	8	77
Elong. (%)	7	–	6	7	–	6	7	–	6
Fatigue: $K_t = 3.0$ @ 10^5, $R = 0.1$ (MPa)	152	10	165	152	10	165	152	10	165
ΔK @ da/dN *; $R = 0.1$ (MPa $\sqrt{m}$)	10	–	10	11	–	11	11	–	11
K_{Ic} (MPa $\sqrt{m}$)	31	–	26	33	–	26	33	–	26
Exfoliation corrosion	D	–	D	B	–	B	B	–	B
Stress Corrosion LT (MPa)	310	–	310	345	–	345	345	–	345
TL (MPa)	276	–	276	345	–	345	345	–	345
ST (MPa)	55	–	55	172	–	172	172	–	172
Density, ($kg/cm^3 \times 10^6$)	0.279	–	0.279	0.279	–	0.279	0.279	7	0.260

*2.5×10^{-7} m/cycle

TABLE 15. - CONCLUDED
(b) Customary Units

CLASSIFICATION	ALLOY A – STRENGTH			ALLOY B – STRENGTH & CR			ALLOY C – STR., STIFF. & CR		
PROPERTY	7075-T6 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET	7075-T76 BASELINE	% IMPROV.	TARGET
F_{tu} (ksi)	81	20	97	75	20	90	75	13	85
F_{ty} (ksi)	72	25	90	65	30	85	65	20	78
F_{cy} (ksi)	72	25	90	65	30	85	65	20	78
E (msi)	10.4	–	10.4	10.4	–	10.4	10.4	8	11.2
Elong. (%)	7	–	6	7	–	6	7	–	6
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	22	10	24	22	10	24	22	10	24
ΔK @ da/dN *; R = 0.1 (ksi $\sqrt{m}$)	9	–	9	10	–	10	10	–	10
K_{Ic} (ksi $\sqrt{m}$)	28	–	24	30	–	24	30	–	24
$K_{app.}$	–	–	–	–	–	–	–	–	–
Exfoliation corrosion	D	–	D	B	–	B	B	–	B
Stress Corrosion LT (ksi)	45	–	45	50	–	50	50	–	50
TL (ksi)	40	–	40	50	–	50	50	–	50
ST (ksi)	8	–	8	25	–	25	25	–	25
Density, ρ (pci)	0.101	–	0.101	0.101	–	0.101	0.101	7	0.094

*10^{-5} in./cycle

TABLE 16. - FINAL PROPERTY IMPROVEMENT GOALS - FORGINGS
(a) S.I. Units

Classification	Alloy A – Strength			Alloy B – Strength & CR		
Property	7075-T6 Baseline	% Improv.	Target	7075-T73 Baseline	% Improv.	Target
F_{tu} (MPa)	517	20	627	455	30	586
F_{ty} (MPa)	441	33	586	386	43	552
F_{cy} (MPa)	462	27	586	400	38	552
E (GPa)	69	4	72	69	4	72
Elong. (%)	7	–	7	7	–	7
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (MPa)	152	10	165	138	20	165
ΔK @ da/dN *; R = 0.1 (MPa $\sqrt{m}$)	10	–	10	11	–	11
K_{Ic} (MPa $\sqrt{m}$)	26	–	26	27	7	29
$K_{app.}$ LT	–	–	–	–	–	–
Exfoliation corrosion	D		D	B		B
Stress Corrosion LT (MPa)	241	–	241	345	–	345
TL (MPa)	172	–	172	345	–	345
ST (MPa)	48	–	48	290	–	241
Density, ρ (kg/cm^3 x 10^6)	0.279	–	0.279	0.279	–	0.279

*2.5 x 10^{-7} m/cycle

FIGURE 16. - CONCLUDED
(b) Customary Units

Classification	Alloy A – Strength			Alloy B – Strength & CR		
Property	7075-T6 Baseline	% Improv.	Target	7075-T73 Baseline	% Improv.	Target
F_{tu} (ksi)	75	20	91	66	30	85
F_{ty} (ksi)	64	33	85	56	43	80
F_{cy} (ksi)	67	27	85	58	38	80
E (msi)	10.0	4	10.4	10.0	4	10.4
Elong. (%)	7	–	7	7	–	7
Fatigue: $K_t = 3.0$ @ 10^5; R = 0.1 (ksi)	22	10	24	20	20	24
ΔK @ da/dN *; 10^5; R = 0.1 (ksi$\sqrt{\text{in}}$)	9	–	9	10	–	10
K_{Ic} (ksi$\sqrt{\text{in}}$)	24	–	24	25	7	26
Exfoliation corrosion	D	–	D	B	–	B
Stress Corrosion LT (ksi)	35	–	35	50	–	50
TL (ksi)	25	–	25	50	–	50
ST (ksi)	7	–	7	42	–	35
Density, ρ (pci)	0.101	–	**0.101**	0.101	–	**0.101**

*10^{-5} in./cycle

2. AIRCRAFT BENEFIT ANALYSIS

Aircraft benefit analyses were conducted to identify the performance and economic benefits of incorporating advanced aluminum alloys into future commercial transport aircraft designs. The analyses were conducted using the Lockheed-developed ASSET (Advanced Synthesis and Evaluation Technique) program described in section 2.4. The benefits were determined by comparing selected reference aircraft designed for introduction to operational capability (IOC) in 1990, with and without incorporation of the advanced aluminum alloys. Three reference aircraft were derived from baseline aircraft: (1) a long-range transport version of the L-1011 aircraft with fuselage plugs and extended wing span, (2) a short-medium range transport representing a 1990 replacement to the Boeing 737-200, and (3) a modern energy-efficient commuter transport for short aircraft trips. The reference aircraft were configured considering the benefits resulting from advances in: (1) aerodynamics, (2) active controls, (3) improved propulsion systems, and (4) aircraft systems, as shown in figure 8. The advanced aluminum aircraft were derived by resizing these reference aircraft to take advantage of the weight reduction potential offered by the new material alloys, as shown in figure 9, to obtain aircraft designed for minimum fuel consumption. The potential benefits from the application of advanced technology are discussed in the following paragraphs.

2.1 Advanced Technology

Prior to 1973, it was difficult to justify the introduction of fuel-efficient technology because the potential benefit of the fuel saved versus the cost of technology was minimal, as shown in figure 10. However, with the escalating fuel prices, the cost of fuel-saving technology can more easily be amortized, even at small amounts of fuel saving, as shown in figure 10. Thus, one way to soften the impact of increasing fuel prices is through aggressive use of advanced, fuel-efficient technology to a new generation of transport aircraft.

2.1.1 Aerodynamic benefits.- The aerodynamic elements considered airfoil technology, planform parameters, and high-lift technology. Over the past few years considerable efforts have gone into developing supercritical wings, which allow cruise speeds between Mach 0.75 and 0.85 without excessive penalty of the transonic drag rise. These advances in aerodynamics also allow greater range of trade-offs between flying at a given drag rise level and reduced wing sweep. Wings with lesser sweep provide weight benefits. The benefits of improved aerodynamics are generally measured in terms of Mach number times the lift-to-drag ratio, $M \cdot (L/D)$, a component of the Breguet range equation. The potential gains in this parameter from improved wing technology is shown in figure 11. In this figure, the L-1011 wing at its midcruise center of gravity is used as a reference. It is shown that by keeping the same static margin, advanced wings show a 13 percent improvement in $M \cdot (L/D)$. The improvement shown is due to a combination of advanced airfoil and increased aspect ratio. However, in translating this benefit to fuel savings the wing weight increase will negate some of the fuel-saving potential. An additional 4 percent improvement is available, as shown in figure 11, but it is ascribed to the use of active controls.

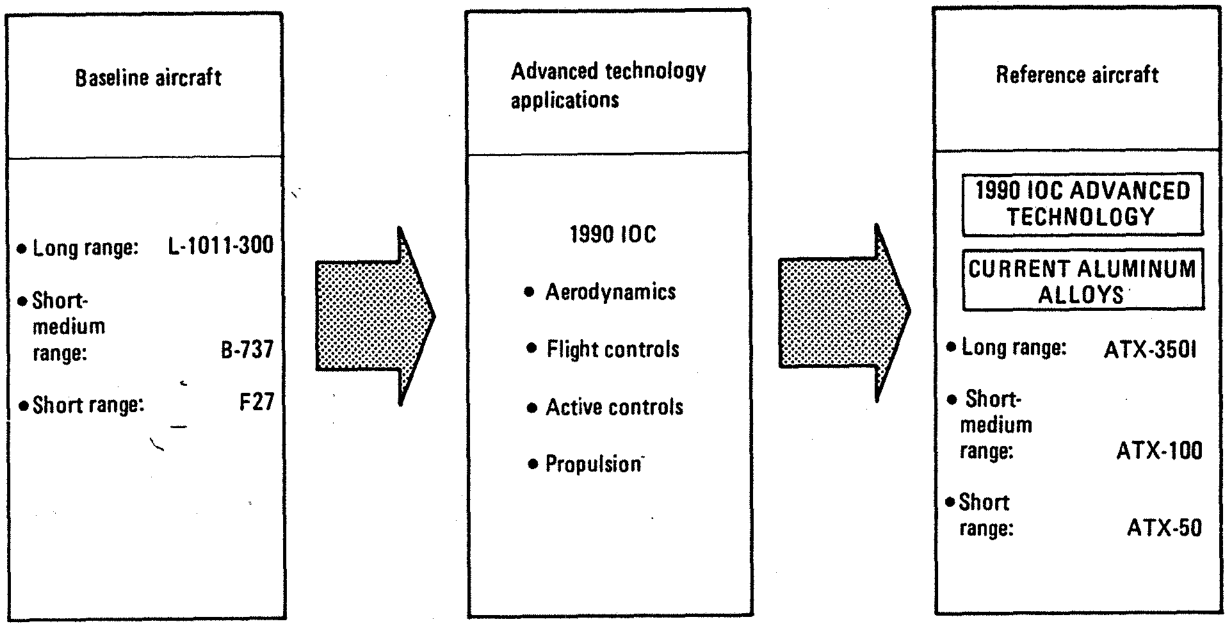


Figure 8. - Reference aircraft definition.

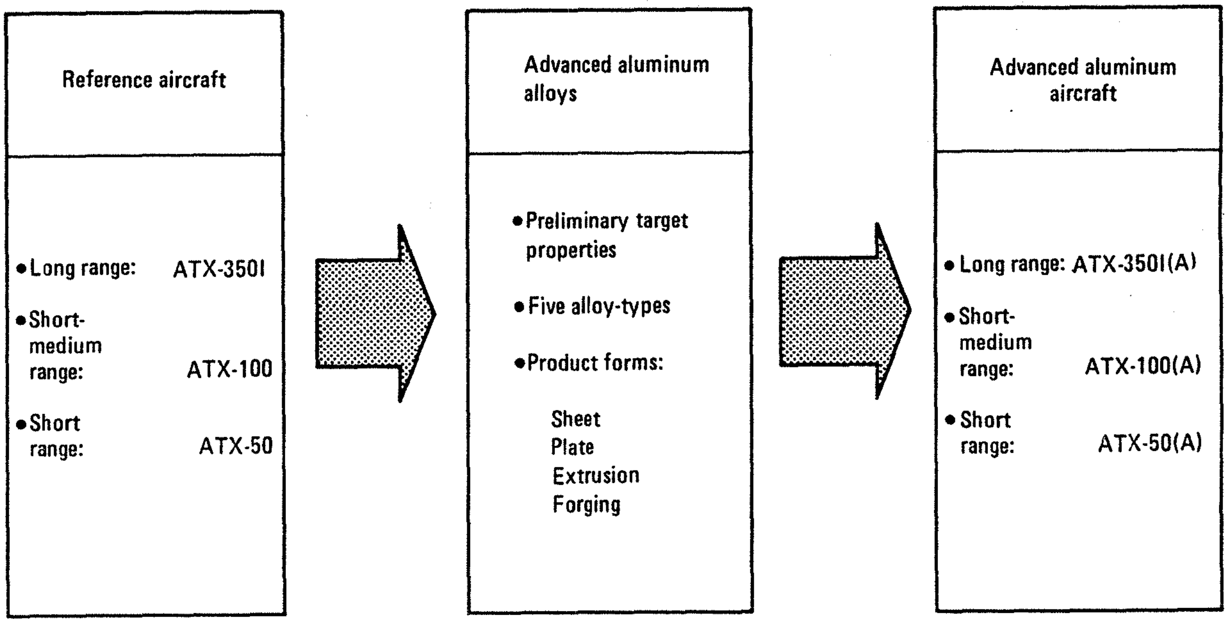


Figure 9. - Advanced aluminum aircraft definition.

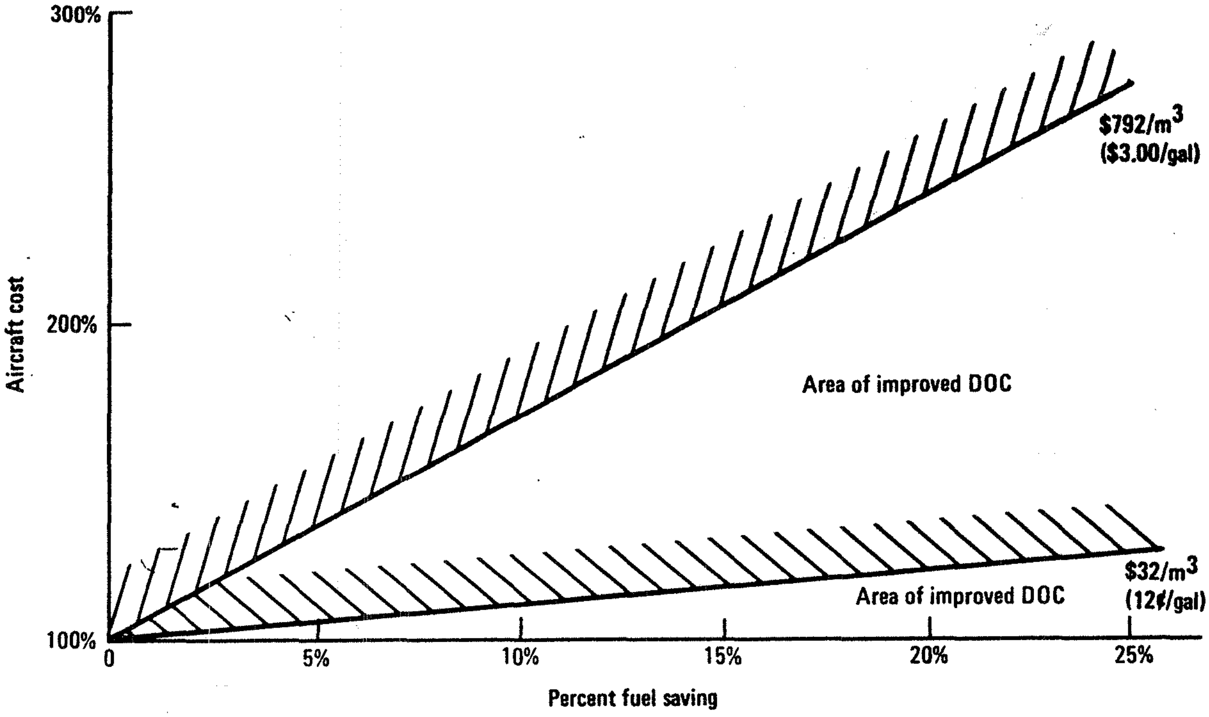


Figure 10. - Initial cost vs. fuel saving trade-off.

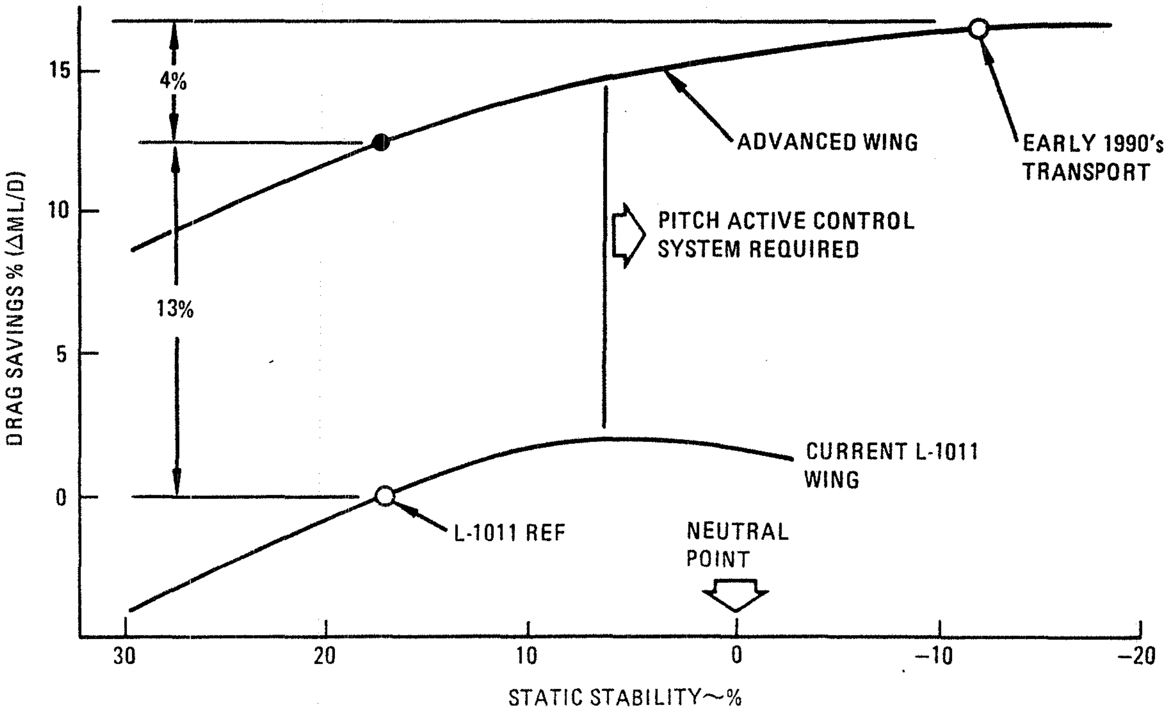


Figure 11. - Potential drag savings for 1990
with negative static stability.

2.1.2 Active controls benefits.- The active control element included maneuver load control, dynamic gust response control, and relaxed static stability. Advances in active control system technology makes possible negative stability aircraft for commercial use. However, the benefits from the additional 4 percent improvement in M·(L/D) shown in figure 11 is not included in this study. Further trade-off must be made which consider the increased complexity of active controls with other factors that must be included when designing the aircraft to operate beyond the neutral point. The maneuver load control and dynamic gust response control benefits have been demonstrated in the already certified L-1011-500 ACS aircraft.

2.1.3 Propulsion benefits.- The propulsion element includes advanced propulsion systems and airframe/propulsion integration. Over the past few years, the NASA-sponsored energy-efficient engine (E^3) studies (reference 6) have identified considerable potential improvements in the specific fuel consumption (SFC) of jet engines over the engines in current use. The improved fuel consumption is attained by using advanced materials and new cycle characteristics. Another major benefit of the E^3 engines will be the improved deterioration characteristics with accumulated flight hours.

The long-range and short-medium range aircraft for this study postulated an E^3 turbofan. The projected SFC improvement realized from an E^3 turbofan is shown in figures 12 and 13. The improvement shown is relative to the current technology CF6-50C and the low-bypass turbojet JT8D-15; the SFC reduction amounts to 15 and 30 percent, respectively. The supercommuter aircraft uses an advanced propfan propulsion system identified in recently completed NASA-contracted studies (reference 7). Advances in propulsion technology show the greatest impact on fuel efficiency.

2.1.4 Aircraft systems benefits.- The flight control element includes digital fly-by-wire control surfaces, multiplexing, electric actuators and integrated actuator packages. The aircraft systems of the next generation commercial transport will undergo the most pronounced changes of any of the aircraft components. Most of the changes will result from inroads made by advances in electronics and computer systems. Many of the benefits derived are not directly measurable in terms of block fuel saved, as they will be in terms of aircraft safety, reliability, and reduced maintenance cost.

2.2 Baseline Aircraft

Some of the more prominent fuel-saving technologies considered for incorporation into the reference aircraft were discussed above. To obtain a picture of the net benefits in terms of aircraft performance and costs, aircraft systems analyses were performed on the baseline aircraft described below.

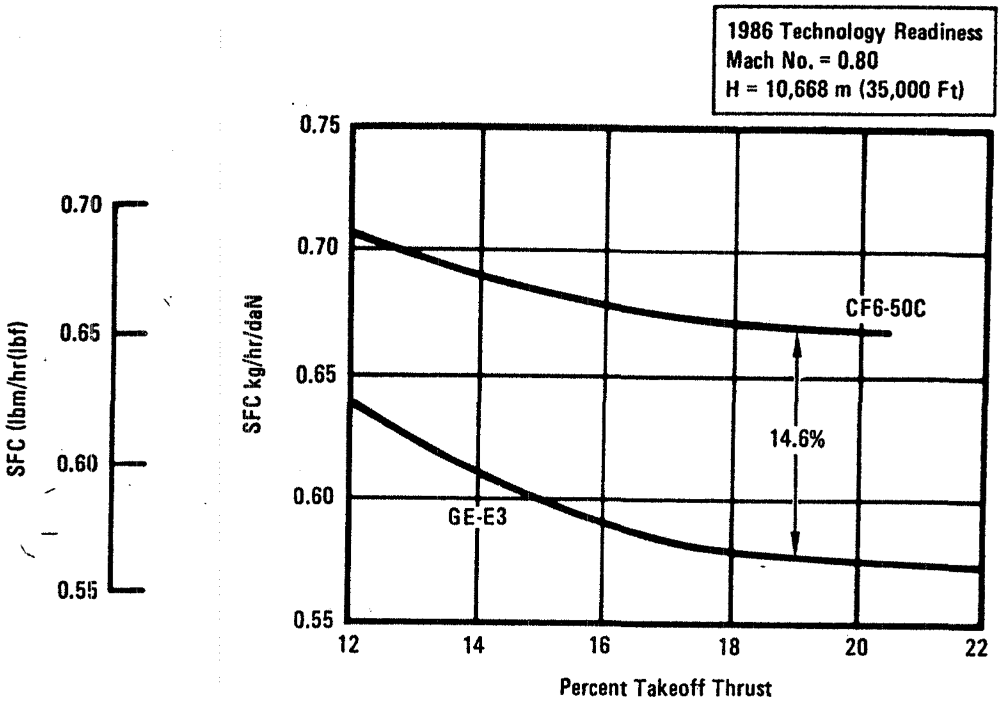


Figure 12. - Advanced propulsion technology comparison - long range aircraft.

2.2.1 Long-range transport aircraft.- The basic L-1011-1 aircraft was modified to arrive at a baseline long-range transport aircraft. The modifications, shown by the shaded regions of figure 14 encompasses: (1) a fuselage length extension of 7 m (280 in.) consisting of a 3 m (120 in.) fuselage plug located forward of the wing and a 4 m (160 in.) plug aft of the wing, (2) a 1.57 m (62.0 in.) wing root plug per side, and (3) an extended wing tip with active ailerons. The baseline aircraft, shown in figure 15, represents a long-range, high-density aircraft of conventional design. The aircraft has a takeoff gross weight of 272 000 kg (600,000 lb) requiring a six-wheel main gear. The payload-range requirement is to carry 350 passengers a distance of 8520 km (4600 n.mi.). The aircraft has a cargo capacity for twenty LD3 containers with an underfloor galley. Space limit cargo is 14 300 kg (31,600 lb). The latter is not included in the payload-range calculations. Other performance requirements are to have a takeoff field length of 3,200 m (10,500 ft) at sea level with a 2130 m (7000 ft) landing distance. Initial cruise altitude capability is 10 700 m (35,000 ft) with 91 m/min (300 ft/min) climb capability and a 1.3g buffet margin. The General Electric CF6-50C engine was used as the baseline propulsion system. The CF6-50C engine is a relatively high-bypass ratio turbofan with SFC levels representative of early 1970s technology. The engine was resized to meet the baseline aircraft thrust requirements.

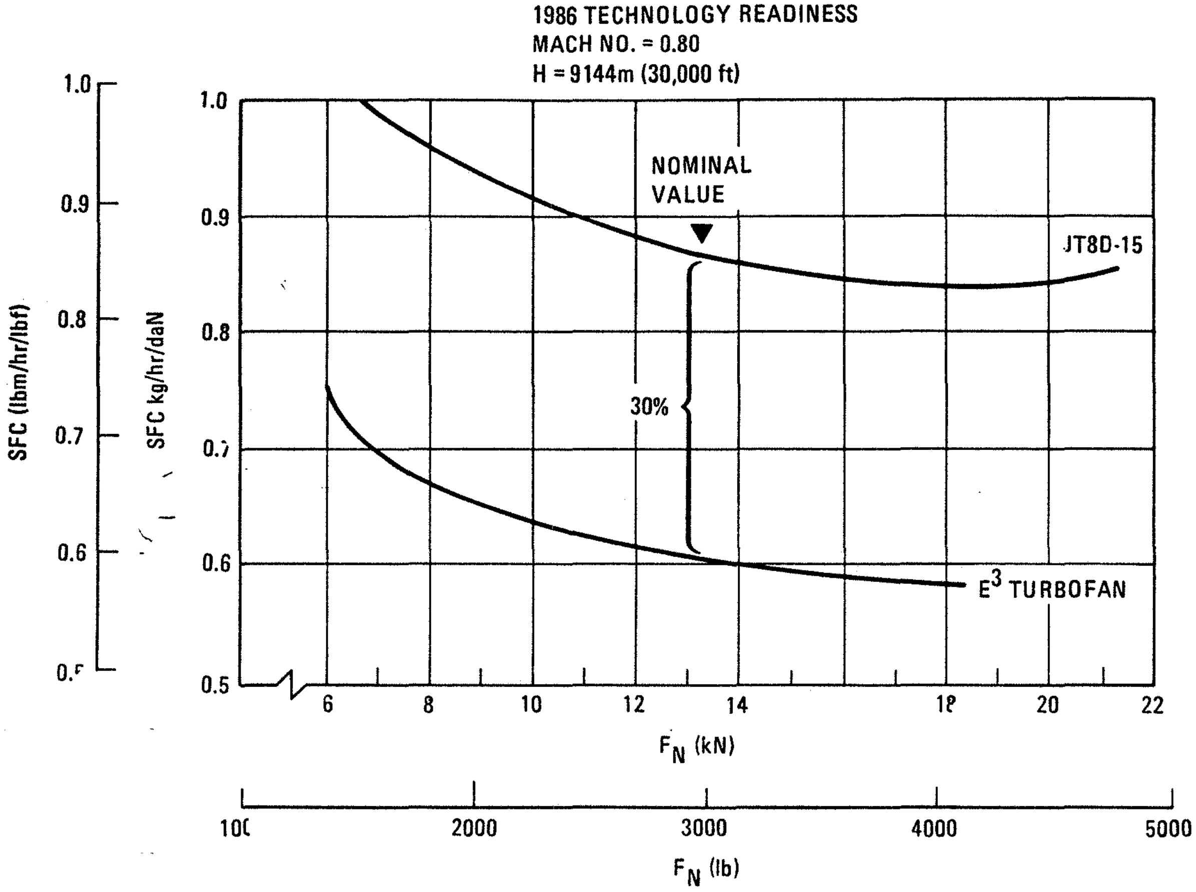


Figure 13. - Advanced propulsion technology comparison - short-medium range aircraft.

2.2.2 Short-medium range transport aircraft.- The second aircraft selected was one of the advanced technology aircraft of interest and under investigation by Lockheed in their Fuel Efficient Commercial Transport Design Program (reference 8). The aircraft concept, designated ATX-100, carries 100 passengers and represents a 1990 replacement for the Boeing 737-200. The general arrangement for the ATX-100 baseline concept is shown in figure 16. The aircraft has a takeoff gross weight of 40 870 kg (90,100 lb) and employs a supercritical, 0.44 rad (25 deg) swept wing with an aspect ratio of 10. The wing thickness ratio is an average of 11 percent. The landing gear stowage requirement represented a major constraint on the wing thickness distribution. The propulsion system was based on E^3 studies. The Pratt and Whitney 477/E^3 advanced turbofan engine has a bypass ratio of about 6 and static thrust rating of approximately 80 kN (18,000 lb).

The design requirements for the aircraft include: (1) takeoff field length of 1674 m (5500 ft) at sea level, (2) engine out ceiling of 4900 m (16,000 ft),

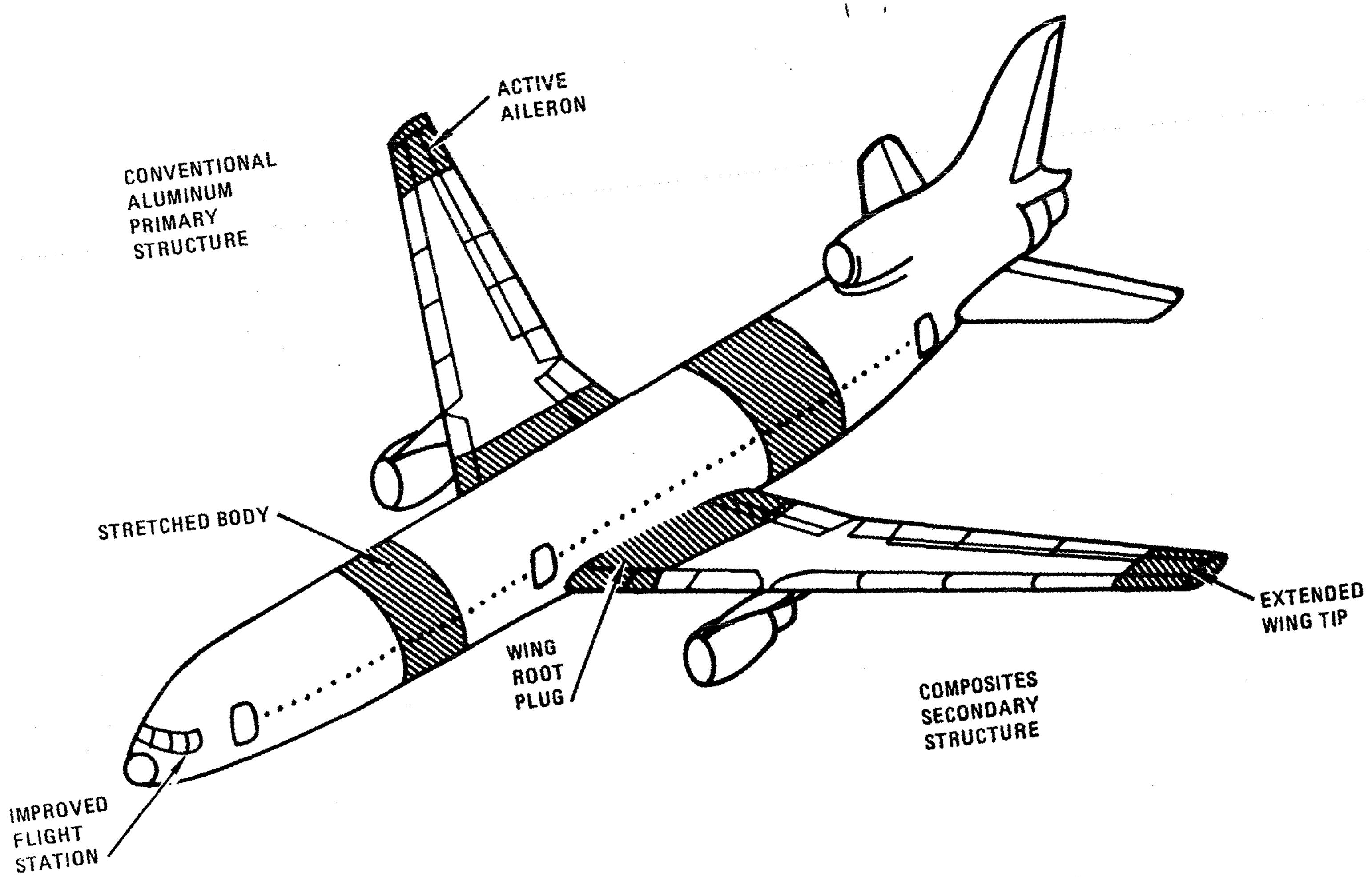


Figure 14. - Modifications to the basic L-1011-1 aircraft.

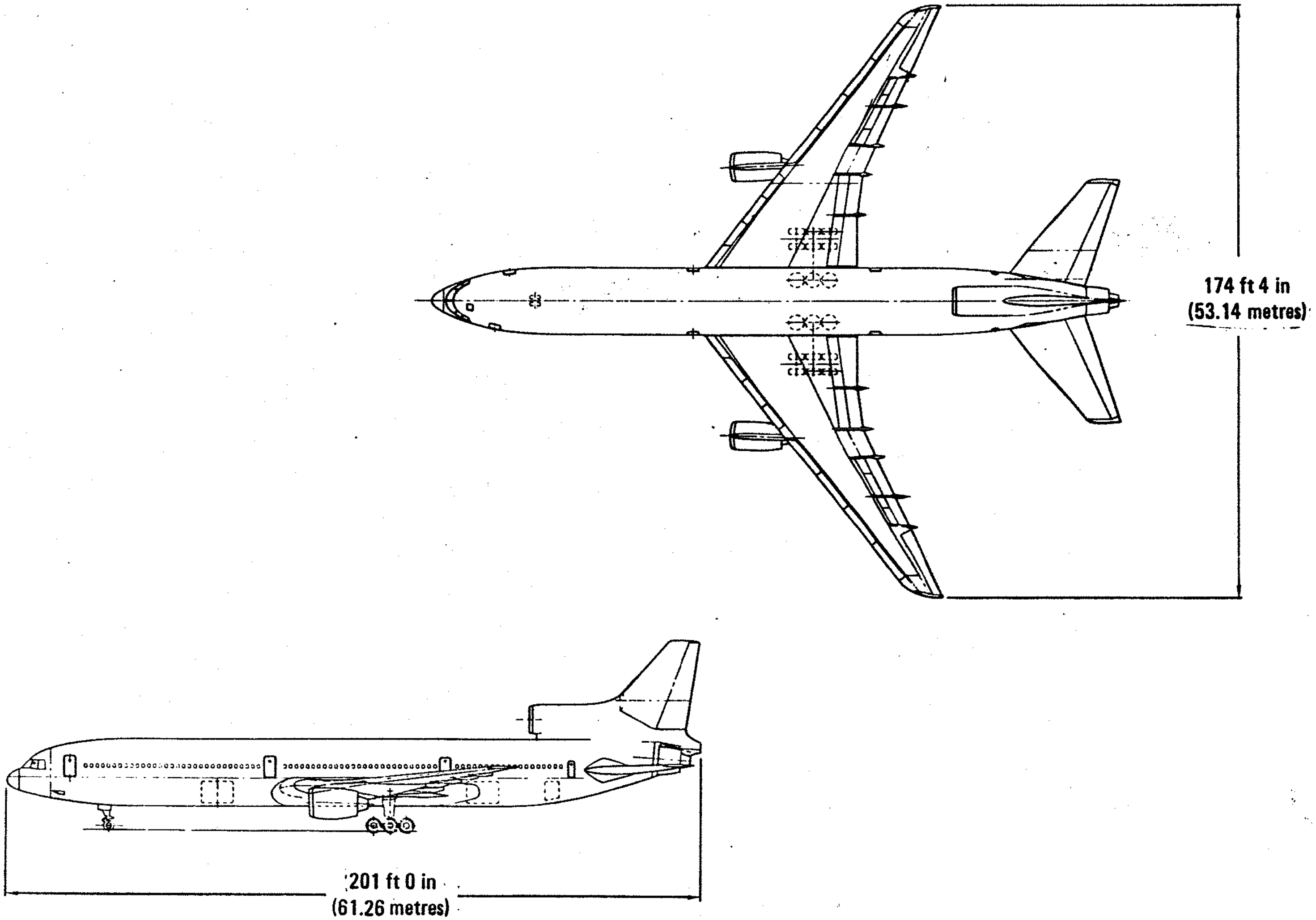


Figure 15. - Baseline concept L-1011-300 international.

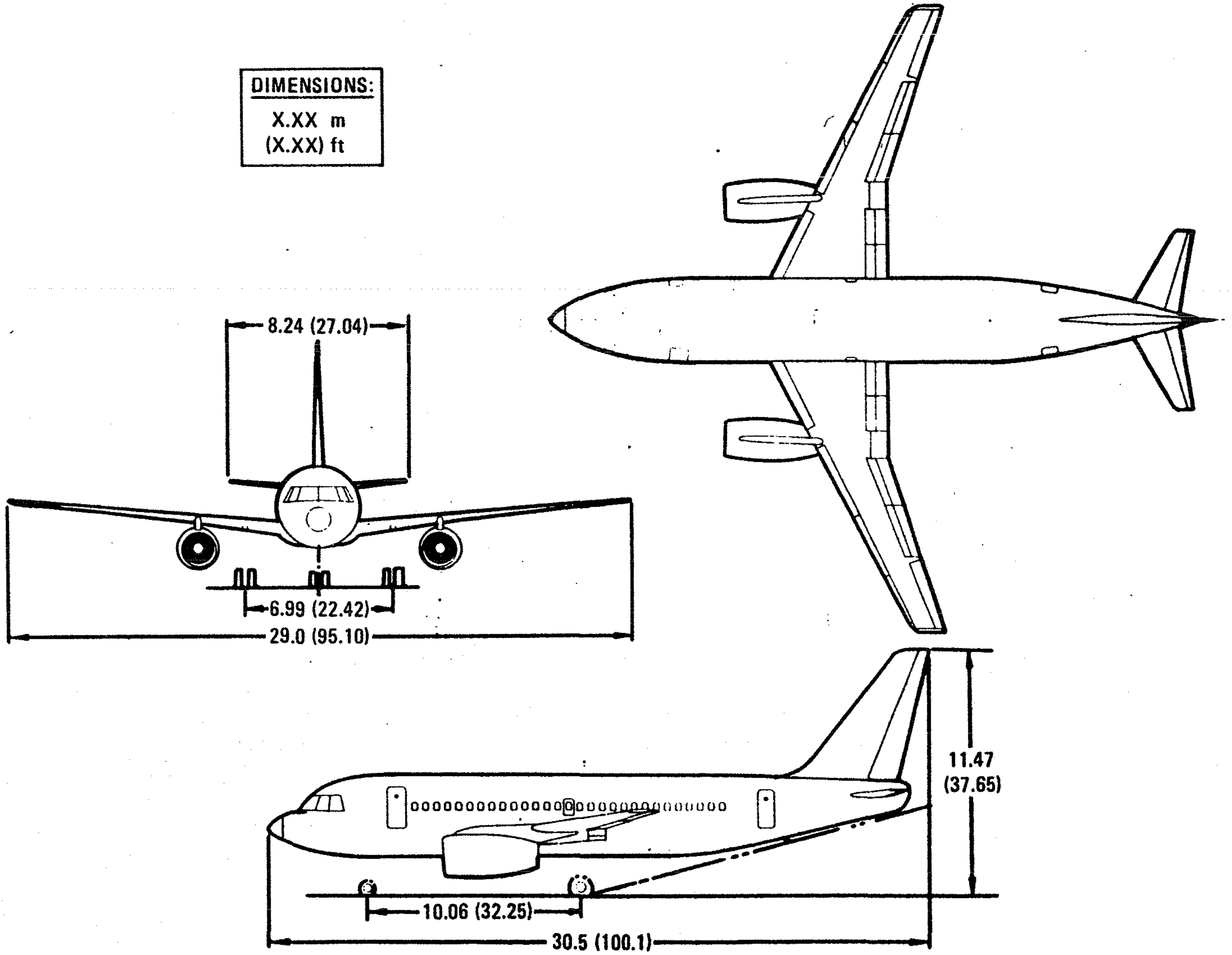


Figure 16. - ATX-100 baseline concept general arrangement.

(3) cruise speed of Mach 0.8, (4) approach speed of 62 m/s (120 knot), (5) domestic fuel reserves, (6) design range of 1852 km (1000 n.mi.) and (7) average stage length of 556 km (300 n.mi.).

2.2.3 Short haul commuter aircraft.- Lockheed studies of small, short-haul commercial aircraft for the post-1985 time frame identified an aircraft concept with current airliner type performance to provide an advanced technology aircraft for local carrier service. The 50-passenger short-haul concept (figure 17) derived in the reference 7 was used as the third aircraft concept for this investigation. The aircraft was configured to provide a cruise speed capability of Mach 0.7 for a design range of 1110 km (600 n.mi.). The wing employs a NASA GAW-1 type airfoil with an average thickness ratio of 16 percent and an aspect ratio of 10. The propfan engines are overwing mounted to minimize gear length for the required ground clearance.

2.3 Reference Aircraft

Each of the baseline aircraft were updated to a reference aircraft incorporating advanced aerodynamics, active controls, propulsion and aircraft systems (flight controls) technologies. The current aluminum alloys were used for the airframe structure. The application of these technologies were consistent with those levels Lockheed believes to be attainable for aircraft with a 1990 IOC. The payload-range performances were consistent with the respective baseline aircraft.

2.3.1 Long-range transport aircraft - ATX-350I.- Optimization of the baseline long-range transport aircraft was performed to configure the reference aircraft designated ATX-350I. The aircraft was optimized for minimum block fuel while complying to the following requirements:

Takeoff field length	3.2 km (10,500 ft) at sea level, 302 K (84°F)
Landing field length	2.1 km (7000 ft) at sea level, 302 K (84°F)
Initial cruise altitude	9.4 km (31,000 ft) with 91 m/min (300 ft/min) and 1.3g buffet
Approach speed	75 m/s (145 knot) at sea level, 302 K (84°F)
Wing fuel capacity	1.1 x Fuel required
Design range	8520 km (4600 n.mi.) with full payload on standard day

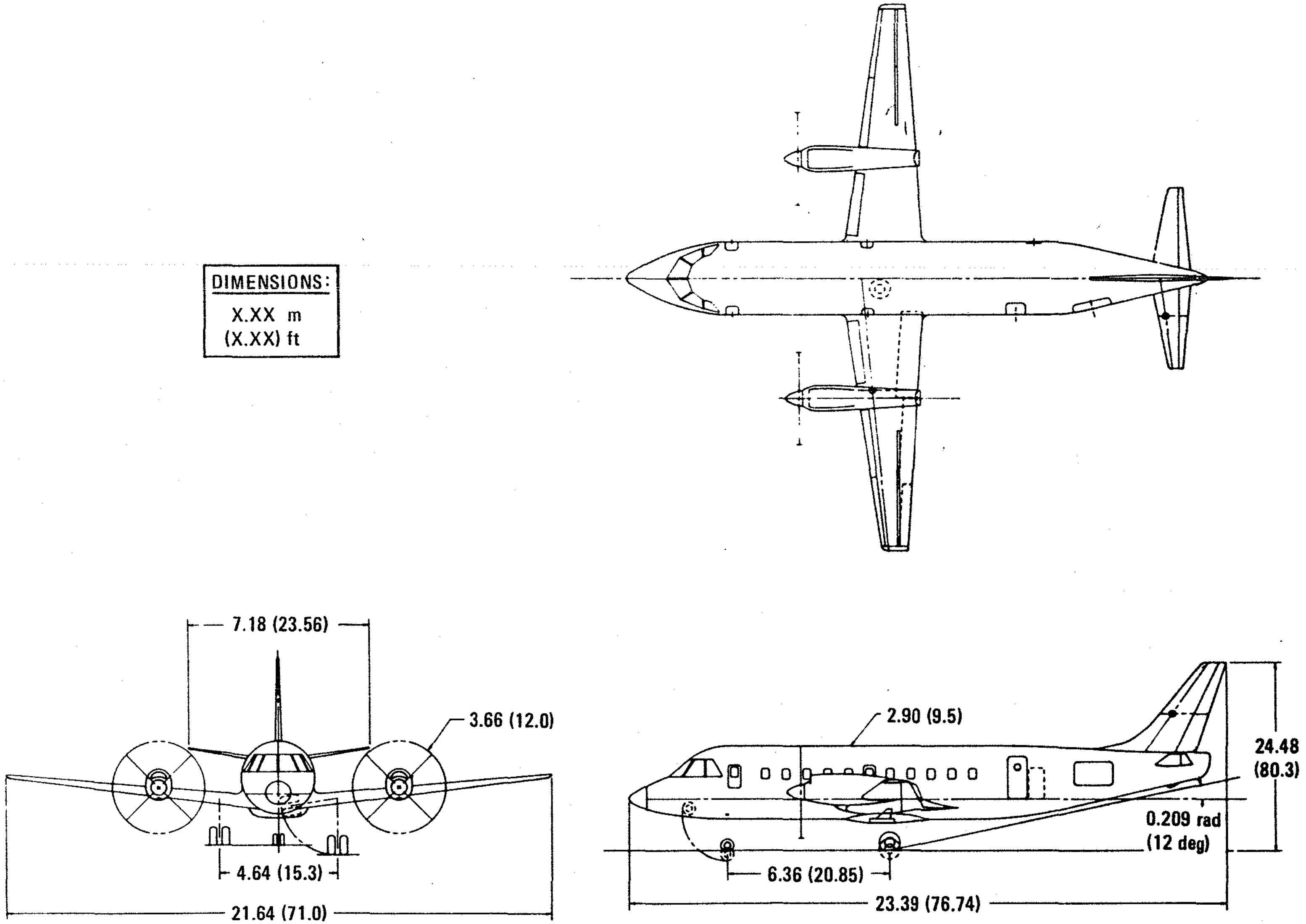


Figure 17. - Baseline 50 passenger short-haul.

Average stage length	4630 km (2500 n.mi.)
Second segment gradient	0.027

The optimization effort was performed as part of the NASA-Lockheed ACEE Integrated Technology Wing Study (Contract NAS1-16273). Advanced technology aircraft were defined by variations in parameters encompassing wing loading (W/S), thrust loading (T/W), sweep at quarter chord, AR, and t/c; all sized to meet a 8520 km (4600 n.mi.) design range mission with international fuel reserves. The constraints of takeoff field length, landing field length, approach speed, initial cruise altitude, wing fuel capacity and specific excess power were superimposed upon the 4630 km (2500 n.mi.) block fuel matrix to narrow the number of acceptable aircraft. The determination of the optimum aircraft involved the following steps:

- The optimization of wing loading and thrust loading to obtain minimum block fuel aircraft for constant values of wing sweep, aspect ratio, and wing thickness ratio.
- The application of specific constraints of engine-out takeoff field length, wing fuel limit, and specific excess power upon the 4630 km (2500 n.mi.) block fuel mission.

The minimum block fuel aircraft, based on the above has a wing sweep of 0.52 rad (30 deg), an aspect ratio of 13 and a t/c of 12 percent as shown in figure 18. This wing design, however, was impractical when the main landing gear (MLG) placement was considered. The carpet plot of figure 19 shows the required location of the MLG. Presented is the percent chord on the MLG-chord which corresponds to the aircraft center-of-gravity location of 42 percent MAC for ground operation, plus 0.17 rad (10 deg) tip-up margin. It shows that as sweep and aspect ratio increase, the required position of the MLG moves further aft along the MLG chord. An additional check must be made to ensure that the wing section has sufficient thickness at the landing gear location. Preliminary landing gear layouts show that the MLG could be located at about 73 percent of the MLG chord. With this constraint applied to the carpet plot of figure 19, the wing sweep of 0.52 rad (30 deg) is limited to an AR = 9.75, and the sweep of 0.44 rad (25 deg) to an AR = 11.75. Thus, decreasing wing sweep to 0.44 rad (25 deg) to enhance landing gear placement incurred a 1 percent block fuel penalty for a 4630 km (2500 n.mi.) stage length, as shown in the knot hole curve of figure 20.

The ATX-350I reference aircraft was derived from the advanced technology aircraft discussed above. The wing loading and thrust loading were adjusted to account for the weight increase resulting from the use of conventional aluminum alloy materials in the wing, tail, and body of the aircraft. The general arrangement of the ATX-350I is shown in figure 21. The aircraft characteristics and performance data are presented in table 17. The aircraft has a takeoff gross weight of 243 600 kg (537,050 lb) with a wing loading of 664 kg/m^2 (136 lb/ft^2). The aircraft complies with the requirements specified in terms of takeoff, landing, and cruise performance as shown in the table. The weight description of the aircraft is presented in table 18. The airframe structure

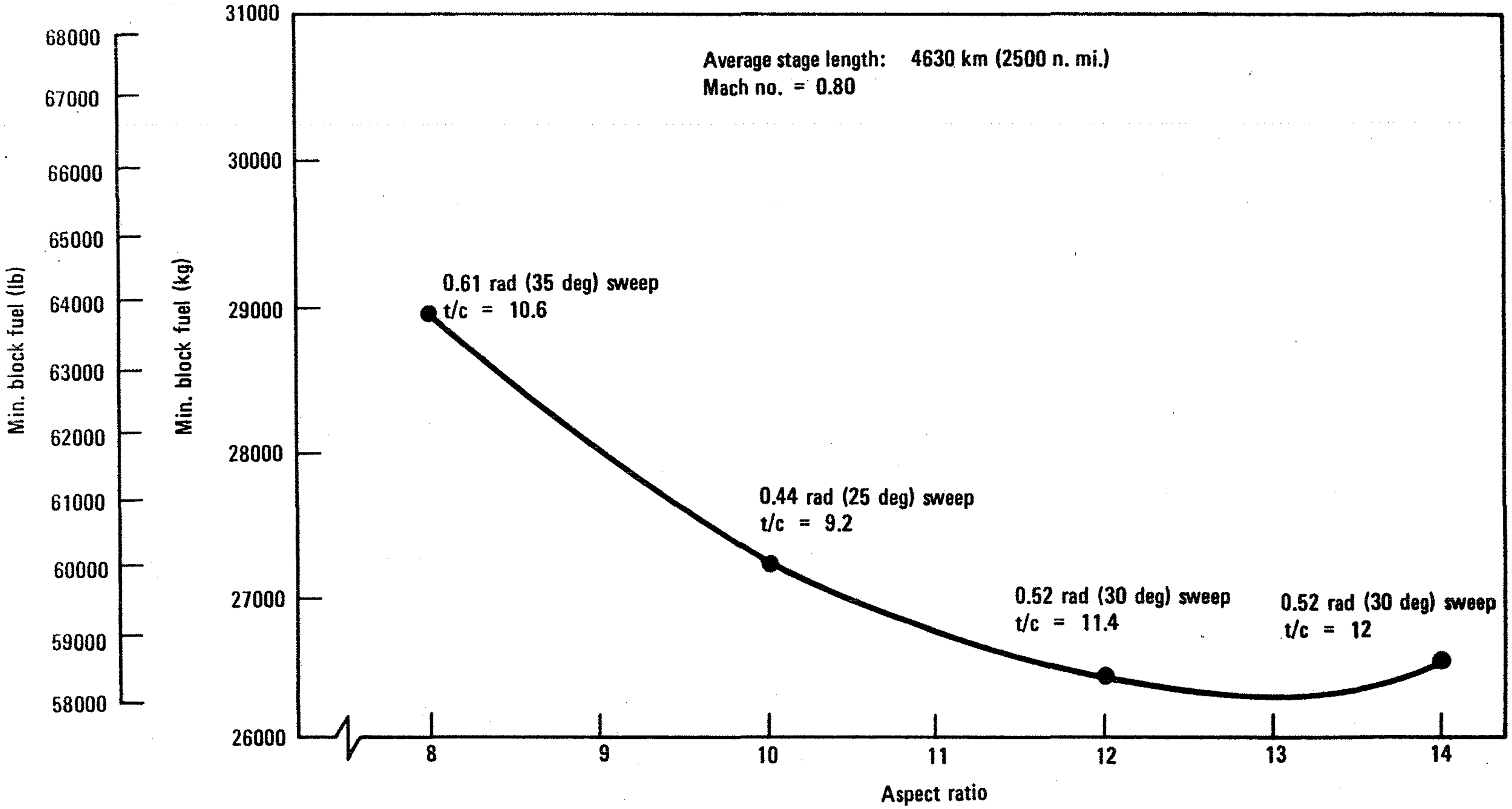


Figure 18. - Minimum block fuel aircraft vs. aspect ratio - ATX-350I.

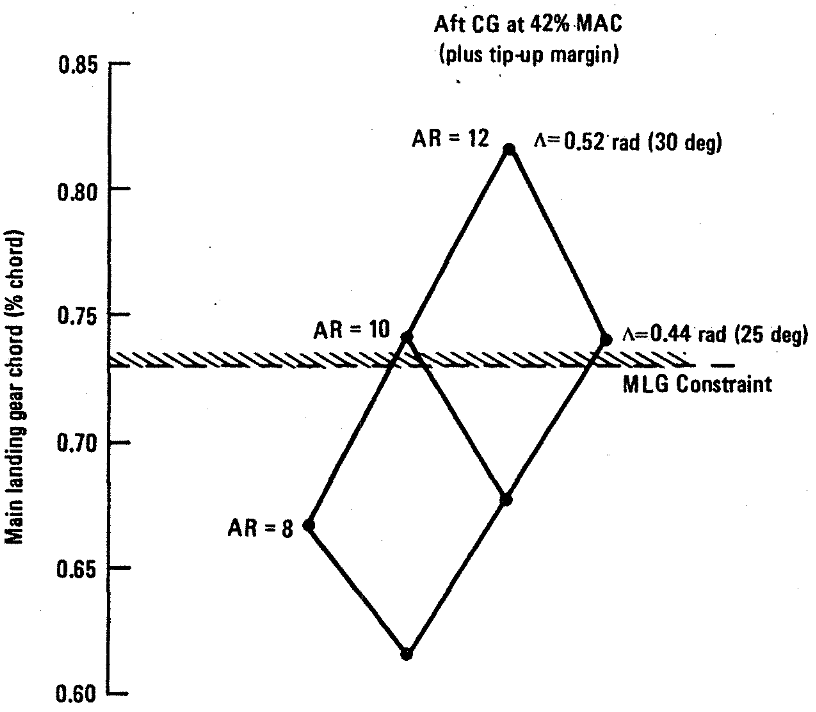


Figure 19. Required Location of Main Landing Gear

weight of 86 788 kg (191,335 lb) represents approximately 36 percent of the takeoff gross weight; the fuel available represents 30 percent of the aircraft weight at takeoff. The airframe weight was classified by component and material as shown in table 19. The structure contains approximately 80 percent conventional aluminum alloy by weight in various product forms. Titanium alloy and steel are employed in certain space-limited and temperature-sensitive regions of the aircraft.

2.3.2 Short-medium range transport aircraft - ATX-100.- Optimization studies of the ATX-100 baseline aircraft were performed to derive the reference aircraft. The reference aircraft represents a minimum block-fuel aircraft which features an optimum combination of wing loading, thrust loading, wing sweep, wing aspect ratio and wing reference thickness, while conforming to specified design requirements and performance constraints. The mission requirements for the ATX-100 were defined utilizing inputs from U.S. regional carriers and the Association of European Airlines. The major points encompass:

Takeoff field length	1.7 km (5500 ft) at sea level, 302 K (84°F)
Minimum cruise altitude	9.1 km (30,000 ft)
Approach speed	62 m/s (120 knot)

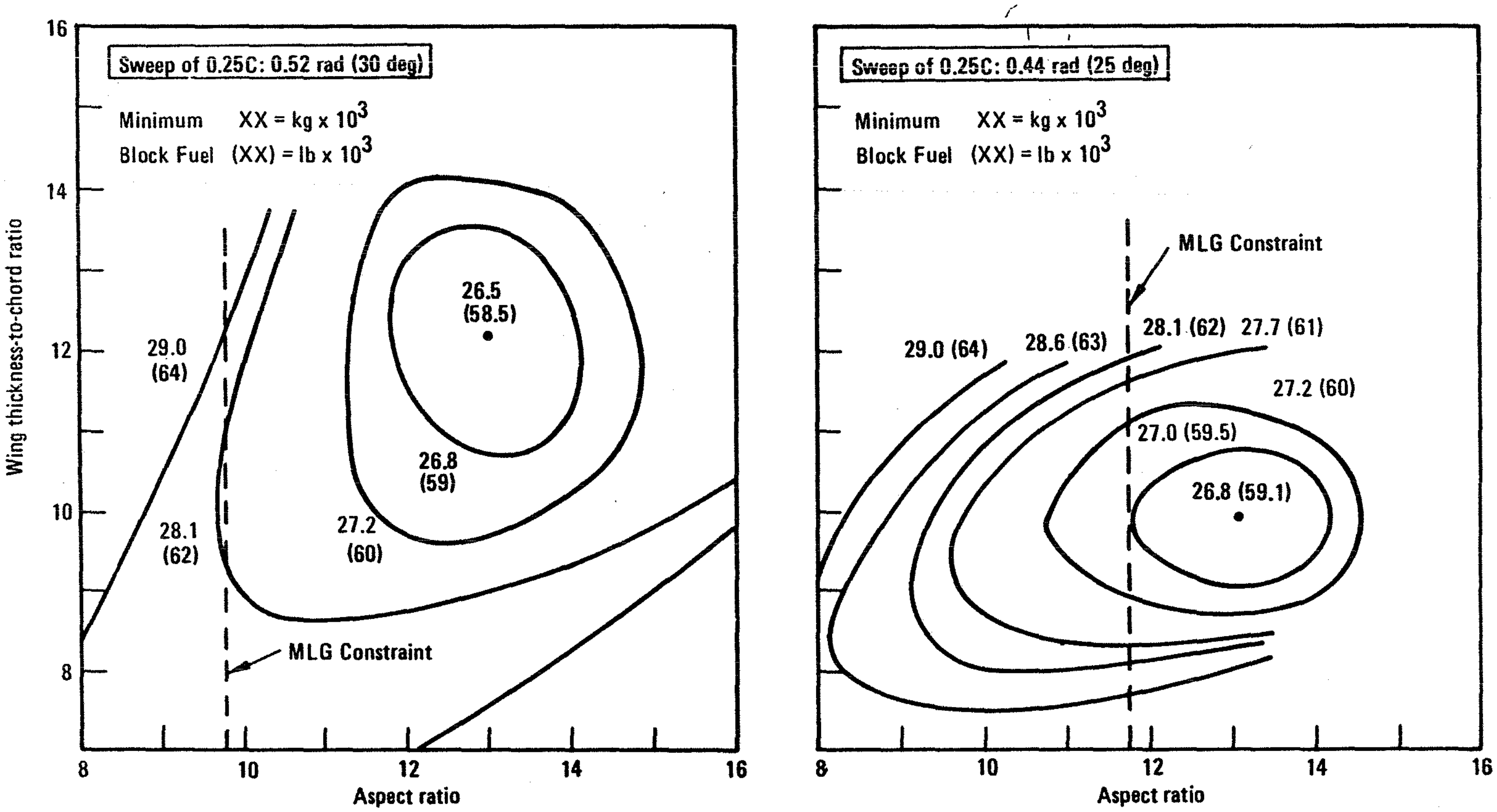


Figure 20. - Knot-hole for minimum block fuel aircraft - ATX-350I.

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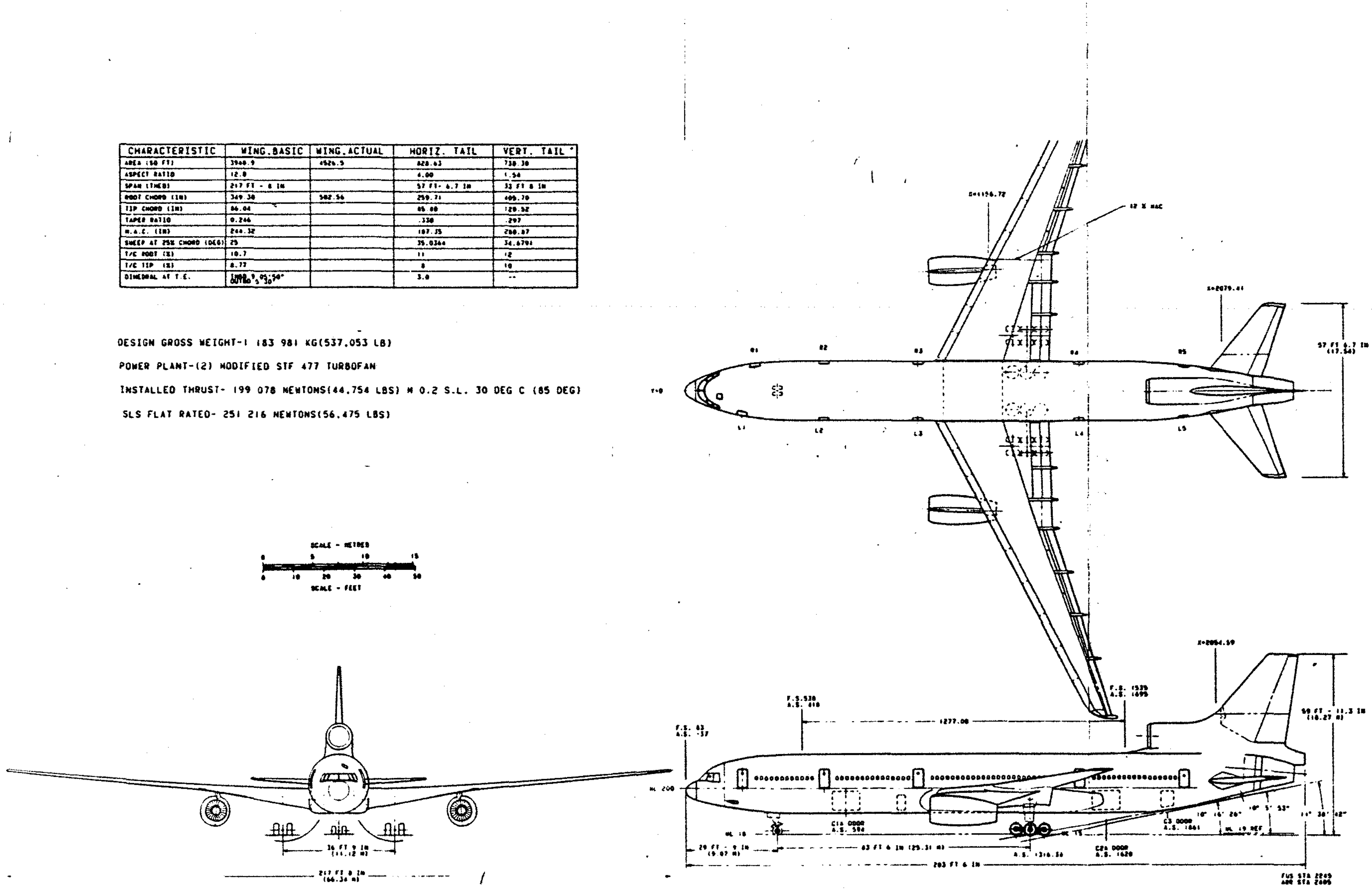

CHARACTERISTIC	WING.BASIC	WING.ACTUAL	HORIZ. TAIL	VERT. TAIL *
AREA (SQ FT)	3940.9	4526.5	828.63	738.30
ASPECT RATIO	12.0		4.00	1.54
SPAN (THEO)	217 FT - 8 IN		57 FT- 6.7 IN	33 FT 8 IN
ROOT CHORD (IN)	349.30	582.56	259.71	405.70
TIP CHORD (IN)	86.04		85.80	120.52
TAPER RATIO	0.246		.330	.297
M.A.C. (IN)	244.32		187.35	280.87
SWEEP AT 25% CHORD (DEG)	25		35.0364	34.6794
T/C ROOT (%)	10.7		11	12
T/C TIP (%)	8.77		8	10
DIHEDRAL AT T.E.	INBD 9°05'50" OUTBD 5°30'		3.0	--

DESIGN GROSS WEIGHT-1 183 981 KG(537,053 LB)

POWER PLANT-(2) MODIFIED STF 477 TURBOFAN

INSTALLED THRUST- 199 078 NEWTONS(44,754 LBS) M 0.2 S.L. 30 DEG C (85 DEG)

SLS FLAT RATED- 251 216 NEWTONS(56,475 LBS)

Figure 21. - ATX-350I general arrangement.

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TABLE 17. - ATX-350I REFERENCE AIRCRAFT CHARACTERISTICS AND PERFORMANCE DATA

Takeoff gross weight, TOGW	243 600 kg	(537,050 lb)
Takeoff thrust to weight, T/W	2.45 N/kg	(0.25)
Wing loading, W/S	664 kg/m^2	(136 lb/ft^2)
Aspect ratio, AR	12	(12)
Wing thickness, percent	10	(10)
Wing sweep at 0.25C	0.44 RAD	(25 deg)
FAA Takeoff field length at S.L., 302 K (84°F)	3.19 km	(10,467 ft)
Landing field length at S.L., 302 K (84°F)	1.92 km	(6,293 ft)
Initial cruise altitude with 1.52 m/s (300 ft/min) and 1.3g buffet	9.4 km	(31,000 ft)
Wing fuel capacity (X fuel required)	1.1 X	(1.1 X)
Range with full load on std. day; cruise at Mach 0.8	8 520 km	(4,600 n.mi.)
Engine out, second segment gradient	0.04	(0.04)

Wing fuel capacity	Domestic reserves
Maximum cruise speed	Mach 0.80
Engine-out altitude	4.9 km (16,000 ft)
Design range	1852 km (1000 n.mi.) with full payload on standard day
Average stage length	556 km (300 n.mi.)

TABLE 18. - WEIGHT STATEMENT - ATX-350I REFERENCE AIRCRAFT

(a) S.I. Unit

	MASS – kg			MASS FRACTION – PERCENT	
GROSS WEIGHT			243 603		
Fuel Available		71 917		Fuel	29.52
ZERO FUEL WEIGHT			171 686		
Payload		33 339		Payload	13.69
● Passengers	26 195				
● Baggage	7 144				
OPERATIONAL EMPTY WEIGHT			138 347		
Operational and Std Items		9 037		Opera. Items	3.71
EMPTY WEIGHT			129 310		
Structure		86 788		Structure	35.63
● Wing	37 737				
● Tail	3 747				
● Body	30 138				
● Others	15 184				
Propulsion		15 458		Propulsion	6.35
Systems		27 064		Systems	11.11

(b) Customary Units

	WEIGHT – lb			WEIGHT FRACTION – PERCENT	
GROSS WEIGHT			537,053		
Fuel Available		158,549		Fuel	29.52
ZERO FUEL WEIGHT			378,503		
Payload		73,500		Payload	13.69
● Passengers	57,750				
● Baggage	15,750				
OPERATIONAL EMPTY WEIGHT			305,003		
Operational and Std Items		19,924		Opera. Items	3.71
EMPTY WEIGHT			285,079		
Structure		191,335		Structure	35.63
● Wing	83,196				
● Tail	8,261				
● Body	66,443				
● Others	33,476				
Propulsion		34,080		Propulsion	6.35
Systems		59,665		Systems	11.11

TABLE 19. - WEIGHT MATRIX - ATX-350I REFERENCE AIRCRAFT
(PERCENT OF STRUCTURE WEIGHT)

MATERIAL / COMPONENT	ALUMINUM	TITANIUM	STEEL	COMPOSITE	OTHER	TOTAL
Wing	0.391	0.009	0.030	0	0.004	0.434
Tail	0.039	–	0.003	0	–	0.042
Body	0.312	0.014	0.003	0.007	0.010	0.346
Others	0.054	0.023	0.086	–	0.015	0.178
Total	0.796	0.046	0.122	0.007	0.029	1.000

$W_{Structure}$ = 86 788 kg (191,335 lb)

The optimization effort was performed as part of a Lockheed funded Advanced Technology Aircraft program (reference 8). The optimization matrix encompassed the following range of parameters:

Aspect ratio:	8, 10, 12
Wing sweep:	0.44 rad (25 deg), 0.52 rad (30 deg), 0.61 rad (35 deg)
Wing reference t/c:	8%, 10%, 12%
Wing loading:	464 kg/m^2 (95 lb/ft^2); 488 kg/m^2 (100 lb/ft^2); 513 kg/m^2 (105 lb/ft^2); 537 kg/m^2 (110 lb/ft^2)
Thrust loading:	3.1 N/kg (0.32 lbf/lbm); 3.3 N/kg (0.34 lbf/lbm); 3.5 N/kg (0.36 lbf/lbm); 3.7 N/kg (0.38 lbf/lbm)

On account of the many parameters, the distillation of the optimum aircraft from the above matrix involved several steps, similar to that performed for the ATX-350I aircraft. The steps encompassed:

- The determination of the minimum block-fuel aircraft for an optimum wing loading and thrust loading, but for constant values of wing sweep aspect ratio and wing thickness ratio.
- The establishment of constraints for landing gear storage requirements.

A series of minimum block-fuel aircraft with varying wing thickness-to-chord ratio were configured for three wing sweeps as typically shown in figure 22. The data shown in the figure are for aspect ratio 10 wing designs. Identical sets of data were also developed for aspect ratio 8 and 12. It is noted that each point presents an aircraft optimized with respect to wing loading and thrust loading. The primary constraint for these data are engine-out balanced field length, and engine-out at en route altitude. As shown in figure 22, the former constraint dominates the selection of minimum block-fuel aircraft. Without considering t/c constraints, a wing sweep of 0.44 rad (25 deg) and t/c of 8 percent results in the minimum block fuel aircraft.

The landing gear storage requirement sets the secondary constraint and influences the selection of the wing thickness-to-chord ratio. The ATX-100 is a relaxed-stability aircraft with the most aft center of gravity location at 42 percent M.A.C. This center of gravity location plus the requirement for a wing section thickness of 0.43 m (17 in.) at the landing gear post location to fit the gear, determined the wing reference thickness ratio. As indicated in figure 23, the minimum t/c for the 0.44 rad (25 deg) wing is 10.7; 12.5 for the 0.52 rad (30 deg) wing; and is undefined for the 0.61 rad (35 deg) wing.

The optimum advanced technology minimum block-fuel aircraft which conforms to the requirements and constraints has a wing sweep of 0.44 rad (25 deg), a wing t/c of 10.7 percent, aspect ratio of 10, a wing loading of 483 kg/m^2 (99 lb/ft^2) and a thrust loading of 3.4 N/kg (0.35 lbf/lbm). Since optimum aircraft also exist for aspect ratio of 8 and 12, a cross plot of these optimum aircraft were developed using aspect ratio as the independent parameter as shown in figure 23. The data presented are for a 0.44 rad (25 deg) wing sweep since the other sweep values did not result in a minimum block fuel aircraft when considering constraints. Figure 23 shows two curves. One defines the variation in minimum block fuel versus aspect ratio assuming no constraint on wing thickness ratio. The lowest t/c value indicated is about 8 percent (limit of the study). The upper curve of the figure represents all minimum block fuel aircraft for which the landing gear can be fitted into the wing. Note that the optimum t/c increases with increasing aspect ratio. This arises from the fact that as aspect ratio is increased, the wing chord is shortened and the t/c must be raised to result in a thicker wing section at the gear location.

The wing parameters selected for the ATX-100 reference aircraft includes: aspect ratio of 10, a wing sweep of 0.44 rad (25 deg) and a wing t/c of 11 percent. The wing loading is 483 kg/m^2 (99 lb/ft^2) and thrust loading 3.4 N/kg (0.35 lbf/lbm). The wing area and engine size were adjusted to reflect application of conventional aluminum alloy materials. The general arrangement of the ATX-100 is shown in figure 24. The aircraft characteristics and performance data are presented in table 20. The aircraft has a takeoff gross weight of 45 057 kg (99 333 lb). The aircraft complies with the specified requirements in terms of takeoff, landing, and cruise performance as shown in the table. The weight description of the aircraft is presented in table 21. The airframe structure weight of 14 912 kg (32 876 lb) represents one-third of

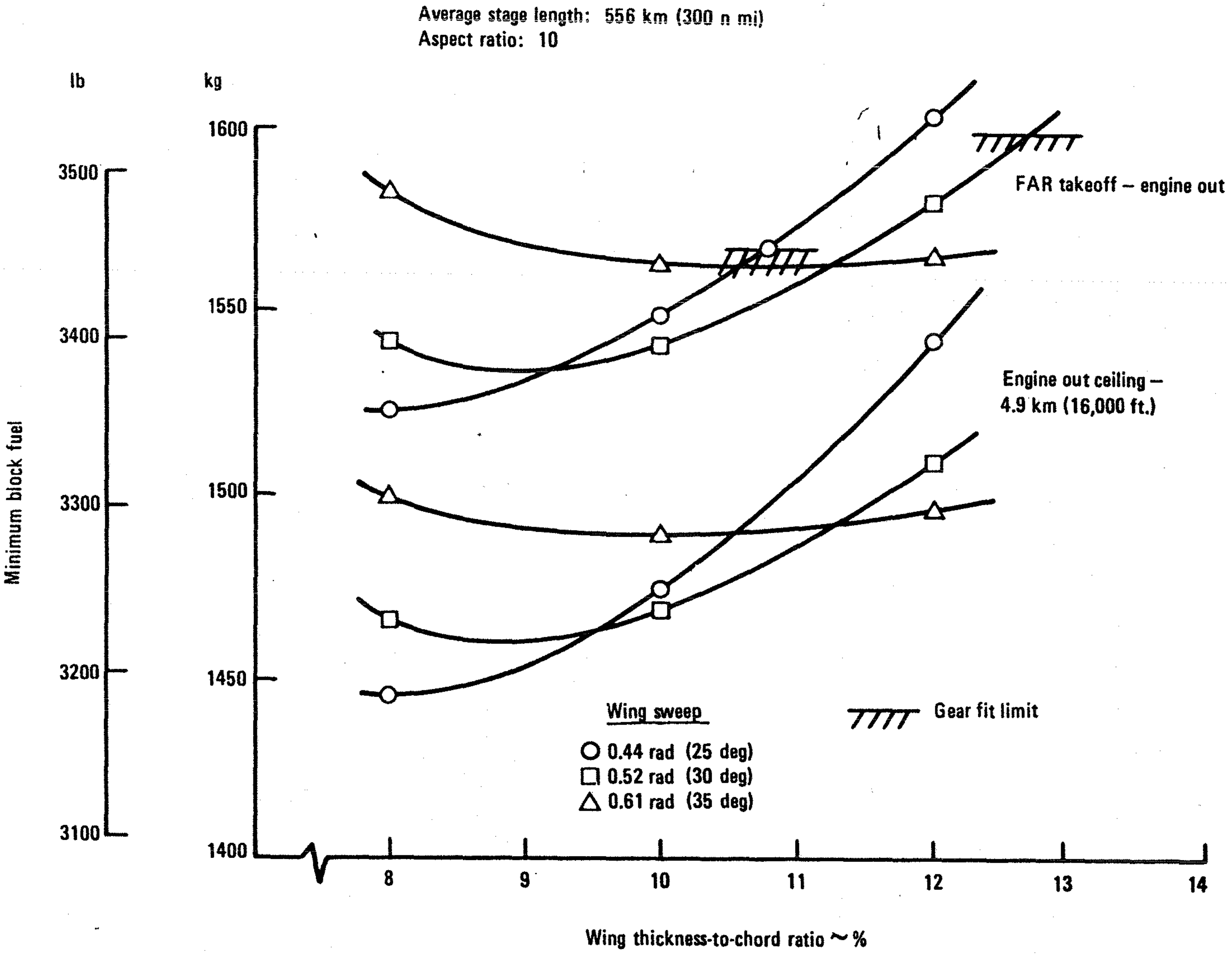


Figure 22. - Minimum block fuel vs. wing reference t/c - ATX-100.

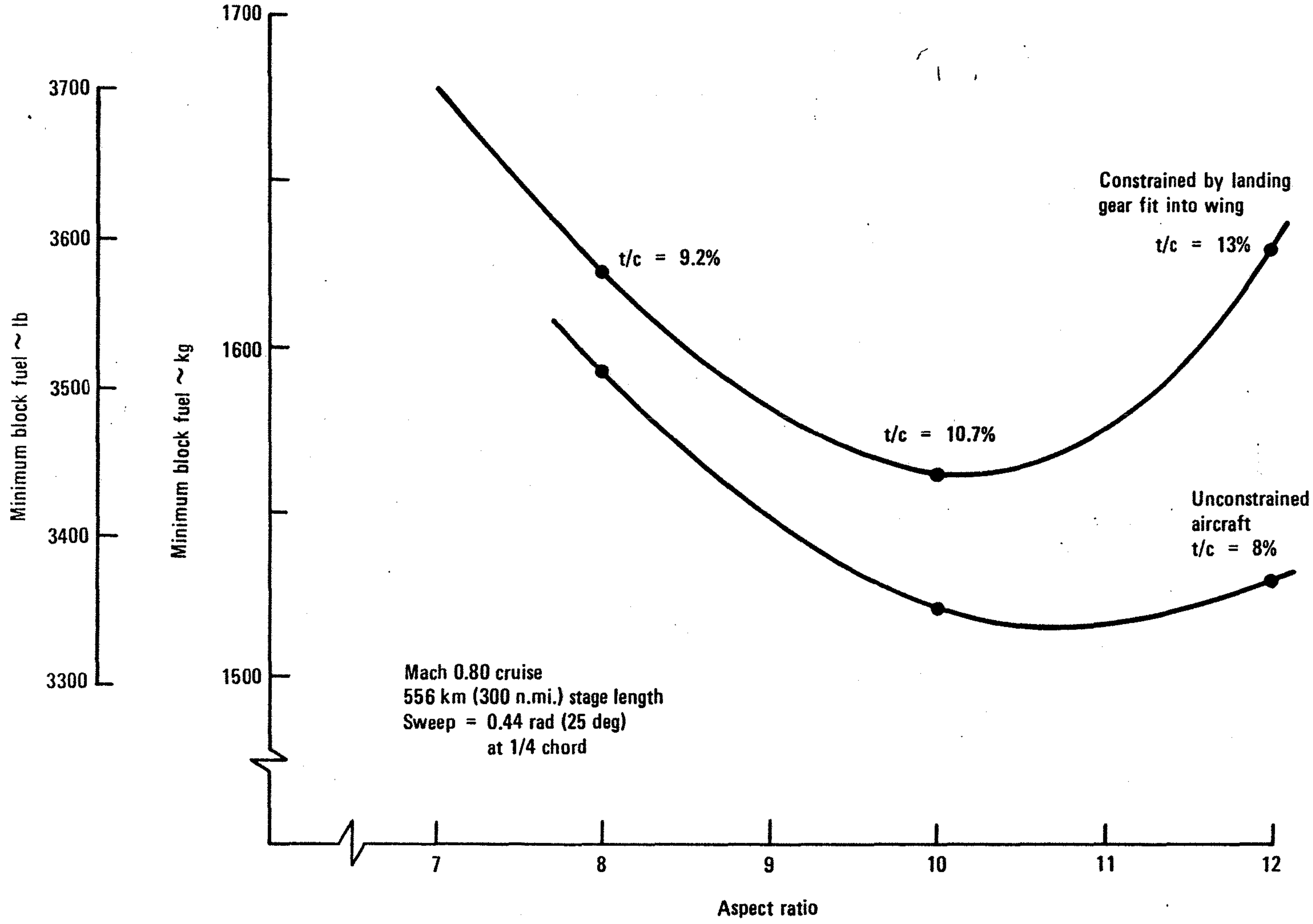


Figure 23. - Minimum block fuel aircraft vs. aspect ratio - ATX-100.

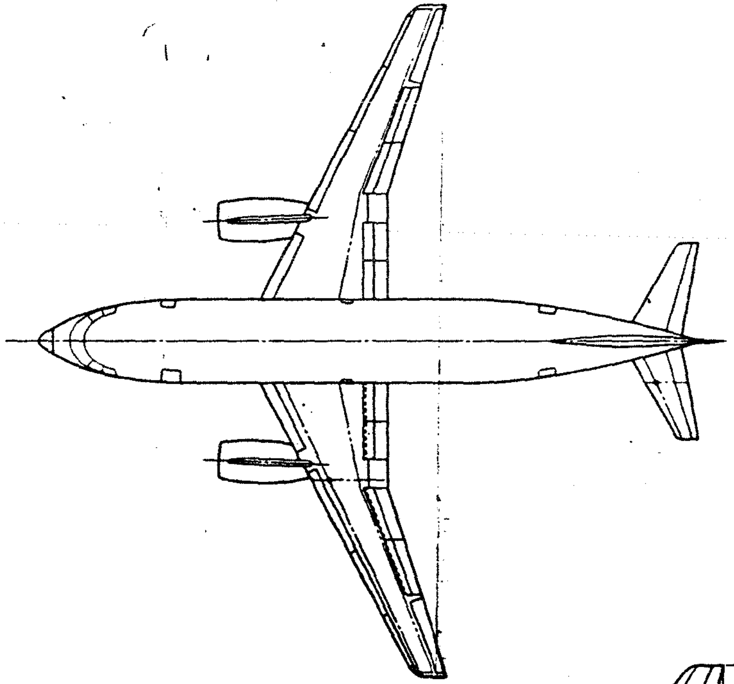
CHARACT'. STICS	WING	HORIZONTAL TAIL	VERTICAL TAIL
AREA SQ. m (SQ. FT.)	93.22 (1003.40)	16.01 (172.33)	21.59 (232.44)
ASPECT RATIO	10.0	5.0	2.0
SPAN m (FT)	30.53 (100.17)	8.94 (29.32)	6.57 (21.56)
ROOT CHORD m (IN.)	4.60 (181.3)	2.65 (104.29)	5.06 (199.1)
TIP CHORD m (IN.)	1.52 (59.8)	.93 (36.5)	1.52 (59.73)
TAPER RATIO	0.33	0.35	0.30
MAC m (IN.)	3.31 (130.3)	1.92 (75.61)	3.60 (141.93)
SWEEP RAD (DEG.)	25	25	35
T/C ROOT %	12.5	10.0	10.0
T/C TIP %	8.7	10.0	10.0

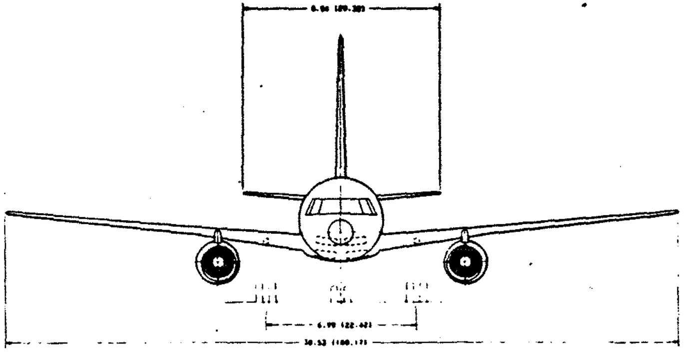
TOGW = 45151 KG (99333 LB)

POWERPLANT-P&W STF-505

.INSTALLED THRUST = 34766 LB SLS

DIMENSIONS:
X.XX m
(X.XX) ft





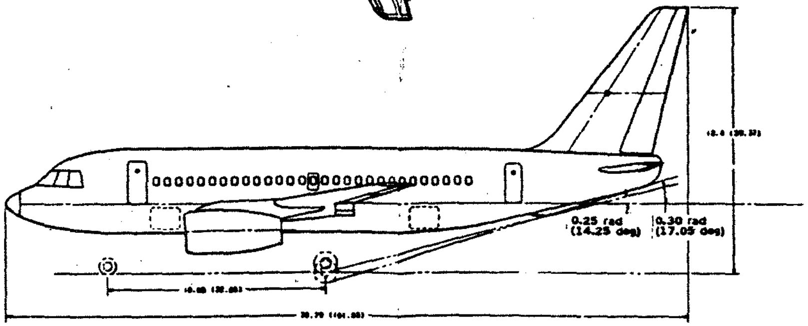


Figure 24. - ATX-100 general arrangement.

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TABLE 20. - ATX-100 REFERENCE AIRCRAFT CHARACTERISTICS AND PERFORMANCE DATA

Takeoff gross weight, TOGW	45 057 kg	99,333 lb
Takeoff thrust to weight, T/W	3.4 N/kg	0.35 lbf/lbm
Wing loading, W/S	483 kg/m^2	99 lb/ft^2
Aspect ratio, AR	10	10
Wing thickness, percent	11	11
Wing sweep at 0.25C	0.44 rad	25 deg
FAA Takeoff field length at S.L., 302K (84°F)	1.6 km	5,243 ft
Minimum cruise altitude	10.6 km	35,000 ft
Approach speed	62 m/s	120.3 kt
Maximum cruise speed	0.80	0.80
Engine-out altitude	5.6 km	18,397 ft
Design range with full payload	1 852 km	1,000 n.mi.
Average stage length	556 km	300 n.mi.

the takeoff gross weight; whereas the fuel required represents approximately 15 percent. The airframe weight is classified by component and material as shown in table 22. Aluminum alloys make up 76 percent of the structural weight in various product forms. Approximately 20 percent of the airframe is manufactured from steels and titanium alloys.

2.3.3 Short-haul commuter aircraft - ATX-50.- The reference aircraft was derived from the results of the NASA-sponsored small transport aircraft technology program (reference 7). The mission characteristics, performance requirements, design requirements and technology applications were consistent with the reference study to provide comparative data.

The aircraft, shown in figure 25, was configured to provide a cruise speed capability of Mach 0.70 for a design range of 1110 km (600 n.mi.). A NASA GAW-1 type airfoil with an average thickness ratio of 16 percent and an aspect ratio of 10 is employed. The engines are overwing mounted to minimize gear length for the required ground clearance.

TABLE 21. - WEIGHT STATEMENT - ATX-100 REFERENCE AIRCRAFT

(a) S.I. Units

	MASS – kg			MASS FRACTION – PERCENT	
GROSS WEIGHT			45 057		
Fuel Available		6,603		Fuel	14.66
ZERO FUEL WEIGHT			38 454		
Payload		9 525		Payload	21.14
● Passengers	7 484				
● Baggage	2 041				
OPERATIONAL EMPTY WEIGHT			28 929		
Operational and Std Items		1 835		Opera. Items	4.07
EMPTY WEIGHT			27 093		
Structure		14 912		Structure	33.10
● Wing	5 650				
● Tail	761				
● Body	5 265				
● Others	3 235				
Propulsion		4 183		Propulsion	9.28
Systems		7 997		Systems	17.75

(b) Customary Units

	WEIGHT – lb			WEIGHT FRACTION – PERCENT	
GROSS WEIGHT			99,333		
Fuel Available		14,557			
ZERO FUEL WEIGHT			84,777	Fuel	14.65
Payload		21,000		Payload	21.14
● Passengers	16,500				
● Baggage	4,500				
OPERATIONAL EMPTY WEIGHT			63,777		
Operational and Std Items		4,046		Opera. Items	4.07
EMPTY WEIGHT			59,730		
Structure		32,876			
● Wing	12,457				
● Tail	1,678				
● Body	11,608				
● Others	7,132				
Propulsion		9,222		Propulsion	9.28
Systems		17,631		Systems	17.75

TABLE 22. - WEIGHT MATRIX - ATX-100 REFERENCE AIRCRAFT
(Percent of Structure Weight)

MATERIAL / COMPONENT	ALUMINUM	TITANIUM	STEEL	COMPOSITE	OTHER	TOTAL
Wing	0.341	0.008	0.027	0	0.003	0.379
Tail	0.046	0.001	0.004	0	–	0.051
Body	0.318	0.014	0.004	0.007	0.010	0.353
Others	0.056	0.031	0.111	–	0.019	0.217
Total	0.761	0.054	0.146	0.007	0.032	1.000

$W_{Structure}$ = 14 912 kg (32,876 lb)

The mission requirements for the ATX-50 aircraft were specified as 1110 km (600 n.mi.) design range with full payload and reserve fuel for 184 km (100 n.mi.) alternate plus 45 minutes at maximum endurance. Additionally, the aircraft was sized for minimum DOC characteristics at a stage length of 184 km (100 n.mi.) with full payload with the stated reserves.

On account of the high-wing loadings on the ATX-50 aircraft, a very effective high-lift system as shown in figure 25 was required to keep landing and takeoff distance to a minimum. Thus, a full-span single-slotted Fowler flap with a 30 percent chord extension and 0.73 rad (42 deg) maximum deflection is incorporated with roll control relegated solely to spoilers. The flaps extend from the fuselage side to the inboard side of the engine nacelle, then from the outboard side of the nacelle to the wing tip. Flap extension is accomplished by fixed tracks and flap mounted rollers, and actuation is via torque tube driven jack screw. Also included are full span leading edge slats with the same coverage as the flaps. A desireable feature of the flap design is that the flap translation reaches 23 percent extension before its deflection exceeds 0.17 rad (10 deg). The benefit of this feature is increased lift-to-drag ratio at the higher C_L values. The resultant takeoff roll is shorter due to reduced drag at the takeoff flap settings.

The ATX-50 was designed to meet the following performance requirements:

Takeoff and landing field length:	1.2 km (4000 ft) at sea level, 306 K (90°F)
Initial cruise altitude:	>9.1 km (31 000 ft)
Cruise Mach no.:	0.70

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CHARACTERISTICS	WING	HORIZONTAL TAIL	VERTICAL TAIL
AREA m^2 (FT2)	44.45 (478.5)	7.13 (76.76)	5.69 (61.25)
ASPECT RATIO	10	6.67	2.0
SPAN	21.64 (71.0)	7.19 (23.6)	3.52 (11.6)
ROOT CHORD	3.32 (10.9)	1.53 (5.03)	2.50 (8.20)
TIP CHORD	1.00 (3.3)	.536 (1.76)	.762 (2.99)
TAPER RATIO	0.30	0.45	0.35
MAC	2.37 (7.8)	1.16 (3.8)	1.80 (6.22)
SWEEP RAD (DEG)	.094 (5.38)	.131 (7.5)	.61 (35)
T/C ROOT (%)	16.8	10	10
T/C TIP (%)	13.5	10	10

TOGW= 17399 KG (38278 LB)
POWERPLANT= ADV. ALLISON TURBOSHAFT
INSTALLED SHP= @ 4700 SLS

DIMENSIONS:
X.XX m
(X.XX) ft

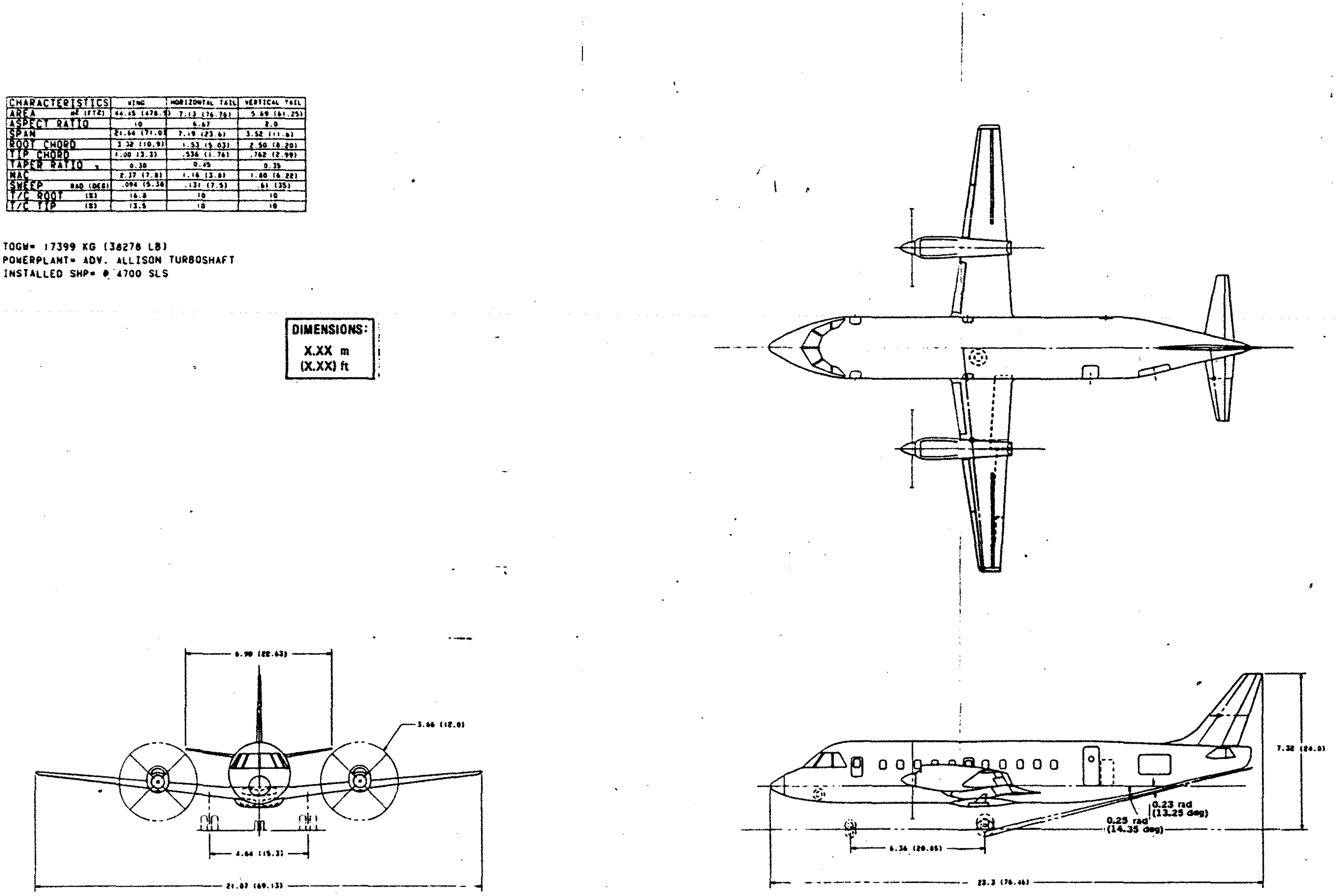

Figure 25. - ATX-50 general arrangement.

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Stall speed in landing configuration:	<48 m/s (93 knot)
Design range with full payload:	1110 km (600 n.mi.)
Average stage length:	185 km (100 n.mi.)

To meet the performance requirements, selected advanced technology features identified in the reference 6 study were incorporated in the ATX-50 reference aircraft. Active flap systems are used to provide gust-load alleviation during cruise operation (other than flap-down configuration). Active controls concepts can also be used to greater advantage for short-haul because the type of wing on this aircraft is more sensitive to turbulence.

The aircraft characteristics and performance data are presented in table 23. The aircraft has a takeoff gross weight of 17 363 kg (38,278 lb) with a wing loading of 390 kg/m^2 (80 lb/ft^2). The aircraft complies with the specified requirements in terms of takeoff, landing, and cruise performance as shown in the table. The weight description of the aircraft is presented in table 24. The structure weight represents 28 percent of the gross weight; the fuel available is less than 9 percent of the gross weight for the short-haul commuter aircraft. The airframe weight was classified by component and material system in table 25. The data are presented in terms of percent of structure weight of 4847 kg (10,686 lb). The aluminum alloy usage is 77 percent; the titanium alloy and steel applications are 19 percent of the airframe weight.

2.4 Reference Aircraft Analysis

Analyses were conducted to identify the performance and economic benefits of incorporating advanced aluminum alloys in the three reference aircraft. The benefits for each reference aircraft were determined by comparing the appropriate reference aircraft, with and without incorporation of the advanced aluminum alloys. The analysis was conducted using the Lockheed-developed ASSET (Advanced Synthesis and Evaluation Technique) program schematically shown in figure 26. Structural, weight, and cost analyses were performed to provide inputs to reflect advanced aluminum alloys weight and cost data. These data were considered "uncycled" as compared to "recycled" data which considered resizing of the reference aircraft to perform the same payload-mission with incorporation of the advanced aluminum alloys.

2.4.1 Aircraft systems analysis.- A conceptual design for each of the three aircraft types was made. Each design was input to the ASSET model along with mission, performance, and payload requirements. The three major subprograms of ASSET are sizing, performance, and costing: (1) The sizing program sizes each parametric aircraft to a design mission. The design characteristics and component weights of the sized aircraft are then transferred to; (2) the costing program, which computes cost on the basis of component weights and materials, engine cycle and size, learning curves, and input cost factors; and (3) the performance program which computes maneuverability, maximum speed, ceiling, landing and takeoff distances and other performance parameters. The

TABLE 23. - ATX-50 REFERENCE AIRCRAFT CHARACTERISTICS AND PERFORMANCE DATA

Takeoff gross weight, TOGW	17 363 kg	38,278 lb
Takeoff thrust to weight, T/W	3.37 N/kg	0.344
Wing loading, W/S	390 kg/m^2	80 lb/ft^2
Aspect ratio, AR	10	10
Wing thickness, percent	16	16
Wing sweep at 0.25C	0.09 rad	5.38 deg
Takeoff field length at S.L., 306K (90°F)	1.2 km	4001 ft
Landing field length at S.L., 306K (90°F)	1.2 km	3996 ft
Cruise Mach No.	0.70	0.70
Stall speed in landing configuration:	43.6 m/s	84.5 knots
Design range range with full payload	1110 km	600 n.mi.
Average stage length	185 km	100 n.mi.

output includes a point design description, group weight statement, aircraft geometry description, mission profile summary, aircraft performance evaluation, RDT&E program cost, aircraft production cost, and procurement cost per aircraft. A summary of aircraft operational costs (direct and indirect), and return-on investment were determined for a fixed fare price assuming a hypothetical fleet size.

The evaluation of benefits from incorporating advanced aluminum alloys is accomplished by defining the airframe component and system weight savings, and inputting these into the ASSET weight and sizing subroutine. Appropriate cost data were also developed and added to the ASSET program for analysis of the aircraft economic benefits.

Three separate advanced aluminum aircraft were defined to the same payload-range performance as the comparable long-range (ATX-350I), short-medium range (ATX-100), and short-haul commuter (ATX-50) reference aircraft. The benefits are presented as variations to the base value (reference aircraft). The net benefit of advanced aluminum technology was determined by comparing the total operational cost and flyaway cost of the advanced aluminum aircraft relative to the aluminum alloy technology development cost.

TABLE 24. - WEIGHT STATEMENT - ATX-50 REFERENCE AIRCRAFT
(a) S.I. Units

	MASS – kg			MASS FRACTION – PERCENT	
GROSS WEIGHT			17 363		
Fuel Available		1 485		Fuel	8.55
ZERO FUEL WEIGHT			15 878		
Payload		4 536		Payload	26.12
● Passengers	3 856				
● Baggage	680				
OPERATIONAL EMPTY WEIGHT			11 342		
Operational and Std Items		527		Opera. Items	3.03
EMPTY WEIGHT			10 815		
Structure		4 847		Structure	27.92
● Wing	1 262				
● Tail	211				
● Body	2 357				
● Others	1 017				
Propulsion		1 785		Propulsion	10.28
Systems		4 182		Systems	24.09

(b) Customary Units

	WEIGHT – lb			WEIGHT FRACTION – PERCENT	
GROSS WEIGHT			38,278		
Fuel Available		3,274		Fuel	8.55
ZERO FUEL WEIGHT			35,004		
Payload		10,000		Payload	26.12
● Passengers	8,500				
● Baggage	1,500				
OPERATIONAL EMPTY WEIGHT			25,004		
Operational and Std Items		1,161		Opera. Items	3.03
EMPTY WEIGHT			23,842		
Structure		10,686		Structure	27.92
● Wing	2,783				
● Tail	465				
● Body	5,196				
● Others	2,243				
Propulsion		3,936		Propulsion	10.28
Systems		9,221		Systems	24.09

TABLE 25. - WEIGHT MATRIX - ATX-50 REFERENCE AIRCRAFT
(Percent of Structure Weight)

MATERIAL / COMPONENT	ALUMINUM	TITANIUM	STEEL	COMPOSITE	OTHER	TOTAL
Wing	0.234	0.005	0.018	0	0.003	0.260
Tail	0.039	0.001	0.003	0	0.001	0.044
Body	0.438	0.019	0.005	0.010	0.014	0.486
Others	0.055	0.031	0.108	–	0.016	0.210
Total	0.766	0.056	0.134	0.010	0.034	1.000

$W_{Structure}$ = 4 847 kg (10,686 lb)

Parametric analyses were accomplished for each of the aircraft types to determine the sensitivity of takeoff gross weight, operating weight empty, block fuel, aircraft cost, and operating cost to variations in material properties of advanced aluminum alloys.

2.4.2 Structural analysis.- Analyses were performed to arrive at component weight reduction factors for advanced aluminum alloy applications. The analytical model developed by Lockheed for the Defense Advanced Research Projects Agency (DARPA) study (reference 4 and 9) was used for the weight evaluation of advanced aluminum alloy application to the three reference aircraft. The method permits the estimation of weight savings resulting from material substitution in specific airframe components. The weight ratio data corresponding to the various design criteria were employed as shown in table 26. An estimate of weight savings was obtained by employing the preliminary target and baseline material property data. Both primary and secondary failure modes were considered for the selected components using the appropriate strength, modulus of elasticity, density, and fatigue and fracture toughness properties.

The application of the above design methodology required the knowledge of the failure-mode criteria for the specific component. The application of the new alloys to the cover panels (skin plus stringers) of high aspect ratio, moderately swept wings of the ATX-350I and ATX-100 aircraft fall outside the bounds of known design criteria. Rather than estimating the allocation of failure modes to the upper and lower covers, analysis of the cover panels were performed using a computer program entitled SPOT (stringer panel optimization technology). The program was used to size the skin-stringer combination

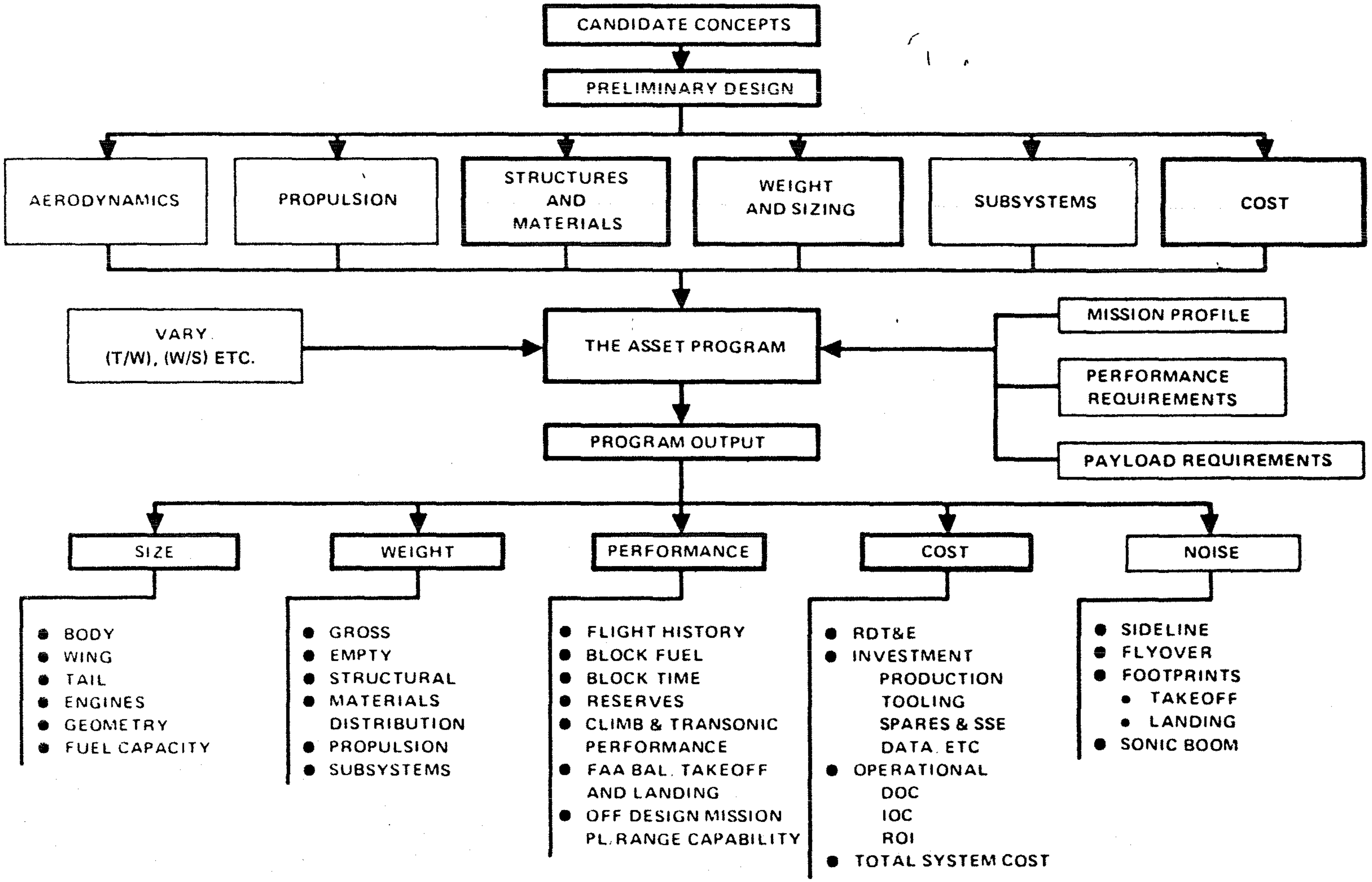


Figure 26. - The ASSET synthesis cycle.

TABLE 26. - WEIGHT RATIO VERSUS FAILURE MODE

CATEGORY NO.	FAILURE MODE	WEIGHT RATIO $\frac{W_2}{W_1}$
1	Tensile strength	$\frac{\rho_2}{\rho_1} \frac{Ftu_1}{Ftu_2}$
2	Compressive strength	$\frac{\rho_2}{\rho_1} \frac{Fcy_1}{Fcy_2}$
3	Crippling	$\frac{\rho_2}{\rho_1} \left[\frac{E_{s_1}}{E_{s_2}}\right]^{.25} \left[\frac{Fcy_1}{Fcy_2}\right]^{.26}$
4	Compression surface column and crippling	$\frac{\rho_2}{\rho_1} \left[\frac{E_1}{E_2}\right]^{.4} \left[\frac{Fcy_1}{Fcy_2}\right]^{.2}$
5	Buckling compression or shear	$\frac{\rho_2}{\rho_1} \left[\frac{E_1}{E_2}\right]^{.33}$
6	Aeroelastic stiffness	$\frac{\rho_2}{\rho_1} \frac{E_1}{E_2}$
7	Durability and damage tolerance cutoff (DADT)	$\frac{\rho_2}{\rho_1} \frac{F_1}{F_2}$
8	General instability compression or shear	$\frac{\rho_2}{\rho_1} \left[\frac{E_1}{E_2}\right]^{.5}$
9	Minimum gage	$\frac{\rho_2}{\rho_1} \frac{t_2}{t_1}$

for a set of combined loads from a static strength and buckle-resistance standpoint. The features of the program include the following capabilities:

- Accounts for the nonlinearity of the material stress-strain relationship by using the material yield stress, Ramberg-Osgood shape parameter, and modulus of elasticity (program input data).
- Allows postbuckling in the material's elastic range (buckling in the nonlinear portion of the stress-strain curve is considered a failure).
- Limits the design to stress levels not to exceed the tension stress allowed by fatigue considerations. This cutoff tension stress due to fatigue consideration is contained in the material data set.
- Prevents the tension stress at limit load to exceed the allowable residual strength after an assumed damage (cracked skin). The allowable residual strength is a function of stiffener spacing, assumed crack length and critical stress intensity factor. The latter is a function of skin thickness for a particular material.

To satisfy the torsional stiffness requirement, additional skin thickness was included considering the complete wing box cross section (i.e., spar webs and wing covers).

The wing cover cross section geometry was held invariant for the ATX-350I and ATX-100 aircraft. The wing covers were optimized using J-stiffened (lower) and Z-stiffened (upper) configurations for a rib spacing of 66.0 cm (26.0 in.). A constant stringer spacing of 13.2 cm (5.2 in.) and 18.8 cm (7.4 in.) was used for the upper and lower cover designs, respectively. Practical skin thickness and stiffener geometry constraints were also used.

The capability of the SPOT computer program to size wing cover panels with reasonable accuracy was verified by analysis of the upper surface panels of the L-1011-500 ACS (active control system) aircraft. The five point design regions selected for analysis verification are shown in figure 27. The internal loads resulting from the nine most severe loading conditions at each spanwise location were obtained. For design analysis of the upper covers, the property data for the baseline alloys of 7075-T76 high-strength clad plate and 7075-T6 extrusion were used to size the seven point design regions shown in figure 27. The solid-line of figure 28 represents analysis results using the baseline alloys to size the skin-stringer cover designs. The solid triangles are the weight per unit span of the actual skin and stringers of the L-1011-500 ACS aircraft at the five point design regions. Close correlation between the SPOT analysis and actual skin-stringer design was thus demonstrated.

The dash-line of figure 28 shows analysis results obtained from the use of the high-strength corrosion-resistant alloy B for the skin and stringer material. A potential weight savings of 12 percent is indicated by comparison

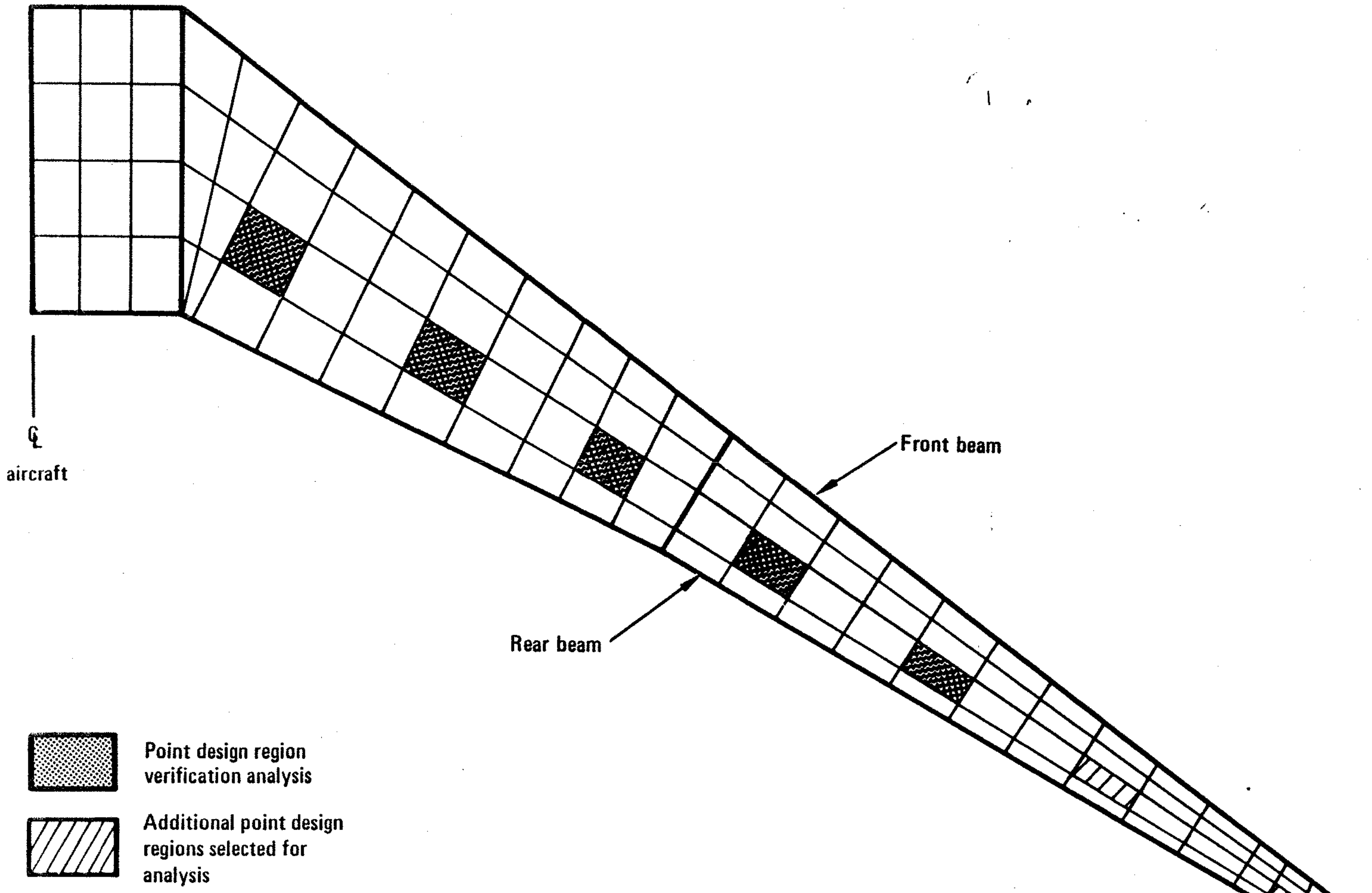


Figure 27. - Wing box geometry - long-range transport aircraft.

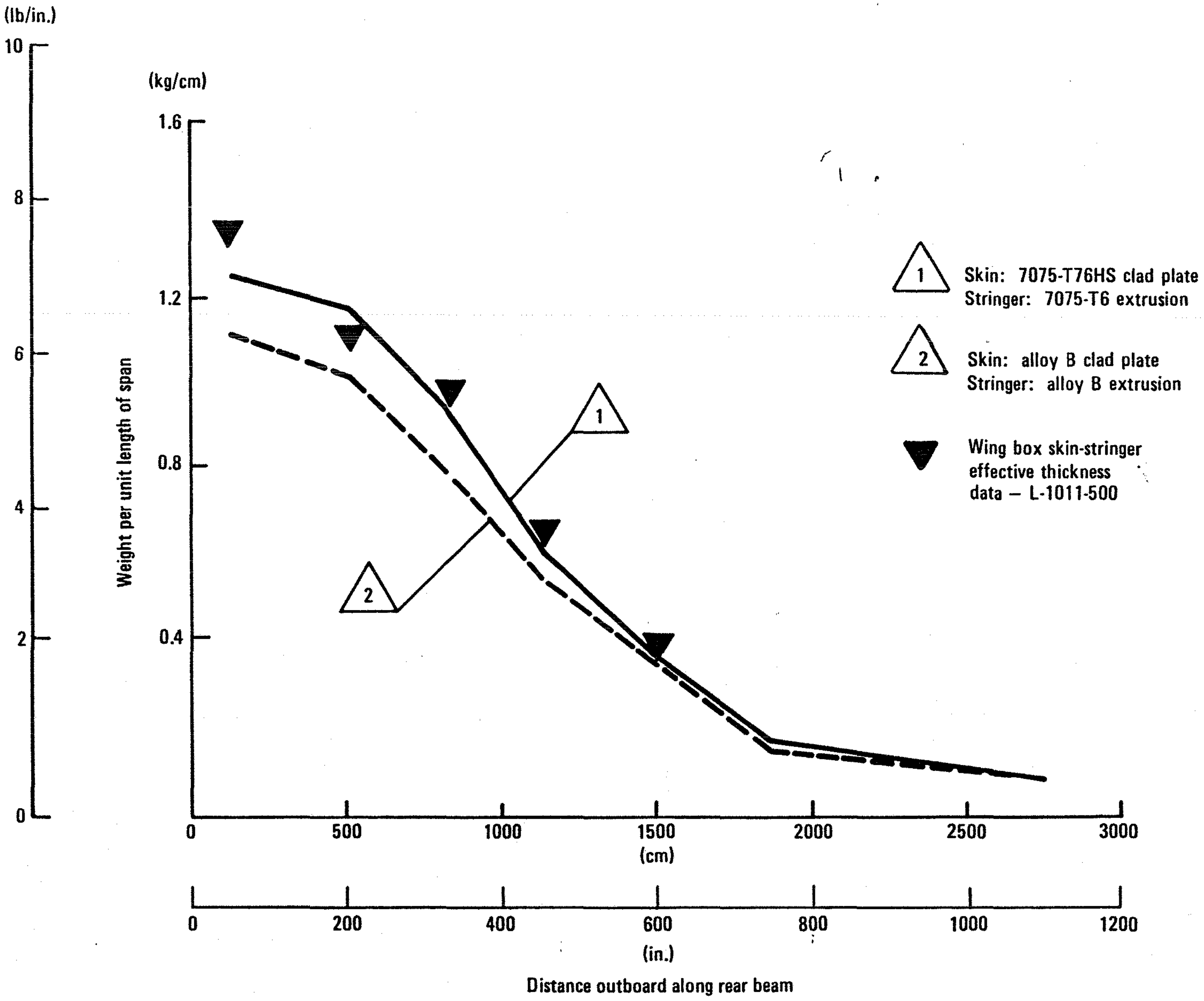


Figure 28. - Weight trends for wing upper cover - long-range transport aircraft.

of the baseline 7075-T76/T6 alloy design to the alloy B design. Similar analysis was performed for the lower cover design using the baseline alloy and the damage-tolerant alloy D skin/high-strength corrosion-resistant alloy B stringers (figure 29). For the lower cover design the weight savings potential is 18 percent.

A similar procedure was employed to size the upper and lower covers for the ATX-350I and ATX-100 reference aircraft. The cover panels were optimized for conventional and selected advanced aluminum alloy. The weight savings for candidate alloys were obtained from the delta-weight resulting from the analysis process. Representative maximum spanwise axial loading for both upper-surface and lower-surface design is presented in figure 30. The maximum loads occur at approximately 42 percent of the wing box semispan. The peak loads for the ATX-350I are twice that of the ATX-100 aircraft with magnitudes of -61 000 kN/m (-35,000 lb/in.). The loads at the side of the fuselage, however, are significantly greater (2.5X) for the larger aircraft. To assess the aeroelastic requirements, data were extrapolated from the L-1011-500 aircraft accounting for the difference in geometry, aspect ratio, and span, etc. The torsional stiffness requirement is presented in figure 31 at selected percent semispan locations. The results of these analyses are presented for the lower surface and upper surface in terms of weight per unit length versus percent semispan in figures 32 through 35. The weight increment due to the torsional stiffness requirement is represented by the cross-hatched region. Significant material must be added to the skin to satisfy this requirement on the ATX-350I design. This requirement is significantly reduced for the smaller, lower-gross-weight aircraft. Because of the torsional stiffness requirement, alloy C-high-strength stiffness, reduced-density alloy was selected for upper cover applications for both aircraft. To provide compatibility between the skin and stringer, alloy C was also selected for the extruded stringer application. The fatigue-resistant, damage-tolerant alloy D was selected for lower cover application for both aircraft. The potential weight savings for the skin-stringer cover panel design are presented in table 27. For the ATX-350I the weight savings is 12 percent for both the upper and lower cover. For the ATX-100, the weight savings for the upper and lower cover design is 11 and 16 percent, respectively.

The weight-reduction factors were determined for the wing, tail, and body groups by classifying each group into their significant components in terms of weight and product form. Based on the component design criteria a hypothetical alloy (e.g., Alloy A) was selected. With the target properties specified and design criteria known, the weight reduction of the selected component was determined. The latter was obtained either by detailed structural analysis or material property - failure mode criteria. The group weights for the wing, tail, and body employing conventional aluminum alloy and advanced aluminum alloy constructure are presented in tables 28, 29, and 30 respectively. The advanced aluminum alloy weights represent unresized aircraft weights. Also indicated on the tables are the weight savings for the primary structure and the secondary structure. The results show that the weight savings for the secondary structure and small primary structure are similar when comparing component data for the reference aircraft. The weight-savings trends for the larger aircraft are greater, as expected. The ATX-50 airframe is constrained

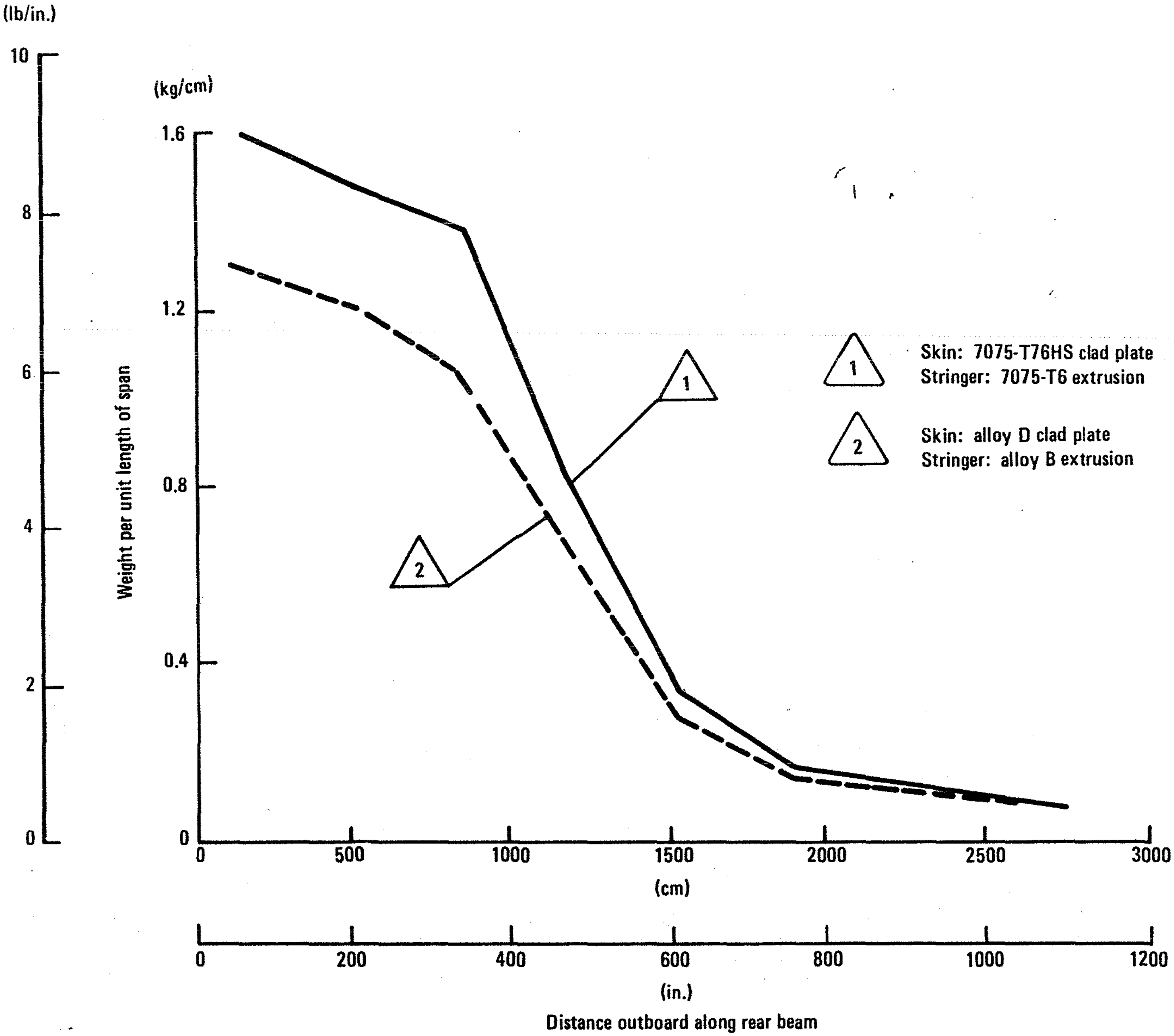
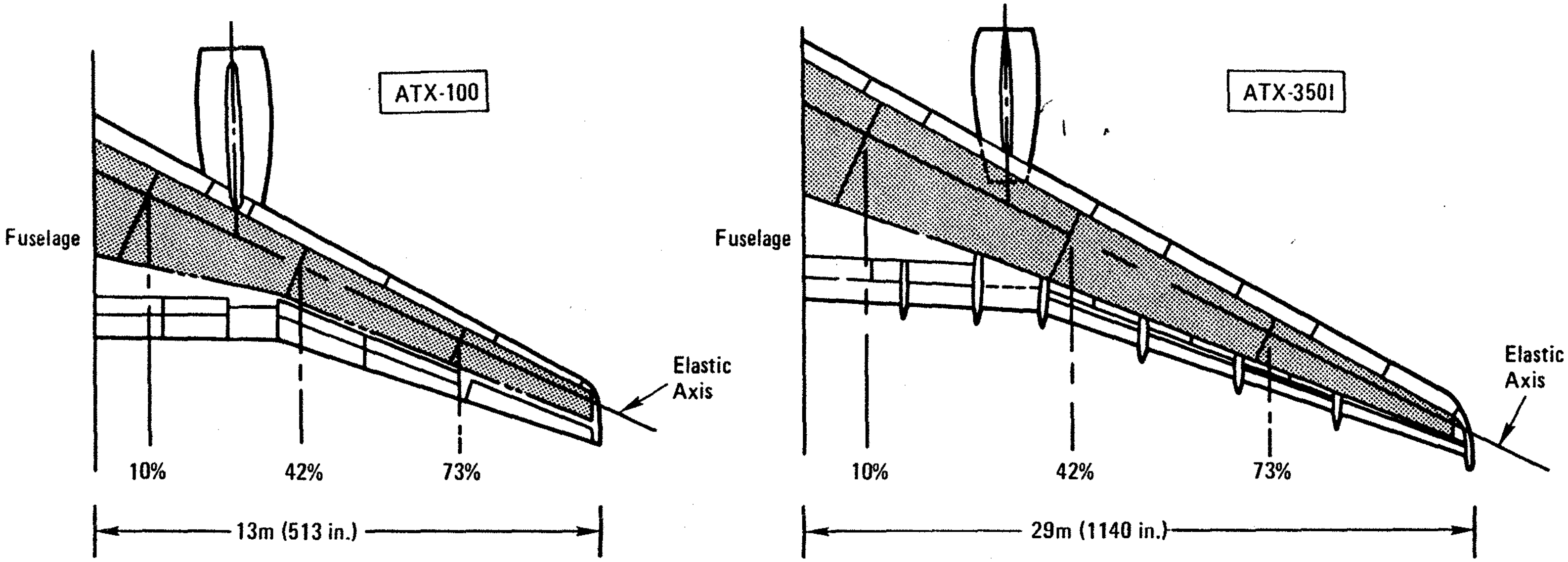
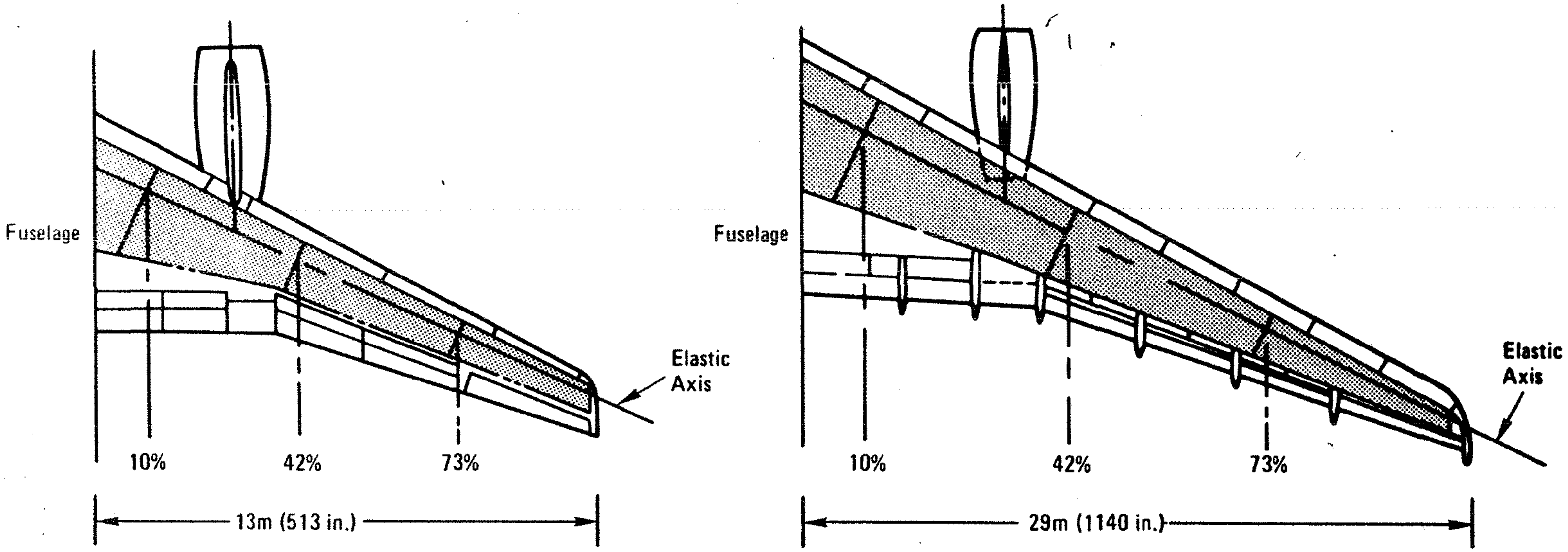


Figure 29. - Weight trends for wing box lower cover - long-range transport aircraft.



Percent semi-span			10	42	73
ATX-350I	Upper	kN/m	-5379	-6071	-2977
		lb/in.	-30716	-34669	-16997
	Lower	kN/m	5173	6250	2527
		lb/in.	29538	35687	14428
ATX-100	Upper	kN/m	-2101	-3065	-963
		lb/in.	-12000	-17500	-5500
	Lower	kN/m	2101	3065	963
		lb/in.	12000	17500	5500

Figure 30. - Maximum upper and lower surface spanwise axial loading.



Percent semi-span		10	42	73
ATX-350I	MN m^2	3989	459	29
	lb-in.^{2} x 10^9	1390	160	10
ATX-100	MN m^2	129	32	9
	lb-in.^{2} x 10^9	45	11	3

Figure 31. - Wing torsional stiffness requirement.

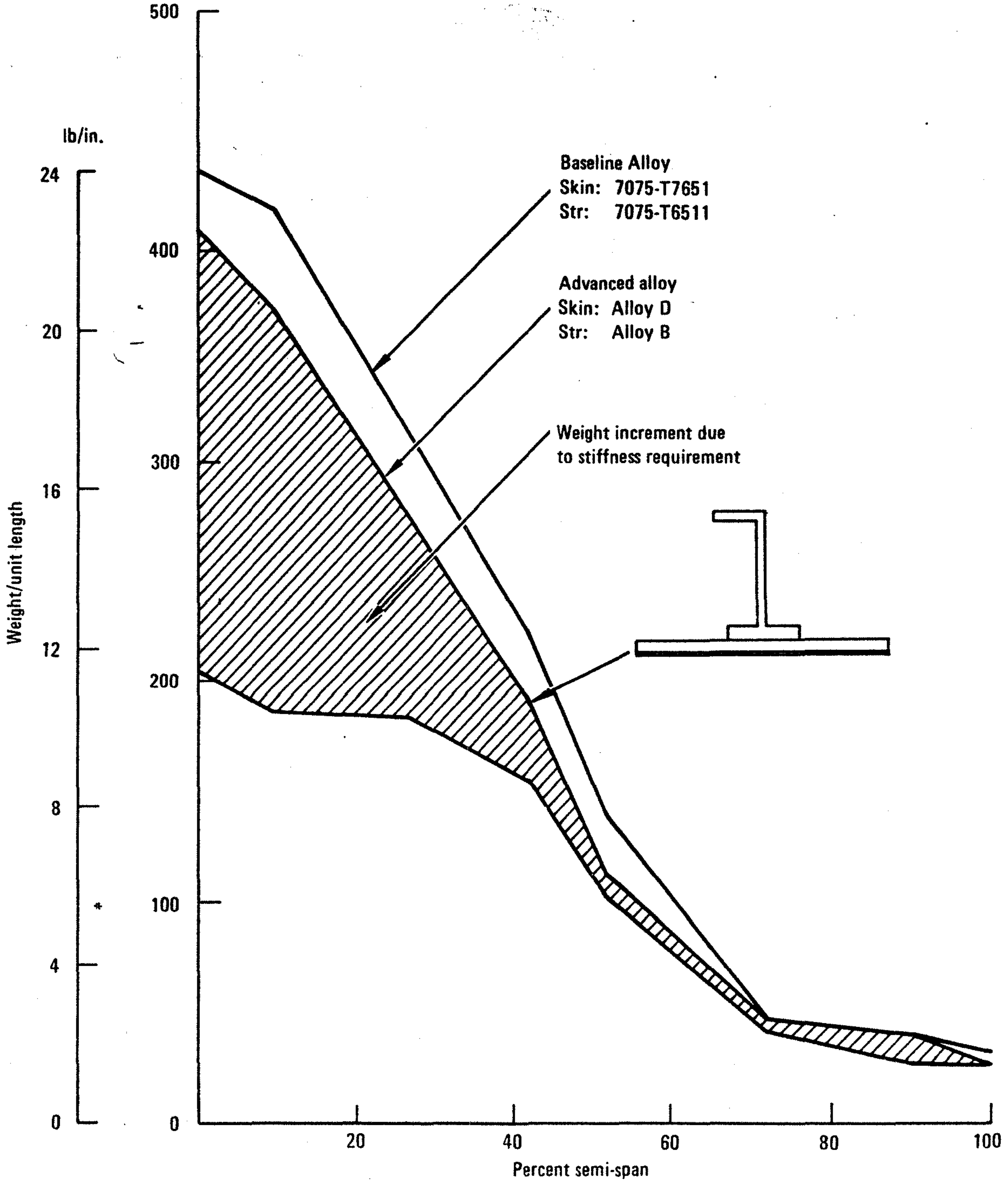


Figure 32. - Lower surface wing weight - ATX-350I.

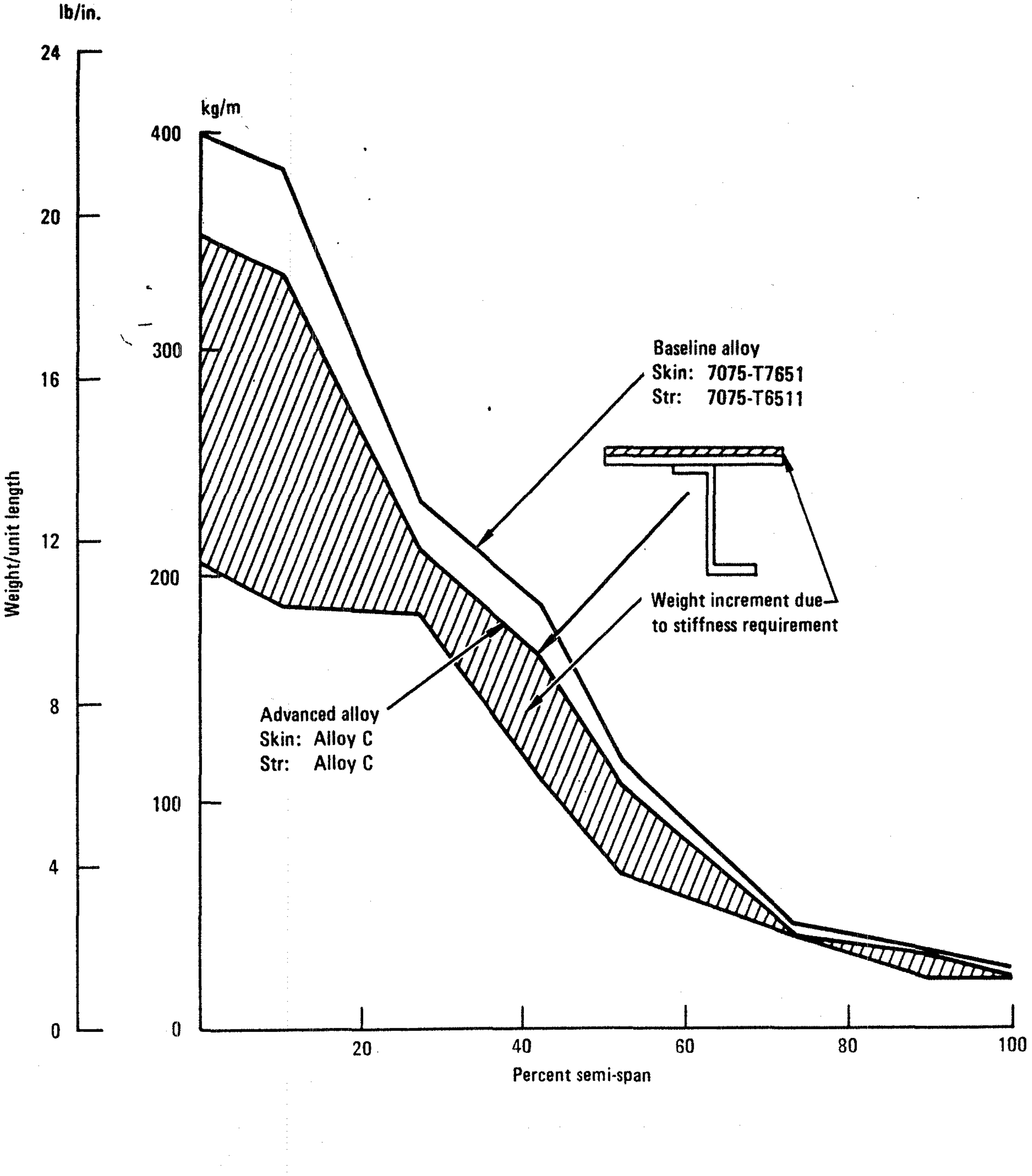


Figure 33. - Upper surface wing weight - ATX-350I.

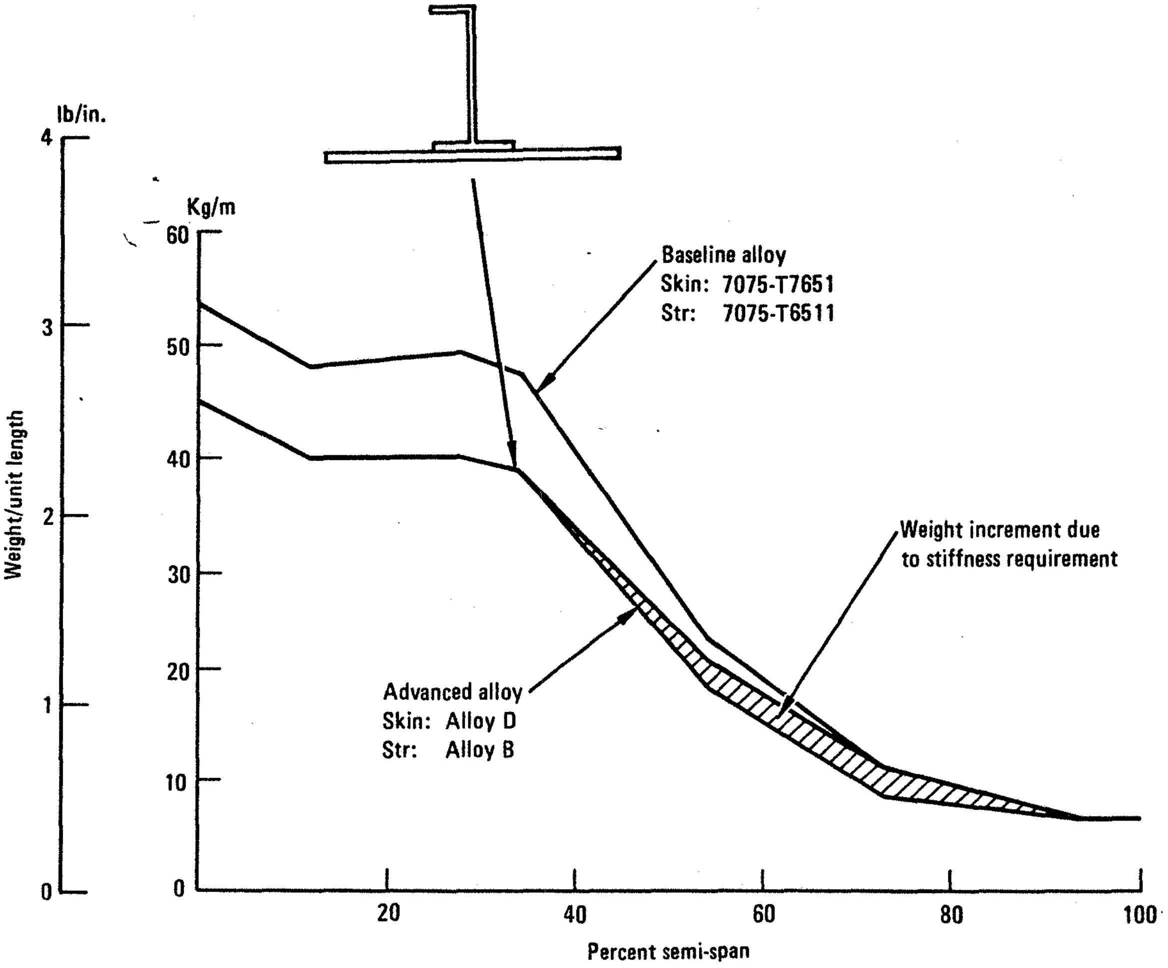


Figure 34. - Lower surface wing weight - ATX-100.

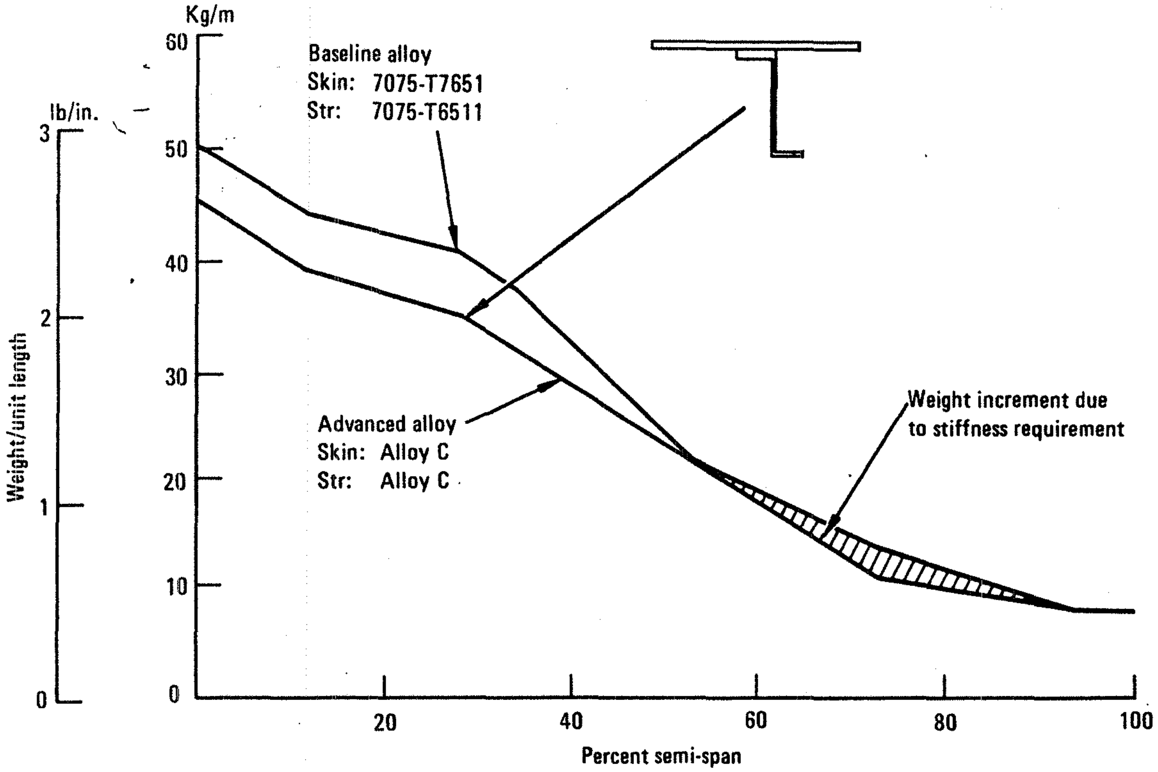


Figure 35. - Upper surface wing weight - ATX-100.

TABLE 27. - UNCYCLED SEMISPAN WING WEIGHT COMPARISON

REFERENCE AIRCRAFT	WING COVER		ALLOY TYPE		PERCENT SAVED
			CONVENTIONAL	ADVANCED	
ATX-350I	Upper Surface	kg	5972	5255	12
		lb	13166	11586	
	Lower Surface	kg	6891	6064	12
		lb	15192	13369	
ATX-100	Upper Surface	kg	482	429	11
		lb	1062	946	
	Lower Surface	kg	533	448	16
		lb	1176	988	

TABLE 28. - UNCYCLED WING GROUP WEIGHT SAVINGS

Component	Materials	ATX-350I		ATX-100		ATX-50	
		kg	lb	kg	lb	kg	lb
Wing Box	Conventional Aluminum	31 266	68,929	4 138	9,122	836	1,843
	Advanced Aluminum	27 378	60,358	3 616	7,971	760	1,675
	Weight Savings	888	8,571	522	1,151	76	168
	Percent Savings	12.4		12.6		9.1	
Secondary	Conventional Aluminum	6 453	14,227	1 513	3,335	426	940
	Advanced Aluminum	5 902	13,011	1 388	3,059	393	866
	Weight Savings	551	1,216	125	276	33	74
	Percent Savings	8.5		8.3		8.2	
Wing Group	Conventional Aluminum	37 719	83,156	5 650	12,457	1,262	2,783
	Advanced Aluminum	33 280	73,369	5 003	11,030	1,152	2,541
	Weight Savings	4 439	9,787	647	1,427	110	242
	Percent Savings	11.8		11.4		8.7	

TABLE 29. - UNCYCLED TAIL GROUP WEIGHT SAVINGS

Component	Materials	ATX-350I		ATX-100		ATX-50	
		kg	lb	kg	lb	kg	lb
Primary Box	Conventional Aluminum	1 859	4,099	404	891	98	216
	Advanced Aluminum	1 613	3,556	350	773	87	191
	Weight Savings	246	543	54	118	11	25
	Percent Savings	13.2		13.2		11.6	
Secondary	Conventional Aluminum	1 888	4,162	357	787	113	249
	Advanced Aluminum	1 684	3,713	320	705	101	222
	Weight Savings	204	449	37	82	12	27
	Percent Savings	10.8		10.4		10.8	
Tail Group	Conventional Aluminum	3 747	8,261	761	1,678	211	465
	Advanced Aluminum	3 297	7,269	670	1,478	187	413
	Weight Savings	450	992	91	200	24	52
	Percent Savings	12.0		11.9		11.2	

by standard sheet metal gage construction and areas of minimum gage application. The component weights are for each of the reference aircraft and were further classified into product form and alloy type. The data are presented in tables 31 through 33.

Similar alloy application trends are noted for the ATX-100 (B-737 class) and ATX-350I (L-1011 class) aircraft. High-strength-type alloys (Alloy A and Alloy B) represent approximately 37 percent of the airframe weight for each aircraft. The use of the aluminum-lithium type alloys (Alloy C and Alloy E) and the fatigue-resistant, damage-tolerant alloy (Alloy D) are equal in percentage of the respective airframe weight. The short-haul aircraft (ATX-50) alloy usage is dominated by the aluminum-lithium alloy.

The product forms used in each of the components of the reference aircraft are presented in terms of uncycled weight in the tables. The larger aircraft (ATX-100 and ATX-350I) employs a mix of product forms as noted by the percent applications. Extruded product forms are the major contributor to the airframe weight. The product form data are used to obtain cost factors for the advanced aluminum alloys and to provide insight into the process development and scale-up required to attain usable product forms for airframe design.

TABLE 30. - UNCYCLED BODY GROUP WEIGHT SAVINGS

Component	Materials	ATX-350I		ATX-100		ATX-50	
		kg	lb	kg	lb	kg	lb
Primary Shell	Conventional Aluminum	18 293	40,329	2 900	6,394	1 343	2,961
	Advanced Aluminum	16 316	35,971	2 590	5,710	1 225	2,700
	Weight Savings	1 997	4,358	310	684	118	261
	Percent Savings	10.8		10.7		8.8	
Secondary	Conventional Aluminum	11 845	26,114	2 365	5,214	1 014	2,235
	Advanced Aluminum	11 239	24,778	2 248	4,956	973	2,146
	Weight Savings	606	1,336	117	258	41	89
	Percent Savings	5.1		4.9		4.0	
Body Group	Conventional Aluminum	30 138	66,443	5 265	11,608	2 357	5,196
	Advanced Aluminum	27 555	60,749	4 838	10,666	2 198	4,846
	Weight Savings	2 583	5,694	427	942	159	350
	Percent Savings	8.6		8.1		6.7	

2.4.3 Economics and cost analysis. - The cost analysis for the reference aircraft was performed in an attempt to arrive at realistic costs (flyaway, operational) for the aircraft considered. Appropriate cost input data were developed to accomplish analysis of the aircraft economic benefits.

The costs for each reference and advanced aluminum aircraft were based on the following study guidelines:

- The development and production costs were determined from cost estimating relations (CERs) developed from total Lockheed experience. The development cost is amortized into production cost for determining depreciation expense.
- The development and production costs were Lockheed's actual January 1980 levels for direct, overhead, and general and administrative rates, plus profit factor.
- The operating costs were determined from 1967 Air Transport Association (ATA) equations with coefficients updated to January 1980 experience.
- Passenger load factors of 60 percent at average stage length and 100 percent at design range.

TABLE 31. - WEIGHT CLASSIFICATION OF COMPONENTS - ATX-350I

ATX-350I WING GROUP

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A		3.1	–	3.7	–	–	2 259	4,981	6.8
B		–	3.5	14.0	2.9	–	6 802	14,997	20.4
C		–	17.4	16.6	–	–	11 322	24,962	34.0
D		–	26.5	–	–	–	8 829	19,464	26.5
E		3.9	–	–	–	–	1 306	2,879	3.9
Others		–	–	–	–	8.3	2 760	6,086	8.3
Σ	kg	2 346	15 797	11 414	962	2 760	33 280	–	–
	lb	5,172	34,827	25,164	2,120	6,086	–	73,369	–
Percent Product Form		7.0	47.5	34.3	2.4	8.3	–	–	100

ATX-350I TAIL GROUP

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A		–	–	–	–	–	–	–	–
B		–	–	–	7.7	–	255	563	7.7
C		–	–	35.5	–	–	1 172	2,583	35.5
D		–	–	–	–	–	–	–	–
E		42.6	–	–	–	–	1 405	3,098	42.6
Others		–	–	–	–	14.1	465	1,025	14.1
Σ	kg	1 405	–	1 172	255	465	3 297	–	–
	lb	3,098	–	2,583	563	1,025	–	7,269	–
Percent Product Form		42.6	–	35.5	7.7	14.1	–	–	100

TABLE 31. - CONCLUDED

ATX-350I BODY GROUP

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A		21.9	–	28.6	–	–	13 935	30,722	50.6
B		–	–	–	4.6	–	1 270	2,800	4.6
C		–	–	–	–	–	–	–	–
D		21.9	–	–	–	–	6 025	13,283	21.9
E		–	–	–	–	–	–	–	–
Others		–	–	–	–	23.0	6 325	13,944	23.0
Σ	kg	12 071	–	7 889	1 270	6 325	27 555	–	–
	lb	26,612	–	17,393	2,800	13,944	–	60,749	–
Percent Product Form		43.8	–	28.6	4.6	23.0	–	–	100

ATX-350I AIRFRAME

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A		11.0	–	14.2	–	–	16 145	35,703	25.2
B		–	1.8	7.3	3.9	–	8 328	18,360	13.0
C		–	9.0	10.4	–	–	12 494	27,545	19.4
D		9.4	13.8	–	–	–	14 854	32,747	23.2
E		4.2	–	–	–	–	2 720	5,977	4.2
Others		–	–	–	–	14.9	9 550	21,055	14.9
Σ	kg	15 822	15 797	20 475	2 487	9 550	64 132	–	–
	lb	34,882	34,827	45,140	5,483	21,055	–	141,387	–
Percent Product Form		24.6	24.6	31.9	3.9	14.9	–	–	100

TABLE 32. - WEIGHT CLASSIFICATION OF COMPONENTS - ATX-100

ATX-100 WING GROUP

Alloy	Product Form					Σ Weight		Percent Alloy
	Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A	5.2	–	4.2	–	–	473	1,042	9.4
B	–	3.7	10.2	4.8	–	929	2,049	18.6
C	–	15.6	13.2	–	–	1 439	3,172	28.8
D	–	19.1	–	–	–	954	2,104	19.1
E	5.8	–	–	–	–	292	645	5.8
Others	–	–	–	–	18.3	915	2,018	18.3
Σ kg	553	1 916	1 380	238	915	5 003	–	–
Σ lb	1,220	4,224	3,043	525	2,018	–	11,030	–
Percent Product Form	11.0	38.4	27.6	4.8	18.3	–	–	100

ATX-100 TAIL GROUP

Alloy	Product Form					Σ Weight		Percent Alloy
	Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A	–	–	–	–	–	–	–	–
B	–	–	–	5.6	–	38	83	5.6
C	–	–	33.2	–	–	223	491	33.2
D	–	–	–	–	–	–	–	–
E	42.2	–	–	–	–	283	624	42.2
Others	–	–	–	–	18.9	127	280	18.9
Σ kg	283	–	223	38	127	670	–	–
Σ lb	624	–	491	83	280	–	1,478	–
Percent Product Form	42.2	–	33.2	5.6	18.9	–	–	100

TABLE 32. - CONCLUDED

ATX-100 BODY GROUP

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A		20.6	–	26.6	–	–	2 286	5,039	47.2
B		–	–	–	4.8	–	234	516	4.8
C		–	–	–	–	–	–	–	–
D		21.5	–	–	–	–	1 040	2,294	21.5
E		–	–	–	–	–	–	–	–
Others		–	–	–	–	26.4	1 278	2,817	26.4
Σ	kg	2,039	–	1 287	234	1 278	4 838	–	–
	lb	4,496	–	2,837	516	2,817	–	10,666	–
Percent Product Form		42.2	–	26.6	4.8	26.4	–	–	100

ATX-100 AIRFRAME

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A		12.0	–	14.2	–	–	2 758	6,081	26.2
B		–	1.7	4.8	4.8	–	1 201	2,648	11.4
C		–	7.4	8.4	–	–	1 662	3,663	15.8
D		9.9	9.1	–	–	–	1 995	4,398	19.0
E		5.5	–	–	–	–	576	1,269	5.5
Others		–	–	–	–	22.1	2 320	5,115	22.1
Σ	kg	2 876	1 916	2 890	510	2 320	10 512	–	–
	lb	6,340	4,224	6,371	1,124	5,115	–	23,174	–
Percent Product Form		27.4	18.2	27.4	4.8	22.1	–	–	100

TABLE 33. - WEIGHT CLASSIFICATION OF COMPONENTS - ATX-50

ATX-50 WING GROUP

Alloy	Product Form					Σ Weight		Percent Alloy
	Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A	–	–	–	–	–	–	–	–
B	–	–	–	3.1	–	36	80	3.1
C	–	–	13.5	–	–	156	343	13.5
D	20.4	–	–	–	–	235	519	20.4
E	31.2	–	–	–	–	429	945	37.2
Others	–	–	–	–	25.7	247	654	25.7
Σ kg	664	–	156	36	297	1 152	–	–
lb	1,464	–	343	80	654	–	2,541	–
Percent Product Form	57.6	–	13.5	3.1	25.7	–	–	100

ATX-50 TAIL GROUP

Alloy	Product Form					Σ Weight		Percent Alloy
	Clad Sheet	Plate	Extrusion	Forging	Other	kg	lb	
A	–	–	–	–	–	–	–	–
B	–	–	–	5.6	–	10	23	5.6
C	–	–	13.8	–	–	26	57	13.8
D	–	–	–	–	–	–	–	–
E	67.8	–	–	–	–	127	280	67.8
Others	–	–	–	–	12.8	24	53	12.8
Σ kg	127	–	26	10	24	187	–	–
lb	280	–	57	23	53	–	413	–
Percent Product Form	67.8	–	13.8	5.6	12.8	–	–	100

TABLE 33. - CONCLUDED

ATX-50 BODY GROUP

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A B C D E Others		– – – 29.0 20.5 –	– – – – – –	– 6.1 12.0 – – –	– 4.6 – – – –	– – – – – 27.8	– 235 263 638 450 612	– 518 580 1,407 992 1,349	– 10.7 12.0 29.0 20.5 27.8
Σ	kg	1 088	–	397	101	612	2 198	–	–
	lb	2,399	–	875	223	1,349	–	4,846	–
Percent Product Form		49.5	–	18.1	4.6	27.8	–	–	100

ATX-50 AIRFRAME

Alloy		Product Form					Σ Weight		Percent Alloy
		Clad Sheet	Plate	Extrusion	Forging	Others	kg	lb	
A B C D E Others		– – – 24.7 28.4 –	– – – – – –	– 3.8 12.5 – – –	– 4.2 – – – –	– – – – – 26.4	– 282 445 874 879 933	– 621 980 1,926 2,217 2,056	– 8.0 12.5 24.7 28.4 26.4
Σ	kg	1 752	–	578	149	932	3 411	–	–
	lb	4,141	–	1,275	326	2,056	–	7,800	–
Percent Product Form		53.1	–	16.3	4.2	26.4	–	–	100

- Fuel prices of \$264 (\$1), \$528 (\$2) and \$792 (\$3) per cubic meter (gallon).

- Crew of two for short-haul and short-medium range aircraft; crew of three for long-range aircraft.

Three cost components are used in defining advanced technology aircraft costs. These are: development, production, and operation.

For cost development, basic program elements were identified within each of the phases. These basic elements were selected at a component or function level where significant cost variations may occur. This is a level where configuration and program variations can be directly reflected in cost and yet at a level compatible with conceptual design analysis. Cost-significant configuration and program parameters were identified and combined into cost estimating relationships (CER) for each basic element. These CERs are programmed within the cost module of the Lockheed ASSET computer program for calculation of investment cost, operating expenses, and ROI.

The CERs for the development and production costs are formulated from a comprehensive analysis of Lockheed aircraft. Tooling and engine CERs are provided by a RAND Corporation analysis augmented by data from the engine manufacturers. The Lockheed database includes 14 prototypes and 16 production programs.

The output of the development and production CERs are, for the most part, in the form of labor hours and material dollars. Hours are translated to dollars, using Lockheed's actual January 1980 direct, overhead and general and administrative rates plus a profit factor of 15 percent.

Development costs include all the costs necessary to design, develop, and demonstrate that the aircraft meets its requirements culminating in FAA certification.

Operational expense includes both direct operating cost (DOC) and indirect operating cost (IOC). The 1967 Air Transportation Association (ATA) equations with coefficients updated to January 1980 experience are used to calculate all elements of DOC.

Indirect operating costs are based on a Lockheed-Boeing method of coefficients and factors. The factors were extracted from U.S. Civil Aeronautics Board (CAB 41) data reflecting inputs through 1978.

Economic data for the reference aircraft consists of a cost summary which details total RDT&E program costs, aircraft production cost, and procurement cost (flyaway cost) per aircraft. A summary of the aircraft operational costs (both direct and indirect) and rate of return on investment were determined for a hypothetical airline operator.

An estimate of projected market quantities and costs for the advanced aluminum alloys were made to arrive at material cost factors for the economic benefit analysis. The material alloy-product form classification of tables 31 through 33 were used as the fly-weight for each reference aircraft. The buy-weight was determined considering the product form applications including chip or trim weight plus scrap weight. The estimated material quantities required for the reference aircraft are presented in table 34. Both conventional alloy demands and projected advanced aluminum alloy demands are presented. The buy-weights were determined for each product form usage on the respective reference aircraft. The average value of buy-weight to fly-weight ratio varies between 1.97 for the smaller ATX-50 short-haul commuter aircraft, to 2.3 for the long-range ATX-350I transport aircraft. Sheet product form with buy-to-fly ratio of 1.8 is predominant in the smaller aircraft manufacture.

TABLE 34. - ESTIMATED MATERIAL QUANTITIES (PER UNCYCLED REFERENCE AIRCRAFT)

Configuration Product Form	Conventional Aluminum				Advanced Aluminum			
	Fly-Weight		Buy-Weight		Fly-Weight		Buy-Weight	
	kg	lb	kg	lb	kg	lb	kg	lb
ATX-350I								
Sheet	17 348	38,246	31 227	68,843	15 822	34,882	28 480	62,788
Plate	16 425	36,212	45 992	101,394	15 797	34,827	44 232	97,516
Extrusion	22 654	49,944	49 839	109,877	20 475	45,140	45 045	99,308
Forging	2 711	5,976	8 945	19,721	2 487	5,483	8 207	18,094
Σ	59 138	130,378	136 003	299,835	54 581	120,332	125 964	277,706
ATX-100								
Sheet	3 182	7,015	5 728	12,627	2 876	6,340	5 176	11,412
Plate	2 229	4,915	6 242	13,762	1 916	4,224	5 365	11,827
Extrusion	3 459	7,625	7 609	16,775	2 890	6,371	6 358	14,016
Forging	487	1,074	1 608	3,544	510	1,124	1 682	3,709
Σ	9 357	20,629	21 187	46,708	8 192	18,059	18 581	40,964
ATX-50								
Sheet	2 035	4,486	3 663	8,075	1 879	4,143	3 382	7,457
Plate	–	–	–	–	–	–	–	–
Extrusion	690	1,521	1 518	3,346	578	1,275	1 272	2,805
Forging	173	381	570	1,257	148	326	488	1,076
Σ	2 898	6,388	5 751	12,678	2 605	5,744	5 142	11,338

The material cost increment of the advanced PM and IM aluminum alloys over the current aluminum alloys were determined using the buy-weights of each product form and the associated costs. The material product form cost are based on available information using January 1980 costs. The appropriate factors for the new material cost for each product form were determined in consultation with Alcoa. The material costs for ASSET cost input are presented in table 35. The delta values for the advanced aluminum are approximately \$22 per kilogram (\$10 per lb).

2.5 Advanced Aluminum Aircraft

The benefits in aircraft performance and economics by incorporation of advanced aluminum alloys were determined for the three reference aircraft. This was accomplished by applying weight reduction factors (table 36) to the airframe components as determined from the reference aircraft structural analysis.

TABLE 35. - MATERIAL COST FOR ADVANCED ALUMINUM ALLOYS (INPUT TO ASSET)

	Conventional Aluminum		Advanced Aluminum		Δ Advanced Aluminum	
Configuration	\$/kg	\$/lb	\$/kg	\$/lb	\$/kg	\$/lb
Product Form						
Sheet	4.96	2.25	13.64	6.19	8.75	3.94
Plate	5.07	2.30	13.93	6.32	8.86	4.02
Extrusion	9.48	4.30	21.80	9.89	16.73	7.59
Forging	9.92	4.50	19.84	9.00	9.92	4.50
ATX-350I						
Wing	16.80	7.60	42.10	19.10	25.30	11.50
Tail	18.10	8.20	37.90	17.80	19.80	9.00
Body	15.00	6.80	35.70	16.20	20.70	9.40
ATX-100						
Wing	16.80	7.60	41.70	18.90	24.90	11.30
Tail	15.40	7.00	37.00	16.80	21.60	9.80
Body	14.80	6.70	35.70	16.20	20.90	9.50
ATX-50						
Wing	12.30	5.60	30.60	13.90	18.30	8.30
Tail	12.30	5.60	30.90	14.00	18.50	8.40
Body	13.90	6.30	33.00	15.00	19.20	8.70

TABLE 36. - UNCYCLED WEIGHT REDUCTION FACTORS FOR ADVANCED ALUMINUM ALLOYS

Component	ATX-3501(A)	ATX-100(A)	ATX-50(A)
Wing Group	11.8	11.4	8.7
Tail Group	12.0	11.9	11.2
Body Group	8.6	8.1	6.7
Others	11.0	9.7	8.4

Advanced technology factors were also applied to the other structural component weights (landing gears, nacelles, and air induction system) to reflect the structures-materials-manufacturing technology for 1990 IOC aircraft. The inclusion of these factors in the aircraft resizing resulted in aircraft weight and costs (production and operating) reflecting an advanced technology aircraft employing advanced aluminum alloys as its primary material system. This would also permit a direct comparison with an advanced technology aircraft in which organic composites are employed as the primary construction material.

2.5.1 Long range advanced aluminum aircraft - ATX-350I(A).- The application of advanced aluminum alloys to the reference aircraft (ATX-350I) resulted in benefits in aircraft weight and cost, as summarized in table 37.

A reduction in takeoff gross weight of 9 percent and operating empty weight of 11 percent was indicated. The block fuel required for both design range and average stage length missions was reduced by 8 percent. The direct operating costs were reduced by approximately 6 percent based on a fuel price of \$528/m^3 (\$2/gal). The aircraft production cost was reduced by 2.5 percent or approximately \$1.50 million per aircraft. The production cost includes material and labor for manufacture of the structure, propulsion and systems installation, systems integration, engine cost, avionics cost, warranty, sustaining engineering and quality assurance costs. The flyaway cost was also reduced by 2.5 percent. This cost element consists of the aircraft production, production development plus the total nonrecurring and recurring development cost. The latter was amortized over 300 production aircraft. Although the total dollars were reduced, the unit flyaway cost per operating weight empty increased by approximately 10 percent. This increase is attributed to the reduced size and weight of the aircraft (including propulsion and systems installation).

2.5.1.1 Structural weight: The weight benefits to the airframe are summarized in table 38. An overall reduction in the structural weight of 16 percent is indicated. The maximum reduction results for the tail of approximately 20 percent. This reduction results from (1) the efficiency of the advanced materials on the tail components and (2) the reduction in tail size

TABLE 37. - RECYCLED ADVANCED ALUMINUM BENEFITS - ATX-350I(A)
FUEL AT \$528/m^3 (\$2.00/gal.)

Benefit Parameter		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Takeoff Gross Weight	kg lb	243 603 537,053	222 037 489,615	-8.8
Operating Empty Weight	kg lb	138 347 305,003	122 686 270,538	-11.3
Structure Weight	kg lb	86 788 191,335	72 974 160,916	-15.9
Block Fuel – Design Range (A)	kg lb	60 602 133,604	55 606 122,617	-8.2
Block Fuel – Average Stage Length (B)	kg lb	30 450 67,131	27 889 61,498	-8.4
DOC (A)(C)	¢/seat km ¢/seat mi	2.23 4.13	2.10 3.88	-5.8
DOC (B)(C)	¢/seat km ¢/seat mi	2.23 4.13	2.10 3.89	-5.8
Aircraft Production Cost (C) (D)	\$M \$/kg \$/lb	58.36 672.00 305.00	56.90 780.00 354.00	-2.5 +16.0
Flyaway Cost (C)(E)	\$M \$/kg \$/lb	68.49 495.00 225.00	66.79 544.00 247.00	-2.5 +9.9

(A) Design Range: 8519 km (4600 n.mi.)
(B) Average Stage Length: 4630 km (2500 n.mi.)
(C) Production Quantity: 300 Aircraft
(D) Unit Cost per Structure Weight
(E) Unit Cost per Operating Weight Empty

for the resized (smaller) aircraft. It is noted that the tail-arm remains invariant since the fuselage geometry is not altered during the resizing process. The wing and body weight reductions are 19 and 10 percent, respectively, for the resized aircraft. Again, the reduction in the wing weight is attributable to the smaller wing for the resized aircraft, the body weight reduction is minimal since the fuselage size and geometry is invariant.

TABLE 38. - RECYCLED STRUCTURAL WEIGHT BENEFITS - ATX-350I(A)

COMPONENT		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	kg lb	86 788 191,335	72 974 160,916	-15.9
Wing	kg lb	37 719 83,156	30 463 67,175	-19.2
Body	kg lb	30 138 66,443	27 004 59,547	-10.4
Tail	kg lb	3 747 8,261	3 001 6,617	-19.9
Other	kg lb	15 184 33,476	12 506 27,576	-17.6

2.5.1.2 Production cost: The production cost comparison between the reference aircraft with conventional aluminum alloys and the recycled advanced aluminum aircraft are presented in table 39. The costs shown in the table represent only those costs relegated to the manufacture of the structure. The structure production cost represents approximately 35 percent of the total aircraft production cost. The costs include both material and labor dollars for the components indicated. The cost increases noted for the advanced aluminum aircraft are attributed to the increase in material costs compensated by a reduction in labor costs resulting from the manufacture of a smaller aircraft. The wing production cost is unchanged, whereas the body production cost is increased by $480,000. The tail cost, however, is less for the advanced aluminum application because the labor cost reduction to manufacture the smaller tail is greater than the material cost increase.

2.5.1.3 Operating cost: The total operating costs for the long-range transport aircraft are presented in figure 36. The data are for a hypothetical fleet of 23 aircraft operating for 1 year at a fuel price of \$528/m^3 (\$2/gal). A savings of $38.6 million is indicated for this class of aircraft.

2.5.2 Short-medium range advanced aluminum aircraft - ATX-100(A).- The advanced IM and PM alloy application to the reference aircraft (ATX-100), resulted in the benefits presented in table 40.

TABLE 39. - PRODUCTION COST COMPARISON - ATX-350I(A)

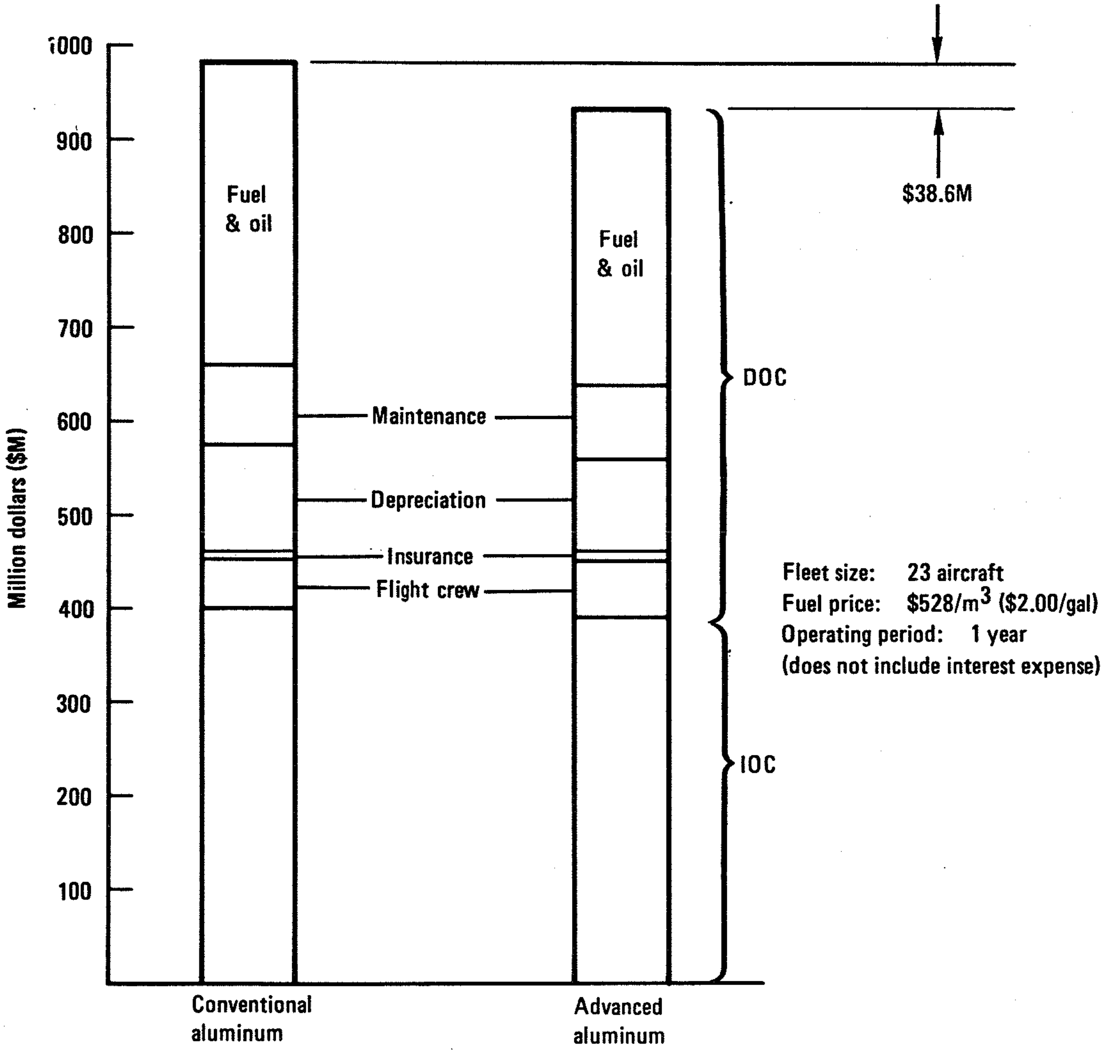
ATX-350I Long Range		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	$M $/kg $/lb	19.86 229.00 104.00	20.01 274.00 124.00	+0.8 +19.2
Wing	$M $/kg $/lb	7.66 203.00 92.00	7.68 251.00 114.00	+0.3 +23.9
Body	$M $/kg $/lb	7.60 251.00 114.00	8.08 298.00 135.00	+6.3 +18.4
Tail	$M $/kg $/lb	0.88 234.00 106.00	0.85 282.00 128.00	-3.4 +20.7
Others	$M $/kg $/lb	3.72 245.00 111.00	3.40 271.00 123.00	-8.6 +10.6

The takeoff gross weight was reduced by 6 percent with a 9 percent reduction in operating empty weight is realized. The block fuel required to perform the design range and average stage length missions were reduced by approximately 5 percent. The direct operating cost was reduced by approximately 4 percent for a fuel price of $528/m^3$ (\$2/gal). The aircrafr production cost and flyaway cost were reduced by approximately 2 percent.

2.5.2.1 Structure weight: The material efficiency resulted in an overall structure weight savings of approximately 15 percent.

The wing weight savings was 18 percent for the resized aircraft, as shown in table 41, as compared to the 11 percent shown in table 36 for the fixed sized aircraft. The body group weight saving was 9 percent, as compared to the input value of 8 percent. The body does not realize the benefit of resizing because of its intended purpose.

2.5.2.2 Production cost: The production cost for the ATX-100 structure is presented in table 42 for the airframe components. The structure production cost, which represents approximately 24 percent of the total aircraft



Fleet size: 23 aircraft
Fuel price: $528/m^3 ($2.00/gal)
Operating period: 1 year
(does not include interest expense)

Figure 36. - Total operating cost for long range transport aircraft - ATX-350I(A).

TABLE 40. - RECYCLED ADVANCED ALUMINUM BENEFITS - ATX-100(A)
FUEL AT \$528/m^3 (\$2/gal.)

ATX-100 Short-Medium Range		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Takeoff Gross Weight	kg lb	45 057 99,333	42 200 93,035	-6.3
Operating Empty Weight	kg lb	28 929 63,777	26 421 58,249	-8.7
Structure Weight	kg lb	14 912 32,876	12 735 28,075	-14.6
Block Fuel – Design Range (A)	kg lb	4 492 9,903	4 217 9,299	-5.1
Block Fuel – Average Stage Length (B)	kg lb	1 665 3,670	1 574 3,470	-5.4
DOC (A) (C)	¢/seat km ¢/seat mi	2.72 5.03	2.42 4.85	-3.6
DOC (B) (C)	¢/seat km ¢/seat mi	3.77 6.98	3.63 6.72	-3.7
Aircraft Production Cost (C) (D)	\$M \$/kg \$/lb	12.02 806.00 366.00	11.77 929.00 419.00	-2.1 +14.6 –
Flyaway Cost (C) (E)	\$M \$/kg \$/lb	12.93 447.00 203.00	12.66 479.00 217.00	-2.1 +7.0

(A) Design Range: 1852 km (1000 n.mi.)
(B) Average Stage Length: 556 km (300 n.mi.)
(C) Production Quantity: 1000 aircraft
(D) Unit Cost per structure weight
(E) Unit Cost per operating empty weight

production cost, is increased by 1.4 percent over the reference aircraft employing conventional aluminum alloys. This is contrary to the decrease in aircraft production cost shown in table 40. Although the material cost increases the cost of the structure, the material property improvements contribute to reduce the size of the aircraft. This directly impacts the engine and systems integration costs and reduces the aircraft production cost.

2.5.2.3 Operating cost: The total operating cost for the short-medium range aircraft are compared and presented in figure 37. The data are for a hypothetical fleet of 45 aircraft operating for a 1-year period at a fuel price of \$528/m^3 (\$2/gal). The operational cost savings (IOC plus DOC) is approximately \$10.7 million.

TABLE 41. - RECYCLED STRUCTURAL WEIGHT BENEFITS - ATX-100(A)

COMPONENT		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	kg	14 912	12 735	-14.6
	lb	32,876	28,075	
Wing	kg	5 650	4 624	-18.3
	lb	12,457	10,194	
Body	kg	5 265	4 774	-9.3
	lb	11,608	10,526	
Tail	kg	761	514	-20.6
	lb	1,678	1,133	
Others	kg	3 236	2 731	-15.6
	lb	7,133	6,022	

TABLE 42. - PRODUCTION COST COMPARISON - ATX-100(A)

ATX-100 Short-Medium Range		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	$M	2.77	2.81	+1.4
	$/kg	185.00	221.00	+19.5
	$/lb	84.00	100.00	
Wing	$M	1.02	1.03	+1.0
	$/kg	180.00	223.00	+23.9
	$/lb	82.00	101.00	
Body	$M	1.16	1.25	+7.8
	$/kg	220.00	262.00	+19.1
	$/lb	100.00	119.00	
Tail	$M	0.16	0.15	-6.2
	$/kg	210.00	248.00	+17.9
	$/lb	95.00	112.00	
Others	$M	0.43	0.38	-11.6
	$/kg	133.00	139.00	+4.5
	$/lb	60.00	63.00	

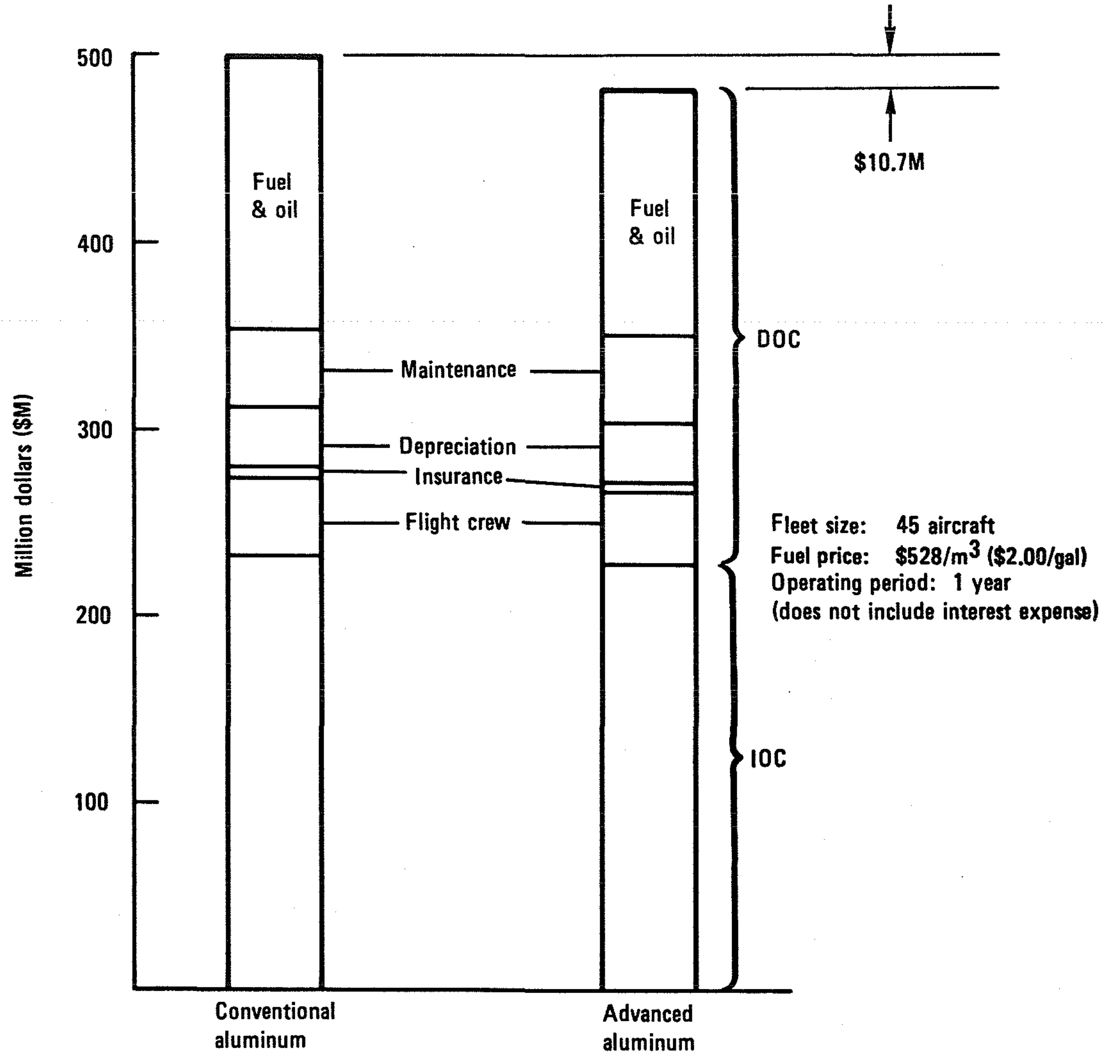


Figure 37. - Total operating costs for short-medium range transport aircraft - ATX-100(A).

2.5.3 Supercommuter aircraft - ATX-50(A).-The application of the advanced IM low-density alloys to the short-haul reference aircraft (ATX-50) are presented in table 43. For the smaller aircraft the weight and cost benefits are reduced as noted in the table.

The takeoff gross weight is reduced by 3 percent; the operating empty weight, 5 percent. The block fuel effect is more sensitive to the mission requirements for this class of aircraft. For the design range of 1110 km (600 n.mi.), the block fuel savings is 2 percent. For the average stage length mission of 185 km (100 n.mi.), the block fuel savings is 2.5 percent. Direct operating cost for the aircraft indicates a 2-percent reduction for a fuel price of $\$528/m^3$ (\$2/gal). The aircraft production cost and flyaway cost are reduced by 1.9 and 1.6 percent respectively.

2.5.3.1 Structural weight: The benefit of the advanced alloy applications are shown in table 44 for the ATX-50 aircraft. An overall reduction in structure weight is 10 percent. The weight savings from resizing results in 12 percent for the wing, 7 percent for the body and 15 percent for the tail. The body weight saving is less than 1 percent.

2.5.3.2 Production cost: An overall reduction in production costs of approximately 3 percent is shown in table 45 for the supercommuter aircraft. The wing shows a 4 percent cost reduction with the body and tail cost remaining unchanged.

2.5.3.3 Operating cost: The total operating cost comparison is presented in figure 38 for the supercommuter aircraft. The hypothetical fleet size of 15 aircraft operating for 1 year using a fuel price of $\$528/m^3$ (\$2/gal) results in an overall operational cost saving of $\$0.840 \times 10^6$.

2.5.4 Fuel price effect on DOC.- With the uncertainty of the fuel prices during the next decade of aircraft operation, a variation of fuel price on direct operating cost was assessed. The fuel prices of $\$264/m^3$ (\$1/gal) $\$528/m^3$ (\$2/gal) and $\$792/m^3$ (\$3/gal) were used. The variation of these fuel prices in the three aircraft are presented in figures 39, 40, and 41 for the ATX-350I(A), ATX-100(A), and ATX-50(A), respectively. The cost increment for flight crew, insurance, depreciation, and maintenance remain unchanged for all aircraft. The percentage of the fuel price-to-direct operating cost increase from 37 percent, to 55 percent to 64 percent for the ATX-350I aircraft (figure 39). The trends are similar for the ATX-100 and ATX-50, as shown in figures 40 and 41.

2.6 Benefits of Advanced Aluminum Technology

The baseline values for each reference aircraft were compared with values obtained for the corresponding advanced aluminum aircraft. The payoffs and penalties were presented as deltas to the base values. The net benefit derived

TABLE 43. - RECYCLED ADVANCED ALUMINUM BENEFITS - ATX-50(A) FUEL AT $\$528/\text{m}^3$ ($\$2$/gal.)

BENEFIT PARAMETER		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Takeoff Gross Weight	kg lb	17 362 38,278	16 799 37,035	-3.2
Operating Empty Weight	kg lb	11 342 25,004	10 806 23,824	-4.7
Structure Weight	kg lb	4 847 10,686	4 380 9,657	-9.6
Block Fuel – Design Range (A)	kg lb	1 018 2,245	997 2,198	-2.1
Block Fuel – Average Stage Length (B)	kg lb	360 794	351 774	-2.5
DOC (A) (C)	¢/seat km ¢/seat mi	2.70 5.00	2.66 4.92	-1.6
DOC (B) (C)	¢/seat km ¢/seat mi	5.81 10.76	5.70 10.56	-1.9
Aircraft Production Cost (C) (D)	\$M \$/kg \$/lb	5.22 1077.00 488.00	5.12 1169.00 530.00	-1.9 +8.5 —
Flyaway Cost (C) (E)	\$M \$/kg \$/lb	6.22 575.00 261.00	6.12 595.00 270.00	-1.6 +3.5 —

(A) Design Range: 1111 km (600 n.mi.)
(B) Average Stage Length: 185 km (100 n.mi.)
(C) Production Quantity: 250 aircraft
(D) Unit cost per structure weight
(E) Unit cost per operating empty weight

from the advanced aluminum technology was determined for each class of aircraft by assessing development, production, and operational cost required and resulting from the incorporation of the structurally efficient advanced PM and IM aluminum alloys. Of significance were the operational cost and flyaway cost benefits, as shown in tables 46 through 48. The operational cost data are presented for the fuel prices of $\$264/\text{m}^3$ ($\$1$/gal), $\$528/\text{m}^3$ ($\$2$/gal) and $\$792/\text{m}^3$ ($\$3$/gal). The annual cost benefits for the total estimated production quantity of aircraft are shown. The net cost benefit before interest for the ATX-350I(A) aircraft using a fuel price of $\$528/\text{m}^3$ ($\$2$/gal) and based on 300 aircraft is $\$504 \times 10^6$ for 1 year; the flyaway cost saving is $\$510 \times 10^6$. For the ATX-100(A) aircraft, based on 1000 aircraft, the operational cost saving is $\$238 \times 10^6$; the flyaway cost saving for the production quantity is $\$270 \times 10^6$. The ATX-50(A) supercommuter cost is based on a 250 aircraft

TABLE 44. - RECYCLED STRUCTURAL WEIGHT BENEFITS - ATX-50(A)

Component		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	kg lb	4 847 10,686	4 380 9,657	-9.6
Wing	kg lb	1 262 2,783	1 110 2,447	-12.0
Body	kg lb	2 357 5,196	2 182 4,811	-7.4
Tail	kg lb	210 465	178 392	-15.2
Others	kg lb	1 017 2,243	910 2,007	-10.5

production quantity. The net operational cost benefit for a fuel price of \$528/m^3 (\$2/gal) is \$14 x 10^6. The flyaway cost saving for the production quantity is \$25 x 10^6.

Thus, significant operational cost benefit are shown for incorporation of the advanced aluminum technology to future transport and supercommuter aircraft. The cost to develop the technology is estimated at 150 equivalent person years or \$15 x 10^6 (at an hourly rate of \$50). This amount is significantly less than the operational cost benefit that can be realized by the airline operators using the proposed fuel-efficient aircraft during the next decade.

2.7 Sensitivity Study

Parametric studies were performed to determine the sensitivity of the advanced aluminum aircraft characteristics, performance, and costs to variations in material properties of advanced aluminum alloys (figure 42). For this investigation, the weight of the structural components (e.g., wing, body, and airframe) were changed by ±10 percent to reflect decrease or improvement in target properties. In each case, the aircraft was resized without modifying the wing planform characterisitcis or changing the wing loading or thrust loading. This approach resulted in aircraft that maintained approximately the same performance characteristics.

TABLE 45. - PRODUCTION COST COMPARISON - ATX-50(A)

Component		Reference Aircraft	Advanced Aluminum Aircraft	Δ (%)
Structure	$M	1.13	1.10	-2.6
	$/kg	234.00	251.00	+7.3
	$/lb	106.00	114.00	
Wing	$M	0.25	0.24	-4.0
	$/kg	198.00	216.00	+9.1
	$/lb	90.00	98.00	
Body	$M	0.62	0.62	0
	$/kg	262.00	284.00	+8.4
	$/lb	119.00	129.00	
Tail	$M	0.04	0.04	0
	$/kg	190.00	225.00	+18.4
	$/lb	86.00	102.00	
Others	$M	0.22	0.20	-4.5
	$/kg	216.00	231.00	+6.9
	$/lb	98.00	105.00	

The weight and cost sensitivities to the change in component weights are presented in tables 49 through 51 for the ATX-350I, ATX-100, and ATX-50 aircraft. The data represent seven configurations each for the three classes of transport aircraft. Within the ±10 percent range, the trends are approximately linear and asymmetric about the advanced aluminum aircraft reference point.

The results of the weight sensitivity analysis are graphically presented in figures 43 through 53 for the average stage length mission using a fuel price of $\$528/m^3$ (\$2/gal). The increase (plus value) in component weight-change reflects a decrease in material property over target values. Conversely, a decrease (negative value) reflects increases in material properties affecting the specific component design. Figures 43 through 45 present the individual wing, body, and airframe (wing + body + tail) component weight trends, as affected by the changes in material property and resizing. The affect of the individual component weight change on the other components noted on the figures are not included. The recycled wing and airframe weights are greater than the corresponding input values as affected by the resizing process of the aircraft to perform the same mission. The body weights, however, remain essentially invariant when compared to the input values. The latter occurs since the body geometry parameters (i.e., body diameter, length) are invariant to provide internal volume for the specified payload (passenger and cargo).

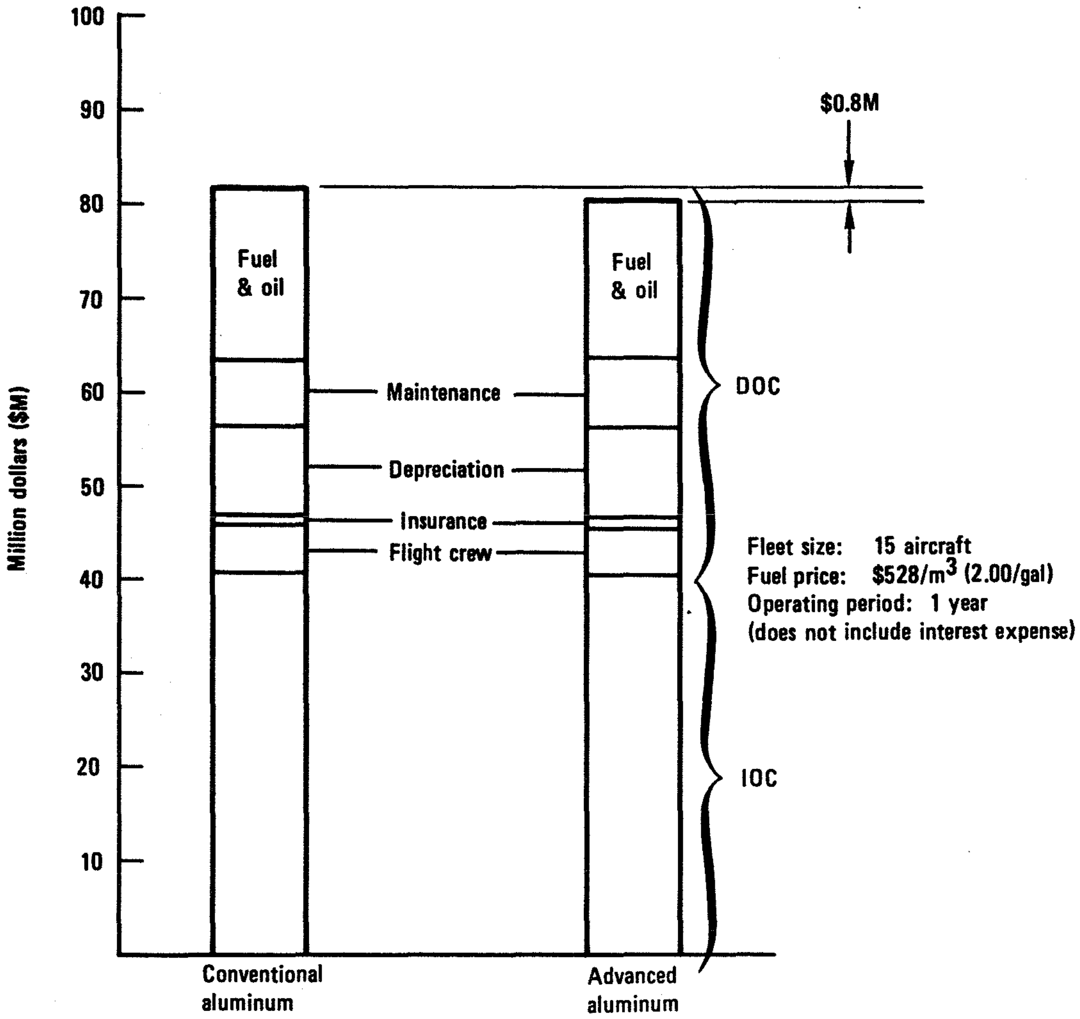


Figure 38. - Total operating costs for short range supercommuter aircraft - ATX-50(A)

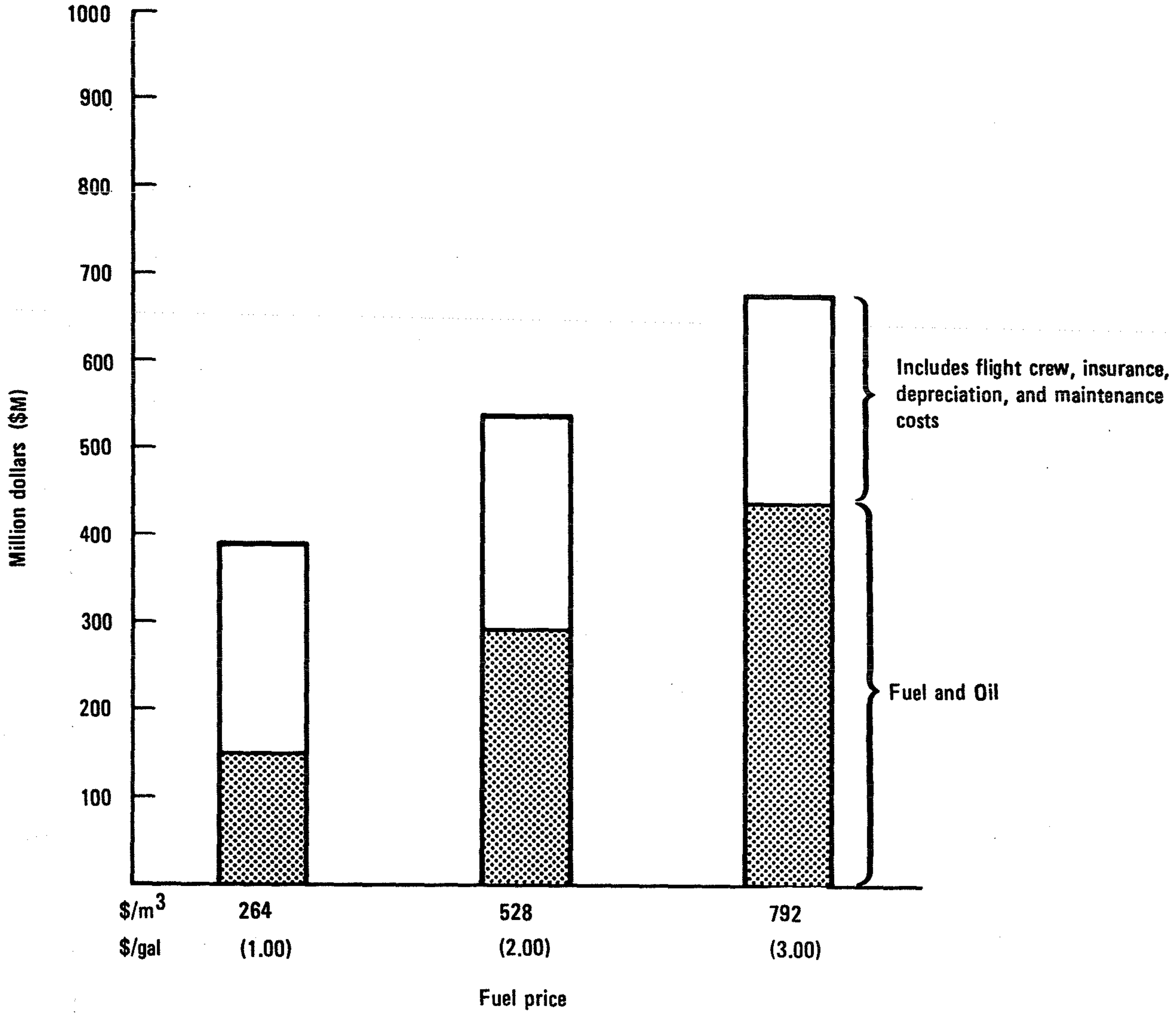


Figure 39. - Effect of fuel price on direct operating cost - ATX-350I(A).

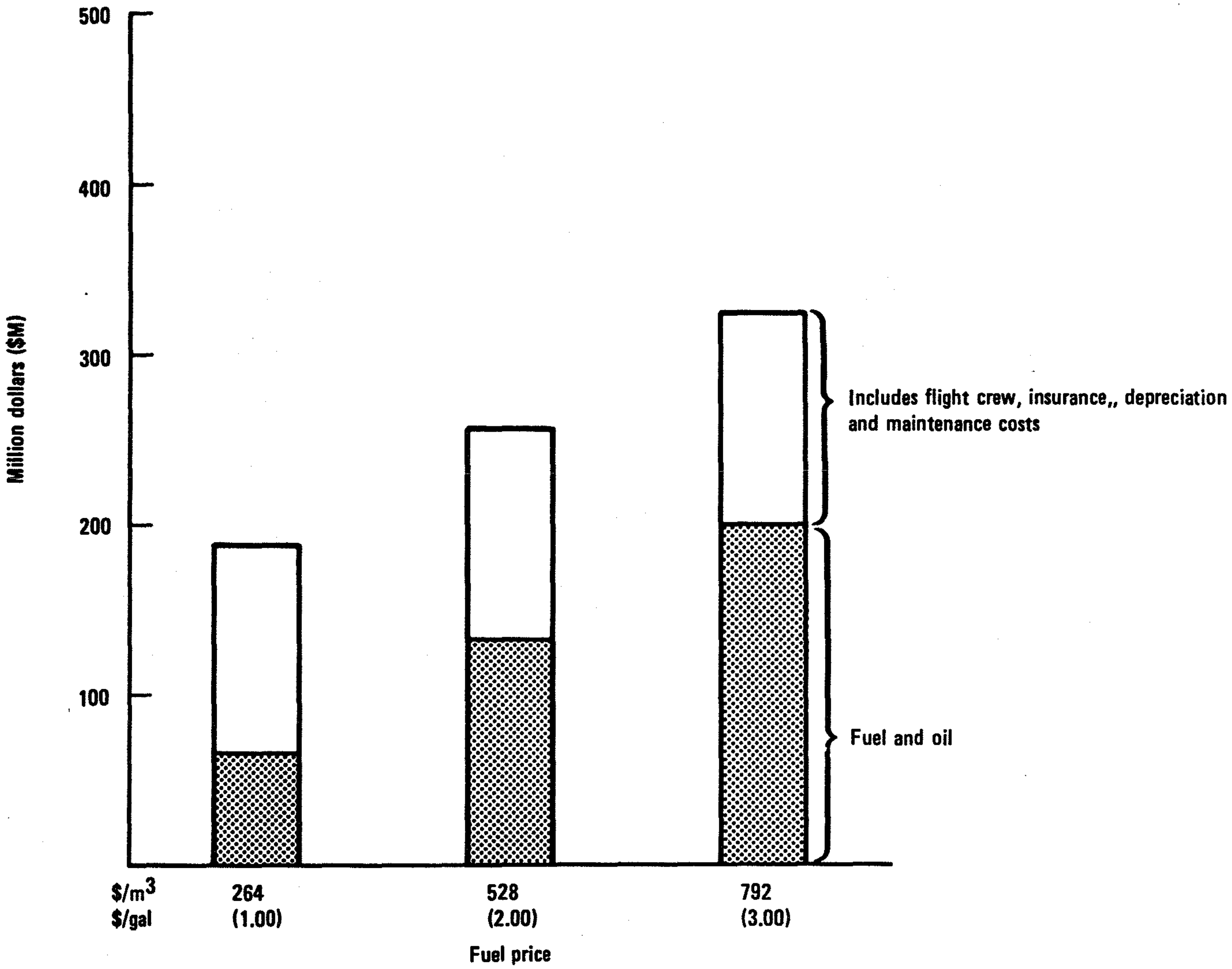


Figure 40. - Effect of fuel price on direct operating cost - ATX-100(A).

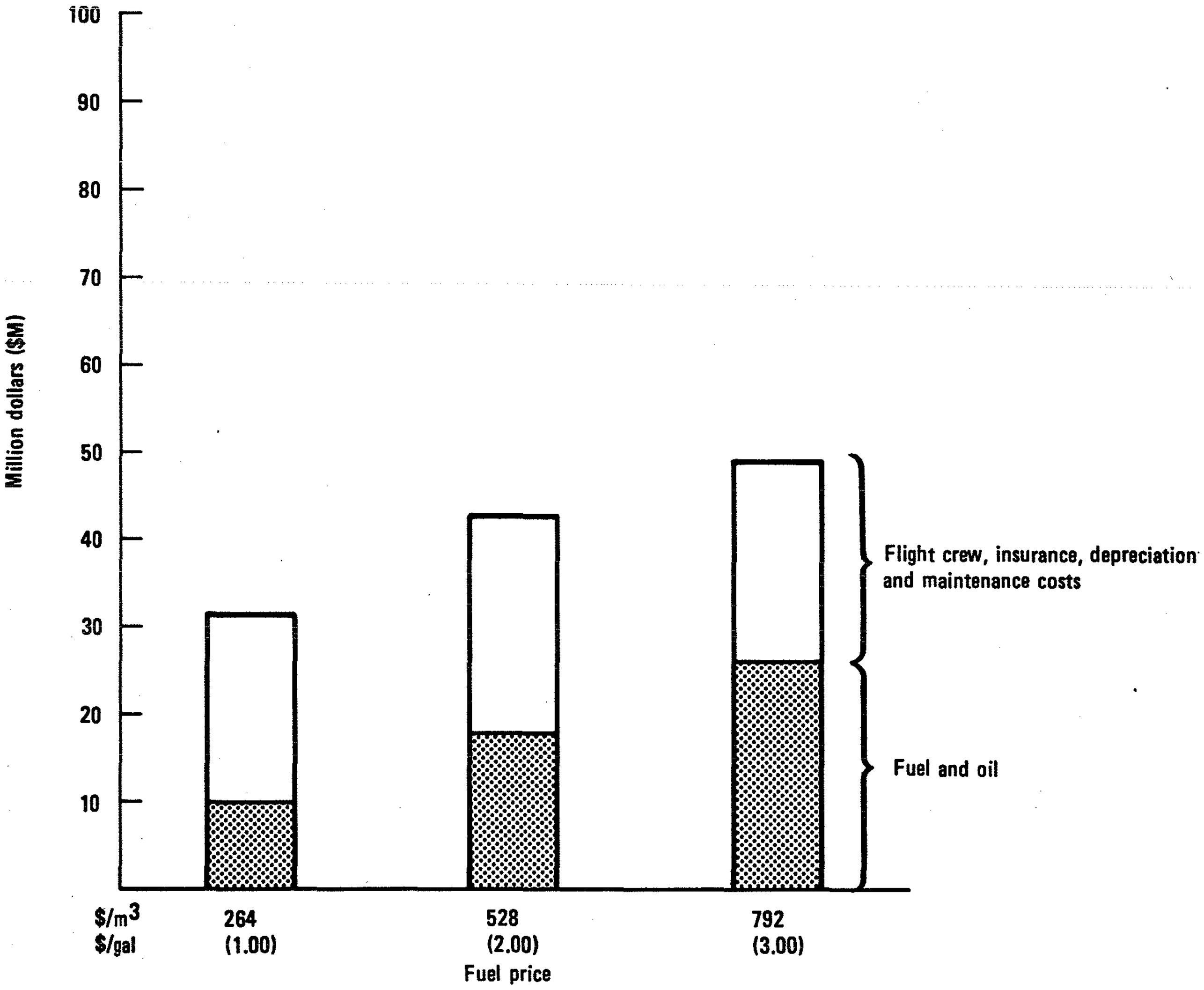


Figure 41. - Effect of fuel price on direct operating cost - ATX-50(A).

TABLE 46. - NET VALUE OF ADVANCED ALUMINUM TECHNOLOGY - ATX-350I(A)

ATX-350I Long Range Transport Aircraft	Total Operational Cost(A) Fuel Price $264/m^3 ($1.00/gal.)	$528/m^3 ($2.00/gal.)	$792/m^3 ($3.00/gal.)	Flyaway Cost Per Aircraft	Flyaway Cost 300 Aircraft	RDT&E Cost 300 Aircraft
Reference Aircraft (Conventional Aluminum)	$10,585M	$12,779M	$14,948M	$68.49M	$20,547M	$2823M
Advanced Aluminum Aircraft	$10,265M	$12,275M	$14,271M	$66.79M	$20,037M	$2753M
Net Cost Benefit	$ 320M	$ 504M	$ 677M	$ 1.70M	$ 510M	$ 70M

(A) Annual cost for 300 aircraft based on Average Stage Length of 4630 km (2500 n.mi.)

TABLE 47. - NET VALUE OF ADVANCED ALUMINUM TECHNOLOGY - ATX-100(A)

ATX-100 Short-Medium Range Transport Aircraft	Total Operational Cost(A) Fuel Price $264/m^3 ($1.00/gal.)	$528/m^3 ($2.00/gal.)	$792/m^3 ($3.00/gal.)	Flyaway Cost Per Aircraft	Flyaway Cost 1000 Aircraft	RDT&E Cost 1000 Aircraft
Reference Aircraft (Conventional Aluminum)	$9447M	$11,067M	$12,695M	$12.93M	$12,930M	$791M
Advanced Aluminum Aircraft	$9287M	$10,829M	$12,361M	$12.66M	$12,660M	$780M
Net Cost Benefit	$ 160M	$ 238M	$ 334M	$ 0.27M	$ 270M	$ 11M

(A) Annual cost for 1000 aircraft based on Average Stage Length of 556 km (300 n.mi.)

TABLE 48. - NET VALUE OF ADVANCED ALUMINUM TECHNOLOGY - ATX-50(A)

ATX-50 Supercommuter Aircraft	Total Operational Cost(A)			Flyaway Cost		RDT&E Cost
	Fuel Price					
	$264/m^3 ($1.00/gal.)	$528/m^3 ($2.00/gal.)	$792/m^3 ($3.00/gal.)	Per Aircraft	250 Aircraft	250 Aircraft
Reference Aircraft (Conventional Aluminum)	$1208M	$1366M	$1524M	$6.22M	$1555M	$231M
Advanced Aluminum Aircraft	$1197M	$1352M	$1505M	$6.12M	$1530M	$230M
Net Cost Benefit	$ 11M	$ 14M	$ 19M	$0.10M	$ 25M	$ 1M

(A) Annual cost for 250 aircraft based on Average Stage Length of 185 km (100 n.mi.)

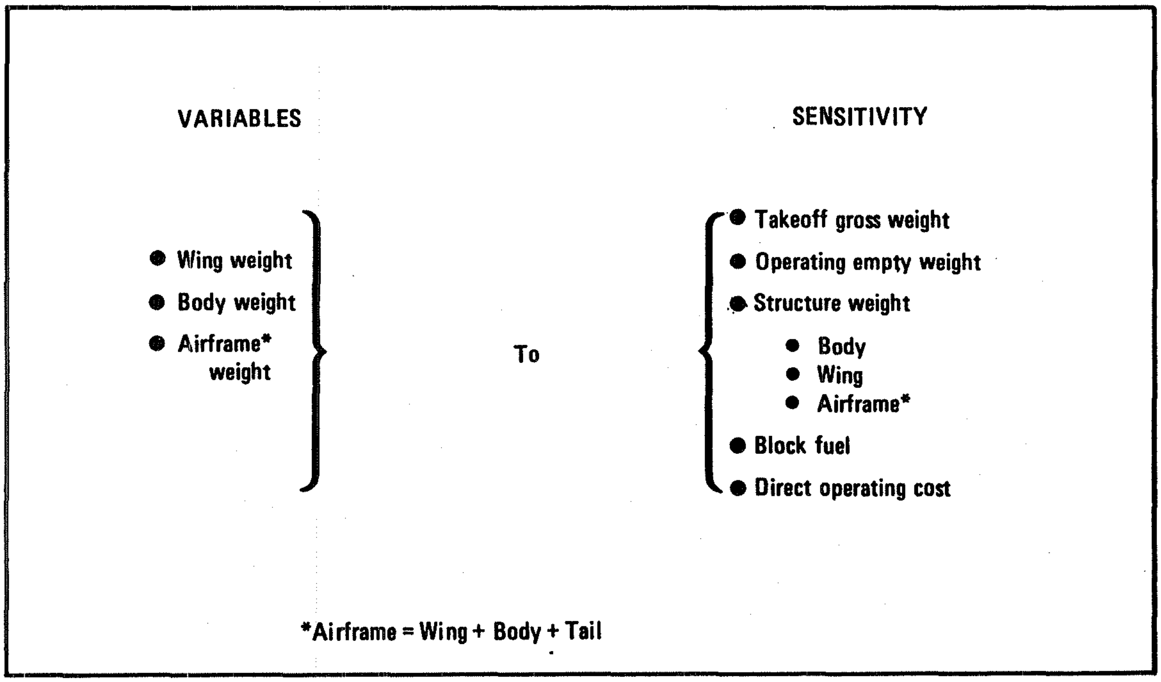


Figure 42. - Advanced aluminum aircraft sensitivity study parameters.

TABLE 49. - RECYCLED WEIGHT AND COST SENSITIVITY - ATX-350I(A)

UNCYCLED COMPONENT WEIGHT CHANGES	GROSS WEIGHT		BLOCK FUEL(A)		DOC(A)	
	kg (lb)	% Change	kg (lb)	% Change	c/s.km (c/s.mi)	% Change
Advanced Aluminum	222 086 (489,615)	–	27 895 (61,498)	–	2.10 (3.88)	–
Advanced Aluminum + 10% Wing	229 570 (506,117)	+3.37	28 794 (63,480)	+3.22	2.15 (3.99)	+2.84
Advanced Aluminum – 10% Wing	215 230 (474,501)	-3.09	27 065 (59,668)	-2.98	2.04 (3.78)	-2.58
Advanced Aluminum + 10% Body	229 550 (506,070)	+3.36	28 791 (63,474)	+3.21	2.15 (3.99)	+2.84
Advanced Aluminum – 10% Body	215 000 (473,995)	-3.19	27 035 (59,602)	-3.08	2.04 (3.78)	-2.58
Advanced Aluminum + 10% Airframe(B)	237 791 (524,240)	+7.07	29 776 (65,646)	+6.74	2.22 (4.11)	+5.93
Advanced Aluminum -10% Airframe(B)	207 755 (458,022)	-6.45	26 161 (57,676)	-6.21	1.98 (3.67)	-5.41

(A) Mission: 4630 km (2500 n.mi); fuel price: $\$528/\text{m}^3$ ($2/gal)

(B) Airframe = wing + body + tail

Figures 46 through 54 indicate the sensitivity of the structure weight, operating empty weight (OEW), takeoff gross weight (TOGW), block fuel, and direct operating cost with variations in wing, body, and airframe weight. The sensitivity data are presented for the wing, body, and airframe for the three transport aircraft types. For the ATX-350I aircraft (figure 46), a +5 percent increase in wing weight (resulting from a decrease in key material properties affecting the overall wing design) results in a 3.5 percent increase in structure weight, a 2 percent increase in OEW, a 1.7 percent increase in TOGW and block fuel requirements and 1.4 percent increase in DOC at a fuel price of $\$528/\text{m}^3$ ($2/gal). The sensitivity decreases for the smaller aircraft, as shown in figure 52. A 5-percent wing weight increase for the ATX-50 results in a 1.5 percent increase in structure weight. The block fuel required increases by 0.5 percent for the average stage length mission of 185 km (100 n.mi.) and the DOC increases by 0.3 percent. The importance of meeting the material property goals for the larger aircraft is emphasized by these sensitivity data.

TABLE 50. - RECYCLED WEIGHT AND COST SENSITIVITY - ATX-100(A)

Uncycled Component Weight Changes	Gross Weight		Block Fuel[(A)]		DOC[(A)]	
	kg (lb)	% Change	kg (lb)	% Change	¢/seat km ¢/seat mi	% Change
Advanced Aluminum Aircraft	42 200 (93,035)	–	1 574 (3,470)	–	3.63 (6.72)	–
Advanced Aluminum +10% Wing	43 061 (94,934)	2.0	1 601 (3,530)	1.7	3.69 (6.83)	1.5
Advanced Aluminum -10% Wing	41 388 (91,244)	1.9	1 548 (3,412)	1.7	3.58 (6.62)	1.5
Advanced Aluminum +10% Body	43 157 (95,146)	2.3	1 604 (3,536)	1.9	3.69 (6.84)	1.8
Advanced Aluminum -10% Body	41 272 (90,989)	2.2	1 544 (3,404)	1.9	3.57 (6.61)	1.7
Advanced Aluminum +10% Airframe[(B)]	44 164 (97,364)	4.7	1 636 (3,607)	4.0	3.76 (6.96)	3.6
Advanced Aluminum -10% Airframe[(B)]	40 373 (89,008)	4.3	1 515 (3,341)	3.7	3.51 (6.50)	3.3

(A) Mission: 556 km (300 n.mi.); Fuel Price: \$528/m^3 (\$2/gal)

(B) Airframe = Wing + Body + Tail

TABLE 51. - RECYCLED WEIGHT AND COST SENSITIVITY - ATX-50(A)

Uncycled Component Weight Changes	Gross Weight		Block Fuel(A)		DOC(A)	
	kg (lb)	% Change	kg (lb)	% Change	¢/seat km ¢/seat mi	% Change
Advanced Aluminum Aircraft	16 799 (37,035)	–	351 (773)	–	5.70 (10.56)	–
Advanced Aluminum +10% Wing	16 958 (37,386)	1.0	353 (779)	0.7	5.74 (10.63)	0.7
Advanced Aluminum -10% Wing	16 637 (36,678)	-1.0	348 (768)	-0.8	5.66 (10.48)	-0.8
Advanced Aluminum +10% Body	17 131 (37,768)	2.0	357 (786)	1.6	5.79 (10.73)	1.6
Advanced Aluminum -10% Wing	16 460 (36,287)	-2.0	345 (761)	-1.6	5.61 (10.39)	-1.6
Advanced Aluminum +10% Airframe(B)	17 329 (38,205)	3.2	360 (793)	2.5	5.85 (10.83)	2.6
Advanced Aluminum -10% Airframe (B)	16 277 (35,884)	-3.1	342 (754)	-2.5	5.56 (10.30)	-2.5

(A) Mission: 185 km (100 n.mi.); Fuel Price: $528/m^3$ ($2/gal)

(B) Airframe = Wing + Body + Tail

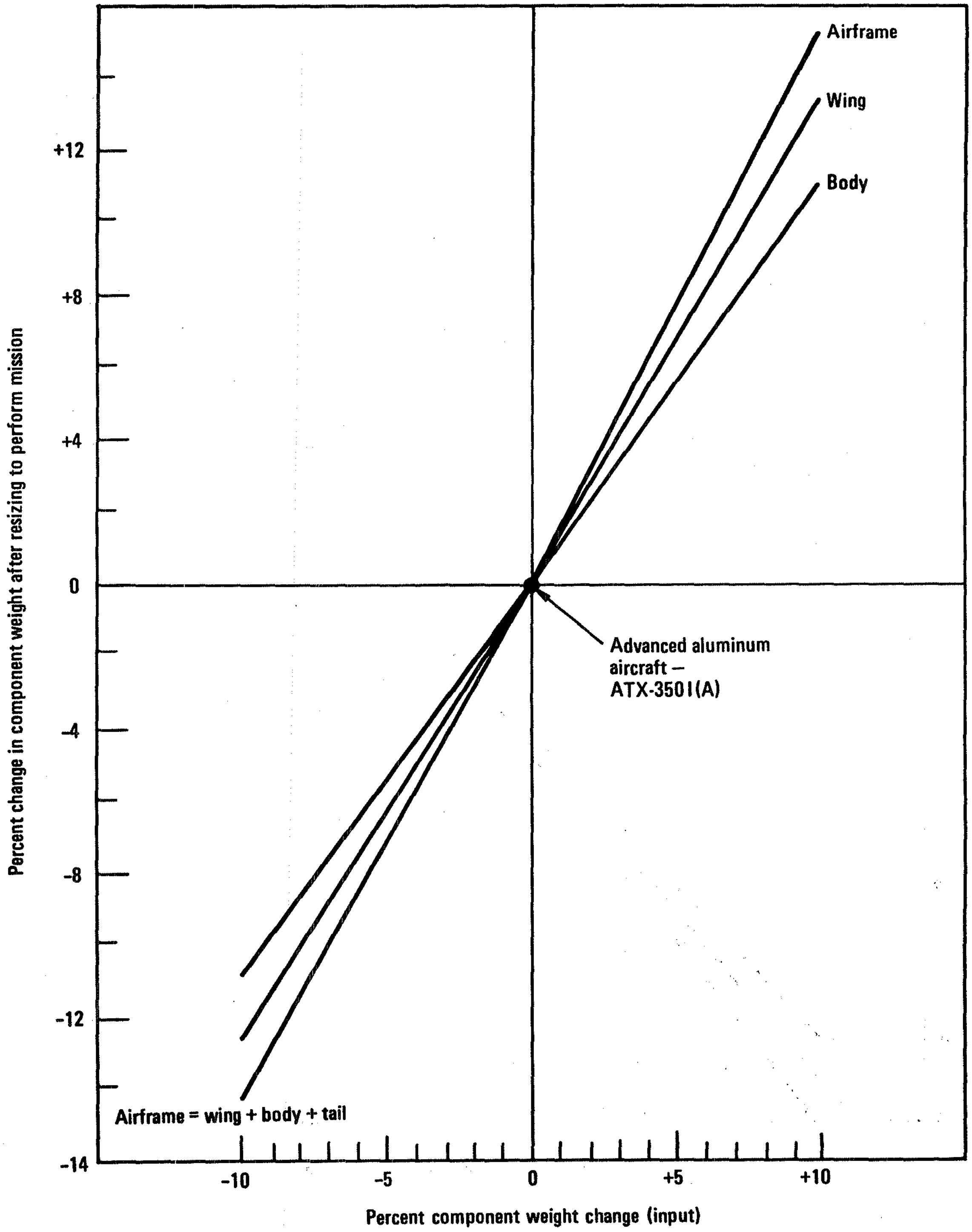


Figure 43. - Component weight change effects - ATX-350I(A).

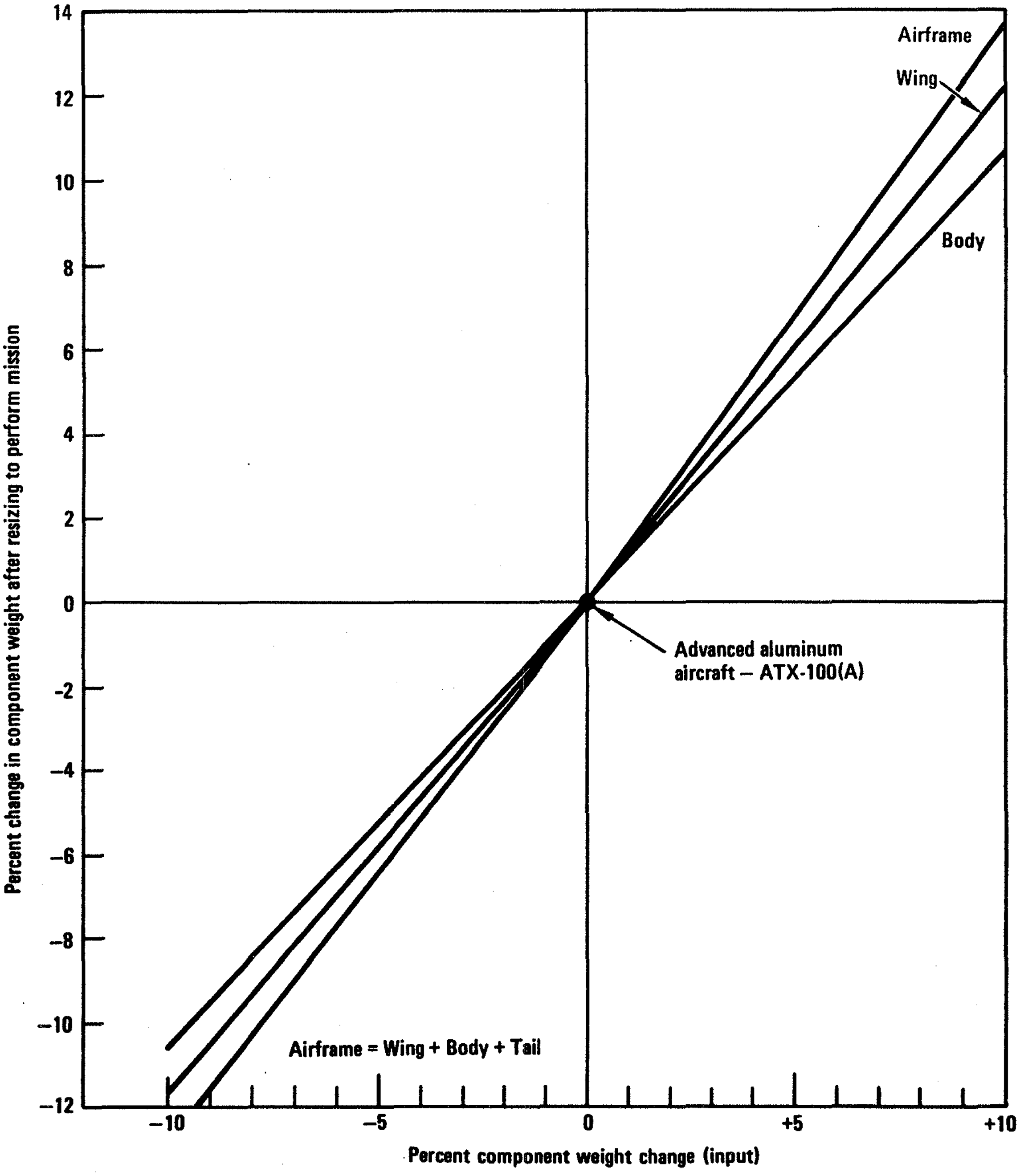


Figure 44. - Component weight change effects - ATX-100(A).

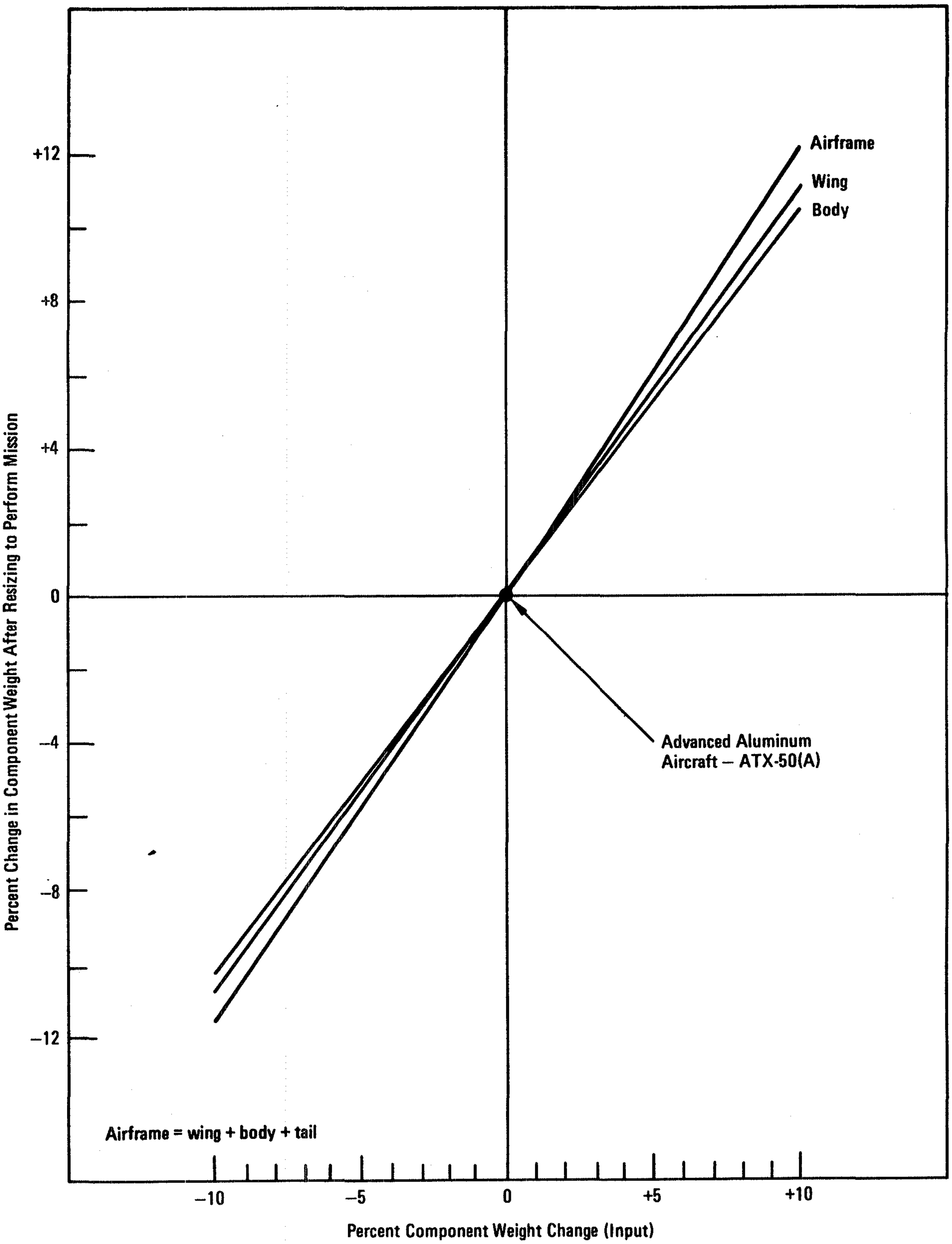


Figure 45. - Component weight change effects - ATX-50(A).

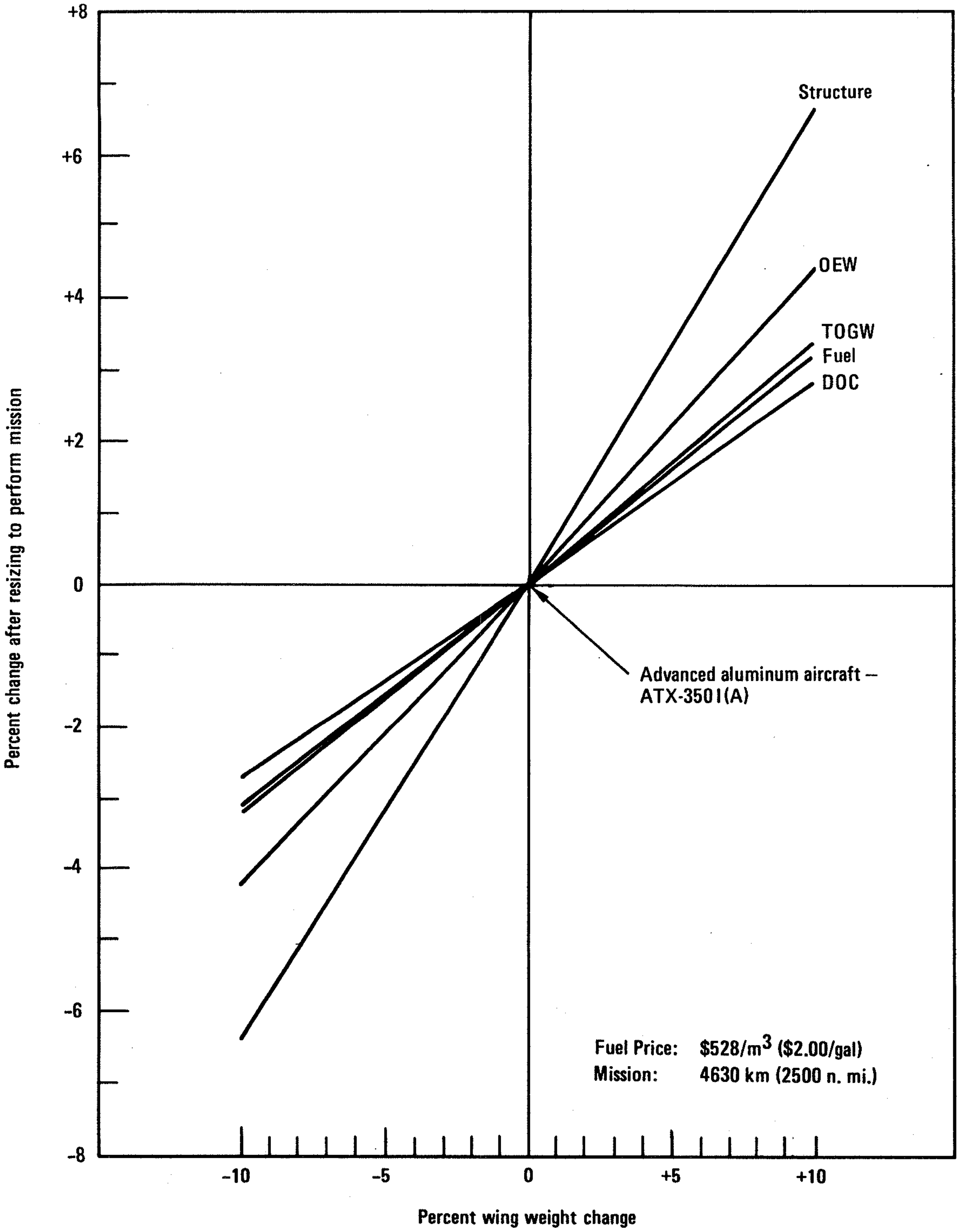


Figure 46. - Sensitivity to wing weight change - ATX-350I(A).

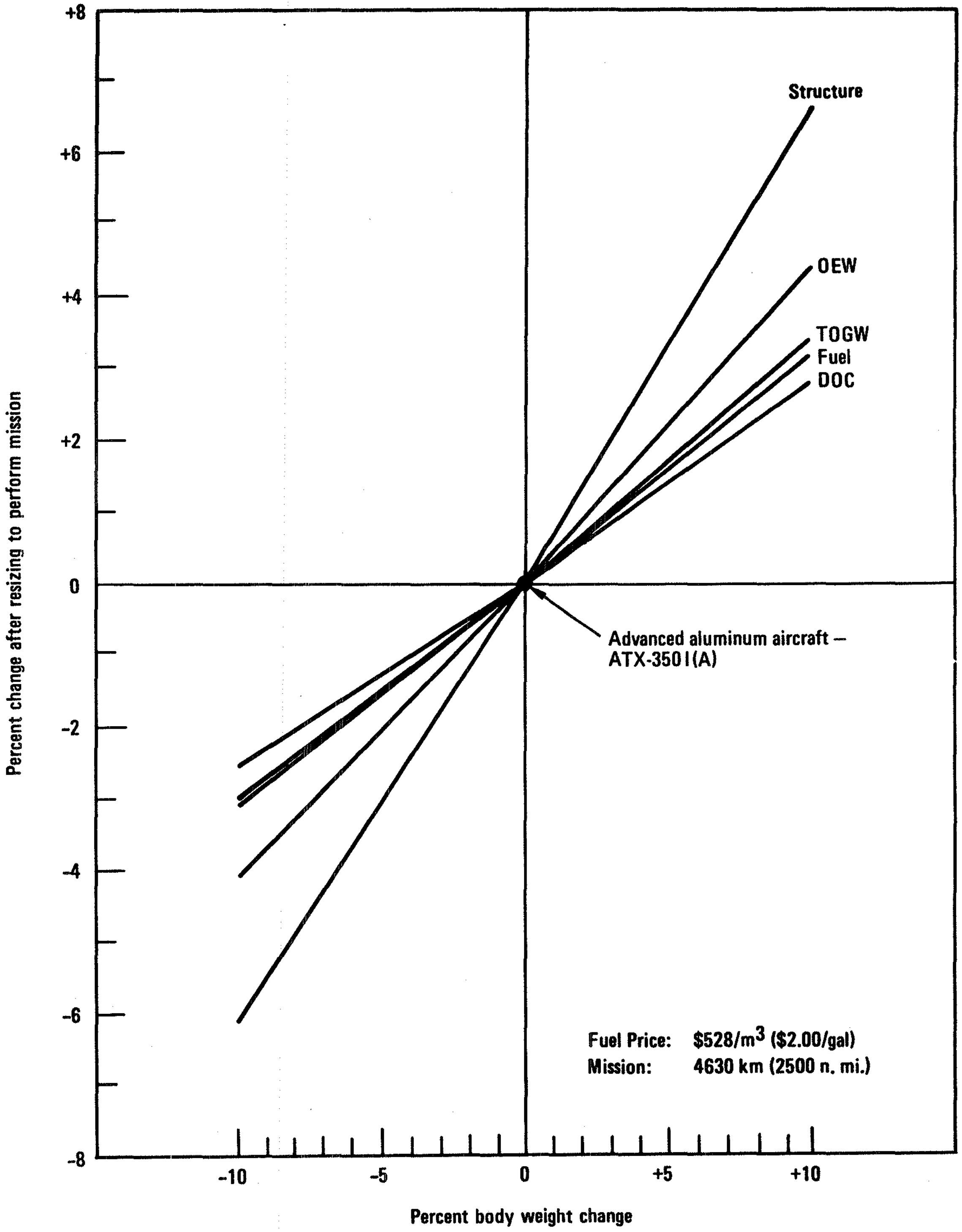


Figure 47. - Sensitivity to body weight change - ATX-350I(A).

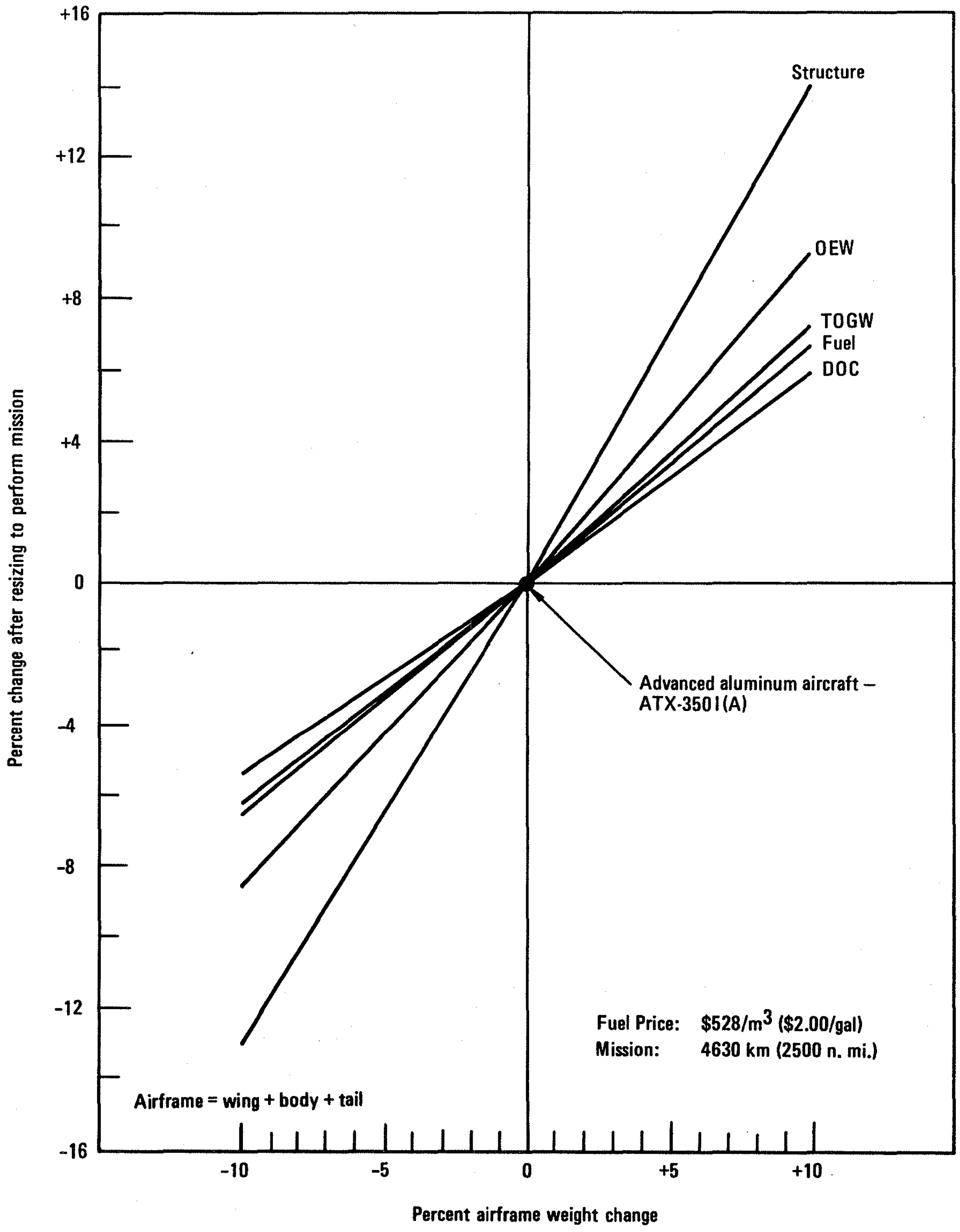


Figure 48. - Sensitivity to airframe weight change - ATX-350I(A).

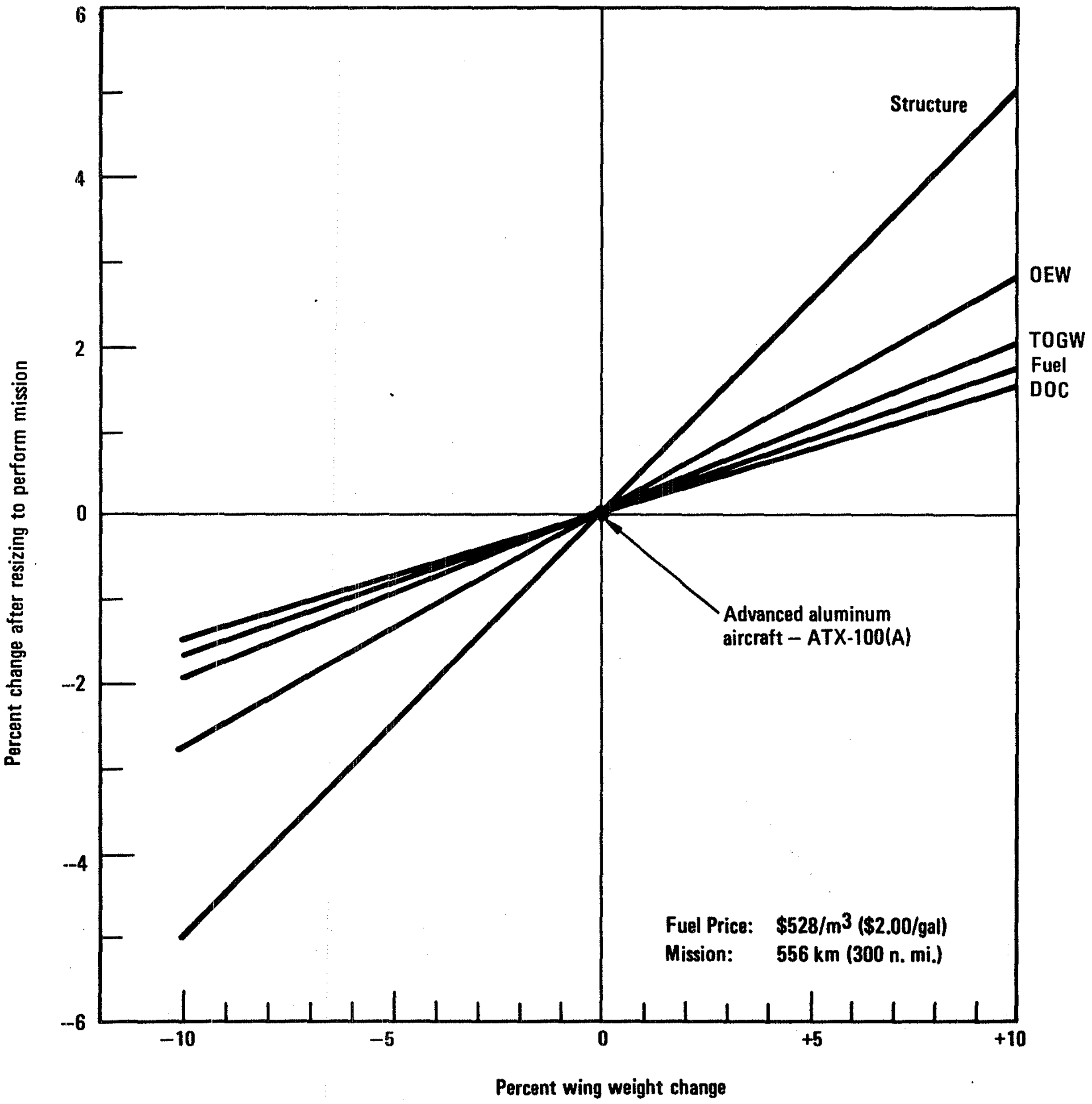


Figure 49. - Sensitivity to wing weight change - ATX-100(A).

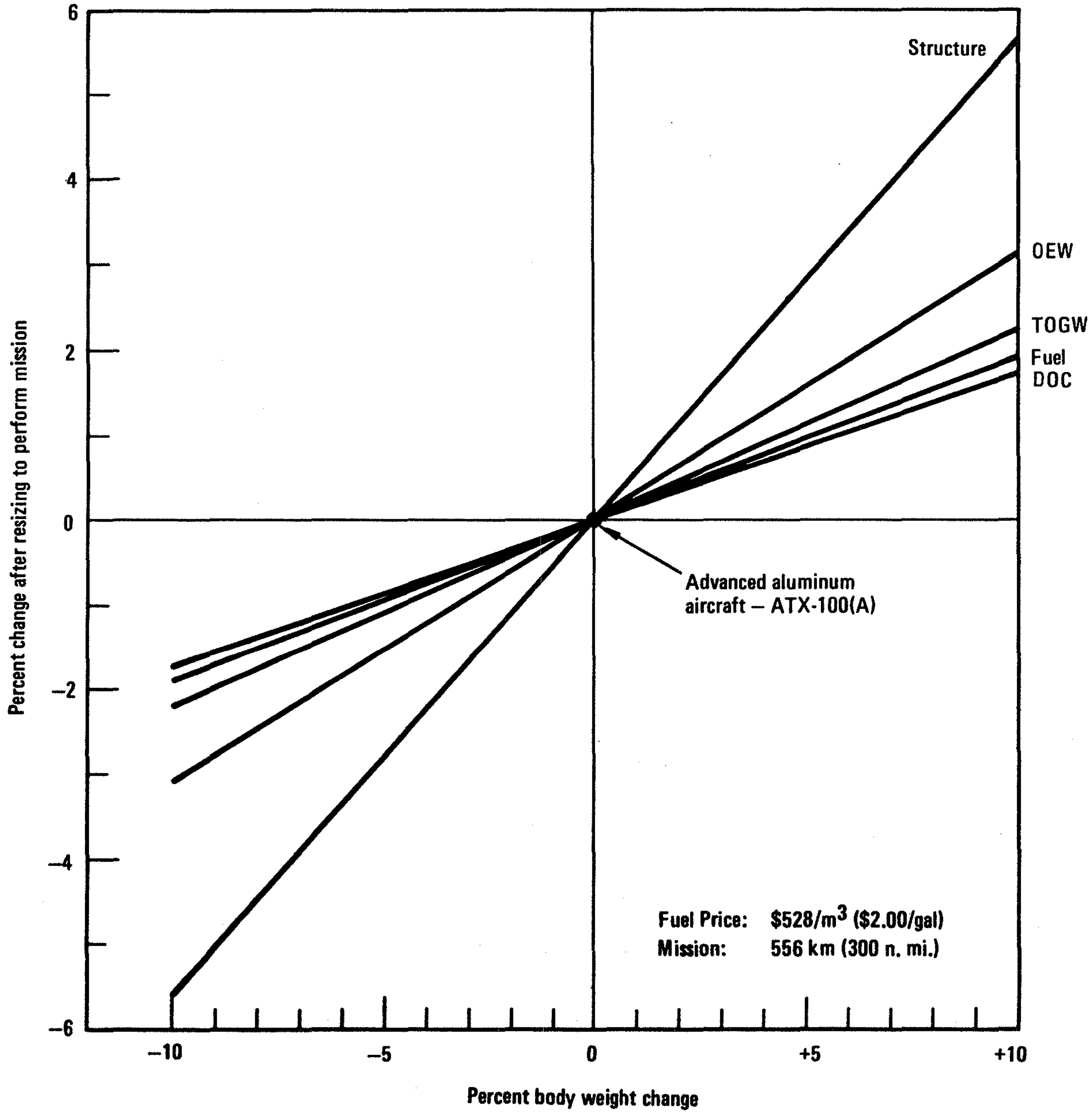


Figure 50. - Sensitivity to body weight change - ATX-100(A).

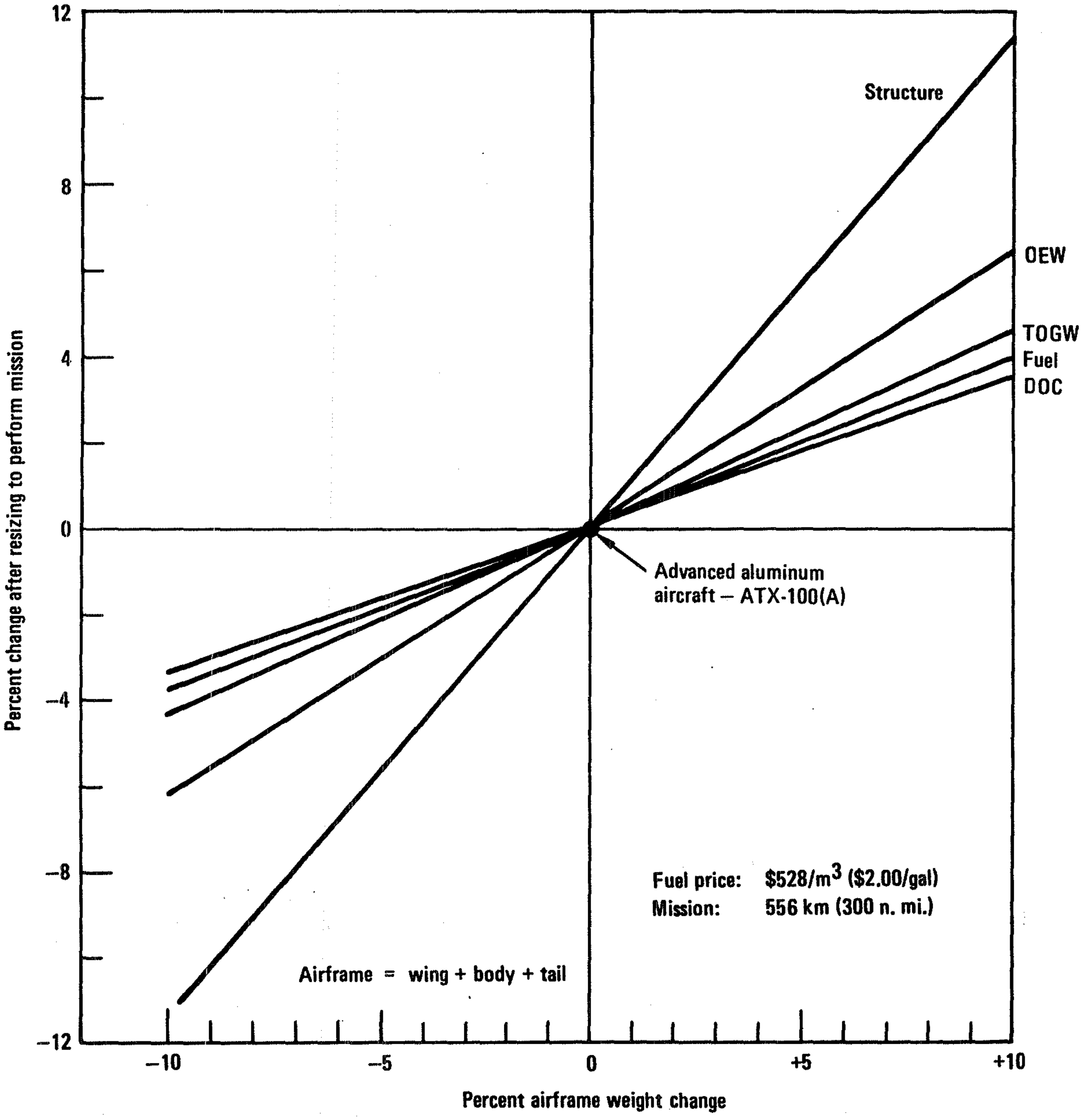


Figure 51. - Sensitivity to airframe weight change - ATX-100(A).

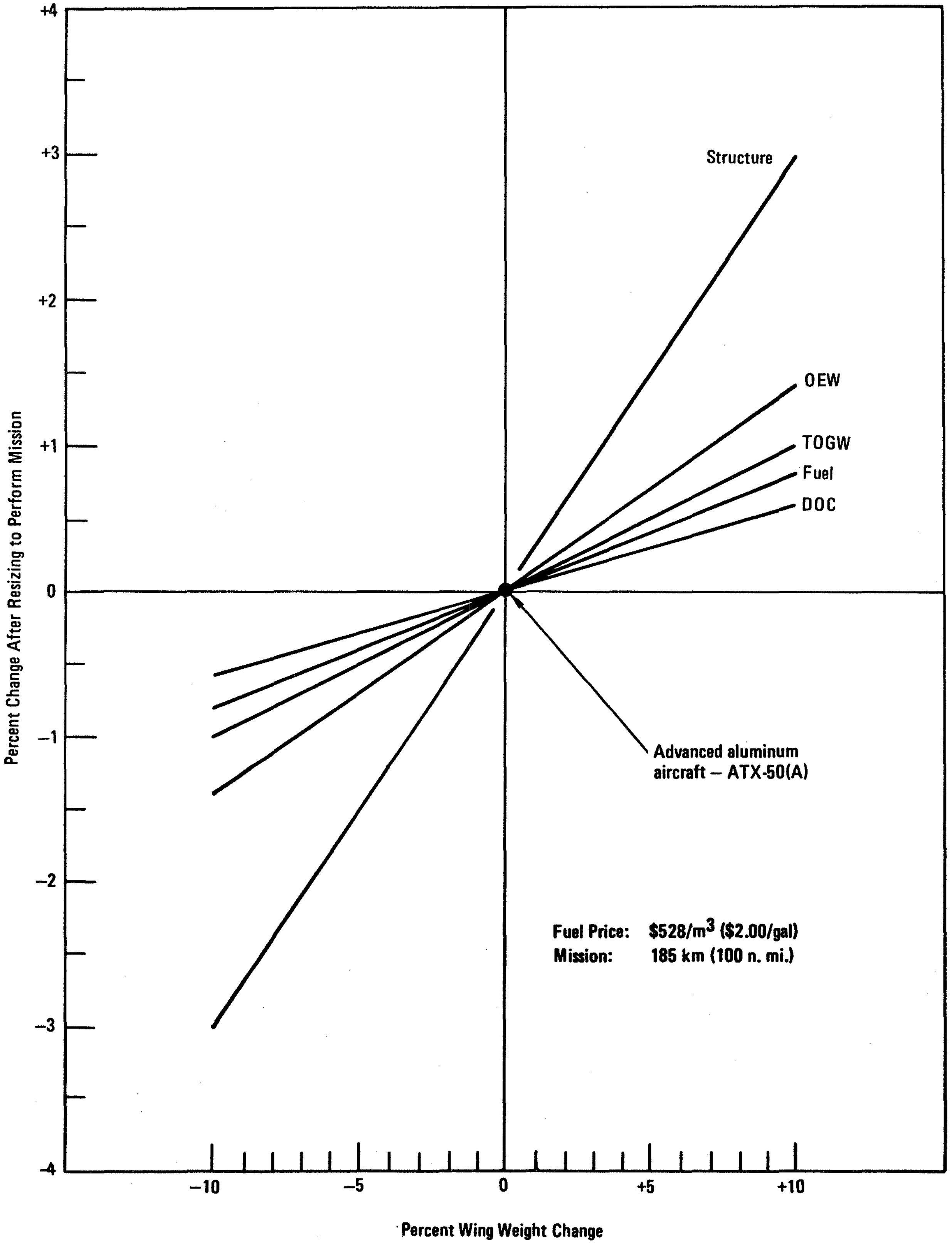


Figure 52. - Sensitivity to wing weight change - ATX-50(A).

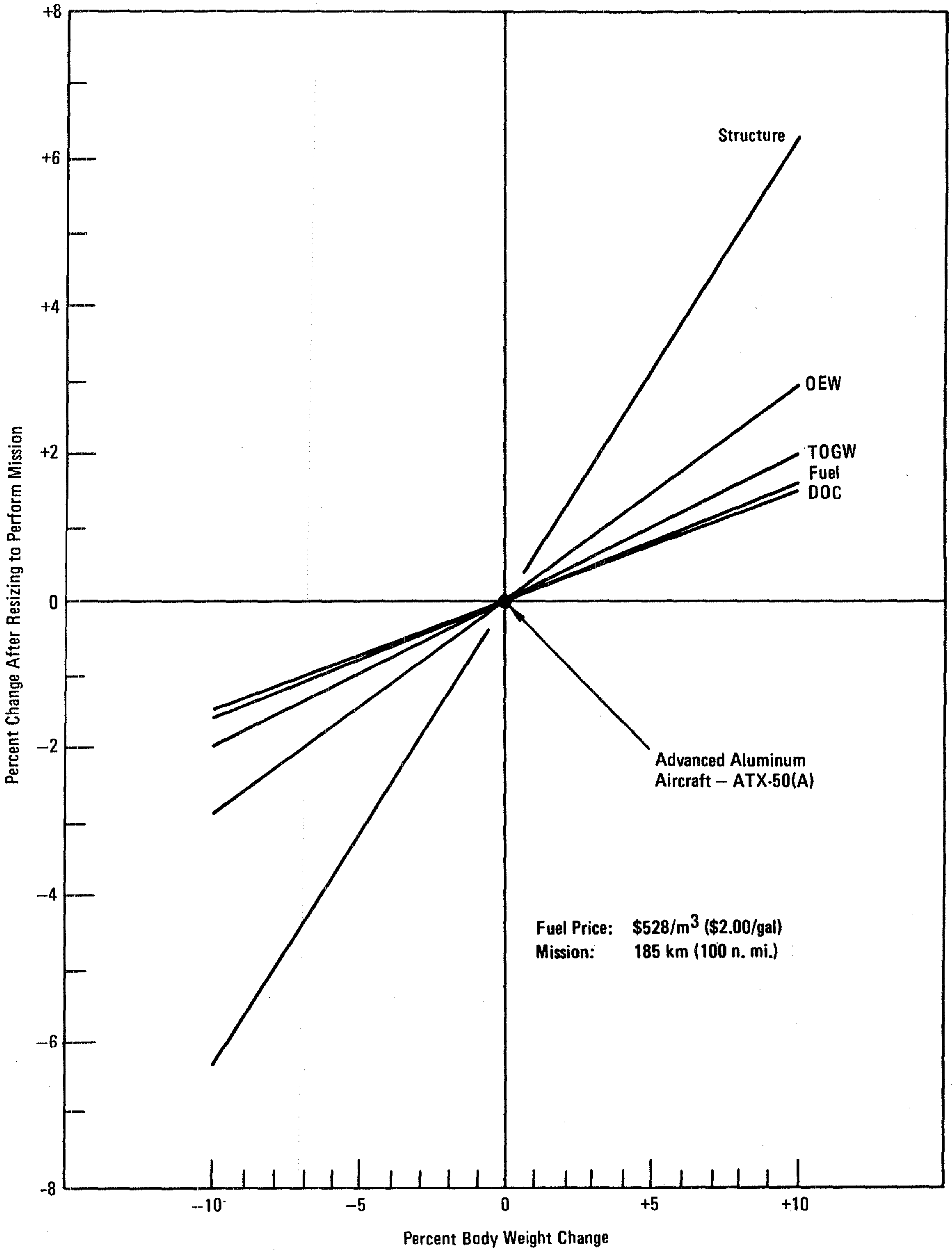


Figure 53. - Sensitivity to body weight change - ATX-50(A).

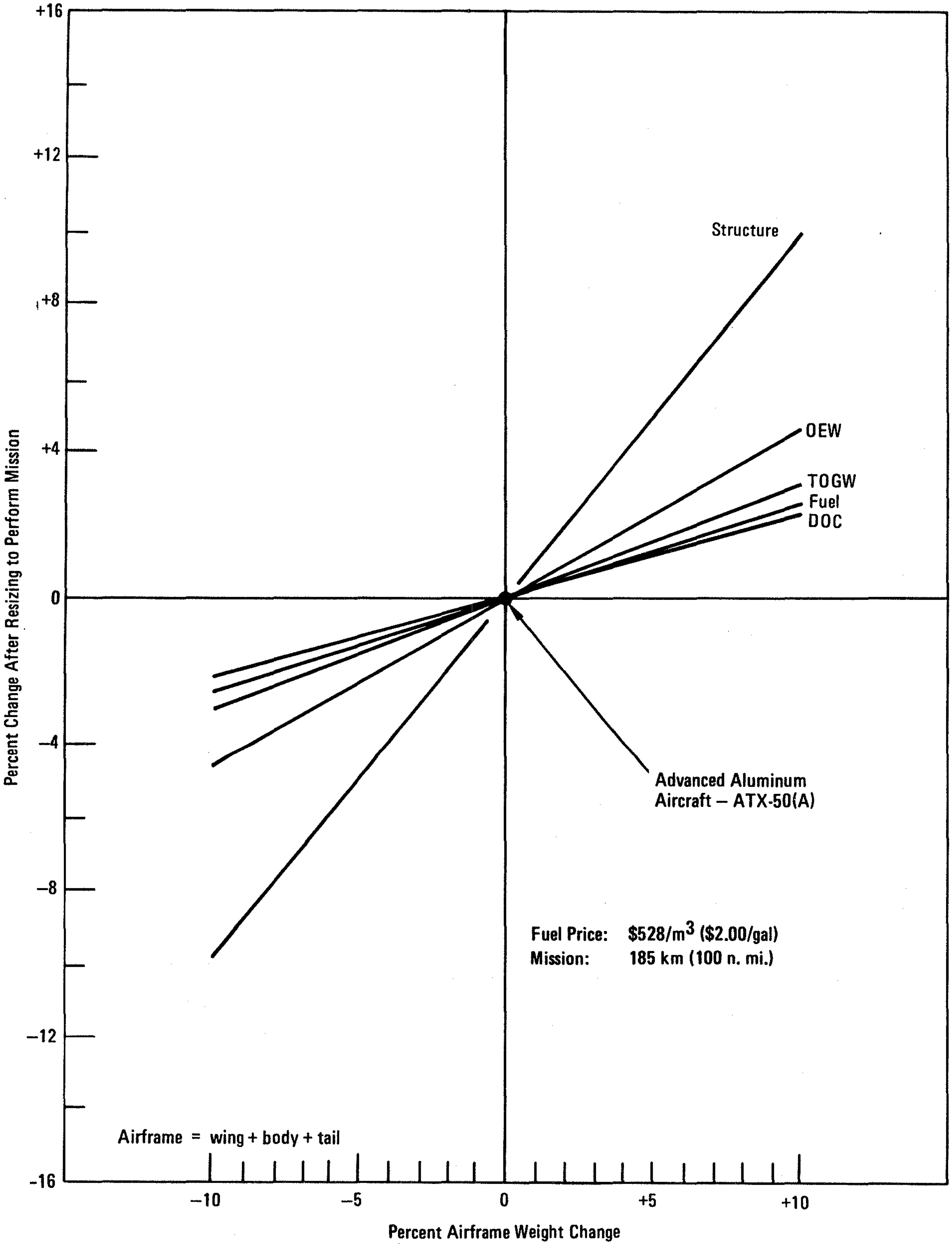


Figure 54. - Sensitivity to airframe weight change - ATX-50(A).

3. MARKET POTENTIAL FOR MATERIALS

The impact of powder metallurgy (PM) technology and new chemical compositions for ingot metallurgy (IM) products and production on the aluminum industry and user community was assessed. New alloys and major applications were considered for transport and supercommuter aircraft, general aviation aircraft, military aircraft, and advanced ground transportation systems. The estimated annual demand for the various applications are presented in table 52. The general aviation and air/intermodal container applications premised that the low density IM alloys are cost competitive with current IM alloys. The annual demand for both PM and IM alloy systems are of the same magnitude. Aircraft benefit analysis established commercial transport and supercommuter aircraft requirements. The military aerospace applications were derived from the reference 9 study, where advanced aluminum alloys are being developed that will provide major payoffs in terms of weight savings for new aerospace structures. The Advanced Tactical Fighter (ATF) was used as a representative aircraft for application of the low density, high strength and stiffness alloy. A production quantity of 500 aircraft was assumed. For general aviation industry usage, Cessna Aircraft Company provided suggested areas and extent for application of the new alloys. One-third of the estimated usage of the 2000 and 7000 series alloy was considered to be reasonable for application of the low density IM Al-Li alloy. Design concepts and trends of advanced ground transportation systems were conducted to estimate advanced aluminum alloy demands. To complement the fuel-efficient transport aircraft, application of IM Al-Li was estimated for air and intermodal container manufacture.

Consultation with Alcoa and others in the aluminum industry was maintained to keep abreast of their commercialization plans for PM and IM technologies. The feasibility for commercial manufacture and application of high-strength PM alloys such as X7090 and X7091 has been demonstrated. On account of the smaller billet size required for extruded and forged products (compared with aerospace plate product starting billet size), PM aluminum alloy billets for extrusions and forgings are now a commercial reality. Market support for these products has prompted the development of working plan for 1981-82 production. However, further developments including new tooling concepts are required to obtain commercial PM plate products to support the aerospace market interest.

3.1 Alternate Applications

A brief analysis was conducted of other potential applications for the advanced aluminum alloys in addition to civil transports and commuter aircraft. These applications encompassed (1) general aviation aircraft, (2) military aircraft, (3) advanced mass transit, and (4) surface and air cargo transportation systems. A rough order to magnitude estimate of advanced aluminum alloy demands for these applications was made. The results indicated an annual demand of approximately 4.5 Gg (10^7 lb) of advanced aluminum lithium alloy.

TABLE 52. - ESTIMATED ANNUAL ADVANCED ALUMINUM DEMAND

APPLICATION	PM ALLOY		IM ALLOY	
	Gg	lb x 10^6	Gg	lb x 10^6
Transport and Supercommuter Aircraft	9.8	22.2	4.1	9.1
General Aviation Aircraft	–	–	2.3*	5.0*
Military Aircraft – ATF	–	–	1.1	2.5
Air/Intermodal Containers	–	–	1.1*	2.5*
Total	9.8	22.2	8.6	19.1

*Must be cost competitive with current IM alloys

3.1.1 General aviation applications.- The general aviation advanced materials application study was performed by Cessna Aircraft Company, Wichita, Kansas. The study was performed by the Pawnee Division, manufacturer of single and small twin-engine aircraft. The effort was supported by the Wallace Division, manufacturer of large twin and jet engine aircraft. The estimated aluminum alloy demand for general aviation aircraft reflects actual usage (1980) by Cessna for single-engine, multiengine, turbine and jet aircraft, based on production numbers and the empty weight of each model. Based on Cessna's share of the market and the Federal Aviation Administration (FAA) Aviation Forecast, the aluminum usage for the entire industry was determined.

3.1.1.1 Present usage: Nearly all general aviation aircraft currently being manufactured use aluminum as the primary structural material. Although composites are being used more and more, aluminum will probably be the most widely used material in general aviation for the next 10 years. Table 53 lists the alloys currently used by Cessna, their applications, and possible advanced alloy replacements.

This alloy usage is assumed to be typical of the general aviation industry because of the similarity of structural design of the majority of new aircraft. On account of the lower loads in general aviation aircraft, the majority of the structure is made from sheet aluminum. Formed and flat wrap skins and bulkheads, ribs, etc., are formed from sheet aluminum with extrusions and forgings only used in high load areas. On account of the extensive use of sheet aluminum, the alloys used must be very versatile; i.e., lightly formable in the tempered condition and suitable for complex compound forming in the O-condition and heat treatment by the airframe manufacturer.

TABLE 53. - CESSNA AIRCRAFT ALUMINUM ALLOY USE

CURRENT ALLOYS	APPLICATIONS	ADVANCED ALLOY REPLACEMENTS
2024-T3 Sheet	Skins & lightly formed parts	D, E
2024-T4 Sheet	Skins & lightly formed parts	D, E
2024-T42 Sheet	Formed parts heat treated after forming	D, E
6061-0 Sheet	Highly formed parts	E
6061-T6 Sheet	Highly formed parts heat treated	E
2014-T6 Extrusion	Spar caps & machined parts	A, B, C
2024-T3 Extrusion	Raw stock for hog outs	A, B, C
6061-0 Extrusion	Stiffeners, angles, & tubing	A, B, C if weldable
6061-T6 Extrusion	Stiffeners, angles, & tubing heat treated	A, B, C if weldable
2014-T6 Forging	Fittings, spar carry-thru, landing gear	Alloy B if desired characteristics are met
2024-T3 Forging	Fittings	Alloy B if desired characteristics are met
7075-T6 Forging	Landing gear	Alloy B if desired characteristics are met
3000 Series	Skuff plates and other non-structural applications	–
5000 Series	Tubing	–

3.1.1.2 Forecast usage: An estimate of the aluminum usage by the general aviation industry for the next 10 years and the annual usage for 1980 is shown by alloy series in table 54. These estimates are based on FAA general aviation fleet forecasts and 1980 production rates. The source for the forecasts are published production figures for model year 1980 and the 10-year fleet forecast from FAA Aviation Forecast, 1981 to 1991. The method used in obtaining the annual aluminum usage for the industry was the following:

(1) Obtain Cessna (Pawnee and Wallace Divisions) aluminum usage for year 1980.

(2) Divide aluminum usage up between single engine, multiengine, turbine, and jet based on production numbers and empty weight of each model.

(3) Based on Cessna's share of the market calculate an aluminum usage for the entire industry.

This was done for each of the alloy series shown. For the 10-year forecast:

(1) Production for each year was calculated using the FAA forecast numbers, assuming a 2 percent per year attrition rate and the same export percent as 1980.

TABLE 54. - ESTIMATE OF ALUMINUM USAGE BY GENERAL AVIATION INDUSTRY

ALUMINUM SERIES		2000	3000	5000	6000	7000
Annual, 1980	Mg	7,845	1	175	291	442
	lb x 10^3	17,295	3	386	641	974
Next 10 years	Mg	62,471	11	1,394	2,314	2 435
	lb x 10^3	137,725	25	3,073	5,102	5,368

(2) The 10-year production numbers were calculated for each type of aircraft: single, multi, turbine, and jet. Based on the 1980 aluminum usage, the total 10-year usage was calculated for each alloy series for each aircraft type then totaled to give the 10-year result in table 54.

3.1.1.3 Design considerations: The design considerations for potential use of the advanced aluminum alloys to the airframe are discussed by product form and alloy-type, as follows:

Sheet product form: Sheet aluminum alloys find application to the majority of the airframe of general aviation aircraft.

- Alloy A - Cessna uses very little 7075 sheet and, therefore, negligible usage is envisioned for this material.
- Alloy D - This material is attractive from the viewpoint of improved fatigue and toughness characteristics. These improvements point toward pressurized fuselage skins and wing skins on the inboard one-third to one-half of the wing. It would be used as an improvement to current aircraft and would not be expected to have a significant influence on future aircraft. Alloy D is more attractive to the twin and larger aircraft designers than to the single-engine aircraft designers due to generally higher pressurization levels and loads.
- Alloy E - This low density (10-percent reduction) alloy is most attractive to the unpressurized fuselage areas and to surfaces that are not highly loaded. This restriction is due to the lower resistance to crack growth as compared to 2024-T3.

  Presently, the single engine aircraft area finds Alloy E more attractive than does the twin and larger aircraft group. The potential reduction in airframe weight appears to be the only significant impact on the aircraft.

Plate product form: Plate material is not used at Cessna except for experimental hog-outs. It can be assumed that this is true throughout the industry. Therefore, no use is projected.

Extruded product form: Although the tensile and compressive yield makes these attractive substitutes for the baseline material, the reduction in toughness offsets the gains for twin-engine aircraft due to their greater usage of highly loaded extruded parts. For twins, alloys B and C would be used extensively only in the wing upper surface stringer applications. The compressive yield, which designs the upper stringers, would necessarily result in smaller sections. The added benefit of lower density for Alloy C, of course, would provide for further weight reduction. For spar caps, lower wing stringers, and fuselage primary structure applications, the new alloys must have crack growth resistance equal to or greater than the baseline alloy before consideration for airframe usage. Single engine aircraft use mostly roll-formed stringers, with the extrusions playing a less critical role. Therefore, advanced material extrusions could be more easily substituted in these aircraft.

Forged product form: Limited application to light aircraft. Most forgings are designed to transmit both tensile and compressive forces. Toughness must be comparable to baseline alloy before consideration for airframe applications.

3.1.1.4 Manufacturing considerations: Manufacturing characteristics are very important for the economical use of the new alloys. The following are some of the more important considerations:

- Formability - should be able to form on present machines using present tooling.
- Heat treatable by the airframe manufacturer.
- Matching characteristics - the same or improved over current alloys.
- Forging characteristics - forgeable in the same dies that are being used today (allows for minimum change product improvement).
- Weldability - many times the best way to make an assembly is by welding.

Cost considerations: Cost affects all the alloys. The cost of the new alloys must not outweigh the advantages of strength, stiffness, etc. Cost in this case is not just purchase price. It is also made up of costs for new tooling, manufacturing procedures, retesting old designs, and the problems associated with stocking four or five new alloys that may only have limited applications. The cost resulting from material mix-up can be very high, especially if an aircraft gets in the field before the problem is found. Therefore, it is desirable to use as few different alloys as possible.

3.1.1.5 Conclusions: The proposed alloys will not have a significant impact on the design of future light aircraft. However, the increase in strength and reduced density can serve to decrease the weight of the airframe (up to 5 percent). This improvement would be small in comparison to a 5-percent improvement in specific fuel consumption (SFC) of the power plants. However, the incremental improvements in structural weight, aerodynamics, propulsion, etc., can combine to result in significant improvement in the aircraft performance and fuel efficiency. The use of the advanced IM aluminum-lithium alloy was estimated to be one-third of the estimated 2000 and 7000 series alloy of table 54. With improved material toughness characteristics and reduced density, with manufacturing characteristics close to present-day alloys, and with comparable costs, the annual usage was estimated at 2.3 Gg (5 x 10^6 lb).

3.1.2 Military applications. - The advanced aluminum materials application assessment for military aircraft was made using a representative advanced tactical fighter (ATF) configuration shown in figure 55. The Mach 2.0 fighter aircraft has a gross weight of 21 900 kg (48,300 lb).

3.1.2.1 Weight evaluation methodology: The method selected for evaluating structural weight savings by the application of advanced aluminum alloys is from reference 4, and is illustrated in the flow diagram in figure 56. Only the highlighted elements were included in this assessment. The structural weight of the component to be evaluated is distributed according to the primary failure modes that size the structure. Nine failure modes were considered for the weight evaluation. Equations relating changes in weight to the basic material properties are shown for each failure mode in table 26. Derivations for the equations are presented in reference 4.

3.1.2.2 Allocations of structural weight to primary failure modes: The structural arrangement for the ATF selected for analysis is shown in figure 57. The weight breakdown used in this analysis is shown in table 55. Only the wing, fuselage, empennage and control surfaces are considered since the landing gear, nacelle, and air induction system are primarily steel or titanium. The structural components considered weigh 6268 kg (13,819 lb), 81 percent of the total structural weight or 29 percent of the gross weight.

Allocation of baseline weights of individual components into the design failure mode categories was made by reviewing the data in reference 9 and applying prior applicable experience. This weight breakdown, shown in table 56, represents a high performance fighter class of military aircraft.

3.1.2.3 Advanced aluminum alloy applications: The aforementioned methodology and failure mode criteria were used to determine the weight benefits of Alloy C to the airframe design. Alloy C was selected for the fighter aircraft application because of its combined strength, stiffness, and material density characteristics. The minimization of weight by combined selective use of different alloys was not performed. The baseline material properties (7075-T76 extrusion) are compared to Alloy C in table 57.

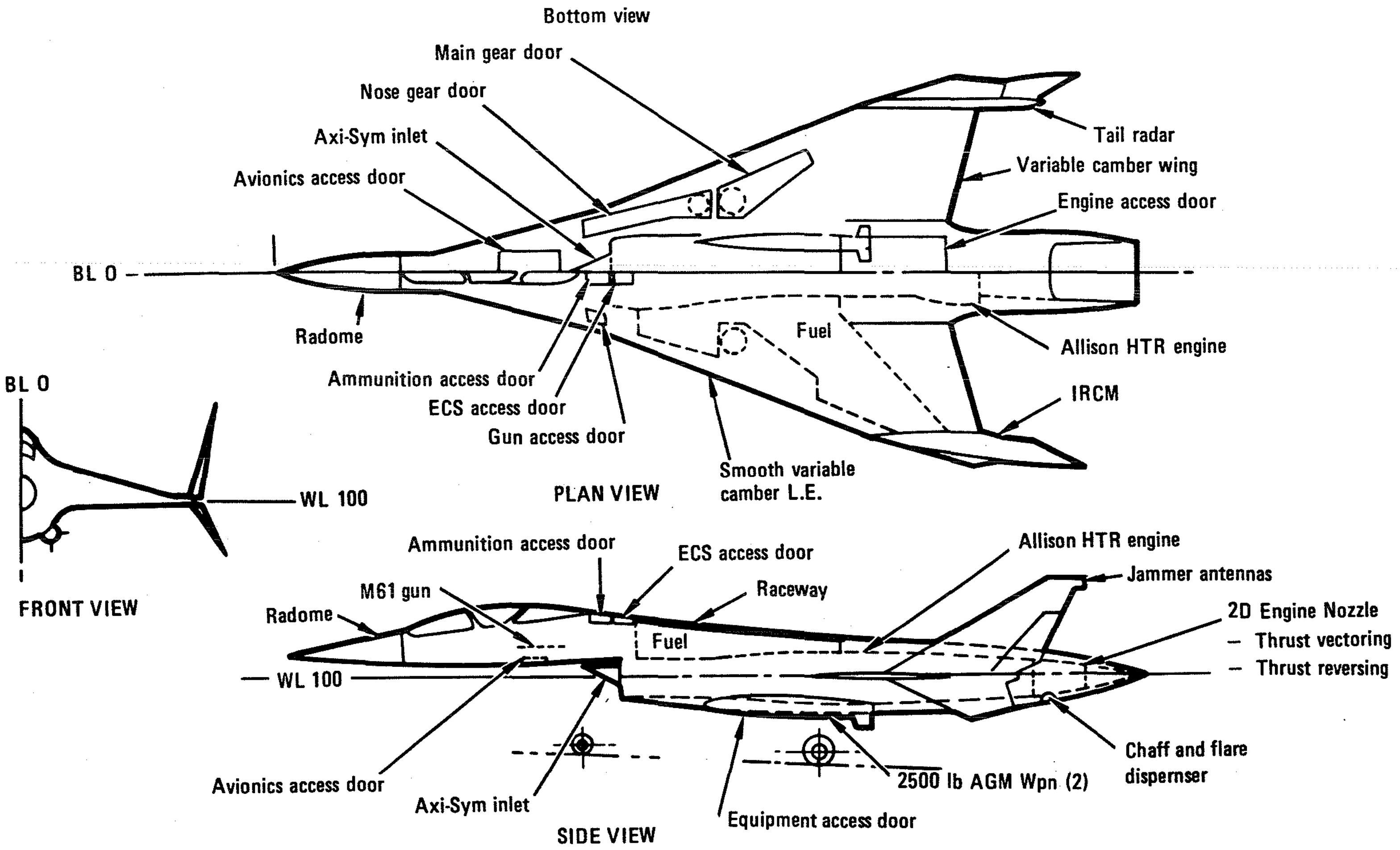


Figure 55. - General arrangement - ATF baseline aircraft.

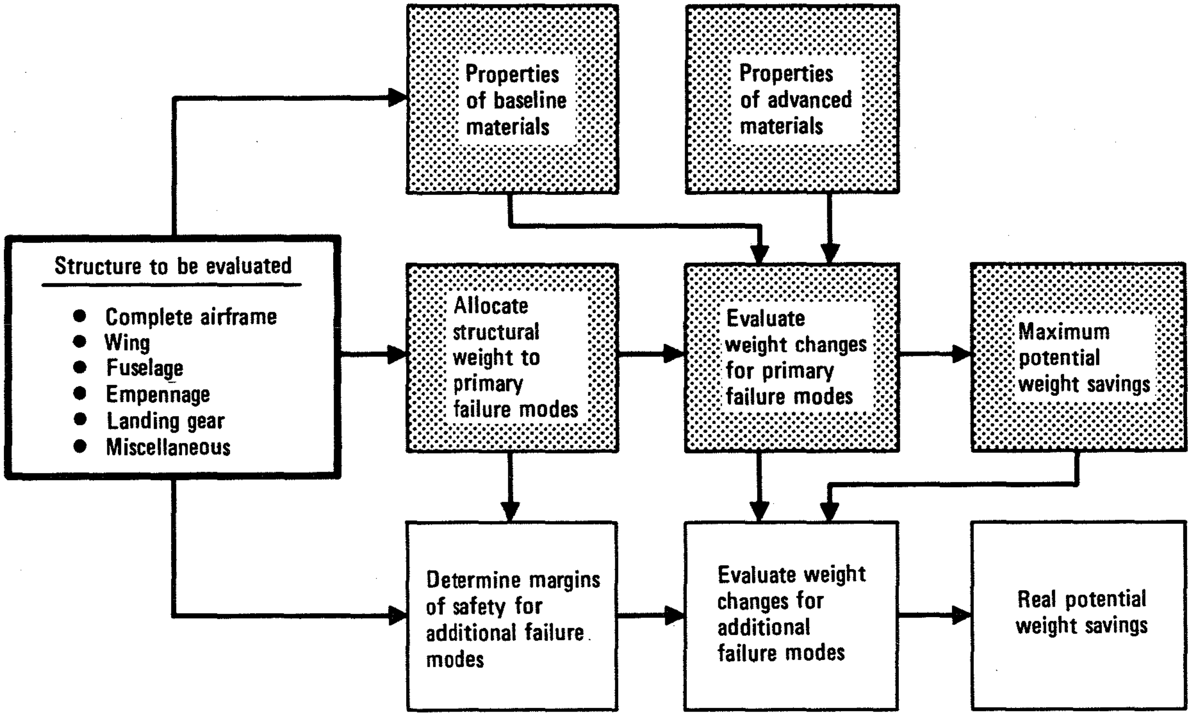


Figure 56. - Aircraft structural weight evaluation of new materials.

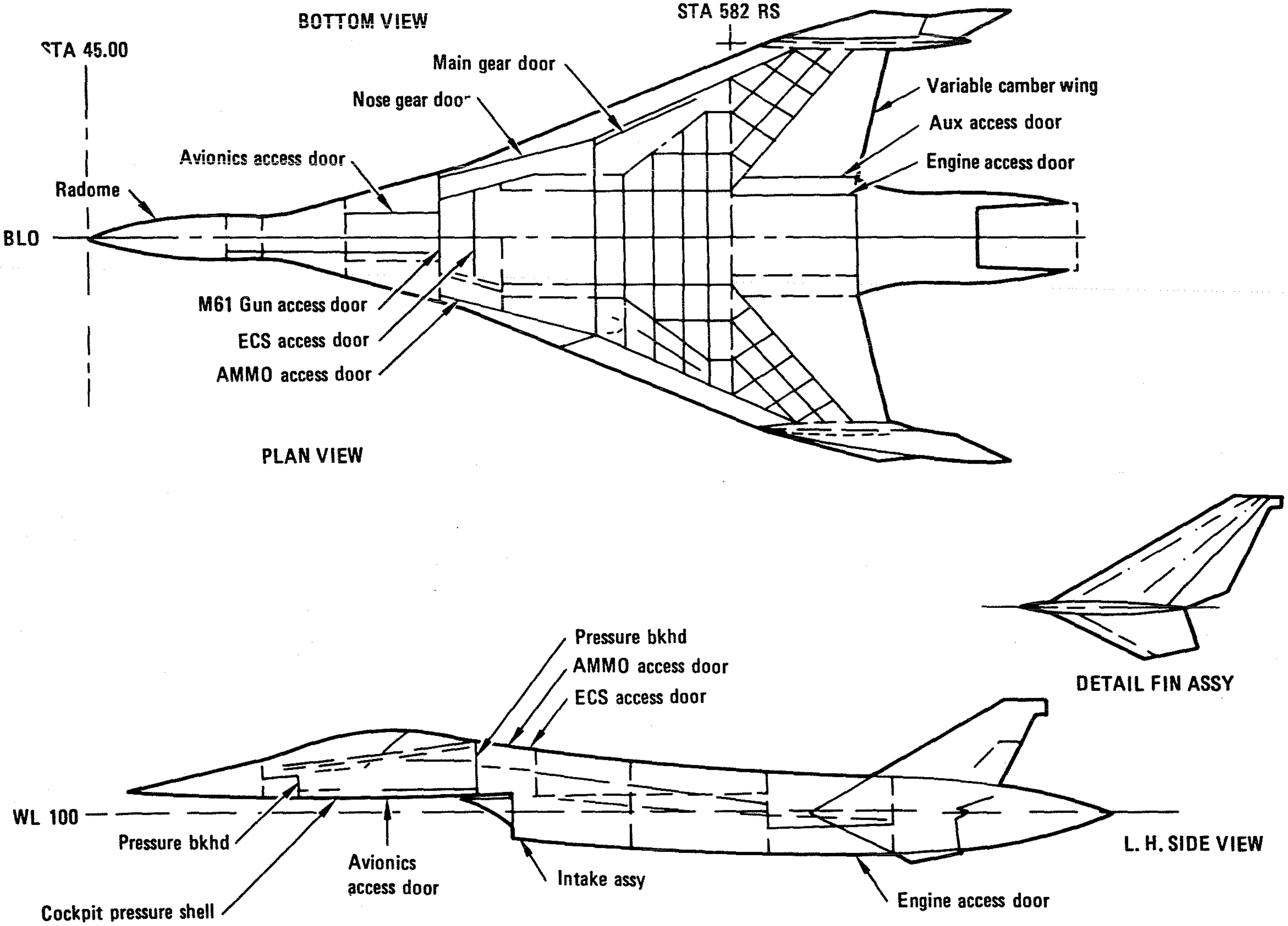


Figure 57. - Structural arrangement - ATF baseline aircraft.

TABLE 55. - ADVANCED TACTICAL FIGHTER (ATF) WEIGHT STATEMENT

GROSS WEIGHT	21 908 kg	(48,300 lb)	PERCENT OF GROSS WEIGHT
Structure	7 750	(17,086)	35.4
Wing*	2 494	(5,498)	11.4
Fuselage*	2 806	(6,186)	12.8
Tail*	425	(937)	1.9
Control surfaces*	543	(1,197)	2.5
Other	1 428	(3,258)	6.8
Propulsion	3 671	(8,094)	16.8
Fixed Equipment	2 255	(4,993)	10.3
Nonexpend. useful load	547	(1,206)	2.5
Payload	2 345	(5,170)	10.7
Mission fuel	5 330	(11,751)	24.3

*Aluminum components considered for weight savings analysis

The results of the analysis is presented in table 58. The use of Alloy C in lieu of 7075-T76 is shown for the various design failure modes. An 11.7 percent weight savings is indicated for the affected weight items. The weight benefit can be translated into (1) improved aircraft performance or (2) reduced cost by resizing to obtain a smaller aircraft. The estimated annual advanced material demand for military fighter application is estimated for 500 production quantity. The demand could be as high as 1.1 Gg (2.5×10^6 lb) annually.

3.1.3 Advanced ground transportation systems.- The trend in today's ground transportation system market is the increasing demand for economic, fuel-efficient vehicles. This has resulted in a rapidly expanding use of high-strength and lightweight materials to replace steel. Factors that have accentuated fuel economy are increasing fuel prices, emission standards, federal safety requirements and the resultant increases in weight. The rapid escalation of fuel costs since 1972 has had a direct effect on the dollars per mile spent by the consumer. The effect of emission standards on fuel economy is twofold. Reducing the emission levels of NOx, CO, and hydrocarbons in general does not allow the engine to operate at maximum economy. Secondly, the emission control equipment adds extra weight which detracts from fuel economy.

In order to meet the federal safety and impact requirements, either new structural components have to be created or the present structures increased in strength. The previously mentioned factors have brought about an expanded use of aluminum alloys on cars, trucks, trains, buses, and cargo containers.

TABLE 56. - ALLOCATION OF WEIGHT BY DESIGN FAILURE MODE (ATF AIRCRAFT)

DESIGN FAILURE MODE		STRUCTURAL WEIGHT					
		WING	FUSELAGE	EMPENNAGE	CONTROL SURFACES	TOTAL	
CATEGORY	DESCRIPTION	kg (lb)	kg (lb)	kg (lb)	kg (lb)	kg (lb)	PERCENT
1	Tensile strength	499 (1100)	544 (1199)	54 (119)	68 (150)	1165 (2568)	18.6
2	Compression strength	91 (201)	113 (249)	18 (40)	0	222 (490)	3.5
3	Crippling	499 (1100)	544 (1199)	45 (99)	136 (300)	1224 (2699)	19.5
4	Compression surface	249 (549)	222 (490)	91 (201)	45 (99)	607 (1338)	9.7
5	Buckling	408 (899)	567 (1250)	45 (99)	113 (249)	1133 (2498)	18.1
6	Aeroelastic stiffness	249 (549)	272 (600)	68 (150)	136 (300)	725 (1598)	11.6
7	Durability and damage tolerance allowable	299 (659)	250 (551)	50 (110)	15 (33)	614 (1354)	9.8
8	Gen'l. instability shear or comp.	0	0	0	0	0	0
9	Minimum gage	200 (441)	249 (648)	54 (119)	30 (66)	578 (1274)	9.2
Total		2494 (5498)	2806 (6186)	425 (937)	543 (1197)	6268 (13819)	100

Mild steel is the competitor. Thus, economics and maintenance are the prime consideration for design application. The 5000- and 6000-series aluminum alloys provide the necessary strength, stiffness, and crash management capability and are the primary candidates for the current ground vehicle system usage.

Air cargo containers are currently being manufactured with essentially the same design philosophy - low cost. Unsophisticated designs and construction methods are used employing sheet, extrusion, mechanical fasteners, and welding. With the continuing rise in fuel price, the container tare weight will play a more significant role.

3.1.3.1 Ground transportation vehicles: Aluminum alloys are being used for numerous automotive applications: auto bumpers, station wagon floors, hood assemblies, trunk lids, doors, tailgates, and hatchback lids (Reference 10).

TABLE 57. - MATERIAL PROPERTY COMPARISON OF EXTRUDED PRODUCT FORM

PROPERTY	7075-T76 (BASELINE)	ALLOY C
Ultimate tensile strength – F_{tu}	517 MPa (75,000 psi)	586 MPa (85,000 psi)
Compressive yield strength – F_{cy}	448 MPa (65,000 psi)	538 MPa (78,000 psi)
Modulus of elasticity – E	72 GPa (10.4×10^6 psi)	77 GPa (11.2×10^6 psi)
Density – ρ	2796 kg/m^3 (0.101 lb/in^3)	2600 kg/m^3 (0.094 lb/in^3)

The transit car built by Rohr Industries for the San Francisco Bay Area Rapid Transit (BART) District employs extruded 6061-T6 aluminum alloy side panels. The roof is 3003-H14 aluminum alloy (Reference 11). Grumman Flexible 870 bus uses full-length interlocking extrusions for the side walls. Epoxy is used to bond the extrusions together and to fasten the skin to the frames. A smooth exterior is provided with complete elimination of external fasteners and rivet heads, which act as corrosion sites (Reference 12).

As reported in Reference 13, the auto industry currently uses 2036-T4 and 5182-0 aluminum alloy for body sheets. Alcoa 6009-T4 and 6010-T4 have been developed to have the same easy formability as 2036-T4 and 5182-0 and good strength. The alloys are designed to harden during the paint bake cycle to strengths described as well above those of most body sheet steels. In addition, both alloys lend themselves to spot welding. Reynolds Metals has a new extrusion grade 7029 for bumpers with a 20 percent greater yield strength, yet responds well to the high-luster anodic finish that is commonly used.

It is estimated that an aluminum-intensive car using 91 kg (200 lb) more aluminum would cut the car weight by 208 kg (460 lb) and save the car owner 2.3 m^3 (600 gal) of gasoline during the car's lifetime (Reference 14). The 91 kg (200 lb) of aluminum would provide direct weight savings of 138 kg (305 lb) because it would replace 229 kg (505 lb) of steel. Another 69 kg (152 lb) would be saved through secondary weight reductions through the use of smaller structural supports, engines, and transmissions. For a 10-million car production level for 1980, 91 kg (200 lb) of aluminum per car would save the United State 2.4 Mm^3 (633×10^6 gal) of gasoline annually, and 24 Mm^3 (6.3×10^9 gal) over the 10-year life of the cars.

The foregoing illustrates that there is an urgent need for vehicle weight reduction, especially for the automotive industry. The use of aluminum alloys offers the possibility of reduced consumption of energy and materials. However, in the design process, it is important that the functional and performance

TABLE 58. - ALLOCATION OF WEIGHT BY DESIGN FAILURE MODE

(a) S. I. Units

DESIGN FAILURE MODE		ADVANCED ALUMINUM ALLOY C WEIGHT ~ kg					
CATEGORY	DESCRIPTION	WING	FUSELAGE	TAIL	CONTROL SURFACE	TOTAL	%
1	F_{tu}	419	456	45	57	977	17.6
2	F_{cy}	72	89	15	0	176	3.2
3	Crippling	437	476	39	119	1,072	19.3
4	Compr. surf.	221	198	81	40	540	9.8
5	Buckling	378	526	42	105	1,051	19.0
6	Aeroel. stiff.	220	240	60	120	640	11.6
7	DADT	260	218	44	13	535	9.7
8	Gen. instab.	–	–	–	–	–	–
9	Min. gage	190	279	51	29	508	9.8
Σ	Total	2,198	2,483	377	483	5,541	100

$$\text{Weight savings} = \frac{6268 - 5541}{6268} \times 100 = 11.7 \text{ percent}$$

(b) Customary Units

DESIGN FAILURE MODE		ADVANCED ALUM. ALLOY C WEIGHT ~ LB					
CATEGORY	DESCRIPTION	WING	FUSELAGE	TAIL	CONTROL SURFACE	TOTAL	%
1	F_{tu}	923	1,006	100	126	2,155	17.6
2	F_{cy}	159	197	32	–	388	3.2
3	Crippling	963	1,050	87	263	2,363	19.3
4	Compr. surf.	488	436	179	88	1,191	9.8
5	Buckling	834	1,159	92	231	2,316	19.0
6	Aeroel. stiff.	485	530	132	265	1,412	11.6
7	DADT	574	480	96	29	1,179	9.7
8	Gen. instab.	–	–	–	–	–	–
9	Min. gage	419	616	113	63	1 211	9.8
Σ	Total	4,845	5,474	831	1,065	12,215	100

$$\text{Weight savings} = \frac{13{,}819 - 12{,}215}{13{,}819} \times 100 = 11.7 \text{ percent}$$

requirements are not unknowingly compromised in the quest for lightweight design. Cost, fabrication, appearance, durability, environmental factors, energy, availability of material, and structural considerations should be evaluated in the design. The structural consideration, however, is among the most important of these since it dictates the minimum gage (and thus minimum weight) of the structural number in terms of functional requirements (Reference 15). Tables 59 and 60 presented the structural characteristics and material properties that are important to the design of panel members (e.g., hood, roof-panel, and door-panels) and thin-walled-beam members (e.g., chassis frame, pillars, and rocker panels), respectively. It can be seen that the most significant characteristic for design is material modulus of elasticity. Therefore, the development of an aluminum-lithium alloy (Alloy E) at competitive costs can provide the material characteristic which will provide eventual use on ground transportation systems.

3.1.3.2 Cargo containers: Airline requirements currently call for low-cost containers and, the container manufacturers have responded with unsophisticated designs. Simple construction using standard sheet, plate, extrusion, mechanical fasteners, and welding is employed.

Market forecasts are now identifying a need for a large number of fuel-efficient transport required to replace the aging airline fleet during the 1990-2005 time period. It is obvious that lightweight containers are required to complement these new aircraft and contribute to the economics of the airline/airfreight industry.

A revolutionary development in containerized air cargo systems is now in the making. New generations of transport aircraft, intermodal containers, and container modules will significantly increase the efficiency and reduce the cost of transporting freight by air.

The current intermodal containers are relatively efficient in terms of container tare weight per internal volume when compared to the LD-3 and A-series igloo containers. The 6 m (20 ft) intermodal container has a weight of 2.92 kg/m^3 (1.82 lb/ft^3), compared to the more commonly used LD-3 of 3.75 kg/m^3 (2.34 lb/ft^3) and 3.27 kg/m^3 (2.04 lb/ft^3) for the A-series igloo. The Boeing 747 freighter can load twelve 6 m (20 ft) intermodal containers (Reference 16). These containers correspond to 19 000 kg (42,000 lb) of revenueless tare weight or approximately 30 percent of the total payload.

The application of advanced aluminum Alloy E (aluminum-lithium type) on a material substitution basis with reduced density and improved modulus of elasticity can result in a 10 percent weight savings of enable the B747 to carry an additional 1900 kg (4200 lb) of payload. It is estimated that the annual use of Alloy E in various product forms for container manufacture is 1.1 Gg (2.5 x 10^6 lb).

TABLE 59. - STRUCTURAL REQUIREMENTS FOR AUTO PANEL MEMBERS

STRUCTURAL CHARACTERISTIC	RATIO OF STRUCTURAL CHARACTERISTICS*	THICKNESS RATIO REQUIRED FOR EQUAL STRUCTURAL CHARACTERISTICS
Stiffness, S (Oil canning resistance)	$\frac{S_n}{S_o} = \frac{E_n}{E_o} \left(\frac{t_n}{t_o}\right)^2$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n}\right)^{1/2}$
Denting resistance, D	$\frac{D_n}{D_o} = \left(\frac{\sigma_{yn}(\dot{\epsilon}) t_n 2}{\sigma_{yo}(\dot{\epsilon}) t_o 2}\right)^2 \frac{S_o}{S_n}$	$\frac{t_n}{t_o} = \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})} \left(\frac{E_n}{E_o}\right)^{1/2}$
Buckling resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o} \frac{1-\upsilon_o 2}{1-\upsilon_n 2} \left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-\upsilon_o 2}{1-\upsilon_n 2} \frac{E_o}{E_n}\right)^{1/3}$
Stress yield factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\epsilon})}{\sigma_{yo}(\dot{\epsilon})} \frac{E_o}{E_n} \frac{\bar{S}_n}{\bar{S}_o}$	$\frac{\bar{S}_n}{\bar{S}_o} = \frac{E_n \sigma_{yo}(\dot{\epsilon})}{E_o \sigma_{yn}(\dot{\epsilon})}$
Vibration frequency, F	$\frac{F_n}{F_o} = \left(\frac{E_n}{E_o} \frac{t_n}{t_o} \frac{\rho_o}{\rho_n}\right)^{1/2}$	$\frac{t_n}{t_o} = \frac{E_o \rho_n}{E_n \rho_o}$

*Subscripts n and o refer to new material and original material.

3.2 Timing for New Transport Aircraft

The point in time when technology readiness must be established for use of new materials in the airframe structures depends upon:

- The degree of technology advancement required
- The funding support made available to establish the technology
- Production of a new aircraft that incorporates the technology
- Capability of the market place to accept and employ this new advanced technology aircraft.

TABLE 60. - STRUCTURAL REQUIREMENTS FOR THIN-WALLED BEAM MEMBERS

STRUCTURAL CHARACTERISTIC	RATIO OF STRUCTURAL CHARACTERISTICS*	THICKNESS RATIO REQUIRED FOR EQUAL STRUCTURAL CHARACTERISTICS
Bending stiffness, S^b	$\frac{S_n^b}{S_o^b} = \frac{E_n}{E_o} \frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$
Torsional stiffness, S^t	$\frac{S_n^t}{S_o^t} = \frac{G_n}{G_o} \frac{t_n}{t_o}$ (closed section)	$\frac{t_n}{t_o} = \frac{G_o}{G_n}$
	$= \frac{E_n}{E_o} \frac{t_n}{t_o}$ (open section)	$\frac{t_n}{t_o} = \frac{E_o}{E_n}$
Buckling resistance, B	$\frac{B_n}{B_o} = \frac{E_n}{E_o} \frac{t_n}{t_o}$	$\frac{t_n}{t_o} = \frac{E_n}{E_o}$
Local buckling resistance, L	$\frac{L_n}{L_o} = \frac{E_n}{E_o} \frac{1-v_o^2}{1-v_n^2} \left(\frac{t_n}{t_o}\right)^3$	$\frac{t_n}{t_o} = \left(\frac{1-v_n^2}{1-v_o^2} \frac{E_o}{E_n}\right)^{1/3}$
Crippling resistance, C	$\frac{C_n}{C_o} = \left(\frac{E_n}{E_o} \frac{\sigma_{yn}}{\sigma_{yo}}\right)^{½} \left(\frac{t_n}{t_o}\right)^{1.75}$	$\frac{t_n}{t_o} = \left(\frac{E_o}{E_n} \frac{\sigma_{yo}}{\sigma_{yn}}\right)^{1/3.5}$
Stress yield factor, Y	$\frac{Y_n}{Y_o} = \frac{\sigma_{yn}(\dot{\epsilon})}{\sigma_{yo}(\dot{\epsilon})} \frac{E_o}{E_n} \frac{S_n}{S_o}$	$\frac{\bar{S}_n}{\bar{S}_o} = \frac{E_n}{E_o} \frac{\sigma_{yo}(\dot{\epsilon})}{\sigma_{yn}(\dot{\epsilon})}$
Vibration frequency, F	$\frac{F_n}{F_o} = \left(\frac{E_n}{E_o} \frac{\rho_o}{\rho_n}\right)^{½}$	————————

*Subscripts n and o refer to new material and original material.

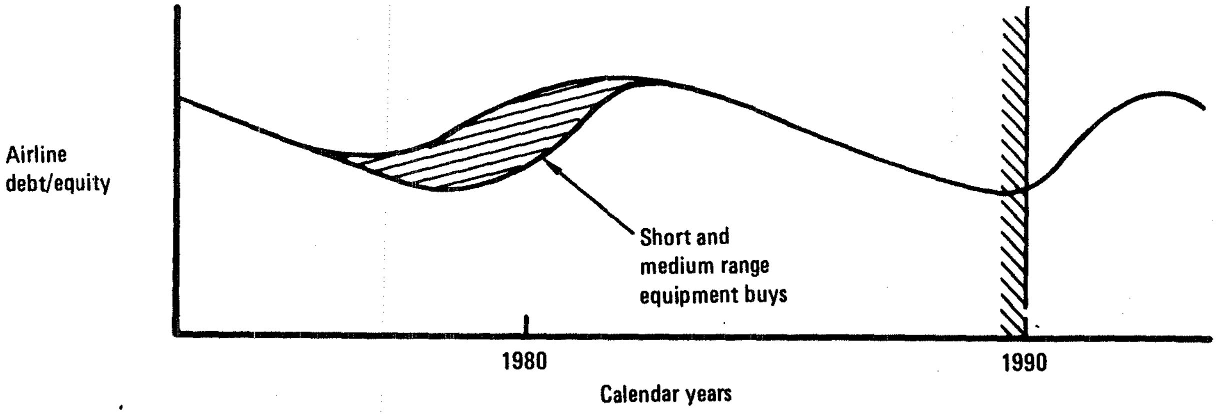


Figure 58. - New aircraft timing.

The ability of airlines to purchase new equipment is related to the airline debt-to-equity ratio. The trends of this economic indicator is cyclic as displayed in figure 58. The purchase of new equipment (B757, B767) by the airlines to replace their current narrowbody equipment (727-100, 707, DC-8) will drive the debt-to-equity ratio back up again. These trends indicate that the early 1990 time period as the earliest date in which the airlines will have the ability to purchase a new equipment.

A look at the historical commercial air transport development further indicates the cyclic nature of the airline industry (figure 59). Starting with the initial passenger aircraft of the 1920s, there has been an introduction of an advanced technology transport approximately every 12 years.

These trends indicate the potential availability of airline resources for new equipment buys for advanced technology aircraft will be in the early 1990s. Targeting technology readiness for the mid-1980s will provide sufficient time to pursue a systematic advanced aluminum material and structural technology development program.

Large benefits will result from advanced aluminum alloys only if used at the onset of development. To apply the material system on a substitute basis will give only a limited weight savings and corresponding fuel savings. For a given mission (payload, range, and speed), a lighter structure would mean a lower takeoff gross weight, which in turn would mean that the wing, tail, engines, etc., could be smaller.

3.3 Production Program Relationship

An important factor in defining a development plan for introducing a new material system is the relationship of such a program to a subsequently new aircraft production program. This relationship is illustrated in figure 60.

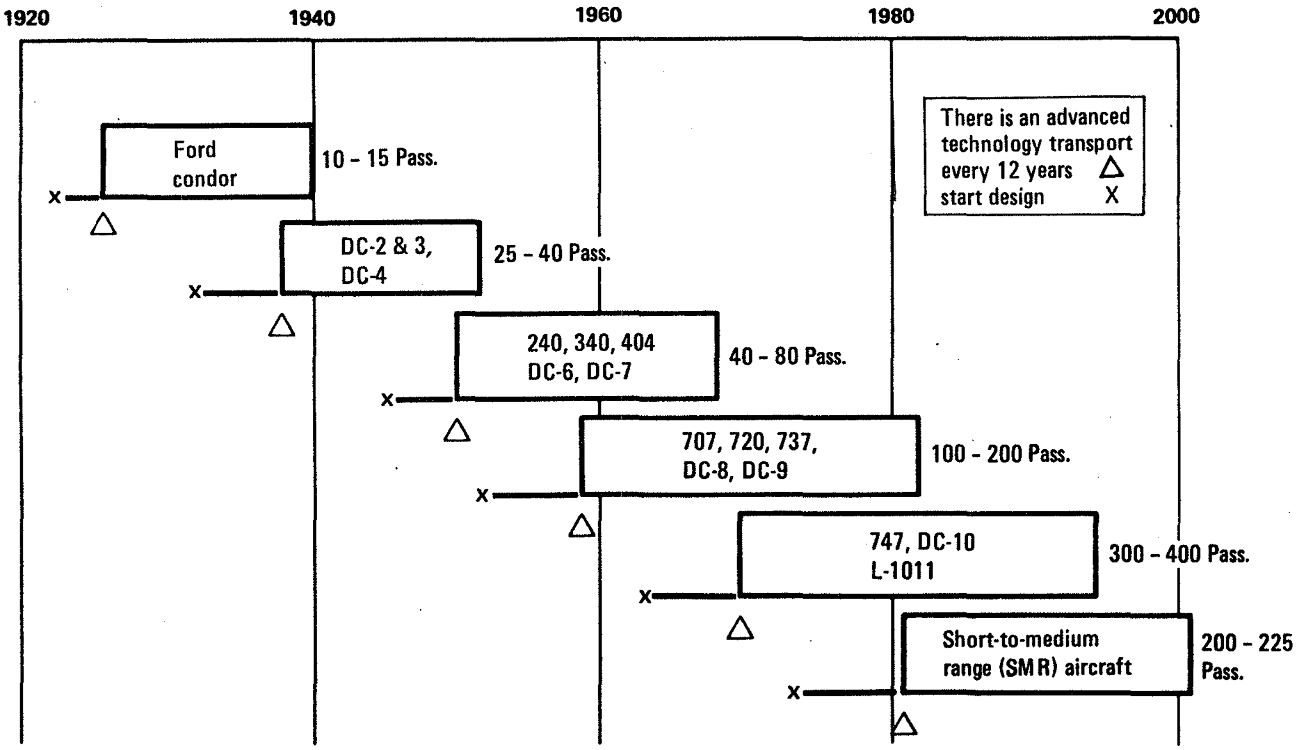


Figure 59. - Commercial air transport development.

In order to introduce a new aircraft into service in the early 1990s, the production program must be initiated in the mid-to-late 1980s. The production program includes the normal design development, design verification, and flight test programs. Prior to go-ahead, the new material and applications development must be carried to the point where the Company management has sufficient data to consider committing to production an airframe design employing advanced aluminum alloys.

3.4 Transport Aircraft Projections

A projection of aircraft deliveries for a 15-year period (1990-2005) is made to arrive at market factors for aircraft that could incorporate the advanced aluminum technology. The projection yields a market for up to 5000-5550 aircraft or an average of 333-370 aircraft per year. Although the 5000-5550 figure and the 333-370 per year are very large, from a historical perspective the numbers appear to be reasonable. For example, taking a similar historical period, 1960-1975, there were 5268 actual aircraft deliveries. Therefore, the projection of 5000-5550 aircraft is almost a perfect fit for a statistical range around 5268 figure. The future aircraft, for the most part, are larger aircraft than those of the previous time period. These larger aircraft are required to cope with the projected traffic growth requiring additional number of seats to meet the anticipated airline demands.

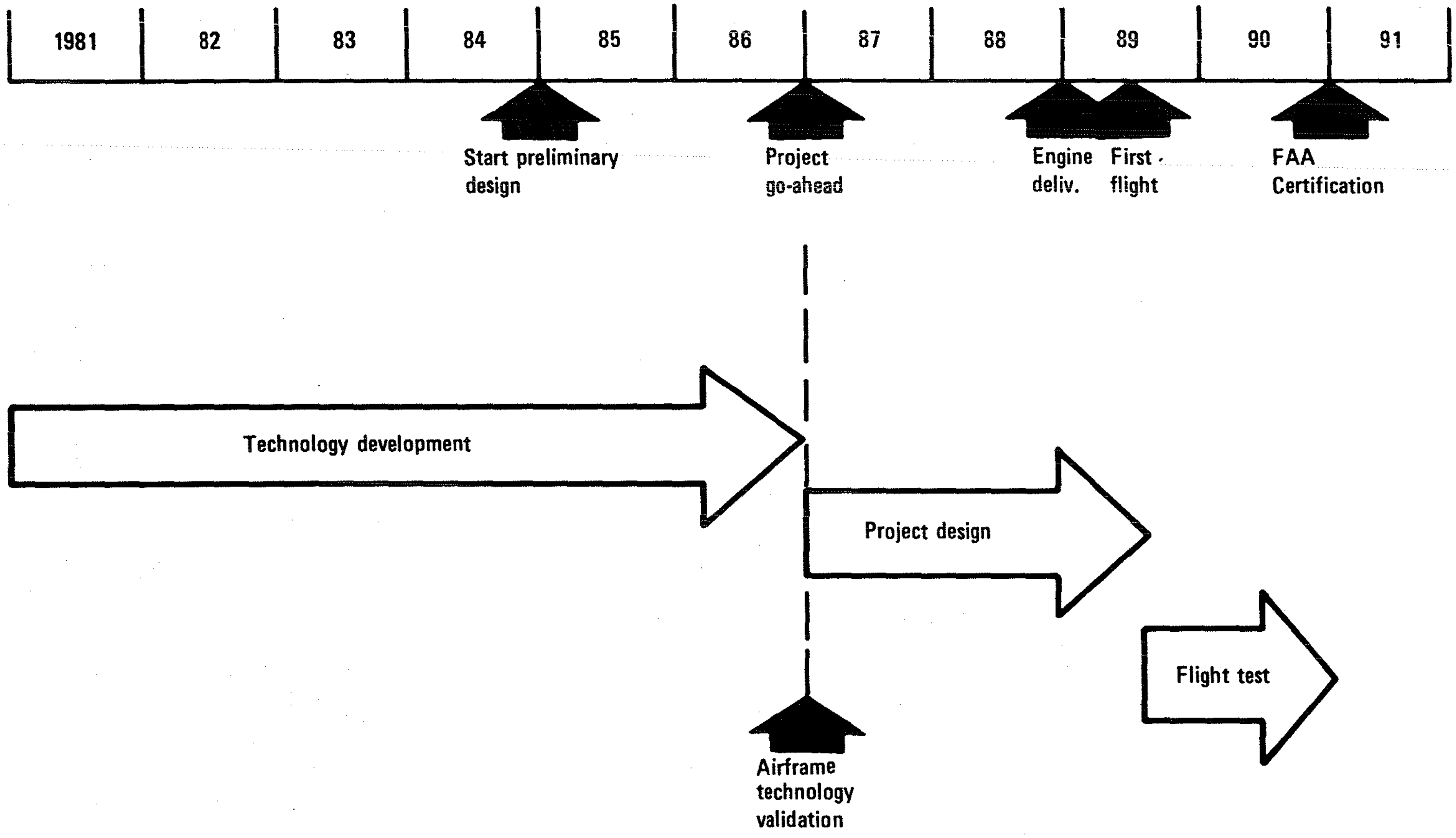


Figure 60. - New aircraft program schedule.

A detailed breakdown of projected aircraft requirements, by type, for the period 1990-2005 is shown below.

Aircraft Type	Requirement MIN. MAX.
100 PAX Short/Medium Range	1500-1650
150 PAX Medium Range	2300-2500
350 PAX Long Range	1200-1400
Grand Total	5000-5550

3.4.1 100 passenger - short-medium range.- The B737 production line is expected to be winding down in the early years of the forecast period. The B737-300 (small stretch) version will start deliveries in the 1983-84 but this airplane is expected to be replaced by Advanced Twin-Engine aircraft presently being planned.

The Advanced Twin aircraft will likely be introduced in about 1987, despite claims of 1985 availability. The delay will be due to the early 1980s traffic slump and lack of availability of a suitable engine before 1987. However, about 900 to 1000 of these Advanced Twins will be delivered in the 1990-2005 time frame.

A new entrant into this market in the early 1990s is expected to be an advanced propfan aircraft with the benefit of sharply decreased fuel costs compared to the turbofan. Introduced in the early 1990s, at least 550 to 600 of this type of aircraft are expected to be delivered in the forecast period.

In summary, the 100-passenger short/medium range market for 1990-2005 is:

	MIN.	MAX.
B737	50	50
Advanced Twin	900 -	1000
Propfan	550 -	600
Total	1500 -	1650

3.4.2 150 passenger - medium range.- Although the range and size differentiation among aircraft types becomes more difficult as improved and better power plants are developed, the Advanced Twin may have an impact on this market as well. For example, the Airbus A320 is stated to have two versions: a 130-seat and a 150-seat model. However, with new technology, a new advanced twin should be introduced in the early 1990s which will have a market of 400 to 500 aircraft. In addition, the B757 twin introduced in 1983 will still be selling with advanced technologies and reduced costs. This market is forecast to range between 950 and 1000 aircraft between 1990 and 2005. Also, B767 and A310 aircraft will continue to sell until the middle 1990s. These two aircraft should realize about 400 to 450 sales in the forecast period.

The last new aircraft predicted to be introduced in this time frame is another longer-range propfan in the middle 1990s. This fuel efficient aircraft will have a potential market of 500 to 550 aircraft between then and the year 2005.

The 150-passenger, medium-range market, consists of:

	MIN. MAX.
Advanced twin	450-500
B757	950-1000
B767/A310	400-450
Propfan	500-550
Total	2300-2500

3.4.3 350 passenger-long range.- A 350-passenger Advanced Trijet will be introduced about 1992, with a stretched version appearing later in the decade. Deliveries between 1992 and 2005 should range between 500 and 600 aircraft. A longer range Advanced Trijet introduced at about the same time should be more successful by limiting sales of the other Advanced Trijet with deliveries running between 700 and 800 aircraft through the year 2005.

In summary, the long-range 350 passenger market is made up of:

	MIN. MAX.
Advanced Trijet/Stretch	500-600
Advanced Trijet/Long range	700-800
Total	1200-1400

3.5 Supercommuter Aircraft Projection

Numerous studies of both domestic scheduled airline and commuter operations have been made by various government agencies (NASA, FAA, DOT, etc.) and private industry. The overall concensus of these studies lead to the following conclusions for the post 1985 market (reference 7):

- Total passenger miles has significantly increased
- Majority of passenger miles and greatest frequency of service is for stage lengths of 920 km (500 n.mi.) or less
- Local service market is currently served with aircraft that are too large (i.e., DC-9, B737, B727) to be economically efficient in this market environment

- Deregulation will increase commuter airline demand to provide service for those communities previously served by the local service in regional carriers.

- Opinions regarding aircraft size are diverse with the most commonly mentioned capacities of 20 to 30 seat, 36 to 44 seat, and 40 to 60 seat.

The predictions as to the number of aircraft required for two market segments are also diverse; however, the results of a recent FAA forecast to the year 2000 predicts a worldwide requirement of up to 3000 aircraft with the capacity of 20 to 39 passengers and 1500 aircraft with a capacity of 40 to 60 passengers.

3.6 Market Factors

The projection of aircraft deliveries for the period between 1990 and 2005 indicates a large number of aircraft that can incorporate the advanced aluminum alloys for increased aircraft fuel efficiency. To determine the yearly production capacity required for the advanced alloy types, market factors for the various aircraft types were used. The factors used are presented in table 61. The number of short-medium range and medium range aircraft do not include the projected production run of the B757, B767, and A310 aircraft.

3.7 Material Demand

3.7.1 Airframe manufacturers demand.- An estimate of projected market quantities of advanced aluminum alloy products were determined. The market factors obtained from the various transport and supercommuter aircraft projections were used to arrive at total weight of material in terms of product form required by the airframe manufacture. The projected material demand by product form is presented in table 62. The ATX-350I usage represents over 70 percent of the material demand. Furthermore the plate and extruded product demand for the long-range aircraft each represents approximately 25 percent of the advanced alloy demand.

3.7.2 Aluminum producers demand.- An estimate of both manufactured weight by the aluminum producer and the purchased weight by the manufacturer was made by Alcoa. The estimate was based on information on product form alloy type usage on the projected market for transport, and supercommuter aircraft. The yearly production capacity was obtained assuming 50 percent recovery from billet and the total volume distributed evenly over 15 years from 1990 to 2005.

The estimated yearly capacity of PM billet in tables 63 and 64 amounts to 19×10^6 kg (44×10^6 lb) per year. Existing plans for PM billet capacity are based on smaller numbers; however, with confidence in the demand for such larger estimated capacity, facilities could be established to meet the demand. The primary limitation posed by these estimates will be billet volume. Capital investment in billet production facilities and possibly atomizing facilities

TABLE 61. - MARKET FACTORS FOR TRANSPORT AND SUPERCOMMUTER
(1990 - 2005 Time Period)

MARKET	DESIGNATION	CAPACITY	NO. AIRCRAFT
Super commuter	ATX-50	50	1500
Short-medium range	ATX-100	100	1500
Medium-range	ATX-150	150	950
Long-range	ATX-350I	350	1200

will be required to meet such production. The exact size of such capital investment is not yet determined due to the uncertainty of the estimated volume.

The estimate for the potential low-density, high-strength alloy demands are presented in tables 63 and 65, for transport and supercommuter aircraft usage. These quantities will double if application to general aviation aircraft, military fighter aircraft and air/intermodal containers are included. Costs, however, must be competitive with current IM alloy if these applications are to be realized. Alcoa identified two ingot alloys, advanced 2020 and Al-Li-X, as the most effective on the basis of cost and properties to meet the needs of Alloy C and Alloy E. If the market demands of table 63 arise, substantial capital will be required. It is Alcoa's opinion that such capital investment, however, would be made by the aluminum industry without government funding.

TABLE 62. - MATERIAL DEMAND FOR TRANSPORT AND SUPERCOMMUTER AIRCRAFT
(1990 - 2005 Time Period)

AIRCRAFT DESIGNATION	PRODUCT FORM	MARKET FACTOR	BUY-WEIGHT/AIRCRAFT		TOTAL WEIGHT PROCURED	
			kg	lb	kg x 10^6	lb x 10^6
ATX:350I	Sheet	1200	28 480	62,788	34.176	75.346
	Plate		44 232	97,516	53.078	117.019
	Extrusion		45 045	99,308	54.054	119.170
	Forging		8 207	18,094	9.848	21.713
			125 964	277,706	151.156	333.248
ATX-150*	Sheet	950	7 764	17,118	7.376	16.262
	Plate		8 048	17,740	7.646	16.853
	Extrusion		9 537	21,024	9.060	19.973
	Forging		2 523	5,564	2.397	5.285
			27 872	61,446	26.479	58.373
ATX-100	Sheet	1500	5 176	11,412	7.764	17.118
	Plate		5 365	11,827	8.048	17.740
	Extrusion		6 358	14,016	9.537	21.024
	Forging		1 682	3,709	2.523	5.564
			18 581	40,964	27.872	61.446
ATX-50	Sheet	1500	3 382	7,457	5.073	11.186
	Plate		–	–	–	–
	Extrusion		1 272	2,805	1.908	4.208
	Forging		488	1,076	0.732	1.614
			5 142	11,338	7.713	17.008
TOTAL					213.220	470.075

*ATX-150 : Advanced technology 150 passenger – medium range transport.
Data extrapolated from ATX-100 product form, alloy application and weight data.

TABLE 63. - SUMMARY OF POTENTIAL ADVANCED PM AND IM ALUMINUM ALLOY DEMANDS FOR TRANSPORT AND SUPERCOMMUTER AIRCRAFT
(1990 - 2005 Time Period)

	EXTRUSIONS 15 YR (PER YEAR)		FORGINGS 15 YR (PER YEAR)		PLATE 15 YR (PER YEAR)		SHEET 15 YR (PER YEAR)		ALL PRODUCT FORMS TOTAL 15 YR (PER YEAR)	
	Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6
PM 7XXX Alloy	99.36 (6.62)	219.06 (14.60)	30.98 (2.07)	68.28 (4.55)	10.68 (0.71)	23.54 (1.57)	37.76 (2.52)	96.46 (6.43)	178.78 (11.92)	407.34 (27.16)
PM 2XXX Alloy	–	–	–	–	75.15 (5.01)	165.68 (11.05)	41.54 (2.77)	91.58 (6.11)	116.69 (7.78)	257.26 (17.15)
IM Advanced 2020-T6	49.40 (3.29)	108.88 (7.26)	–	–	51.54 (3.44)	113.60 (7.57)	–	–	100.94 (6.73)	222.48 (14.83)
IM Al-Li-X	–	–	–	–	–	–	22.30 (1.49)	49.16 (3.28)	22.30 (1.49)	49.16 (3.28)

TABLE 64. - POTENTIAL PM 7XXX, 2XXX ALLOY DEMAND
(1990 - 2005 Time Period)

CONFIGURATION	ADVANCED ALUMINUM ALLOY	EXTRUSION		FORGING		PLATE		SHEET	
		Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6
ATX-350I	Alloy A – PM7XXX-T6	24.04	53.00	–	–	–	–	12.24	33.59
ATX-150*		4.68	10.32	–	–	–	–	3.23	7.13
ATX-100		4.93	10.86	–	–	–	–	3.41	7.51
ATX-50		–	–	–	–	–	–	–	–
Total Purchased Weight		33.65	74.18	–	–	–	–	18.88	48.23
Total Manufactured Weight		67.30	148.36	–	–	–	–	37.76	96.46
ATX-350I	Alloy B – PM7XXX-T7	12.36	27.25	9.91	21.84	3.88	8.55	–	–
ATX-150*		1.58	3.49	2.37	5.23	0.71	1.57	–	–
ATX-100		1.66	3.67	2.50	5.51	0.75	1.65	–	–
ATX-50		0.43	0.94	0.71	1.56	–	–	–	–
Total Purchased Weight		16.03	35.35	15.49	34.14	5.34	11.77	–	–
Total Manufactured Weight		32.06	70.70	30.98	68.28	10.68	23.54	–	–
ATX-350I	Alloy D – PM2XXX-T3 Or IM	–	–	–	–	29.74	65.56	13.02	28.71
ATX-150*		–	–	–	–	3.82	8.42	2.67	5.88
ATX-100		–	–	–	–	4.02	8.86	2.81	6.19
ATX-50		–	–	–	–	–	–	2.27	5.01
Total Purchased Weight		–	–	–	–	37.58	82.84	20.77	45.79
Total Manufactured Weight		–	–	–	–	75.16	165.68	41.54	91.58

(1) Producer Manufactured Weight assuming 50 percent recovery

*ATX-150 data extrapolated from ATX-100 product form, alloy application and weight data.

TABLE 65. - POTENTIAL LOW DENSITY, HIGH STRENGTH ALLOY DEMAND
(1990 - 2005 Time Period)

CONFIGURATION	ADVANCED ALUMINUM ALLOY	EXTRUSION		FORGING		PLATE		SHEET	
		Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6	Gg	lb x 10^6
ATX-350I	Alloy C –	17.61	38.82	–	–	19.40	42.76	–	–
ATX-150*	IM Advanced	2.77	6.10	–	–	3.10	6.84	–	–
ATX-100	2020-T6	2.91	6.42	–	–	3.27	7.20	–	–
ATX-50		1.41	3.10	–	–	–	–	–	–
Total Purchased Weight		24.70	54.44	–	–	25.77	56.80	–	–
Total Manufactured Weight		49.40	108.88	–	–	51.54	113.60	–	–
ATX-350I	Alloy E –	–	–	–	–	–	–	5.82	12.83
ATX-150*	IM Al-Li-X	–	–	–	–	–	–	1.48	3.27
ATX-100	Low Density	–	–	–	–	–	–	1.56	3.44
ATX-50		–	–	–	–	–	–	2.29	5.04
Total Purchased Weight		–	–	–	–	–	–	11.15	24.58
Total Manufactured Weight		–	–	–	–	–	–	22.30	49.16

(1) Producer Manufactured Weight assuming 50 percent recovery

*ATX-150 data extrapolated from ATX-100 product form, alloy application and weight data.

4. MATERIAL DEVELOPMENT PLAN

The study results encompassing property goals, product forms, and market factors for advanced aluminum alloy application were reviewed. The results indicated research needs for three alloy systems: (1) PM 7XXX alloy for high-strength and high-strength corrosion-resistant design; (2) PM 2XXX or PM 7XXX alloy for fatigue and damage-tolerant design; and (3) IM Advanced 2020-T6 alloy for low-density, high-strength design. The development plan, presented in figure 61 encompasses (1) alloy and product development, (2) mill and fabrication process development, (3) material design data development and (4) structural design development. This plan identifies the program elements necessary to develop standards, specifications and data for production design application. The plan spans over a five year period at an estimated cost of 150 equivalent person years of effort.

Much of this cost is relegated to the aluminum producer and airframe manufacturer. The development and introduction of new alloys for design application requires a continuous and extensive interaction between the key scientific and technical personnel of both the aluminum producer-alloy research and airframe manufacturer-engineering research organizations. The work is shared and duplication is confined to verification tests. The advanced material data are incorporated into the industry data bank as engineering specifications, standards, design handbooks, stress manuals, etc. Aluminum producer's mill processing needs and airframe builder's manufacturing research needs are identified through research planning and advanced design studies. The aluminum producers development results in new alloys and product forms for production application. Manufacturing standards and specifications are developed and made available for production design applications.

4.1 Alloy and Product Development

4.1.1 Alloy development.- The alloy development activity is a joint airframe manufacturer, aluminum producer, and NASA materials research effort. Alloy selection consists of a review of existing alloy systems and the selection of candidate alloy systems which have the capability of attaining the target goals. The candidate alloys are proposed to be produced in small lot sizes in wrought product form to provide an assessment of their properties and microstructural behavior. Tensile and notch tensile tests, metallographic and fractographic analyses will be performed. Promising compositions will progress to the product development phase. The task description and key milestones are shown in the schedule (figure 62). The cost for the 18-month effort is estimated at 20 equivalent man-years.

4.1.2 Product development.- The product development activity will commence when the powder and billet production of the alloy development task is to the point where the various product forms can be made. The various tasks shown in figure 63, encompasses the effort necessary to: make the sheet, plate extruded, and forged product forms; develop process specifications; and evaluate the various product forms. This includes the preproduction investigations to ensure the alloys can be produced on production equipment. The need

Requires 150 equivalent person-years (EPY's)

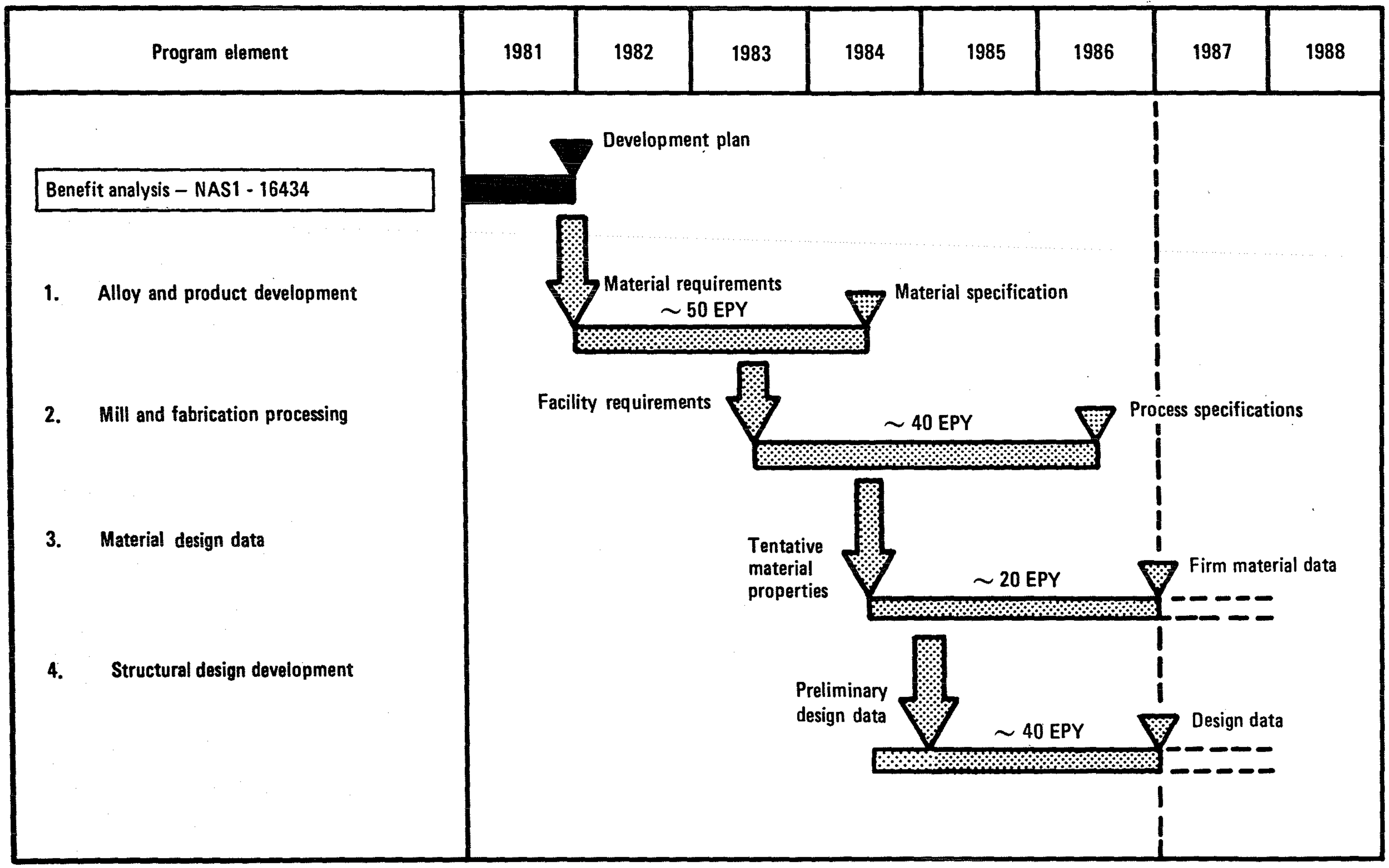


Figure 61. - Advanced aluminum alloy material development plan.

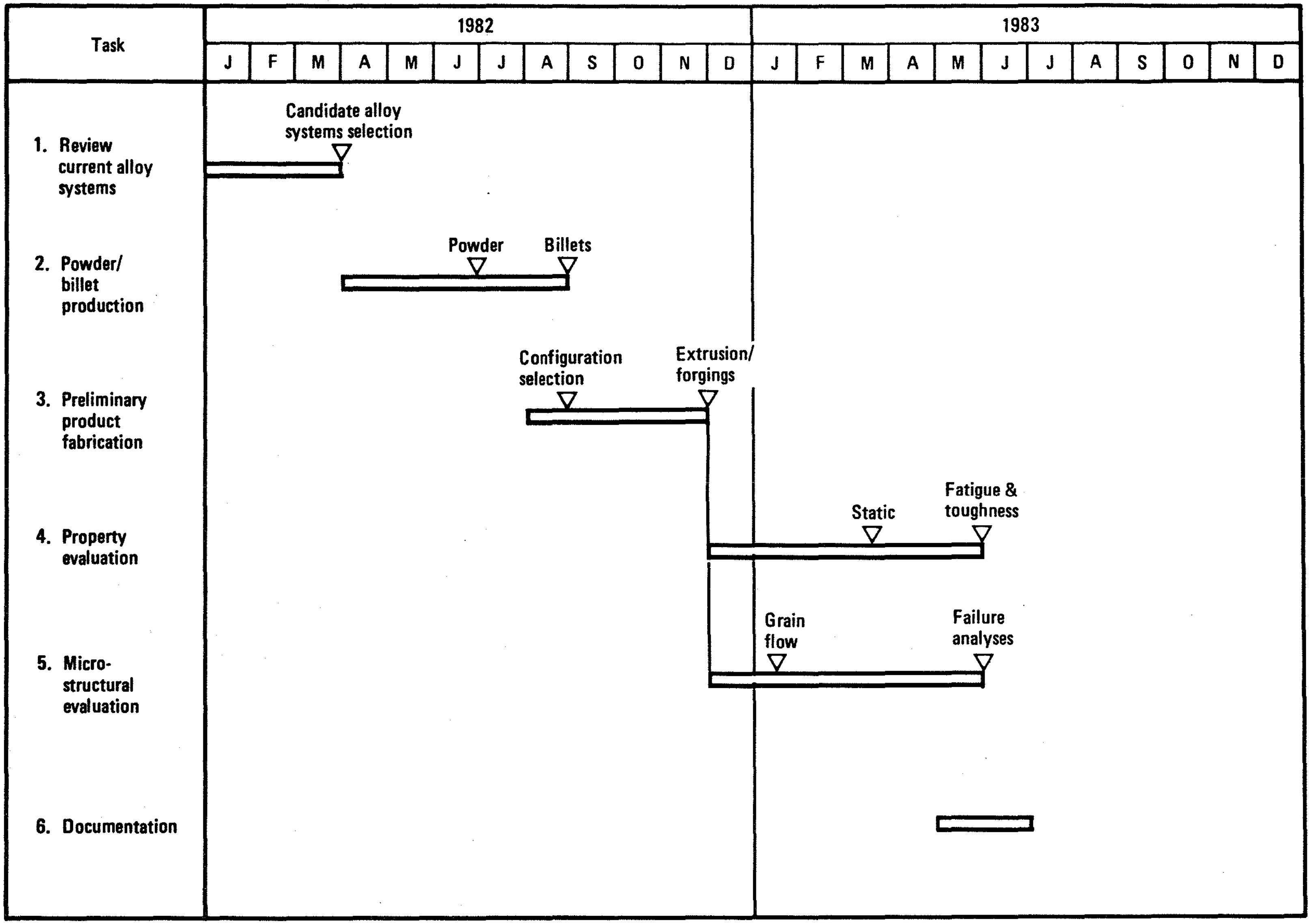


Figure 62. - Advanced aluminum alloy - alloy development.

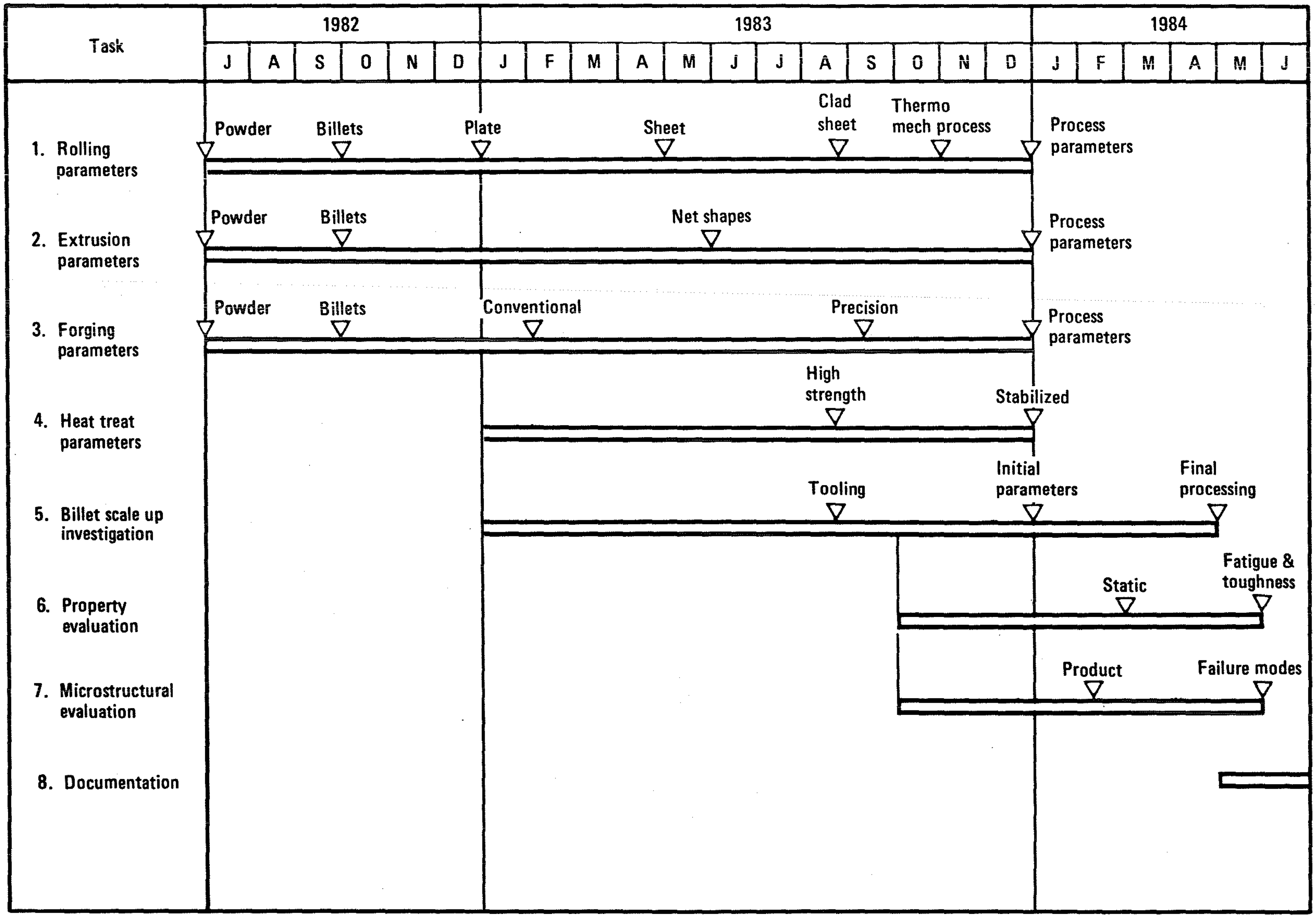


Figure 63. - Advanced aluminum alloy - product development

to pursue sheet and plate products is imperative due to high predicted usage and limited development currently in progress. To support this activity the initial scale-up of billet sizes capable of providing sheet and plate products, large forgings, and heavy extrusions is also included. Process variables and control limits, heat treat, surface finish and preparation will be investigated to develop process specifications.

The largest volume of product form occurs in sheet and plate. Plate and sheet capacity will require development of a PM billet of at least 2700 to 3600 kg (6000 to 8000 lb). Plate and sheet availability is targeted by Alcoa for a 1985 to 1986 time table, which is in approximate agreement with the development plan.

A joint aluminum producer, airframe manufacturer, and government participation is anticipated. Major cost of the planned 24-month effort will be incurred by the aluminum producer ($>$ 20 equivalent man-years). The extent and amount of funding is still being determined. A recommendation will be forthcoming in about 6 months. The airframer and government development testing and evaluation effort is estimated at 10 equivalent man-years.

4.2 Mill and Fabrication Processing

4.2.1 Mill processing development.- The mill processing development task will include the production of large billets capable of producing mill lots of sheet, plate, extrusions and forgings, as shown in figure 64. The initial processing of mill products will be in sufficient quantity to ensure reproducibility. Quality assurance testing, including nondestructive testing, mechanical property testing and micro-evaluation will be performed on mill products.

The 30-month task is heavily oriented toward aluminum producer activity ($>$ 20 equivalent man-years.) The extent and amount of funding required by the producers is being determined. The airframer and government development testing and evaluation effort is estimated at 10 equivalent man-years.

4.2.2 Fabrication processing development.- The fabrication process development effort, shown in figure 65, will evaluate the more common fabrication practices, i.e., hole drilling, bending, stretch forming, joggling, etc., required for aircraft manufacturer. All product forms will be evaluated and compared to current ingot alloy product behavior. Both preproduction and production products will be used to accelerate the fabrication behavior results.

The 30-month effort is primarily an airframe manufacturer activity with government participation in the processing and analysis efforts. An effort of 10 equivalent man-years is estimated.

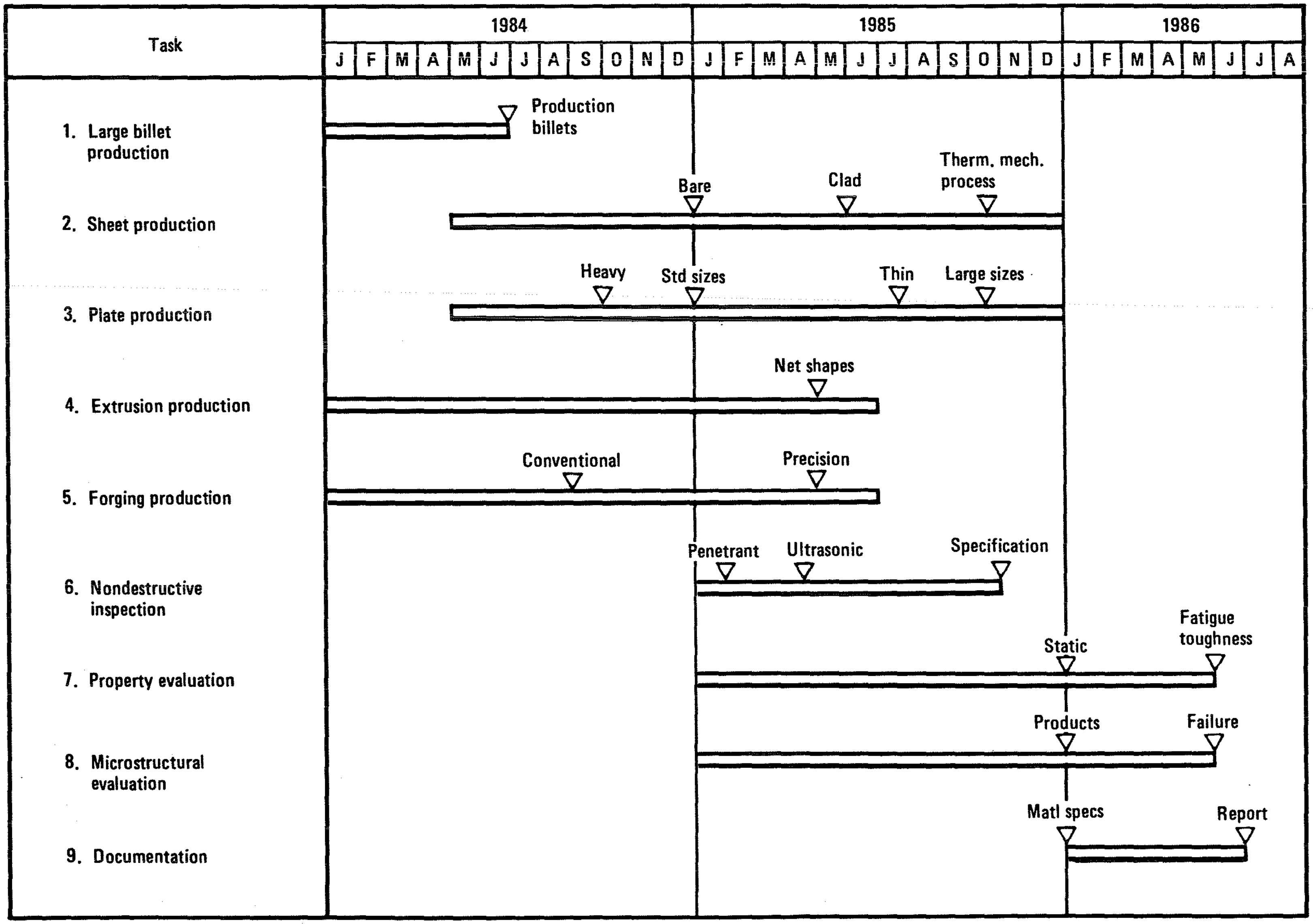


Figure 64. - Advanced aluminum alloy - mill processing development.

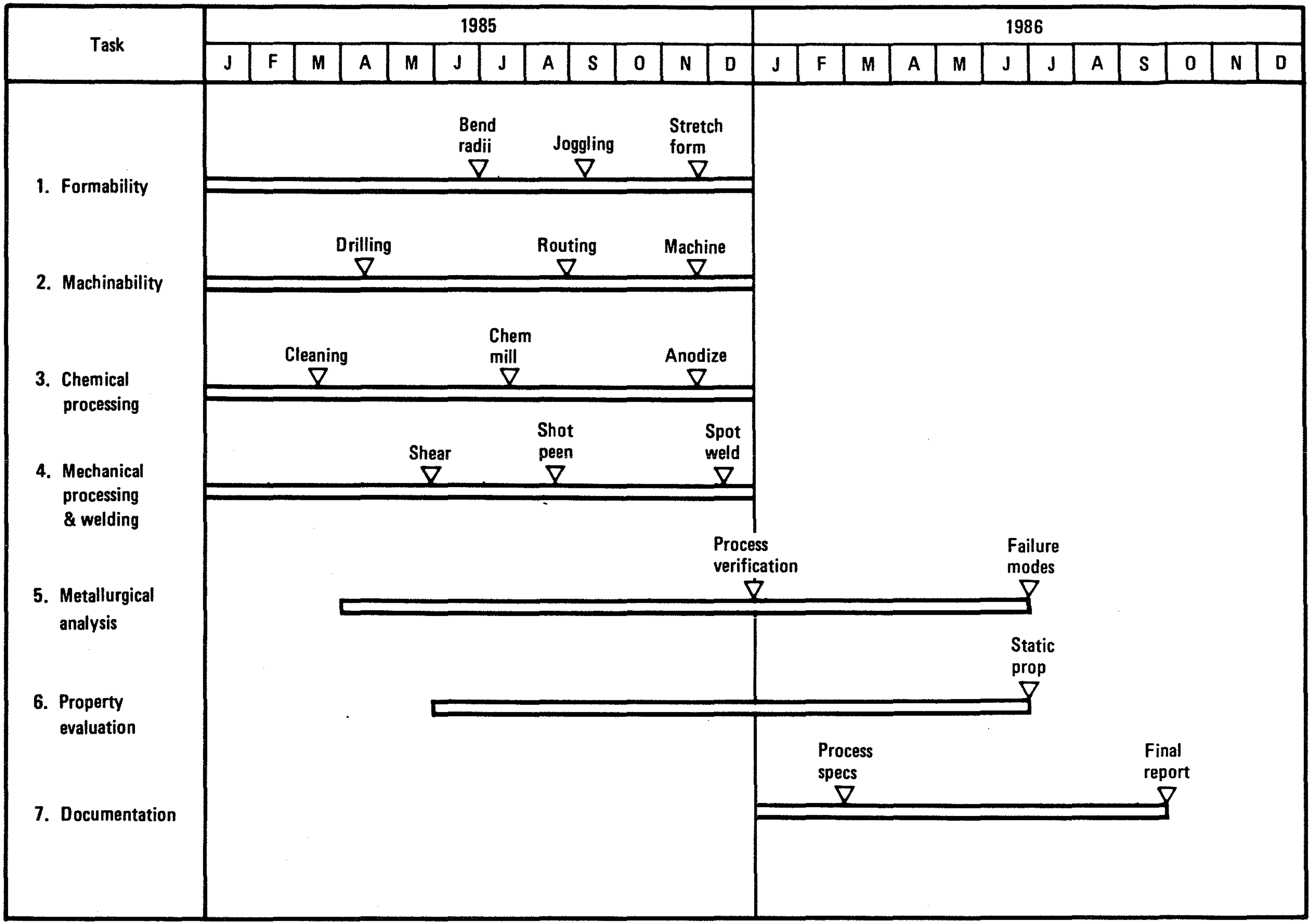


Figure 65. - Advanced aluminum alloy - fabrication processing development.

4.3 Material Design Data

4.3.1 Material properties.- Material design data will be obtained from comprehensive evaluation of mill products to establish a base for MIL-HDBK-5 allowables as shown in figure 66. Static, fatigue, and fracture behavior of all products will be evaluated. Availability of preliminary design allowables is targeted for early 1985 to provide design data for structural element and small structural component design, test and evaluation.

Static properties will be developed from appropriate test coupon configurations for each product form, heat treat, and significant test direction. Design data encompasses: ultimate tensile strength (F_{tu}), tensile yield strength (F_{ty}), compressive yield strength (F_{cy}), ultimate shear strength (F_{su}), ultimate bearing strength (F_{bru}), elongation (e), modules of elasticity (E), compressive modulus of elasticity (E_c), full range stress-strain data, tangent modulus of elasticity (E_T) and Ramberg-Osgood parameter. Both constant-life and stress-lifetime (S-N) data will be obtained for fatigue property evaluation. A minimum of three S-N curves will be developed, each for different stress-ratio. These data will be used to determine constant-life curves. Fracture toughness evaluation will be conducted to obtain stress intensity-thickness data over a full thickness range. Plane-stress, plane-strain and the transitional stress state will be included.

Fatigue crack growth tests will be performed to verify the predicted improvements in crack growth resistance for the new alloys using the specimen geometry specified for the fracture toughness test specimens. Crack growth tests will be performed over a range of effective crack length to test specimen width ratio (a/w) parameters. Stress intensities will be computed and crack growth (da/dN) versus stress intensity (K) data will be obtained.

Selected test specimens from several of the test groups will be metallurgically prepared to verify grain orientation, general microstructure, micrograin structure, gain size, etc., as appropriate. Selected test specimens will be examined by scanning electron microscope (SEM) fractography to characterize fracture surfaces. Comparisons will be made with existing data on IM products.

The 30-month effort will be performed by the airframe manufacturer, certified testing laboratories, and government testing facilities. The estimated cost for this effort is 15 equivalent man-years. Additional resources of approximately 5 equivalent man-years are required to obtain A-basis MIL-HDBK-5 data.

4.4 Structural Design Development

An experimental program is proposed to be conducted over a 30-month period to verify the material property data of the new alloys as shown in figure 67. Structural element and small component tests will be performed to establish a data base for detail design.

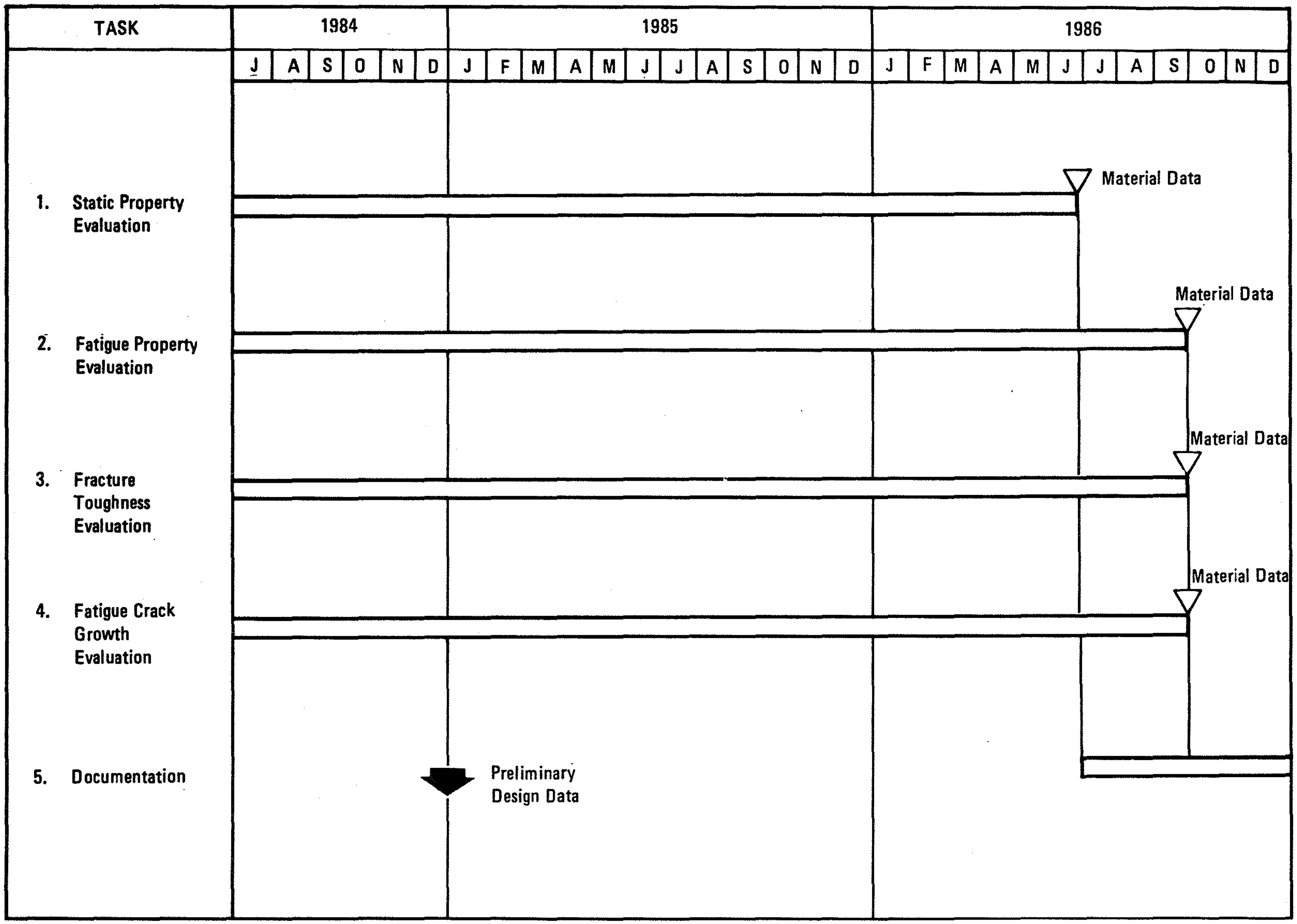


Figure 66. - Advanced aluminum alloy - material design data development.

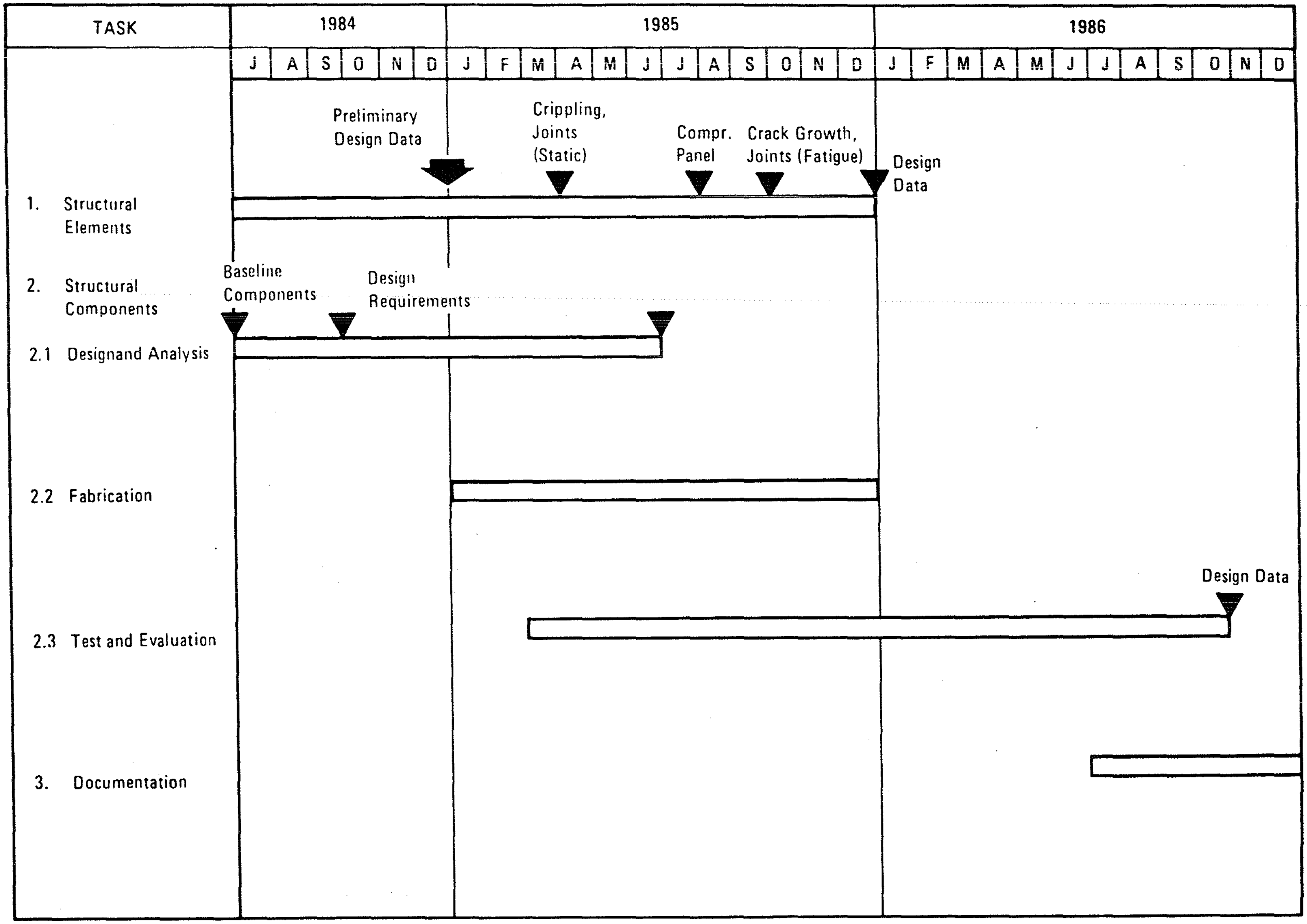


Figure 67. - Advanced aluminum alloy - structural element and component design development.

4.4.1 Structural element development.- A building-block approach is proposed to develop structural element data necessary for detail design of primary airframe structure. Basic tests will encompass: single and multiple element crippling, column buckling, shear buckling, bending and tension; compression panel static, spectrum fatigue, and crack growth; and joint configuration ranging from thin sheet fuselage configurations to more complex and heavily loaded wing joint arrangements. The estimated cost for the 18-month structural element development is 5 equivalent man-years.

4.4.2 Structural components development.- Design analysis, fabrication, test, and evaluation of generic structural components are proposed. Baseline components and design requirements will be established to measure improvement in material performance. Design analyses are proposed using the baseline aluminum alloys and advanced PM or IM aluminum alloys designed to the same criteria. The baseline components will be fabricated using both baseline and selected alloys. Static, fatigue, fail-safe, and residual-strength tests will be performed. The baseline components will encompass:

- Curved fuselage shell,
- Fuselage longitudinal splice,
- Fuselage girth splice,
- Wing upper surface,
- Wing lower surface,
- Wing upper surface with cutout,
- Wing lower surface with cutout,
- Multibay lower surface.

The 30-month design, fabrication, and test effort will be a multidisciplinary effort involving engineering, manufacturing, and quality assurance personnel. The estimated cost for this effort is 35 equivalent man-years.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

There are significant benefits in commercial transport and supercommuter aircraft performance and economics available by development and future incorporation of advanced PM and IM aluminum alloys. Of particular interest is the potential reduction in airframe weight and operational cost to the airline operator. At a fuel price of \$264/m^3 (\$1/gal), the operational cost reduction is approximately one-million dollars per year for a long range transport aircraft. At a fuel price of \$528/m^3 (\$2/gal), the annual operational cost saving is 60 percent greater.

To introduce a new aircraft into service in 1990, the production program must be initiated in the mid-1980s. The advanced aluminum alloy and applications development must be systematically carried out prior to that commitment date.

- Anticipated improvements in material properties used for this study have not been achieved to date; however, current data and trends indicate the properties are reasonable goals.

- Sheet and plate product comprise the largest weight percentage of advanced transport aircraft and currently the PM baseline information for the products shows insufficient data and product availability.

- Fatigue crack growth resistance is currently a significant problem with PM alloys and this factor has an impact on damage tolerant design requirements.

- The low density Al-Li ingot alloys are under aluminum industry development and will not likely require government support. Capital investment in ingot casting facilities and casting technology will be made by the industry without government funding.

The market factor used to project total material demand contributes significantly to determining capital investment by the aluminum producers. Therefore, in order to plan for capital investment, careful analysis of future market needs are of utmost importance.

5.2 Recommendations

In consideration of the current uncertainties concerning the timing, funding and certain technical issues related to PM alloys, early initiation of the following critical and long lead time efforts are recommended.

- Improved toughness aluminum alloys are required for aerospace application. The property improvements of PM alloys demonstrated to date show a lack of improvement in fatigue crack growth resistance. This property is of paramount importance in damage tolerant design. Early efforts are recommended to review current alloy development and initiate activities to support the development of candidate alloy systems. If current activities directed towards achieving this improvement necessitates change in alloy chemistries and/or microstructure additional alloy development time and funds will be required to support the activity.

- Sheet and plate PM products make up a significant portion of the product form needs of future transport aircraft construction. Limited development is currently in progress. It is imperative that efforts be initiated for the development of (1) large, 2350 to 3150 kg (6000 to 8000 lb) PM compacts and (2) sheet and plate PM products. The latter effort should progress as soon as practicable in conjunction with large compact development.

Government funding is required to support these alloy and product development activities.

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15. Supplementary Notes

Final Report
Langley Technical Representative: D. L. Clemmons, Jr.

16. Abstract

A study was performed to quantify the potential benefits of utilizing advanced aluminum alloys in commercial transport aircraft and to define the effort necessary to develop fully the alloys to a viable commercial production capability. The comprehensive investigation (1) established realistic advanced aluminum alloy property goals to maximize aircraft systems effectiveness (2) identified performance and economic benefits of incorporating the advanced alloy in future advanced technology commercial aircraft designs (3) provided a recommended plan for development and integration of the alloys into commercial aircraft production (4) provided an indication of the timing and investigation required by the metal producing industry to support the projected market and (5) evaluate application of advanced aluminum alloys to other aerospace and transit systems as a secondary objective. The results of the investigation provided a roadmap and identified key issues requiring attention in an advanced aluminum alloy and applications technology development program.

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