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ADVANCED SUBSONIC AIRPLANE DESIGN & ECONOMIC STUDIES

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PREFACE

This report was prepared by McDonnell Douglas Corporation for NASA Lewis Research Center under Propulsion/Airframe Integration Technology (PAIT) contract NAS3-25965 Task Assignment 9. The NASA technical monitors were Joseph D. Eisenberg and Felix R. Torres. The McDonnell Douglas Program Manager for this task was Robert H. Liebeck and the McDonell Douglas PAIT Program Manager was James G. McComb. The editor of this report was Raquel Girvin. The members of the McDonnell Douglas team that participated in this task order and deserve recognition for their contributions are as follows:

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I. INTRODUCTION

The purpose of this study is to examine the effect of advanced technology engines on the performance of subsonic transport airplanes and provide a vision of the potential which these advanced engines offer. The year 2005 has been set as the entry-into-service (EIS) date for the engine/airframe combination. A set of four transport airplane classes (passenger and design range) that are envisioned to span the needs for the 2005 EIS period have been defined. This problem could be approached utilizing existing airframes with advanced technology engines, however, since the origin of some the existing (and currently produced) airframes dates back more than two decades, a consistent framework for evaluation becomes difficult. Consequently, 2005 EIS advanced technology airframes have been designed and sized for all classes.

Two airplanes have been designed and sized for each class: one using current technology (1995) engines to provide a baseline, and one using advanced technology (2005 EIS) engines. The resulting engine/airframe combinations have then been compared and evaluated on the basis of sensitivity to the basic engine performance parameters (e.g. SFC and engine weight) as well as DOC+I. Noise and emissions have not been considered in the present study.

Participants in this study include: McDonnell Douglas Aerospace for the design, sizing and evaluation of the airplanes, and the three engine companies; Allison, GE Aircraft Engines, and Pratt and Whitney who have provided the engine data for their current and advanced technology engines. Proprietary considerations preclude the documentation of this study in a single report, and therefore separate appendices have been prepared for each engine company. General discussions pertaining to all airplanes are given in this report.

II. APPROACH

A. Mission Definition

Four airplane design missions have been defined and are summarized in Table 1; the designations SR-150, MR-225, MR-275, and LR-600 are used in these reports to refer to these four airplane types respectively. These were selected to represent the complete spectrum of subsonic transport requirements envisioned for the year 2005 and beyond. Commuter missions have not been considered in this study. To claim that these missions accurately and precisely define air transportation's needs in 2005 would of course be naive, however, they represent the best judgment at this writing.

Of the four missions, the long range (600 passenger, 7500 n.mi.) is the most speculative, particularly with respect to the payload. The 7500 n mi range is regarded as serving all

meaningful city-pair requirements. Very large aircraft (VLA's) are defined as 500 to 1000 passengers, so the choice for this study is somewhat near the lower bound. Increasing the payload would be straightforward, however, the 800-1000 level could begin to deteriorate the accuracy and resolution of existing data bases for weights.

Table 1. Subsonic Airframe/Propulsion Integration
Airplane Design Specifications
2005 EIS

Category	Seats	Rules	Range (N.Mi.)	Cruise Mach No.	ICA (Ft)	VAP (Kts)	TOFL (Ft)
Short Range	150	2 Class Narrow Body	2500	.78	31,000	130	7,000
Medium Range	225	2 Class Twin Aisle	4500	.80	35,000	135	7,500
Medium Range	275	3 Class Interna-tional	6000	.83	35,000	140	9,000
Long Range	600	3 Class Interna-tional	7,500	.85	31,000	150	11,000

B. Airframe Technology Definition

Technology for all airframes is based on a 2005 entry-into-service date. The philosophy used in selecting technology levels was to lean to the optimistic but maintain reality. The resulting airplanes thus show measurable reductions in size and weight over those which would be obtained from simple derivatives of existing airframes. Specific technologies are described below.

1. Aerodynamics

All wing designs are based on advanced supercritical divergent trailing edge airfoils which are highly loaded to minimize wetted area. Selection of a composite wing structure allows a relatively high aspect ratio limit of 11. High-lift system design and performance is based on the technology developed for the MD-12. This utilizes a full-span leading edge slat and a track motion flap system with two segments inboard and a single segment outboard. The system provides high values of C_{Lmax} and L/D for both takeoff and landing configurations.

2. Structure

Advanced composites are used for the entire wing and empennage structure. Fuselage structure utilizes aluminum-lithium longerons with the skins made from GLARE, an aluminum and fiberglass laminate. This combination of materials and structural design yields structural weight reductions.

3. Stability and Control

The Stability & Control terms that strongly affect the aircraft performance are vertical and horizontal tail size, and cruise center-of-gravity (C.G.). The lateral controls affect the available flap span and therefore C_{Lmax}. Further, if the outboard ailerons suffer from aeroelastic reversal, then it is necessary to add inboard ailerons in the stiff mid-span region. Unfortunately, these inboard ailerons also reduce flap area and distort the takeoff and landing spanloads which hurts low-speed L/D. For these reasons the wing structure is sized to preclude aileron reversal in the operational speed range and therefore no inboard aileron is required.

The horizontal tail sizes are based on an advanced high-lift tail with a slotted elevator that can deflect -35^{o} for low-speed takeoff rotation. The slot door is articulated to provide a sealed aerodynamically smooth surface at low elevator deflections. The unaugmented static stability of the airplanes is set to -15%MAC at aft C.G. for the critical V_{FC}/M_{FC} condition where aeroelastic losses are greatest. This static stability level places the C.G. at the Maneuver Point which represents neutral stability from a load-factor standpoint.

The vertical tail is sized for minimum ground control speed (V_{mCG}) on the twin engine airplanes, and two engine-out landing speed (V_{mCL-2}) for the four engine airplanes. In all cases, the all-flying tail concept is used to minimize tail area. This feature requires larger actuators, a pivot shaft, and additional supporting structure, but reduces the tail size by nearly 50% since the fin can be deflected in addition to the rudder.

4. Systems

This arrangement, chosen for the baseline study aircraft, yields weight and complexity reductions, as well as robustness for both the signaling and the power systems.

It should be noted that the secondary power system arrangement chosen for the baseline study aircraft represents the anticipated 2005 EIS technology, which integrates the conventional pneumatic, electrical and hydraulic systems into one electrically powered system. This Power-by-Wire (PBW) system requires only shaft power extraction from the engine. An allowance has been made in this study for other airframe applications which would require engine bleed air, but this has been limited to 1% of the engine core airflow.

This type of secondary power system makes possible the consideration of future very high bypass ratio engines, whose smaller core airflow would not allow the use of conventional bleed air utilization. These PBW secondary power systems are compatible with the present engines used in the study, and therefore provide for a generic evaluation of the results, with respect to engine type versus secondary power system installation. The effect of these newer secondary power systems on weight has not been included in this study.

Table 2 shows the actual anticipated engine extraction expected for each of the study aircraft types.

Table 2. Power Extraction versus Aircraft Type

AIRCRAFT TYPE		POWER EXTRACTION	PER ENGINE
Short Range 150 Passengers	Shaft	225 hp Norm. (167.6 Kva)	281 hp Max. (209.5 Kva)
	Air	1% core flow max;	30 hp
Medium Range 225 Passengers	Shaft	379 hp Norm. (282.7 Kva)	474 hp Max. (353.4 (Kva)
	Air	1% core flow max;	70 hp
Medium Range 275 Passengers	Shaft	394 hp Norm. (293.7 Kva)	492 hp Max. (367.2 Kva)
	Air	1% core flow max;	85 hp
Long Range 600 Passengers	Shaft	559 hp Norm. (416.8 Kva)	698 hp Max. (521.0 Kva)
	Air	1% core flow max;	120 hp

C. Engine Definition

Each of the three engine companies defined their current and advanced technology engines according to each company's design philosophy and technology base. Relative to the current engines, the advanced technology engines incorporate cycle, materials, and turbomachinery efficiency and design improvements. No independent assessment was made on the levels of performance provided by the engine companies for both the current and advanced technology engines.

The three pairs of current and advanced technology engines used in this study are listed below in Table 3. The Allison engines were used for the short-range/150-passenger airplanes, the GE engines were used for the medium-range/225-passenger airplanes, and the P&W engines were used for both the medium-range/275-passenger and long-range/600-passenger airplanes. The short and medium-range airplanes were configured with two engines; the long-range airplanes had four engines.

Table 3. Baseline and Advanced Engine Model Designations

Engine Company	Baseline Engine (1995 EIS)	Advanced Engine (2005 EIS)
Allison	PD577-1A6	PD577-2A5/6
GE Aircraft Engines	Baseline ASTEA	Advanced ASTEA
Pratt & Whitney	PW4484	STS1046

D. Configuration Definition and Rules

A conventional configuration with pylon-mounted wing engines was selected. This arrangement isolates the engine inlets from the airframe so that engine technology changes can be analyzed without airflow complications. Interior accommodations are set using Douglas Aircraft Company (DAC) rules. Flight crew requirements are derived from the FAR Part 121, subpart R, paragraph 121.480.

Once sized, the fuselage is considered a constant, while the engine technology level used will re-size the wing, empennage, landing gear, engine size (thrust), and fuel requirement.

Preliminary un-sized configurations for each of the four missions are presented in Figures 1 through 8, and their corresponding geometric characteristics are given in Tables 4 through 7. All airplanes have aspect ratio 11 wings and all-flying vertical tails. Features of the individual airplanes include:

SR-150: A conventional twin engine configuration. The fuselage has a circular cross section that will accommodate one LD-W container below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 150 seat two class domestic.

MR-225: A conventional twin engine configuration. The fuselage has a near circular cross section and will accommodate two LD-3A (LD-2) containers below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 225 seat two class domestic.

MR-275: A conventional twin engine configuration. The fuselage has a circular cross section and will accommodate two LD-3 containers below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 282 seat (not the target of 275) three class. Economy class seat spacing is slightly greater than specified by Douglas interior rules, and a flight crew rest area is provided due to the long duration of the design flight range.

LR-600: A conventional four engine configuration. The fuselage has a double lobed cross section with seating on both floors; 217 seats on the upper deck and 382 on the lower deck. The upper deck has three class seating with two aisles and the seat count can be substantially increased to approximately 317 with economy only seating. Passenger seating on the lower deck is one class economy with three aisles. A rest area is provided for the crew due to the long duration of the design mission. Provisions to accommodate two LD-3 containers or commercial pallets are below the lower floor forward and aft of the wing box and main landing gear bay. The lower deck can be configured for passengers or cargo. When used for cargo, the floor and cabin area will accommodate two 88 x 108 inch pallets side by side with a height of 8 feet. A visor type nose door is shown on the three view as an option for the lower cargo floor arrangement.

Table 4. SR-150 Aircraft Common Geometric Characteristics

		WING	HORIZONTAL	VERTICAL
ASPECT RATIO		11.00	5.00	1.80
C/4SWEEP ANGLE	DEG	27.00	28.00	30.00
TRAP TAPER		0.28	0.35	0.35
Y SIDE OF BODY	IN	75.00	25.00	0.00
TAIL ARM	IN	N/A	763.63	696.90
VOLUME RATIO		N/A	1.0161	0.0514
DIHERAL ANGLE	DEG	5.00	10.0	0.00
THICKNESS, % CHORD	Average	0.1388	0.10	0.1025
		AIRCRAFT		
OVERALL LENGTH	FT	130.68		

Table 5. MR-225 Aircraft Common Geometric Characteristics

		WING	HORIZONTAL	VERTICAL
ASPECT RATIO		11.00	5.00	1.80
C/4SWEEP ANGLE	DEG	28.00	30.00	35.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	98.09	50.00	0.00
TAIL ARM	IN	N/A	906.00	900.00
VOLUME RATIO		N/A	0.9243	0.0426
DIHERAL ANGLE	DEG	5.00	4.00	0.00
THICKNESS, % CHORD	Average	0.125	0.095	0.11
		AIRCRAFT		
OVERALL LENGTH	FT	163.27		

Table 6. MR-275 Aircraft Common Geometric Characteristics

		WING	HORIZONTAL	VERTICAL
ASPECT RATIO		11.03	5.00	1.80
C/4SWEEP ANGLE	DEG	34.95	35.00	40.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	115.00	50.00	0.00
TAIL ARM	IN	N/A	1045.00	1041.00
VOMUME RATIO		N/A	1.1376	0.0450
DIHERAL ANGLE	DEG	6.00	8.00	0.00
THICKNESS, % CHORD	Average	0.12	0.10	0.10
		AIRCRAFT		
OVERALL LENGTH	FT	195.21		

Table 7. LR-600 Aircraft Common Geometric Characteristics

		WING	HORIZONTAL	VERTICAL
ASPECT RATIO		11.00	4.50	1.80
C/4SWEEP ANGLE	DEG	35.00	35.00	40.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	136.00	84.00	0.00
TAIL ARM	IN	N/A	1382.00	1352.00
VOLUME RATIO		N/A	0.5160	0.0685
DIHERAL ANGLE	DEG	6.00	8.00	0.00
THICKNESS, % CHORD	Average	0.103	0.093	0.10
		AIRCRAFT		
OVERALL LENGTH	FT	244.07		

E. Airplane Sizing and Performance

1. Propulsion model

The airplanes were sized using engine performance data provided by the engine companies for the baseline and advanced engines, either in the form of datapacks or cycle decks. Thrust and fuel flow for a large matrix of flight conditions were extracted from the engine company datapacks or cycle decks and loaded into the McDonnell Douglas airplane sizing program which in turn interpolated and scaled the engine data according to the airplane mission requirements.

2. Weight Estimation Model

MDC's proprietary Conceptual Weight Estimation Program (CWEP) requires inputs such as geometrical parameters, design criteria, and advanced technology multipliers. CWEP uses a series of weight estimating relationships (WERs) and a modified Breguet range equation to develop the initial aircraft sizing parameters, which are then processed by the more sophisticated CASES sizing code. The sizing parameters (shown in Table 8) consist of the partial derivatives of Operational Empty Weight (OEW) with respect to gross weight, wing area, and thrust plus a constant weight. To obtain the final aircraft weight, the CASES wing area, thrust, and gross weight are input to CWEP. The resulting group weight statement is used for cost estimation. Both the sizing derivatives and the group weight statements are shown in the tables at the end of this section.

TABLE 8. Aircraft Sizing Derivatives

$$OEW = W_c + \frac{\partial OEW}{\partial W_g}(W_g - W_{g_o}) + \frac{\partial OEW}{\partial S_w}(S_w - S_{w_o}) + \frac{\partial OEW}{\partial T}(T - T_o)$$

$$W_g = OEW + W_{pl} + W_{fuel}$$

OEW = Operational Empty Weight (lb)

$\frac{\partial OEW}{\partial S_w}$ = Partial derivative of OEW with respect to wing area (lb/ft^2)

$\frac{\partial OEW}{\partial T}$ = Partial derivative of OEW with respect to Thrust (lb / lb)

$\frac{\partial OEW}{\partial W_g}$ = Partial derivative of OEW with respect to MTOGW (lb / lb)

S_w = Wing area (ft^2)

S_{w_o} = Base wing area (ft^2)

T = Thrust per engine, sea level static rated (lbf)

T_o = Base thrust per engine, sea level static rated (lbf)

W_c = Base constant weight (lb)

W_g = Maximum Takeoff Gross Weight (lb)

W_{g_o} = Base Maximum Takeoff Gross Weight (lb)

W_{fuel} = Fuel Weight (lb)

W_{pl} = Payload weight (lb)

Design Criteria

The aircraft's maximum takeoff gross weight (MTOGW) is defined by the requirement to transport the maximum design passenger capacity over the design range. The full complement of passengers and bags at 210 lb each defines the performance payload (WPPL), which is shown in Table 9. The maximum payload (WMPL) reflects the heaviest payload that the aircraft must carry and influences the structural weight. As is typical for commercial aircraft, the configurations for this study are designed for a 2.5 limit load factor and a 10 ft/sec limit landing sink rate.

The SR-150 is designed to provide 8000 feet cabin pressure at 39,000 feet while the other three airplanes provide this pressure at 43,000 feet. This results in a limit differential cabin pressure (PD) of 8.1 for the SR-150 and 8.6 psig for the other aircraft. The maximum speeds in a dive (VD) for the aircraft are also presented in Table 9.

TABLE 9. Design Criteria

CONFIGURATION	WPPL (lb)	RANGE (nm)	WMPL (lb)	PD (psig)	VD (KEAS)
SR-150	31,500	2,500	43,000	8.1	400
MR-225	47,250	4,500	77,000	8.6	410
MR-275	57,750	6,000	100,000	8.6	415
LR-600	126,000	7,500	200,000	8.6	420

Advanced Technology Weight Impacts

CWEP utilizes advanced technology multipliers (ATMs) to reflect the technology level. The ATMs of Table 10 are based on an entry into service date (EIS) of 2005 as referenced to the database of operational aircraft. The structural weight increments of advanced composites in newer operational transports have been factored out in order to normalize the database.

The wing and tail incorporate maximum use of advanced composites, but metallics are assumed for leading edges, aerodynamic surface hinges, and at critical joints. More dramatic weight reductions may be feasible, but commercial transports must emphasize low cost of manufacturing and maintenance. The fuselage uses GLARE skins, Aluminum-Lithium longerons, and advanced composite secondary structure. The landing gear utilizes carbon brakes, radial tires and steel struts with a moderate improvement material properties.

The fixed equipment ATM's are empirically derived trends that reflect numerous weight reductions due to technology improvements, many of which are offset by increased capabilities and improved functionality. The term "fixed equipment" refers to those items whose weight is insensitive to changes in MTOGW and includes furnishings, APU, pneumatics, air conditioning, electrical, instruments and avionics. The weight of fixed equipment items tend to scale with fuselage size. Dividing the sum of actual aircraft fixed equipment weights plus operational item weights by the value estimated by a WER and plotting this versus the EIS date of each aircraft determines the ATM trend versus EIS date. This trend curve, shown in Figure 9, estimates an ATM of 0.918 for a 2005 EIS. However, this factor is not distributed evenly across all of the components.

Table 10. Advanced Technology Multipliers for 2005 EIS

FUNCTIONAL GROUP	ATM	COMMENTS
Wing		
Bending material	0.75	
Spar webs	0.75	
Ribs and bulkheads	0.75	
Aerodynamic surfaces	0.92	
Secondary structure	0.83	
Tail	0.80	
Fuselage	0.95	LR-600 ATM is 0.94
Landing gear	0.91	
Nacelle and Propulsion	NA	By engine manufacturer
Flight controls & Hydraulics	0.95	
APU, Pneumatics, Air Conditioning Electrical, Instruments & Avionics	0.976	
Furnishings & Equipment	0.869	
Operational items	0.976	

Although an EIS 2005 transport may be all-electric, there is scant empirical data on such systems and no reliable rational for identifying related weight increments, therefore none are assumed.

Propulsion System Weights

All engine pod weights are provided by the engine manufacturers. A trend curve of the ratio of pod weight to rated thrust for contemporary turbofans is in Figure 10. The engines used in the present study are not included in the generation of this trend curve.

When adequate detail is provided by the manufacturer, MDC uses a MIL-STD-1374A functional weight reporting format for the propulsion related weights. MIL-STD-1374A allocates the inlet cowl to the Air Induction Group, and the fan cowl doors plus the pylon are charged to the Nacelle Group. The fan exhaust duct, core cowl and nozzle are allocated to the exhaust system, which is part of the Propulsion Group. In some instances, the fan exhaust duct and the thrust reverser weights are reported as an assembly and cannot be separately identified.

MDC estimates the propulsion related items that are external to the pod, such as the engine pylons and the aircraft's fuel system. Lacking detailed engine pylon drawings, all pylons are estimated to weigh 16 % of the pod weight, a value that is typical of the highly cantilevered pylons on modern commercial transport aircraft. All of the PAIT aircraft are assumed to carry fuel in their outer and center wings. With the exception of the SR-150, all configurations are assumed to have a trim tank in their horizontal stabilizer.

3. Aerodynamic model

High Lift System

The high lift system is composed of a slat plus Fowler-motion flap. At takeoff, the slat is sealed, and it is fully open at landing. An "auto-slat" system is utilized to reduce takeoff speed by automatically opening the slats from the sealed takeoff position to the open landing position if stall is approached. This makes available the high C_{Lmax} of the open slat with the high L/D of the sealed slat. The trailing edge system is composed of two spanwise flap segments plus drooped ailerons. Inboard, the flap has two elements with the auxiliary element remaining stowed at takeoff. Midspan and outboard flaps are single element. Maximum flap setting is 30°.

Low speed aerodynamic characteristics were estimated using a combination of flight and wind tunnel test data as well as conceptual handbook methods. Lift and drag data were assembled and trimmed using the MDC CASES aircraft sizing program. All takeoff data and C_{Lmax} were trimmed at the forward CG limit, and all landing data was trimmed at the mid CG position.

Transonic

High speed aerodynamic data were based on a combination of MDC advanced design methodology and empirical data which has been substantiated by wind tunnel tests of advanced technology transport aircraft. Wing design and performance is based on the latest advanced technology supercritical airfoils with divergent trailing edges.

4. Sizing Procedures (CASES)

MDC's proprietary Computer-Aided Sizing and Evaluation System (CASES) was used for the evaluation and optimization of the aircraft in this report. The program is designed to facilitate the sizing of aircraft to meet specific mission requirements for payload, range, takeoff field length, approach speed, initial cruise altitude, and other requirements. The program requires inputs from Aerodynamics, Propulsion, Stability & Control and Weights. The sizing parameters require inputs such as wing area (S_W), TOFL, and thrust. The design optimization is accomplished with interactive plotting routines which provide visual relationships between the geometric variables, design constraints, and optimization criteria used. Figure 11 shows a typical sizing carpet plot created in CASES consisting of a matrix of wing areas (S_W) and thrusts (FN). All points in this plot satisfy the design payload and range requirements. The minimum TOGW configuration that meets the other mission requirements, in this case, approach speed and takeoff field length is then selected as the optimum sized aircraft.

F. Sensitivity Analysis

Sensitivity studies have been conducted to estimate the effect on maximum takeoff gross weight of increases in engine weight and SFC relative to target at entry into service. Both the baseline (1995) and advanced technology (2005 EIS) engined airplanes have been analyzed. Increments of plus 5 percent in engine + pod + pylon weight and SFC have been applied, and the resulting airplanes have then been re-sized to meet the design criteria of Table 1.

G. DOC+I Method and Rules

1. Introduction

This section presents the direct operating cost rules and calculation process used to evaluate and compare the airplane concepts with current-technology and advanced-technology turbofan engines. The economic analysis focus was on the first-level effects of advanced propulsion system technology with respect to airplane performance (block time, block fuel) and airplane economics (DOC for a typical average stage length (ASL)).

The economic criterion used for evaluating and comparing the effect of advanced propulsion systems on airplane design and operation was Direct Operating Cost (DOC). The Air Transportation Association of America, in 1944, published the first universally recognized method for estimating direct operating costs of airplanes. That ATA method was progressively updated through the years with inputs from ATA member airlines and prime airframe and engine manufacturers. The ATA standard method of estimating comparative direct operating costs of turbine powered transport airplanes, last published in December 1967, formed the basis for the method and approach used for this study.

The DOC method used for this study was based on the combination of ground rules and assumptions developed collectively by McDonnell Douglas Corporation (MDC) and its commercial aircraft component, Douglas Aircraft Company (DAC), the Boeing Commercial Airplane Group (BCAG), and NASA's Lewis Research Center (LeRC). The method was referred to as the "DOC+I" method, since the interest cost element was added. In addition, cabin crew costs, landing fees and navigation fees, usually considered to be indirect operating costs by the former Civil Aeronautics Board (CAB), were also added to the original ATA DOC cost element structure. Using DOC+I to describe this method affords a way to discriminate from the basic ATA DOC method.

With the aforementioned additions to the basic ATA DOC method, the DOC+I cost element structure for this study included the following cost elements:

(1) Flight Crew
(2) Cabin Crew
(3) Landing Fees
(4) Navigation Fees
(5) Maintenance - Airframe
(6) Maintenance - Engine
(7) Fuel
(8) Depreciation - Aircraft and Spares
(9) Insurance
(10) Interest

Elements (1) through (7) are commonly referred to as "cash costs"; whereas elements (8) through (10) are referred to as "ownership costs".

For purposes of this study, the terms "DOC" and "DOC+I" may be used interchangeably as they will both mean the same thing.

2. DOC Process

The DOC process shown in Figure 12 is typical of the process used for this study. The block 'standard economic rules sets' includes the ten cost elements just discussed and the specific ground rules and assumptions to calculate each one. The blocks 'Study Parameters' and 'Engineering Data' provide the airplane descriptions for each airplane concept under study, which would include configuration geometry data, design weights, engine description, technology level, and performance data. Airplane study prices, consisting of separate airframe and engine prices, were calculated using parametric methods. Engine company data for each conventional technology and advanced technology engine design were combined with parametrically-determined scaling factors to derive engine study prices for each sized airplane concept. Airplane (airframe and engine) maintenance values were also parametrically determined from DAC's historical database and engine company data for each specific engine concept.

The DOC process is the last part of a generalized aircraft concept study process employed by MDC. Part of that process involves aircraft sizing, which was done using

MDC's internally-developed Computer-Aided Sizing and Evaluation System [CASES] already described in Section II. The CASES results include the design mission configuration, weight, and performance data, as well as the performance data for the economic mission used for DOC evaluation.

3. DOC Groundrules, Assumptions and Element Descriptions

The DOC ground rules and assumptions used for the study are summarized in Table 11. Listed are the various factors for each of the DOC elements, either in narrative or quantitative form. Domestic and international equations are so identified. The DOC values are calculated in mid-1993 dollars.

Following are detailed descriptions of each DOC element. Note that the cost units of any element may differ from one to the next, e.g., $/block hour, $/flight hour, $/trip.

COCKPIT CREW. Based on the aircraft maximum takeoff gross weight [MTOGW].

[Domestic] $/Block Hour = 440 + 0.532*(MTOGW/1000)
[International] $/Block Hour = 482 + 0.590*(MTOGW/1000)

CABIN CREW. Based on the number of seats in the aircraft and a cost-per-block hour rate for each crew member.

[Domestic] $/Block Hour = (Number of Seats/35)*60
[International] $/Block Hour = (Number of Seats/30)*78

LANDING FEE. Based on either the maximum landing gross weight (MLGW) or the maximum take-off gross weight MTOGW.

[Domestic] $/Trip = $1.50 * (MLGW/1000)
[International] $/Trip = $4.25 * (MTOGW/1000)

NAVIGATION FEE. Based on the first 500NM of a trip and the MTOGW, and used only for international DOC cases.

[International] $/Trip = $0.136 * 500NM * (Square Root of MTOGW/1000)

FUEL. Based on the economic mission block fuel, at a density of 6.7 pounds per US gallon, and a price per gallon of either $0.65 (US Domestic) or $0.70 (International).

MAINTENANCE. Total airplane maintenance cost includes the cost of direct maintenance labor, maintenance material, and applied maintenance burden for both the airframe and engines. The airframe direct maintenance labor and maintenance material costs are based on parametric equations developed by the Boeing Commercial Airplane Group (BCAG).

The engine maintenance costs are based on data provided by the engine companies. This data was augmented, where appropriate, by cost data from the McDonnell Douglas Corporation (MDC) commercial transport engine maintenance database. Since the engine company maintenance cost data was for a fixed reference thrust level, the Boeing engine maintenance cost equations were used as general scaling equations based on sea-level static thrust.

Airframe Maintenace Labor [AFLAB]. Based on airframe weight [AFW], defined as manufacturer's empty weight (MEW) less the dry weight of the engines. AFLAB has both a flight-cycle (FC) and a flight-hour (FH) component. The equations produce either maintenance-man-hour-per-flight-cycle (MMH/FC) or maintenance-man-per-flight-hour (MMH/FH) values. Each trip consists of one flight cycle and a variable number of flight hours.

AFLAB:MMH/FH = 1.260+(1.774*AFW/10^5)-.1071*(AFW/10^5)^2
AFLAB:MMH/FC = 1.614+(.7227*AFW/10^5)+.1024*(AFW/10^5)^2
AFLAB:MMH/TRIP = ((MMF/FH)*(FH/TRIP))+MMH/FC

Total maintenance man-hours per trip are converted to direct labor dollars per trip by multiplying by the direct maintenance labor rate ($25/MMH).

Airframe Maintenace Materials [AFMAT]. Same basis as airframe maintenance labor, with both a cyclic and flight-hour component.

AFMAT:$MAT/FH = 12.39+(29.80*AFW/10^5)+.1806*(AFW/10^5)^2
AFMAT:$MAT/FC = 15.20+(97.33*AFW/10^5)-2.862*(AFW/10^5)^2
AFMAT:$MAT/TRIP = (($MAT/FH)*(FH/TRIP))+$MAT/FC

Airframe Applied Maintenance Burden [AAMB]. The airframe maintenance overhead cost is calculated as a function of airframe direct maintenance labor cost.

AAMB = 2.0 * Airframe Direct Labor Cost

All three airframe maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get total airframe maintenance cost.

Engine Maintenance Labor [ENGLAB]. The scaling equation for engine direct maintenance labor is based on the maximum rated uninstalled sea-level static thrust (SLST) per engine, in pounds force (lbf), the flight hours (FH) per trip, and the number of engines per aircraft (NE). In contrast to the airframe, the engine maintenance labor cost is not separated into flight-cycle and flight-hour components.

ENGLAB: MMH/TRIP = ((.645+(.05*SLST/10^4))*(.566+.434/FH)*FH*NE

The engine direct maintenance labor cost is calculated by multiplying the MMH/TRIP by the direct maintenance labor rate ($25/MMH).

Engine Maintenance Material [ENGMAT]. The scaling equation for engine maintenance material cost is based on the same parameters as the engine direct maintenance labor. In contrast to the airframe, the engine maintenance material cost is not separated into flight-cycle and flight-hour components.

ENGMAT: $MAT/TRIP = ((25+(18*SLST/10^4))*((.62+(.38/FH))*FH*NE

Engine Applied Maintenance Burden [EAMB]. The engine maintenance overhead cost is calculated as a function of the engine direct maintenance cost.

EAMB = 2.0 * Engine Direct Maintenance Labor Cost

All three engine maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get the total engine maintenance cost.

Depreciation, interest and insurance are annual costs. Reducing these annual costs to trip costs are accomplished by dividing the annual cost by the number of trips flown per year. As noted in Table 11, the domestic short-range mission of 500 NM will generate 2100 trips/year, and the international missions will generate 625 trips/year at 3000 NM average stage length and 480 trips/year at 4000 NM. .

DEPRECIATION. Depreciation is based on the total airplane (airframe + engines) price and its associated spares price. The airframe and engine spares factors, the depreciation period and the residual value are noted in Table 11.

INTEREST. Most aircraft purchases are financed through the use of long-term debt and a down payment from company funds. To account for the total interest cost to the airline, interest is computed on the total price of the airplane plus spares less the down payment. Although interest payments will decline each year, an average annual interest cost is used in aircraft comparisons to reflect the average effect over the airplane's depreciable life. The interest method assumes a 15-year loan period, two loan payments per year, and equal principle payments. The factors defining the amount financed, the depreciation period, and the interest rate are noted in Table 11.

INSURANCE. The annual hull insurance cost is based on the total airplane price. The insurance rate is 0.35% of the total airplane price.

AIRFRAME AND ENGINE STUDY PRICES. Airframe study price for this study was based on a parametric relationship between airframe study price and a payload-range index or airframe weight. Payload-range index (PRI) was selected as the primary independent variable, since this is the market-driven price. Airframe weight, the secondary independent variable, was also evaluated as an airframe price generator in order to assess the impact of airframe downsizing afforded by advanced engine technology.

However, it should be understood that commercial transport aircraft are not sold on a price-per-pound bases. Its selling price in essence represents a market-based price (without relationship to cost). The commercial product relies on a fixed price based on an end item specification, performance guarantees, service life policies, and warranties. This would apply to airframes as well as to engines.

The airframe payload-range index was determined from a database of US and non-US commercial transports. The airframe prices were derived from MDC's commercial transport database. For all airplanes, a linear regression of airframe price and PRI produced the following airframe study price equations:

Airframe Study Price ($M)	= 16.342 + 0.0462 * PRI	SR-150
	= 45.972 + 0.0239 * PRI	MR-225
	= 43.553 + 0.0282 * PRI	MR-275 and LR-600

A power curve fit of airframe study price versus airframe weight (in pounds, and denoted by AFW) produced the following airframe study price equations:

Airframe Study Price ($M)	= 1.3255 * (AFW/1000) ^ 0.7475	SR-150
	= 0.7822 * (AFW/1000) ^ 0.8937	All other

Engine study prices were developed from MDC's historical database and from engine manufacturer's data. These engine prices represent only the bare engine, as the remainder of the propulsion system price is assumed to be part of the airframe price (e.g., nacelles and thrust reversers). This is in keeping with the original ATA DOC methodology. The parametric trend of engine price vs. engine thrust (i.e., engine price scaling) was derived from the MDC database for current-technology engines, and was segregated into two engine classes: 15,000 to 40,000 lbf for the SR-150, and 50,000 to 90,000 lbf for the larger twin-aisle concepts. This parametric trend was calibrated to the bare-engine price, and used to generate the engine study price for the sized, current-technology engine. The advanced-technology engines were usually priced higher than the current-technology engines for the same thrust level, based on engine company information. The engine study price equations are in log-linear format and are based on uninstalled maximum sea-level static thrust, dimensioned in pounds-force. The engine price dimension is millions of dollars per engine. The characteristics of the engine price equations take on the form y=ax^b where x is thrust.

Table 11. DOC+I Ground Rules And Assumptions

Item	Parameter
DOC+I Basis	SR-150: US domestic rules All other: International rules
Design Mission/Economic Mission (NM)	SR-150: 2500/500 MR-225: 4500/3000 MR-275: 6000/3000 LR-600: 7500/4000
Utilization (trips per year)	SR-150: 2100 MR-225: 625 MR-275: 625 LR-600: 480
Dollar Year	1993
Fuel Price (per US gallon)	SR-150: $0.65 All other: $0.70
Maintenance Labor Rate	$25.00 per man-hour
Maintenance Burden Rate	200% of direct labor
Number of Cockpit Crew	2
Number of Cabin Crew	SR-150: 1 per 35 seats All other: 1 per 30 seats
Landing Fees	SR-150: Function of MLGW All other: Function of MTOGW
Navigation Fees	SR-150: None All other: Function of MTOGW, first 500 NM
Hull Insurance Rate	0.35% of airplane price
Depreciation:Period	15 Years
Depreciation:Residual Value	10% of price (Including spares)
Investment Spares:Airframe	6% of airframe price
Investment Spares:Engine	23% of engine price
Interest:Amount Financed	100% of aircraft & spares
Interest:Period	15 Years
Interest:Rate	8%

III. RESULTS

Specific final results for each of the engine companies are given in the respective appendix reports. The advanced technology engines provided significant reductions in fuel burn, weight and wing area for all four airplanes. Average values are as follows:

percent reduction in fuel burn = 18%
percent reduction in wing area = 7%
percent reduction in TOGW = 9%

This resulted in an average DOC+I reduction of 3.5% and 5%, using the payload-range-index-based and the airframe-weight based pricing models respectively. The DOC+I results varied, depending on the particular airframe and engine price model employed, as well as on the level of performance assumed for the baseline engine.

In all cases, increasing SFC by 5% had a greater impact on aircraft size than increasing engine pod weight by 5%. This is because engine pod weight is a relatively small fraction of takeoff gross weight. The sensitivity of aircraft size to both SFC and engine weight increased with mission range requirement.

IV. SUMMARY

A study to examine the sole effect of advanced technology engines on the performance and DOC+I of subsonic transport airplanes has been completed. Four airplane design missions were studied, in which two airplanes were designed and sized for each: one using current technology (1995) engines as a baseline, and one using advanced technology (2005) engines. All other aircraft-related technologies were kept constant. The year 2005 was selected as the entry-into-service date for the airframe/engine combinations.

The advanced technology engines provided significant reductions in fuel burn, weight and wing area for all four airplane classes. Average values are as follows:

percent reduction in fuel burn = 18%
percent reduction in wing area = 7%
percent reduction in TOGW = 9%

This resulted in an average DOC+I reduction of 3.5% and 5%, using the payload-range-index-based and the airframe-weight based pricing models respectively. The DOC+I results varied, depending on the particular airframe and engine price model employed, as well as on the level of performance assumed for the baseline engine.

It is recommended that the results of this study be viewed from more than a single perspective: the physical characteristics of the airplanes themselves (TOGW, OEW, Sw, Fn, etc.), and the corresponding DOC+I figures. The economic analyses have been defined in two forms: 1. airframe cost based on the mission (number of passengers and range), which results in the airframe cost being invariant between the current and advanced technology airplanes, and 2. airframe cost varying with airframe weight. The first method forces the DOC+I increment between the current and advanced technology airplanes to become dependent solely on engine price, maintenance cost, and fuel burn. No specific reward is offered for the reduction in airplane size and weight provided by the advanced technology powerplants. Alternatively, the second method provides a more direct reward for the advanced technology in both engines and airframe. These two economic algorithms may be regarded as bounding the problem, and the true economic benefit probably lies somewhere in between their DOC+I predictions.

Finally, it should be understood that the scope of the present study did not allow for an optimization of the matching of engines to the airplanes and the design mission. A careful iterative analysis should yield an increase in the performance benefits offered by the advanced technology engines.

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.

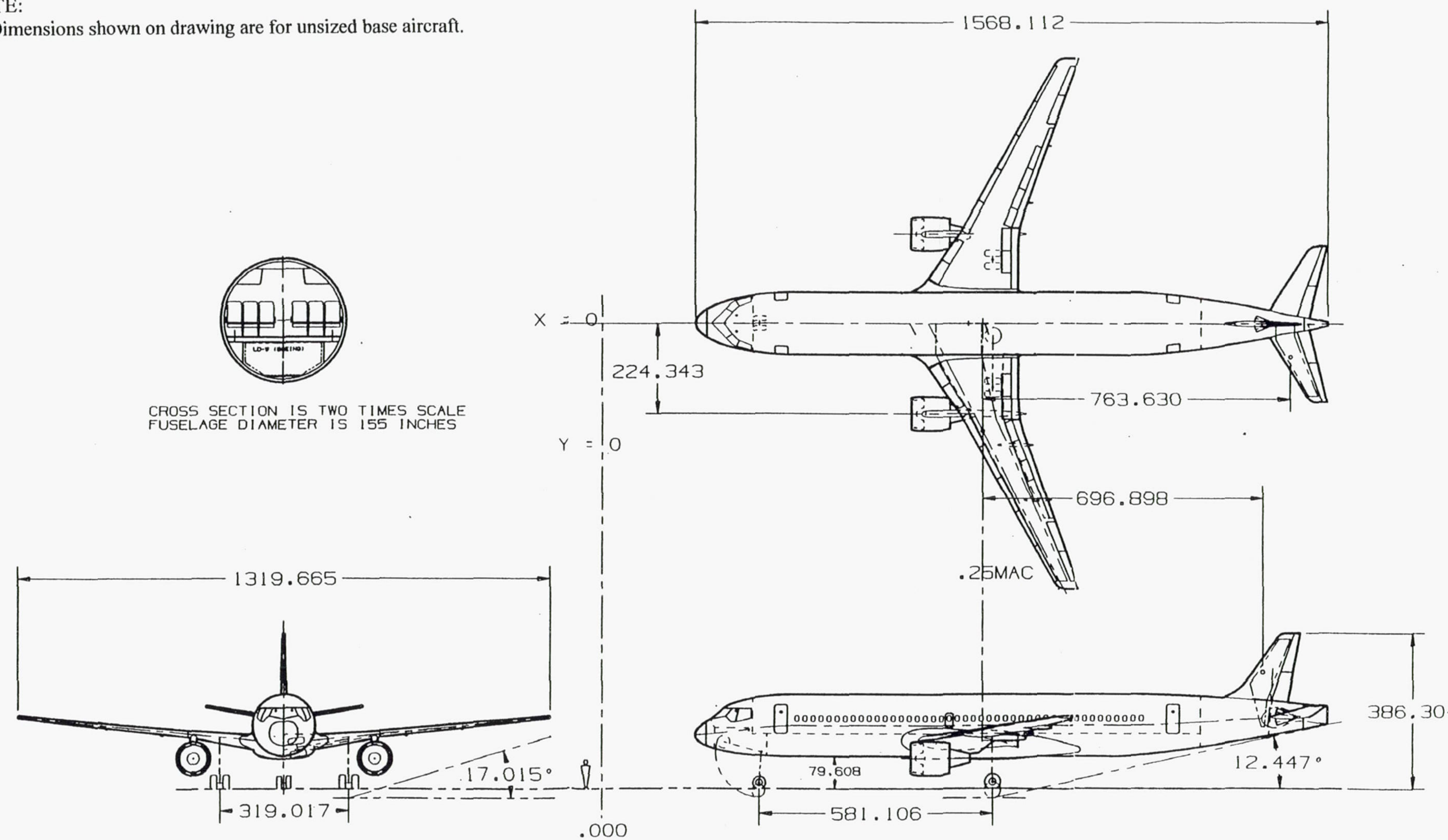

Figure 1. General Arrangement - SR-150

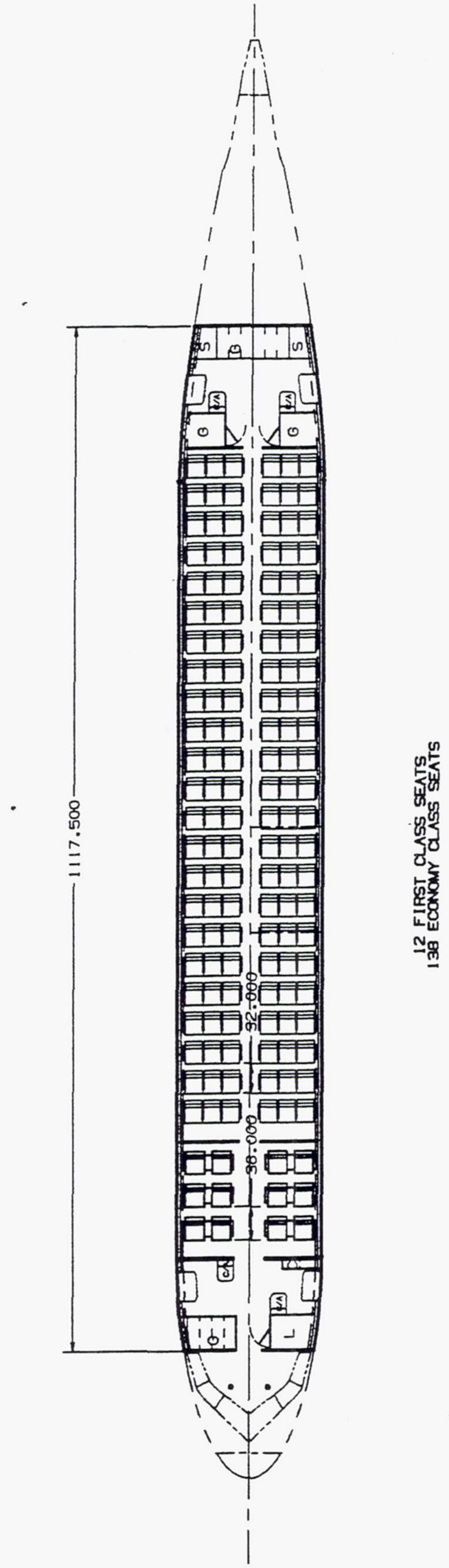

Figure 2. Interior Arrangement - SR-150

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.

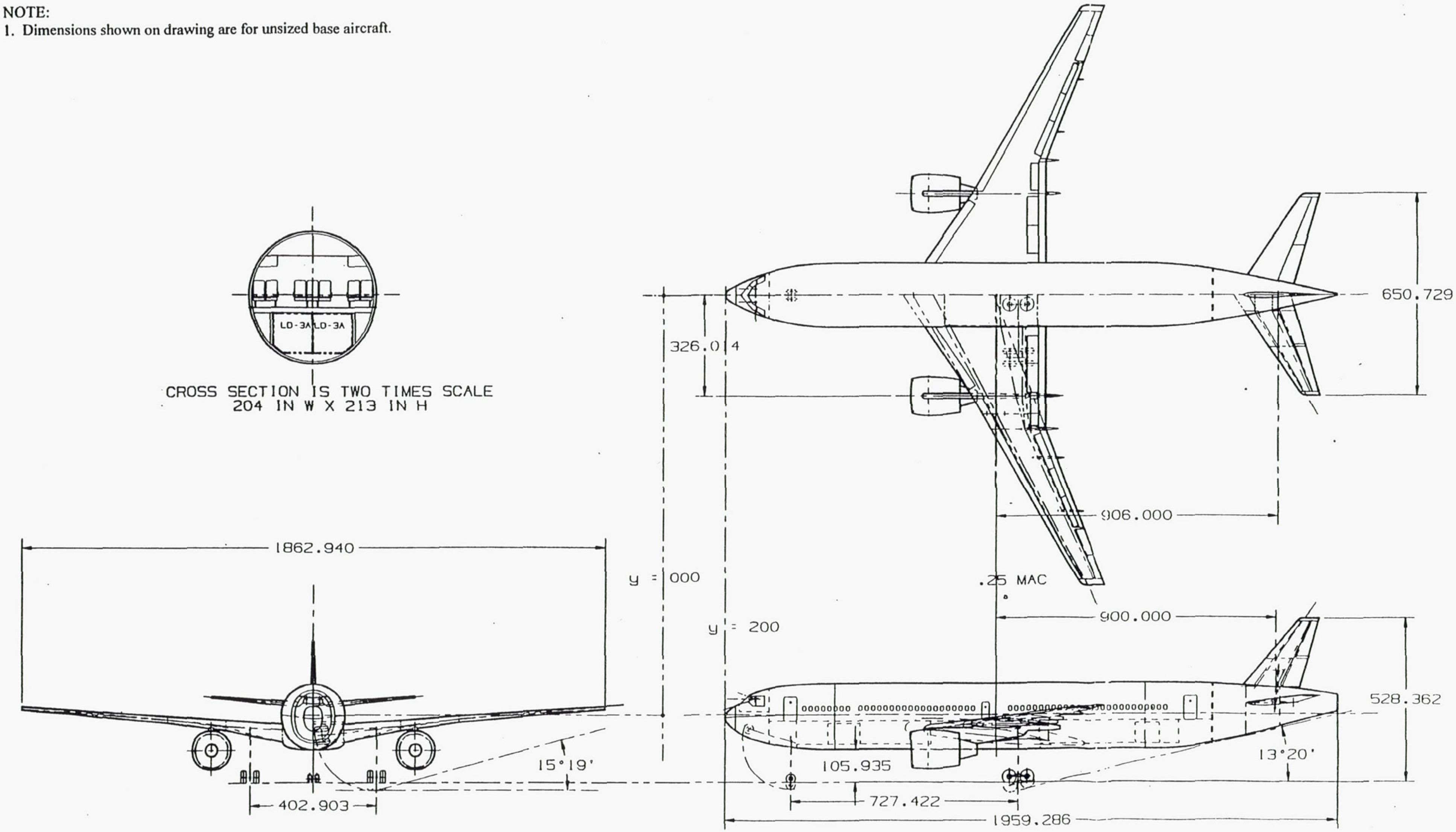

Figure 3. General Arrangement - MR-225

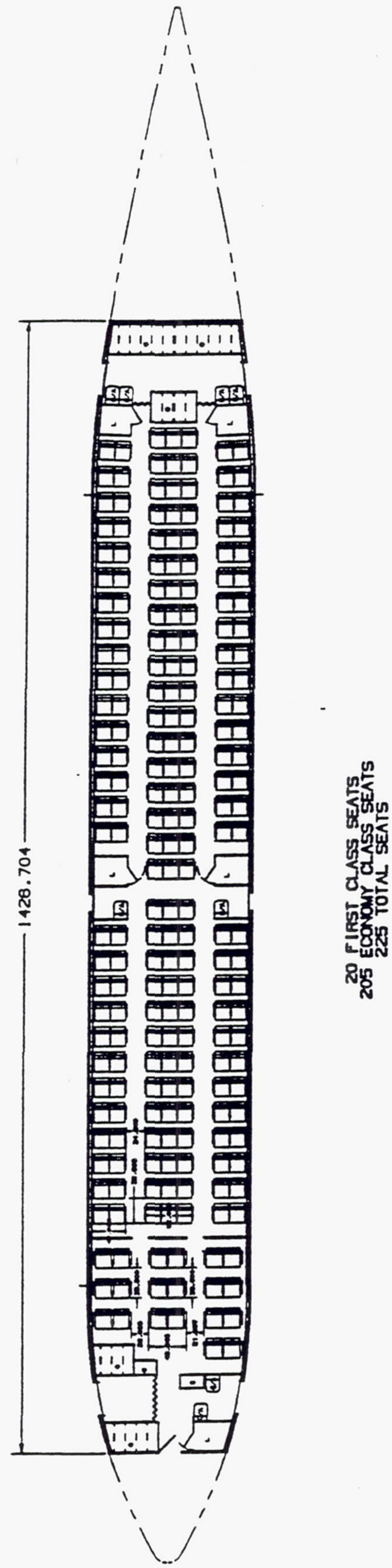

Figure 4. Interior Arrangement - MR-225

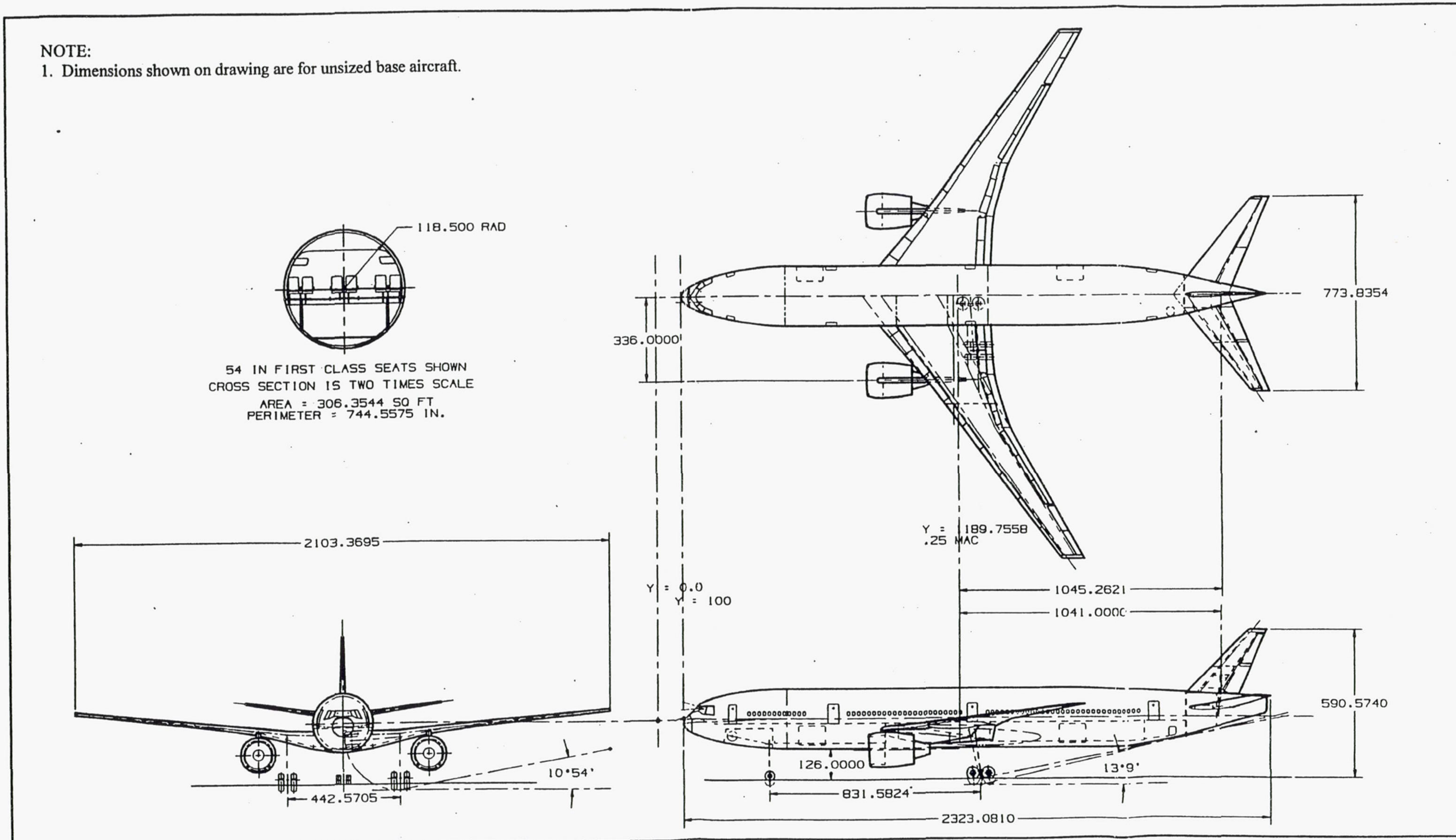

Figure 5. General Arrangement - MR-275

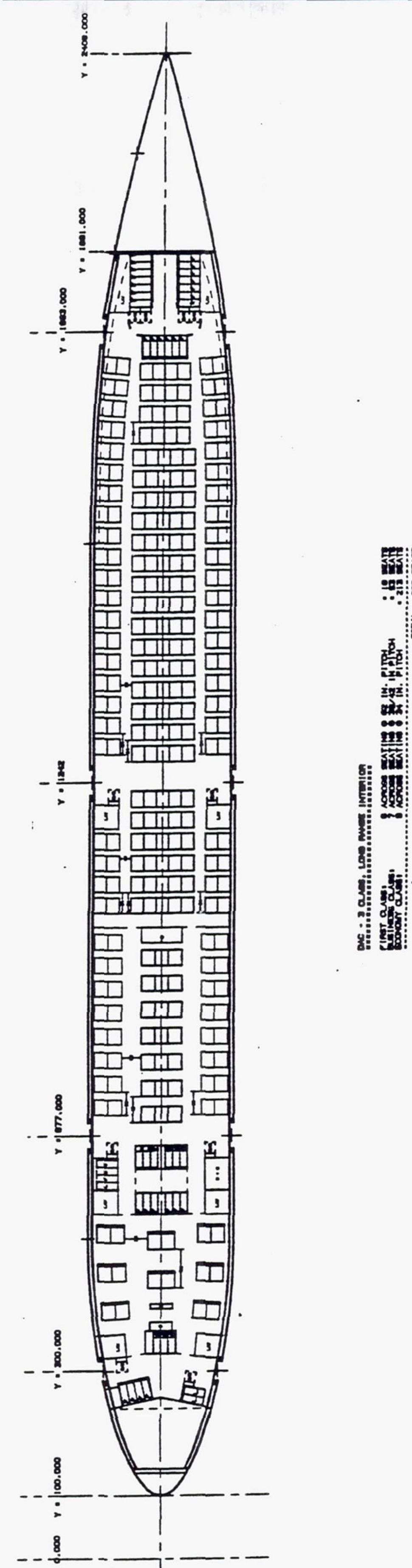

Figure 6. Interior Arrangement - MR-275

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.

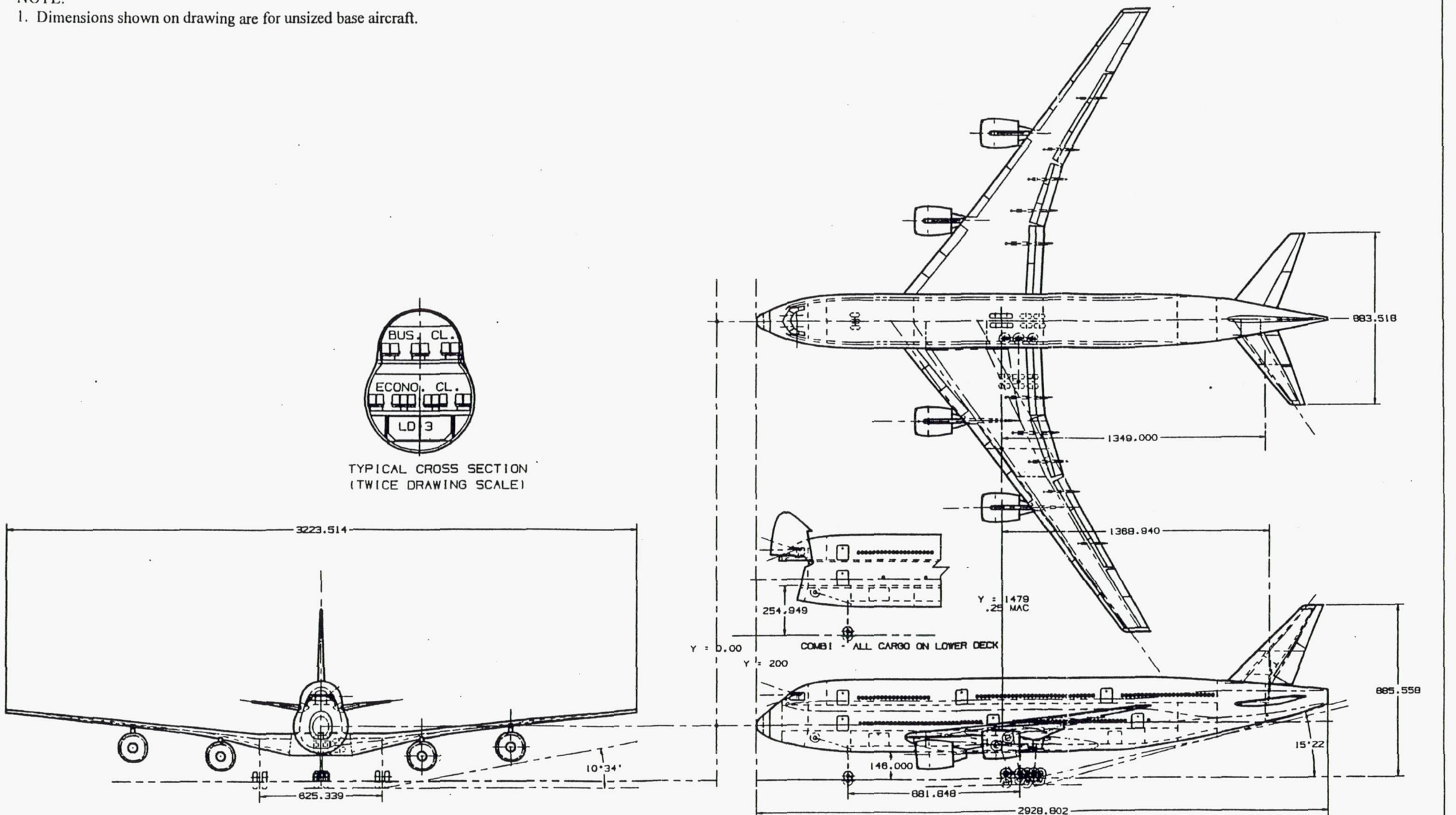

Figure 7. General Arrangement - LR-600

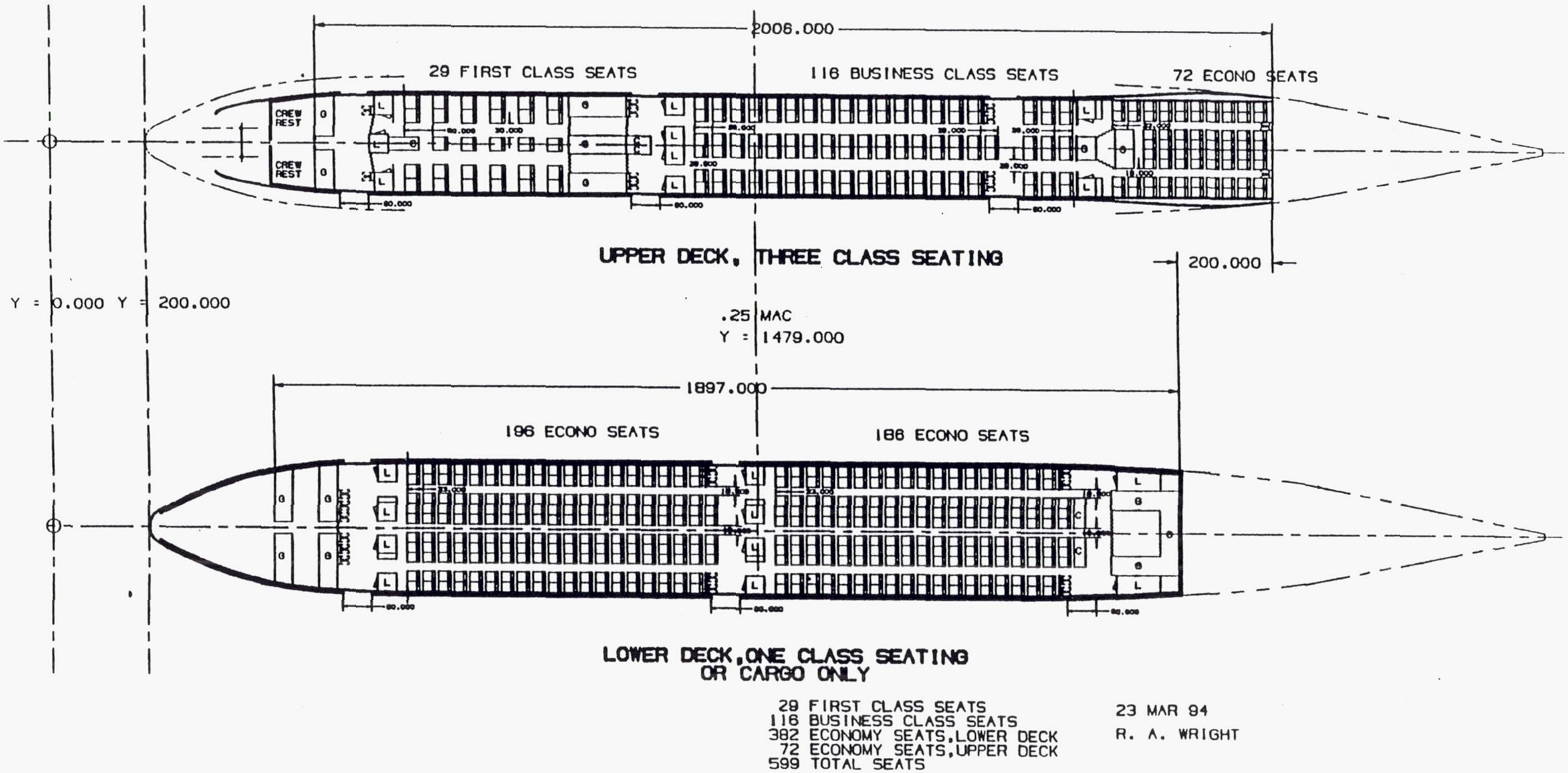

Figure 8. Interior Arrangement - LR-600

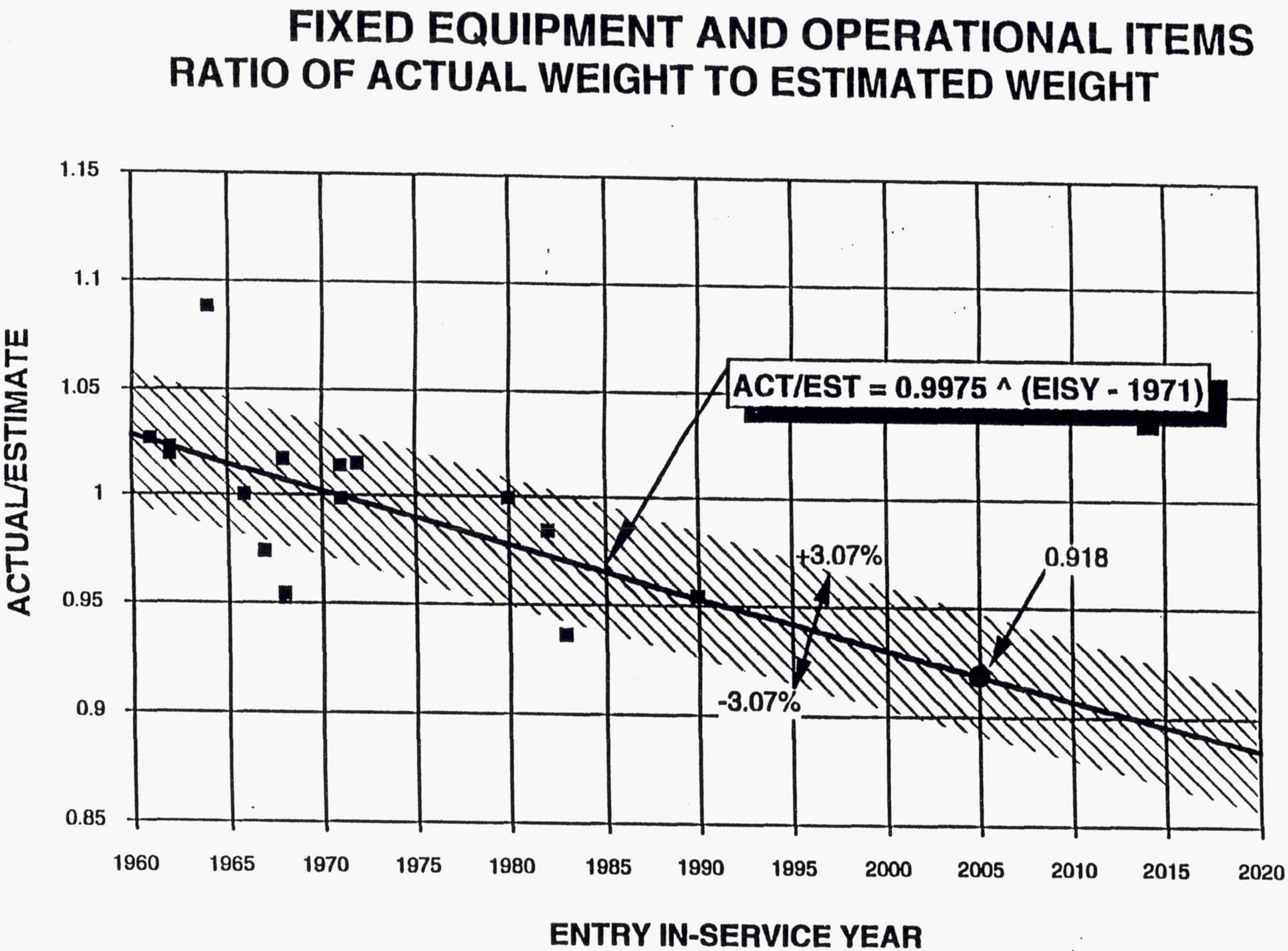

Figure 9. Fixed Equipment and Operational Items Ratio of Actual Weight to Estimated Weights

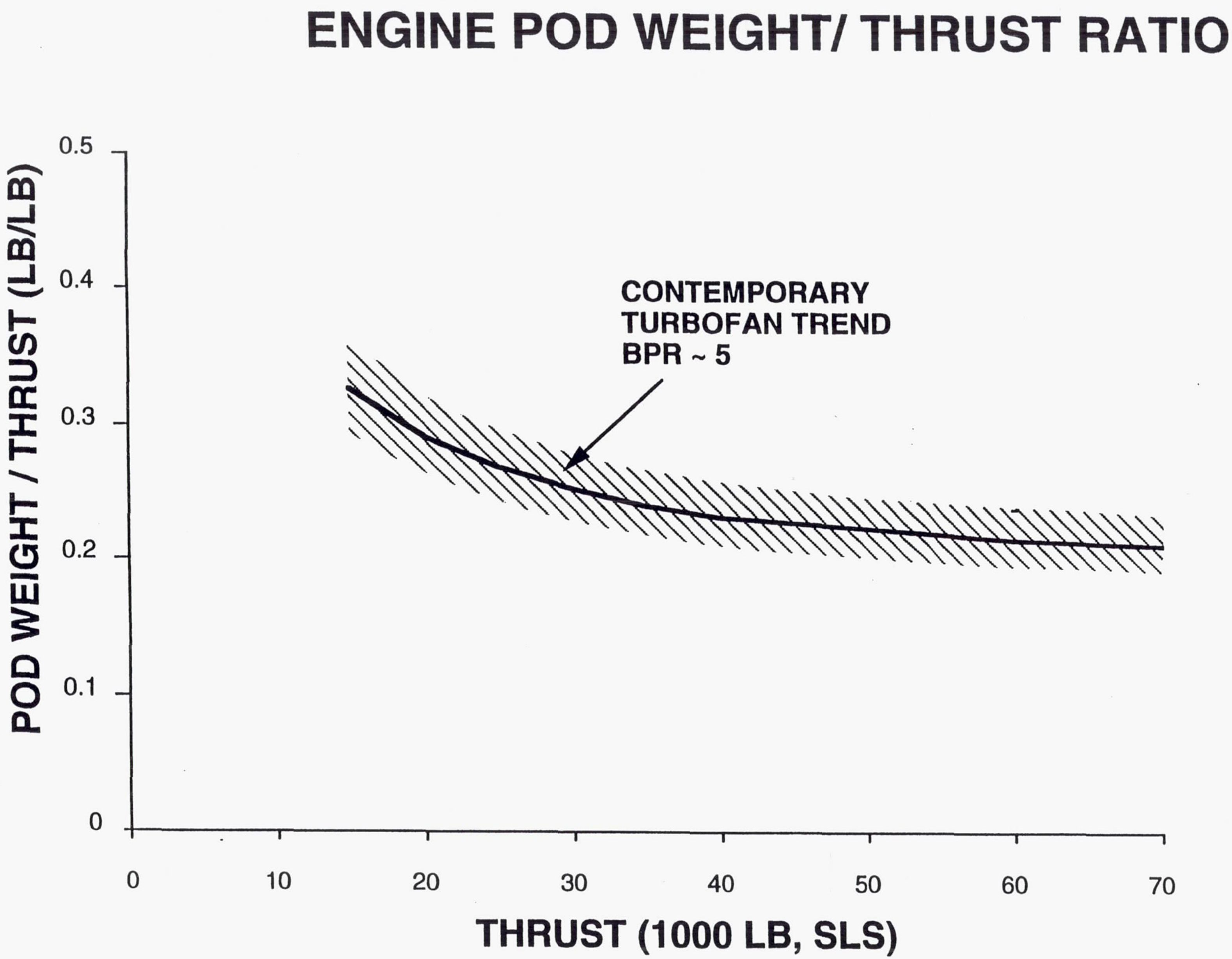

Figure 10. Engine Pod Weight/Thrust Ratio

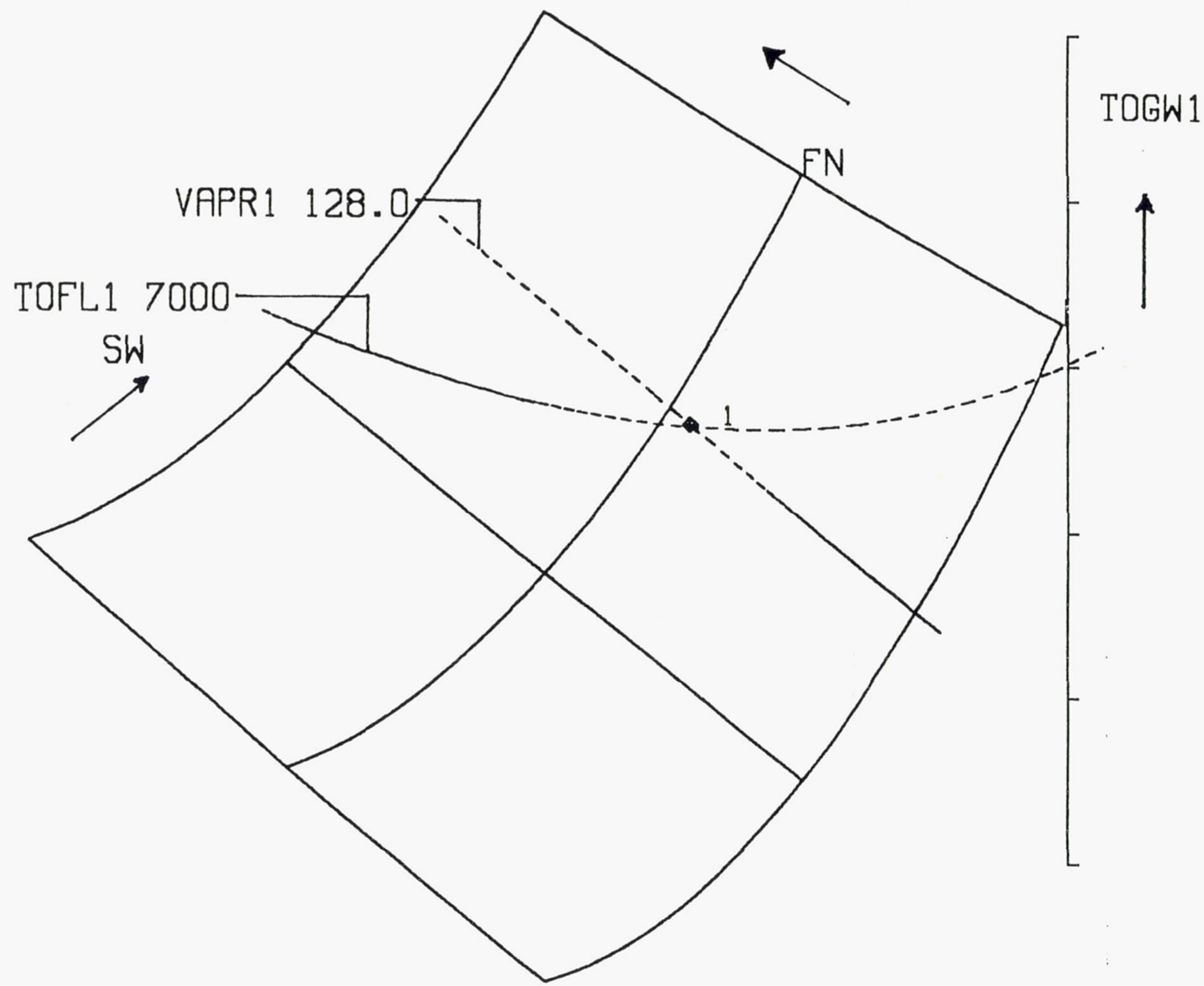

Figure 11. Typical CASES Sizing Carpet Plot

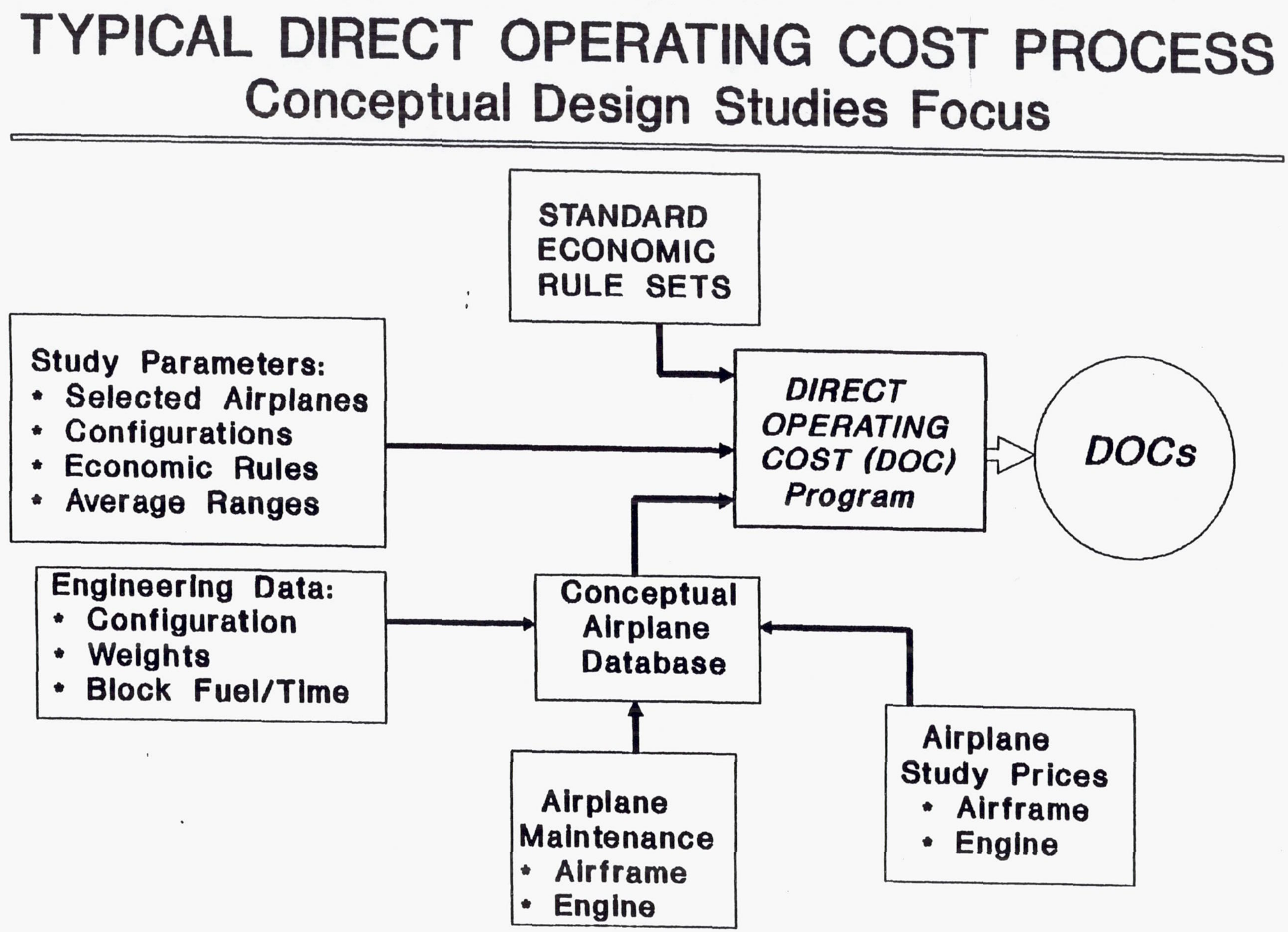

Figure 12. Typical DOC Process

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13. ABSTRACT *(Maximum 200 words)*

A study was made to examine the effect of advanced technology engines on the performance of subsonic airplanes and provide a vision of the potential which these advanced engines offered. The year 2005 was selected as the entry-into-service (EIS) date for the engine/airframe combination. A set of four airplane classes (passenger and design range combinations) that were envisioned to span the needs for the 2005 EIS period were defined. The airframes for all classes were designed and sized using 2005 EIS advanced technology. Two airplanes were designed and sized for each class: one using current technology (1995) engines to provide a baseline, and one using advanced technology (2005) engines. The resulting engine/airframe combinations were compared and evaluated on the basis of sensitivity to basic engine performance parameters (e.g. SFC and engine weight) as well as DOC+I. The advanced technology engines provided significant reductions in fuel burn, weight, and wing area. Average values were as follows: reduction in fuel burn = 18%, reduction in wing area = 7%, and reduction in TOGW = 9%. Average DOC+I reduction was 3.5% using the pricing model based on payload-range index and 5% using the pricing model based on airframe weight. Noise and emissions were not considered.

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ALLISON PROPRIETARY INFORMATION

ADVANCED SUBSONIC AIRPLANE DESIGN & ECONOMIC STUDIES

APPENDIX A: 150-PASSENGER AIRPLANES WITH ALLISON ENGINES

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Contract NAS3-25965, Task 9

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National Aeronautics and
Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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PREFACE

This report was prepared by McDonnell Douglas Corporation under Task Assignment 9 of contract NAS3-25965 for NASA Lewis Research Center as an appendix to NASA CR-195443. This report contains Allison Engine Company proprietary data.

The NASA technical monitors were Joseph D. Eisenberg and Felix R. Torres. The McDonnell Douglas Program Manager was Robert H. Liebeck. The members of McDonnell Douglas team that participated in this task order and deserve recognition for their contributions are as follows:

Aerodynamics	Robert S. Bird, Johnny Chau, Roger Lyon
Configuration	Robert A. Wright, Blaine K. Rawdon
Economics	Donald A. Andrastek, Madeline Ellis
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Secondary Power	Kenneth R. Williams
Weights	Dennis Nguyen, Paul W. Scott

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I. INTRODUCTION

The purpose of this study is to examine the effect of advanced technology engines on the performance of subsonic transport airplanes and provide a vision of the potential which these advanced engines offer. The year 2005 has been set as the entry-into-service (EIS) date for the engine/airframe combination. A set of four transport airplane classes (passenger and design range) that are envisioned to span the needs for the 2005 EIS period have been defined. This problem could be approached utilizing existing airframes with advanced technology engines, however, since the origin of some the existing (and currently produced) airframes dates back more than two decades, a consistent framework for evaluation becomes difficult. Consequently, 2005 EIS advanced technology airframes have been designed and sized for all classes.

Two airplanes have been designed and sized for each class: one using current technology (1995) engines to provide a baseline, and one using advanced technology (2005 EIS) engines. The resulting engine/airframe combinations have then been compared and evaluated on the basis of sensitivity to the basic engine performance parameters (e.g. SFC and engine weight) as well as DOC+I. Noise and emissions have not been considered in the present study.

Participants in this study include: McDonnell Douglas Aerospace for the design, sizing and evaluation of the airplanes, and the three engine companies; Allison, GE Aircraft Engines, and Pratt and Whitney who have provided the engine data for their current and advanced technology engines. Proprietary considerations preclude the documentation of this study in single report, and therefore a separate report has been prepared for each engine company. General discussions pertaining to all airplanes are common to all reports.

II. APPROACH

A. Mission Definition

Four airplane design missions have been defined and are summarized in Table 1; the designations SR-150, MR-225, MR-275, and LR-600 are used in these reports to refer to these four airplane types respectively. These were selected to represent the complete spectrum of subsonic transport requirements envisioned for the year 2005 and beyond. Commuter missions have not been considered in this study. To claim that these missions accurately and precisely define air transportation's needs in 2005 would of course be naive, however, they represent the best judgment at this writing.

Of the four missions, the long range (600 passenger, 7500 n.mi.) is the most speculative, particularly with respect to the payload. The 7500 n mi range is regarded as serving all meaningful city-pair requirements. Very large aircraft (VLA's) are defined as 500 to 1000 passengers, so the choice for this study is somewhat near the lower bound. Increasing the payload would be straightforward, however, the 800-1000 level could begin to deteriorate the accuracy and resolution of existing data bases for weights.

Table 1. Subsonic Airframe/Propulsion Integration
Airplane Design Specifications
2005 EIS

Category	Seats	Rules	Range (N.Mi.)	Cruise Mach No.	ICA (Ft)	VAP (Kts)	TOFL (Ft)
Short Range	150	2 Class Narrow Body	2500	.78	31,000	130	7,000
Medium Range	225	2 Class Twin Aisle	4500	.80	35,000	135	7,500
Medium Range	275	3 Class Interna-tional	6000	.83	35,000	140	9,000
Long Range	600	3 Class Interna-tional	7,500	.85	31,000	150	11,000

B. Airframe Technology Definition

Technology for all airframes is based on a 2005 entry-into-service date. The philosophy used in selecting technology levels was to lean to the optimistic but maintain reality. The resulting airplanes thus show measurable reductions in size and weight over those which would be obtained from simple derivatives of existing airframes. Specific technologies are described below.

1. Aerodynamics

All wing designs are based on advanced supercritical divergent trailing edge airfoils which are highly loaded to minimize wetted area. Selection of a composite wing structure allows a relatively high aspect ratio limit of 11. High-lift system design and performance is based on the technology developed for the MD-12. This utilizes a full-span leading edge slat and a track motion flap system with two segments inboard and a single segment outboard. The system provides high values of C_{Lmax} and L/D for both takeoff and landing configurations.

2. Structure

Advanced composites are used for the entire wing and empennage structure. Fuselage structure utilizes aluminum-lithium longerons with the skins made from GLARE, an aluminum and fiberglass laminate. This combination of materials and structural design yields structural weight reductions which are shown in Table 6.

3. Stability and Control

The Stability & Control terms that strongly affect the aircraft performance are vertical and horizontal tail size, and cruise center-of-gravity (C.G.). The lateral controls affect the available flap span and therefore C_{Lmax}. Further, if the outboard ailerons suffer from aeroelastic reversal, then it is necessary to add inboard ailerons in the stiff mid-span region. Unfortunately, these inboard ailerons also reduce flap area and distort the takeoff and landing spanloads which hurts low-speed L/D. For these reasons the wing structure is sized to preclude aileron reversal in the operational speed range and therefore no inboard aileron is required.

The horizontal tail sizes are based on an advanced high-lift tail with a slotted elevator that can deflect -35° for low-speed takeoff rotation. The slot door is articulated to provide a sealed aerodynamically smooth surface at low elevator deflections. The unaugmented static stability of the airplanes is set to -15%MAC at aft C.G. for the critical V_{FC}/M_{FC} condition where aeroelastic losses are greatest. This static stability level places the C.G. at the Maneuver Point which represents neutral stability from a load-factor standpoint.

The vertical tail is sized for minimum ground control speed (V_{mCG}) on the twin engine airplanes, and two engine-out landing speed (V_{mCL-2}) for the four engine airplanes. In all cases, the all-flying tail concept is used to minimize tail area. This feature requires larger actuators, a pivot shaft, and additional supporting structure, but reduces the tail size by nearly 50% since the fin can be deflected in addition to the rudder.

4. Systems

The digital flight control system is quad-redundant and dispatchable with one channel inoperative to maintain high dispatch reliability. This level of redundancy is required for the high static instability assumed on these configurations. The control system is Fly-by-Light and Power-by-Wire which means the control surfaces are electrically powered and optically signaled. It should be noted that the secondary power system arrangement chosen for the baseline study aircraft represents the anticipated 2005 EIS technology, which integrates the conventional pneumatic, electrical and hydraulic systems into one electrically powered system. This Power-by-Wire (PBW) system requires only shaft power extraction from the engine. An allowance has been made in this study for other airframe applications which would require engine bleed air, but this has been limited to 1% of the engine core airflow.

This type of secondary power system makes possible the consideration of future very high bypass engines, whose smaller core airflow would not allow the use of conventional bleed air utilization. These PBW secondary power systems are compatible with the present engines used in the study, and therefore provide for a generic evaluation of the results, with respect to engine type versus secondary power system installation. Table 2 shows the actual anticipated engine extraction expected for each of the study aircraft types.

Table 2. Power Extraction versus Aircraft Type

AIRCRAFT TYPE		POWER EXTRACTION	PER ENGINE
Short Range 150 Passengers	Shaft	225 hp Norm. (167.6 Kva)	281 hp Max. (209.5 Kva)
	Air	1% core flow max;	30 hp
Medium Range 225 Passengers	Shaft	379 hp Norm. (282.7 Kva)	474 hp Max. (353.4 (Kva)
	Air	1% core flow max;	70 hp
Medium Range 275 Passengers	Shaft	394 hp Norm. (293.7 Kva)	492 hp Max. (367.2 Kva)
	Air	1% core flow max;	85 hp
Long Range 600 Passengers	Shaft	559 hp Norm. (416.8 Kva)	698 hp Max. (521.0 Kva)
	Air	1% core flow max;	120 hp

C. Engine Definition

Each of the three engine companies defined their current and advanced technology engines according to each company's design philosophy and technology base. Relative to the current engines, the advanced technology engines incorporate cycle, materials, and turbomachinery efficiency and design improvements.

The three pairs of current and advanced technology engines used in this study are listed below in Table 3. The Allison engines were used for the short-range/150-passenger airplanes, the GE engines were used for the medium-range/225-passenger airplanes, and the P&W engines were used for both the medium-range/275-passenger and long-range/600-passenger airplanes. The short and medium-range airplanes were configured with two engines; the long-range airplanes had four engines.

Table 3. Baseline and Advanced Engine Model Designations

Engine Company	Baseline Engine (1995 EIS)	Advanced Engine (2005 EIS)
Allison	PD577-1A6	PD577-2A5/6
GE Aircraft Engines	Baseline ASTEA	Advanced ASTEA
Pratt & Whitney	PW4484	STS1046

D. Configuration Definition and Rules

A conventional configuration with pylon-mounted wing engines was selected for the SR-150. This arrangement isolates the engine inlets from the airframe so that engine technology changes can be analyzed without airflow complications. Interior accommodations are set for 150 passengers using Douglas Aircraft Company (DAC) rules for a two class seating arrangement with a single aisle for short/medium range flights with 8 percent first class, and the remainder economy class with a 32 inch seat pitch. Flight crew requirements are derived from the FAR Part 121, subpart R, paragraph 121.480.

Once sized, the fuselage is considered a constant, while the engine technology level used will re-size the wing, empennage, landing gear, engine size (thrust), and fuel requirement.

E. Airplane Sizing and Performance

1. **Propulsion model**

The SR-150 airplanes were sized using engine performance data provided by Allison Engine Company for the baseline, PD577-1A6, and advanced, PD577-2A5 and -2A6 engines. The -2A6 was the most up-to-date version of their 2005 EIS engine. However, due to time constraints, and since the performance differences between the -2A5 and -2A6 were slight, it was agreed that the -2A5 performance would be used in the study. In the remainder of the report, the advanced engine is referred to as the -2A6 because the airplane was sized using the -2A6 weights. Performance data were provided for a large matrix of takeoff and climb/cruise flight conditions. Thrust and fuel flow were extracted from the Allison engine datapacks and loaded into the McDonnell Douglas airplane sizing program which in turn interpolated and scaled the engine data according to the airplane mission requirements.

2. Weight estimation model

MDC's proprietary Conceptual Weight Estimation Program (CWEP) requires inputs such as geometrical parameters, design criteria, and advanced technology multipliers. CWEP uses a series of weight estimating relationships (WERs) and a modified Breguet range equation to develop the initial aircraft sizing parameters, which are then processed by the more sophisticated CASES sizing code. The sizing parameters (shown in Table 4) consist of the partial derivatives of Operational Empty Weight (OEW) with respect to gross weight, wing area, and thrust plus a constant weight. To obtain the final aircraft weight, the CASES wing area, thrust, and gross weight are input to CWEP. The resulting group weight statement is used for cost estimation. Both the sizing derivatives and the group weight statements are shown in the tables at the end of this section.

TABLE 4. Aircraft Sizing Derivatives

$$OEW = W_c + \frac{\partial OEW}{\partial W_g}(W_g - W_{g_o}) + \frac{\partial OEW}{\partial S_w}(S_w - S_{w_o}) + \frac{\partial OEW}{\partial T}(T - T_o)$$

$$W_g = OEW + W_{pl} + W_{fuel}$$

OEW = Operational Empty Weight (lb)

$\frac{\partial OEW}{\partial S_w}$ = Partial derivative of OEW with respect to wing area (lb / ft^2)

$\frac{\partial OEW}{\partial T}$ = Partial derivative of OEW with respect to Thrust (lb / lb)

$\frac{\partial OEW}{\partial W_g}$ = Partial derivative of OEW with respect to MTOGW (lb / lb)

S_w = Wing area (ft^2)

S_{w_o} = Base wing area (ft^2)

T = Thrust per engine, sea level static rated (lbf)

T_o = Base thrust per engine, sea level static rated (lbf)

W_c = Base constant weight (lb)

W_g = Maximum Takeoff Gross Weight (lb)

W_{g_o} = Base Maximum Takeoff Gross Weight (lb)

W_{fuel} = Fuel Weight (lb)

W_{pl} = Payload weight (lb)

Design Criteria

The aircraft's maximum takeoff gross weight (MTOGW) is defined by the requirement to transport the maximum design passenger capacity over the design range. The full complement of passengers and bags at 210 lb each defines the performance payload (WPPL), which is shown in Table 5. The maximum payload (WMPL) reflects the heaviest payload that the aircraft must carry and influences the structural weight. As is typical for commercial aircraft, the configurations for this study are designed for a 2.5 limit load factor and a 10 ft/sec limit landing sink rate.

The SR-150 is designed to provide an 8000 ft cabin pressure at 39,000 ft. This results in a limit differential cabin pressure (PD) of 8.1 psig for the SR-150. The maximum speed in a dive (VD) for the aircraft is also presented in Table 5.

Table 5. Design Criteria

CONFIGURATION	WPPL (lb)	RANGE (nm)	WMPL (lb)	PD (psig)	VD KEAS
SR-150	31,500	2,500	43,000	8.1	400

Advanced Technology Weight Impacts

CWEP utilizes advanced technology multipliers (ATMs) to reflect the technology level. The ATMs of Table 6 are based on an entry into service date (EIS) of 2005 as referenced to the database of operational aircraft. The structural weight increments of advanced composites in newer operational transports have been factored out in order to normalize the database.

The wing and tail incorporate maximum use of advanced composites, but metallics are assumed for leading edges, aerodynamic surface hinges, and at critical joints. More dramatic weight reductions may be feasible, but commercial transports must emphasize low cost of manufacturing and maintenance. The fuselage uses GLARE skins, Aluminum-Lithium longerons, and advanced composite secondary structure. The landing gear utilizes carbon brakes, radial tires and steel struts with a moderate improvement material properties.

The fixed equipment ATM's are empirically derived trends that reflect numerous weight reductions due to technology improvements, many of which are offset by increased capabilities and improved functionality. The term "fixed equipment" refers to those items whose weight is insensitive to changes in MTOGW and includes furnishings, APU, pneumatics, air conditioning, electrical, instruments and avionics. The weight of fixed equipment items tend to scale with fuselage size. Dividing the sum of actual aircraft fixed equipment weights plus operational item weights by the value estimated by a WER and plotting this versus the EIS date of each aircraft determines the ATM trend versus EIS date. This trend curve, shown in Figure 1, estimates an ATM of 0.918 for a 2005 EIS. However, this factor is not distributed evenly across all of the components.

Table 6. Advanced Technology Multipliers for 2005 EIS

FUNCTIONAL GROUP	ATM	COMMENTS
Wing		
Bending material	0.75	
Spar webs	0.75	
Ribs and bulkheads	0.75	
Aerodynamic surfaces	0.92	
Secondary structure	0.83	
Tail	0.80	
Fuselage	0.95	
Landing gear	0.91	
Nacelle and Propulsion	NA	By engine manufacturer
Flight Controls & Hydraulics	0.95	
APU, Pneumatics, Air conditioning Electrical, Instruments & Avionics	0.976	
Furnishings & Equipment	0.869	
Operational items	0.976	

Although an 2005 EIS transport may be all-electric, there is scant empirical data on such systems and no reliable rational for identifying related weight increments, therefore none are assumed.

Propulsion System Weights

ALLISON PROPRIETARY INFORMATION

All engine pod weights are provided by the engine manufacturers. The ratio of these pod weights to their rated thrust is presented in Figure 2. The very high-bypass ratio of the advanced Allison engine more than offsets the weight savings due to advanced technologies and materials, thus causing its weight fraction to fall above the trend curves. The atypical base Allison engine is more than 50 % heavier than the trend curve.

When adequate detail is provided by the manufacturer, MDC uses a MIL-STD-1374A functional weight reporting format for the propulsion related weights. MIL-STD-1374A allocates the inlet cowl to the Air Induction Group, and the fan cowl doors plus the pylon are charged to the Nacelle Group. The fan exhaust duct, core cowl and nozzle are allocated to the exhaust system, which is part of the Propulsion Group. In some instances, the fan exhaust duct and the thrust reverser weights are reported as an assembly and cannot be separately identified.

MDC estimates the propulsion related items that are external to the pod, such as the engine pylons and the aircraft's fuel system. Lacking detailed engine pylon drawings, all pylons are estimated to weigh 16 % of the pod weight, a value that is typical of the highly cantilevered pylons on modern commercial transport aircraft. All of the study aircraft are assumed to carry fuel in their outer and center wings. With the exception of the SR-150, all configurations are assumed to have a trim tank in their horizontal stabilizer.

Detailed Weight Summaries

Tables A1 and A2 in the appendix present the group weight statements for the base engine SR-150 and advanced engine SR-150 configurations respectively. The weight sizing derivatives and maximum fuel capacities are also reported in each table.

3. Aerodynamic model

High Lift System

The high lift system is composed of a slat plus Fowler-motion flap. At takeoff, the slat is sealed, and it is fully open at landing. An "auto-slat" system is utilized to reduce takeoff speed by automatically opening the slats from the sealed takeoff position to the open landing position if stall is approached. This makes available the high C_{Lmax} of the open slat with the higher L/D of the sealed slat. The trailing edge system is composed of two spanwise flap segments plus drooped ailerons. Inboard, the flap has two elements with the auxiliary element remaining stowed at takeoff. Midspan and outboard flaps are single element. Maximum flap setting is 30°.

Low speed aerodynamic characteristics were estimated using a combination of flight and wind tunnel test data as well as conceptual handbook methods. Lift and drag data were assembled and trimmed using the MDA CASES aircraft sizing program. All takeoff data and C_{Lmax} were trimmed at the forward CG limit, and all landing data was trimmed at the mid CG position.

Transonic

High speed aerodynamic data were based on a combination of MDA advanced design methodology and empirical data which has been substantiated by wind tunnel tests of advanced technology transport aircraft. Wing design and performance is based on the latest advanced technology supercritical airfoils with divergent trailing edges.

4. Sizing procedures (CASES)

MDC's proprietary Configuration Aircraft Sizing and Evaluation System (CASES) was used for the evaluation and optimization of the aircraft in this report. The program is designed to facilitate the sizing of aircraft to meet specific mission requirements for payload, range, takeoff field length, approach speed, initial cruise altitude, and other requirements. The program requires inputs from Aerodynamics, Propulsion, Stability & Control and Weights. The sizing parameters require inputs such as wing area (S_W), TOFL, and thrust. The design optimization is accomplished with interactive plotting routines which provide visual relationships between the geometric variables, design constraints, and optimization criteria used. Figure 3 shows the sizing carpet plot created in CASES with varying wing areas (S_W) and thrusts. From the plot, the minimum TOGW or fuel burned to meet the initial cruise altitude can be obtained.

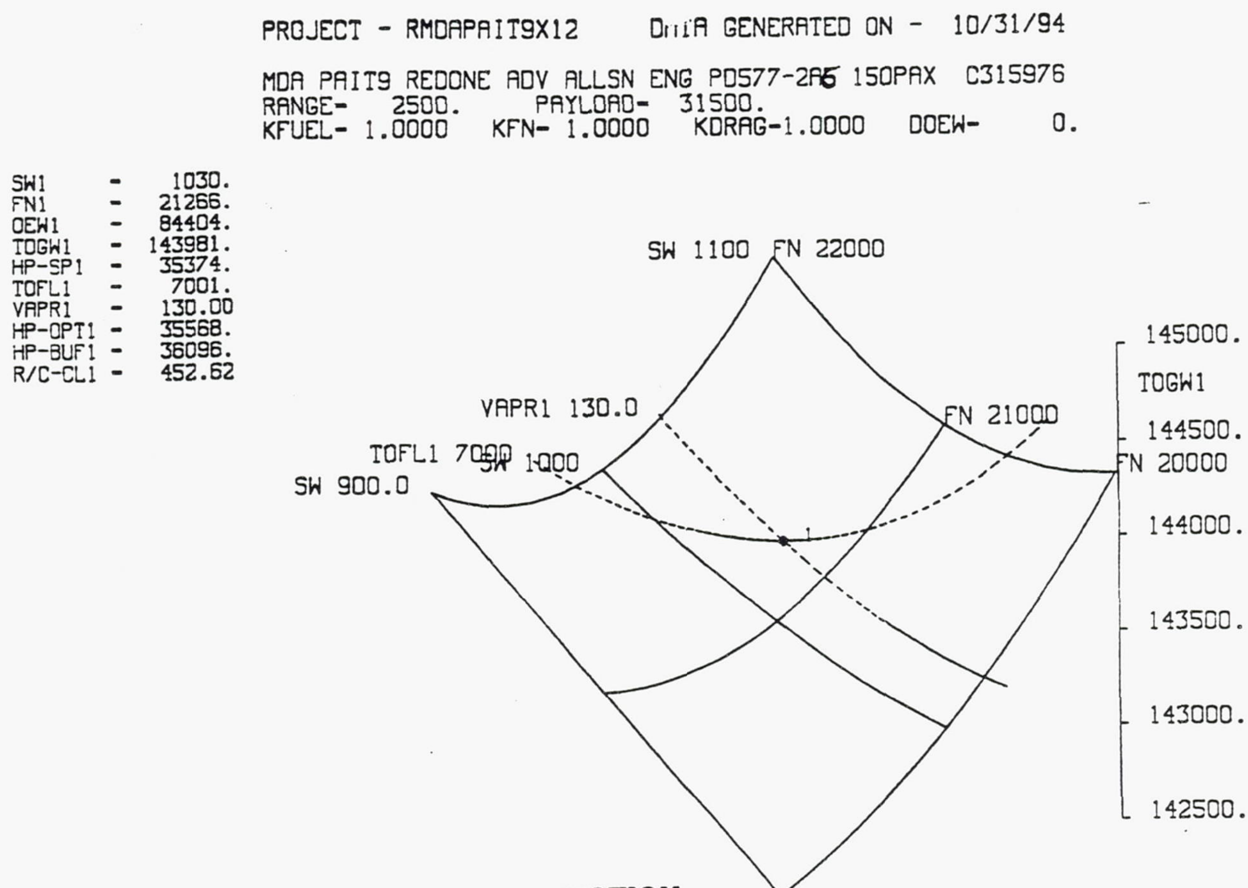

Figure 3. Typical CASES Sizing Carpet Plot

F. Sensitivity Analysis

Sensitivity studies have been conducted to estimate the effect on maximum takeoff gross weight of increases in engine weight and SFC relative to target at entry into service. Both the baseline (1995) and advanced technology (2005 EIS) engined airplanes have been analyzed. Increments of plus 5 percent in engine + pod + pylon weight and SFC have been applied, and the resulting airplanes have then been re-sized to meet the design criteria of Table 1.

G. DOC+I Method and Rules

1. Introduction

This section presents the direct operating cost rules and calculation process used to evaluate and compare the SR-150 airplane concept with current-technology and advanced-technology Allison turbofan engines. The economic analysis focus was on the first-level effects of advanced propulsion system technology with respect to airplane performance (block time, block fuel) and airplane economics (DOC for a typical average stage length (ASL) of 500NM.

The economic criterion used for evaluating and comparing the effect of advanced propulsion systems on airplane design and operation was Direct Operating Cost (DOC). The Air Transportation Association of America, in 1944, published the first universally recognized method for estimating direct operating costs of airplanes. That ATA method was progressively updated through the years with inputs from ATA member airlines and prime airframe and engine manufacturers. The ATA standard method of estimating <u>comparative</u> direct operating costs of turbine powered transport airplanes, last published in December 1967, formed the basis for the method and approach used for this study.

The DOC method used for this study was based on the combination of ground rules and assumptions developed collectively by McDonnell Douglas Corporation (MDC) and its commercial aircraft component, Douglas Aircraft Company (DAC), the Boeing Commercial Airplane Group (BCAG), and NASA Lewis Research Center (LeRC). The method was referred to as the "DOC+I" method, since the interest cost element was added. In addition, cabin crew costs, landing fees and navigation fees, usually considered to be indirect operating costs by the former Civil Aeronautics Board (CAB), were also added to the original ATA DOC cost element structure. Using DOC+I to describe this method affords a way to discriminate from the basic ATA DOC method.

With the aforementioned additions to the basic ATA DOC method, the DOC+I cost element structure for this study included the following cost elements:

(1) Flight Crew
(2) Cabin Crew
(3) Landing Fees

(4) Navigation Fees
(5) Maintenance - Airframe
(6) Maintenance - Engine
(7) Fuel
(8) Depreciation - Aircraft and Spares
(9) Insurance
(10) Interest

Elements (1) through (7) are commonly referred to as "cash costs"; whereas elements (8) through (10) are referred to as "ownership costs".

For purposes of this study, the terms "DOC" and "DOC+I" may be used interchangeably as they will both mean the same thing.

2. DOC Process

The DOC process shown in Figure 4 is typical of the process used for this study. The block 'standard economic rules sets' includes the ten cost elements just discussed and the specific ground rules and assumptions to calculate each one. The blocks 'Study Parameters' and 'Engineering Data' provide the airplane descriptions for each airplane concept under study, which would include configuration geometry data, design weights, engine description, technology level, and performance data.

Airplane study prices, consisting of separate airframe and engine prices, were calculated using parametric methods. Engine company data for each conventional technology and advanced technology engine design were combined with parametrically-determined scaling factors to derive engine study prices for each sized airplane concept. Airplane (airframe and engine) maintenance values were also parametrically determined from DAC's historical database and engine company data for each specific engine concept.

The DOC process is the last part of a generalized aircraft concept study process employed by MDC. Part of that process involves aircraft sizing, which was done using MDC's internally-developed Computer-Aided Sizing and Evaluation System [CASES] already described in Section II. The CASES results include the design mission configuration, weight, and performance data, as well as the performance data for the economic mission used for DOC evaluation.

3. DOC Groundrules, Assumptions and Element Descriptions

The DOC ground rules and assumptions used for the study are summarized in Table 7. Listed are the various factors for each of the DOC elements, either in narrative or quantitative form. Domestic and international equations are so identified. The DOC values are calculated in mid-1993 dollars.

Following are detailed descriptions of each DOC element. Note that the cost units of any element may differ from one to the next, e.g., $/block hour, $/flight hour, $/trip.

COCKPIT CREW. Based on the aircraft maximum takeoff gross weight [MTOGW].

[Domestic] $/Block Hour = 440 + 0.532*(MTOGW/1000)
[International] $/Block Hour = 482 + 0.590*(MTOGW/1000)

CABIN CREW. Based on the number of seats in the aircraft and a cost-per-block hour rate for each crew member.

[Domestic] $/Block Hour = (Number of Seats/35)*60
[International] $/Block Hour = (Number of Seats/30)*78

LANDING FEE. Based on either the maximum landing gross weight (MLGW) or the maximum take-off gross weight MTOGW.

[Domestic] $/Trip = $1.50 * (MLGW/1000)
[International] $/Trip = $4.25 * (MTOGW/1000)

NAVIGATION FEE. Based on the first 500NM of a trip and the MTOGW, and used only for international DOC cases.

[International] $/Trip = $0.136 * 500NM * (Square Root of MTOGW/1000)

FUEL. Based on the economic mission block fuel, at a density of 6.7 pounds per US gallon, and a price per gallon of either $0.65 (US Domestic) or $0.70 (International).

MAINTENANCE. Total airplane maintenance cost includes the cost of direct maintenance labor, maintenance material, and applied maintenance burden for both the airframe and engines. The airframe direct maintenance labor and maintenance material costs are based on parametric equations developed by the Boeing Commercial Airplane Group (BCAG).

The engine maintenance costs are based on data provided by the engine companies. This data was augmented, where appropriate, by cost data from the McDonnell Douglas Corporation (MDC) commercial transport engine maintenance database. Since the engine company maintenance cost data was for a fixed reference thrust level, the Boeing engine maintenance cost equations were used as general scaling equations based on sea-level static thrust.

Airframe Maintenance Labor [AFLAB]. Based on airframe weight [AFW], defined as manufacturer's empty weight (MEW) less the dry weight of the engines. AFLAB has both a flight-cycle (FC) and a flight-hour (FH) component. The equations produce either maintenance-man-hour-per-flight-cycle (MMH/FC) or maintenance-man-per-flight-hour (MMH/FH) values. Each trip consists of one flight cycle and a variable number of flight hours.

AFLAB:MMH/FH = 1.260+(1.774*AFW/10^5)-.1071*(AFW/10^5)^2
AFLAB:MMH/FC = 1.614+(.7227*AFW/10^5)+.1024*(AFW/10^5)^2
AFLAB:MMH/TRIP = ((MMF/FH)*(FH/TRIP))+MMH/FC

Total maintenance man-hours per trip are converted to direct labor dollars per trip by multiplying by the direct maintenance labor rate ($25/MMH).

Airframe Maintenance Materials [AFMAT]. Same basis as airframe maintenance labor, with both a cyclic and flight-hour component.

AFMAT:$MAT/FH = 12.39+(29.80*AFW/10^5)+.1806*(AFW/10^5)^2
AFMAT:$MAT/FC = 15.20+(97.33*AFW/10^5)-2.862*(AFW/10^5)^2
AFMAT:$MAT/TRIP = (($MAT/FH)*(FH/TRIP))+$MAT/FC

Airframe Applied Maintenance Burden [AAMB]. The airframe maintenance overhead cost is calculated as a function of airframe direct maintenance labor cost.

AAMB = 2.0 * Airframe Direct Labor Cost

All three airframe maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get total airframe maintenance cost.

Engine Maintenance Labor [ENGLAB]. The scaling equation for engine direct maintenance labor is based on the maximum rated uninstalled sea-level static thrust (SLST) per engine, in pounds force (lbf), the flight hours (FH) per trip, and the number of engines per aircraft (NE). In contrast to the airframe, the engine maintenance labor cost is not separated into flight-cycle and flight-hour components.

ENGLAB: MMH/TRIP = ((.645+(.05*SLST/10^4))*(.566+.434/FH)*
FH*NE

The engine direct maintenance labor cost is calculated by multiplying the MMH/TRIP by the direct maintenance labor rate ($25/MMH).

Engine Maintenance Material [ENGMAT]. The scaling equation for engine maintenance material cost is based on the same parameters as the engine direct maintenance labor. In contrast to the airframe, the engine maintenance material cost is not separated into flight-cycle and flight-hour components.

ENGMAT: $MAT/TRIP = ((25+(18*SLST/10^4))*((.62+(.38/FH))*
FH*NE

Engine Applied Maintenance Burden [EAMB]. The engine maintenance overhead cost is calculated as a function of the engine direct maintenance cost.

EAMB = 2.0 * Engine Direct Maintenance Labor Cost

All three engine maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get the total engine maintenance cost.

Depreciation, interest and insurance are annual costs. Reducing these annual costs to trip costs are accomplished by dividing the annual cost by the number of trips flown per year. As noted in Table 7, the domestic short-range mission of 500NM will generate 2100 trips/year.

DEPRECIATION. Depreciation is based on the total airplane (airframe + engines) price and its associated spares price. The airframe and engine spares factors, the depreciation period and the residual value are noted in Table 7.

INTEREST. Most aircraft purchases are financed through the use of long-term debt and a down payment from company funds. To account for the total interest cost to the airline, interest is computed on the total price of the airplane plus spares less the down payment. Although interest payments will decline each year, an average annual interest cost is used in aircraft comparisons to reflect the average effect over the airplane's depreciable life. The interest method assumes a 15-year loan period, two loan payments per year, and equal principle payments. The factors defining the amount financed, the depreciation period, and the interest rate are noted in Table 7.

INSURANCE. The annual hull insurance cost is based on the total airplane price. The insurance rate is 0.35% of the total airplane price.

AIRFRAME AND ENGINE STUDY PRICES. Airframe study price was based on a parametric relationship between airframe study price and either a payload-range index or airframe weight. Payload-range index (PRI) was selected as the primary independent variable, since the SR-150 concept was chosen as a possible replacement airplane for this particular market sector (150 seats, 2,500-NM design range). Airframe weight, the secondary independent variable, was also evaluated as an airframe price generator in order to assess the impact of airframe downsizing afforded by advanced engine technology.

However it should be understood that commercial transport aircraft are not sold on a price-per-pound basis. Its selling price in essence represents a market-based price (without relationship to cost). The commercial product relies on a fixed price based on an end item specification, performance guarantees, service life policies, and warranties. This would apply to airframes as well as to engines.

The airframe payload-range index was statistically determined from a database of US and non-US commercial transports with two-class domestic seating capacities ranging from 123 to 196 and design ranges varying from 1,789 to 2,903 NM (US Domestic rules), and is dimensioned in (seat-NM) /1000. For the 150-seat, 2500-NM design, the payload-range index would be 375.0 (150*2500/1000). The airframe prices were derived from

MDC's commercial transport database. For the 150-seat airplane, a linear regression of airframe price and PRI produced the following airframe study price equation:

Airframe Study Price ($M)= 16.342 + 0.0462 * PRI

A power curve fit of airframe study price (in millions of dollars) versus airframe weight (in pounds, and denoted by AW) produced the following airframe study price equation:

Airframe Study Price ($M) = 0.0075814 * (AW ^ 0.74754)

Engine study prices were developed from MDC's historical database and from engine manufacturer's data. These engine prices represent only the bare engine, as the remainder of the propulsion system price is assumed to be part of the airframe price (e.g., nacelles and thrust reversers). This is in keeping with the original ATA DOC methodology. The parametric trend of engine price versus engine thrust (i.e., engine price scaling) was derived from the MDC database for current technology engines, and was segregated into two engine classes: 15,000 to 40,000 lbf for the SR-150 concept discussed in this report, and 50,000 to 90,000 lbf for the larger, twin-aisle concepts discussed in other reports in this series.

Allison provided engine study prices based on two pricing scenarios. The baseline scenario assumed market-based engine prices for both the current-technology (PD577-1A6) and advanced-technology (PD577-2A6) engines. This assumed that each engine was developed independent of the other. Allison also provided a pricing scenario whereby the advanced-technology engine was priced on a delta-cost basis, which assumed that it was considered as a follow-on to the current-technology engine. The reference study price of each engine was based on the following reference thrust levels: PD577-1A6 - 25,929 lbf; PD577-2A6 - 25,472 lbf. These thrust levels were for the following conditions: SLS, flat-rated to ISA+10C, no loss.

The variation of bare engine price with engine thrust is assumed to be identical for both the current- and advanced-technology engines. Fitting a power curve of the form y=aX^b to the engine data, and calibrating that curve to each Allison engine class at its reference thrust and associated price produced characteristics of the engine price scaling equations as shown below. Both equations represent engines priced on a market basis.

Engine	Constant	Exponent
PD577-1A6	0.00124349	0.795216
PD577-2A6	0.00123603	0.795216

When the advanced-technology PD577-2A6 engine is priced on a delta-cost basis relative to the PD577-1A6, the constant in the price scaling equation changes from 0.00123603 as shown to 0.00100769.

The impact of different airframe and engine pricing scenarios on DOC+I will be evaluated and discussed in Section III.

Table 7. DOC+I Ground Rules and Assumptions
SR-150 CONCEPT

Item	Parameter
DOC+I Basis	US domestic rules
Design Mission	2,500 NM
Economic Mission	500 NM
Utilization	2,100 trips per year
Dollar Year	1993
Fuel Price	$0.65 per US gallon
Maintenance Labor Rate	$25.00 per man-hour
Maintenance Burden Rate	200% of direct labor
Number of Cockpit Crew	2
Number of Cabin Crew	1 per 35 seats
Landing Fees	Function of MLGW
Navigation Fees	None
Hull Insurance Rate	0.35% of airplane price
Depreciation:Period	15 Years
Depreciation:Residual Value	10% of price (Including spares)
Investment Spares:Airframe	6% of airframe price
Investment Spares:Engine	23% of engine price
Interest:Amount Financed	100% of aircraft & spares
Interest:Period	15 Years
Interest:Rate	8%

III. RESULTS

A. Description of Configuration

Figure 5 is a general arrangement drawing of the 150 passenger airplane. This is a conventional twin engine configuration with advanced concept features that include an aspect ratio 11 wing and an all-flying vertical tail. The fuselage has a circular cross section and will accommodate one LD-W container below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 150 seat two class-domestic, as shown in the drawing of Figure 6. It should be noted that the wing and empennage sizes shown on the general arrangement drawing of Figure 5 are not to exact scale of the final sized airplanes. The actual dimensions are given in the Characteristics Data below (Table 8) for both current technology (1995) and advanced technology (2005 EIS) engined airplanes.

Table 8. SR-150 Geometric Characteristics Table

		WING	HORIZONTAL	VERTICAL
SREF (PD577-1A6 A/C)	FT^2	1150	207.99	114.48
SREF (PD577-2A6 A/C)	FT^2	1030	176.30	97.03
SPAN (PD577-1A6 A/C)	FT	112.47	32.25	14.35
SPAN (PD577-2A6 A/C)	FT	106.44	29.69	13.22
MAC (PD577-1A6 A/C)	FT	11.33	6.95	8.59
MAC (PD577-2A6 A/C)	FT	10.72	5.90	7.91
COMMON GEOMETRIC CHARACTERISTICS:				
ASPECT RATIO		11.00	5.00	1.80
C/4SWEEP ANGLE	DEG	27.00	28.00	30.00
TRAP TAPER		0.28	0.35	0.35
Y SIDE OF BODY	IN	75.00	25.00	0.00
TAIL ARM	IN	N/A	763.63	696.90
VOLUME RATIO		N/A	1.0161	0.0514
DIHERAL ANGLE	DEG	5.00	10.0	0.00
THICKNESS, % CHORD	Average	0.1388	0.10	0.1025
		AIRCRAFT		
OVERALL LENGTH	FT	130.68		
HEIGHT -1A6	FT	32.64		
HEIGHT -2A6	FT	31.51		

B. Engine Selections

The baseline configuration (Figure 7) is a two-spool, high bypass ratio turbofan, featuring a single stage, large diameter (~85"), wide chord fan gear driven by a three stage low pressure turbine. The fan module is removable on the aircraft and individual blades replaceable. The core consists of a multistage axial, high pressure compressor with variable geometry, an annular, effusion cooled combustor and a two stage axial, air cooled, high pressure turbine. The high compressor's variable setting inlet guide vanes and several vane rows allow smooth power transients and minimum fuel burn throughout the flight envelope. Moderate stage loading provides stall-free operation and low sensitivity to inlet distortion. The cycle and ratings were selected to provide 200°F turbine temperature margin between maximum new engine operational temperatures and certified rating temperatures, providing substantial depreciation margin for long onwing operation and general durability enhancement. The baseline assumption is a short cowl installation, however long cowl installation could also be accommodated.

The advanced engine general configuration (Figure 8) is similar to the baseline, with the incorporation of advanced technology components, features and materials consistent with a year 2005 entry into service. The fan is a "low noise" design achieved through optimizing tip speed, rotor-to-stator spacing, blade/vane airfoil count and acoustic treatment. The high pressure compressor and the high and low pressure turbines have increased loading to reduce compressor stage count and maintain turbine stage count without sacrificing necessary stability margin. All rotating components have improved efficiency by way of advanced 3-D aerodynamic design, and other loss reduction design features such as clearance control and secondary flow management. The resulting overall cycle pressure ratio is considerably higher (~92%) as compared to the baseline, as is the turbine inlet temperature (~17%) thereby requiring higher temperature capability compressor and turbine materials and advanced cooling concepts, including advanced titaniums and titanium-aluminides, and next generation single crystal materials, dual property turbine disks, as well as the Allison developed Castcool/Lamilloy technologies. Improved, high temperature seal concepts shall also be incorporated. The combustor is a low emissions, lean direct injection (LDI) type design being development at Allison. Engine weight was further minimized by extensive use of composite materials (such as OMC's and MMC's) where durability and reliability are not sacrificed and cost (DOC) trades are favorable. Reduced drag nacelle concepts have also been incorporated into the design.

The advanced engine yields significant improvements relative to the baseline in terms of thrust-to-weight ratio (+40% for bare engine and +20-25% for full propulsion system including nacelle), specific fuel consumption (-12-13%), and engine length (-15-20%). Taking advantage of these propulsion system benefits in an aircraft design can lead to very attractive system benefits such as 7-9% reduction in aircraft takeoff gross weight, 14-16% reduction in mission fuel burn, or 2-5% reduction in Direct Operating Cost.

Furthermore, the resulting chemical and acoustic emissions of the engine achieve the NASA AST Program goals of a 70% reduction relative to current ICAO NOx regulation and a 21 EPNdb accumulative reduction relative to FAR Part 36, Stage 3 noise regulation.

C. Final Sized Airplanes

1. Primary sizing constraints

The primary sizing criteria used in this report are shown in Table 1. In all cases, the critical sizing parameters are payload, range and takeoff field length (TOFL). Initial cruise altitude (ICA) was never a critical parameter. Approach speed was critical only for the PD577-2A6 configuration. Takeoff field length is computed at sea level and 84 ^{o}F. The airplanes are sized by the combination of Fn and Sw to meet the takeoff field length and approach speed requirements at a minimum MTOGW and Sw.

2. Effects of engine technology improvements

Table 9 summarizes the results of the final sized SR-150 aircraft with the PD577-1A6 and PD577-2A6 engines. In comparing the performance characteristics of these airplanes, the aircraft with the advanced engine, PD577-2A6, has an overall better performance. Its operating empty weight (OEW) is lighter, and specific fuel consumption (SFC) is 12% better than the PD577-1A6. The advanced engine effects are a reduction in wing area (Sw), thrust required (Fn), and fuel burned. As a result, the aircraft sized with the -2A6 engines resulted in a lighter maximum takeoff gross weight (MTOGW) compared to the PD577-1A6.

Table 9. SR-150 Aircraft Sizing Results

Engine	PD577-1A6	PD577-2A6
Bypass Ratio	11	17
MTOW (LB)	158,000	144,000
OEW (LB)	92,600	84,400
Sw (SQ FT)	1,150	1,030
Fn (LB)	23,000	21,300
Block Fuel (LB)	28,900	24,100
Block Time (Hr)	6.087	6.08
Wt/Sw (LB/SQ FT)	137.28	139.85
Fn/Wt	0.2914	0.2957
ICA (FT)	36.3K+(Cl Ceil)	35.4K+(Cl Ceil)
TOFL (FT)	7,000	7,000
Vappr (KEAS)	127.91	130
1st Seg Grad (%)	1.59	1.53
2nd Seg Grad (%)	2.4	2.4
V2 (KEAS)	144.13	144.87
CL Avg @ 35000	0.587	0.598
L/D Avg @ 35000	17.83	17.44
SFC Avg @ 35000	0.5976	0.5340

D. Sensitivity Results

Tables 10 and 11 below show the sensitivity of aircraft sizing to increases in SFC and pod & pylon weights for the SR-150 with the base and advanced Allison engines. Increasing SFC has greater impact on TOGW, Fn and S_W than increasing engine weight. The aircraft sized with a 5% SFC increase have heavier MTOGW compared to the aircraft sized with a 5% engine weight increase. The overall effect of SFC on TOGW is about 0.5% greater than in the engine weight case. Since the aircraft are sized to meet the sizing criteria stated in Table 1, an increase in either SFC or engine weight would also result in an increase in S_W and Fn. Takeoff thrust (Fn) and wing area (S_W) for the SFC case increased by 0.5-1% and 0.5% respectively relative to aircraft sized with engine weight. In general, the aircraft sized with advanced engines have a smaller effect in TOGW compared to the base engines because of the better performance of the advanced engines relative to the base engines.

Table 10. Sizing Effects of 5% SFC Increase

	Allison PD577-1A6	Allison PD577-2A6
Δ TOGW (lb)	1.7%	1.5%
Δ OEW (lb)	0.8%	0.6%
Δ Fn (lb)	1.3%	2.0%
Δ S_W (ft^2)	2.4%	0.6%

Table 11. Sizing Effects of 5% Engine Weight Increase

	Allison PD577-1A6	Allison PD577-2A6
Δ TOGW (lb)	1.3%	1.0%
Δ OEW (lb)	0.7%	0.4%
Δ Fn (lb)	0.8%	0.9%
Δ S_W (ft^2)	2.1%	1.0%

E. Direct Operating Cost Analysis And Comparison

The direct operating cost method described in Section II was used to evaluate and compare the impact of propulsion system technology on the DOC+I of the SR-150 concept at a 500-NM stage length using US domestic rules. For the SR-150 this was done using two different airframe and engine pricing scenarios. The results for the SR-150 concept with both the baseline (PD577-1A6) and the advanced (PD577-2A6) Allison propulsion systems are shown in Figure 9 and in Tables 12, 13 and 14.

The summary results, shown graphically in Figure 9, indicate that when the airplane is configured with the advanced-technology Allison PD577-2A6 engine and that engine is priced on a market basis, the DOC+I is 3.1% less than the airplane configured with the current-technology PD577-1A6 engine. When the advanced-technology PD577-2A6 engine is developed as a follow-on to the PD577-1A6 engine and is priced on a delta-cost basis, the DOC+I difference increases to 4.8%. These conclusions assume the airframe is priced on a payload-range basis. When the airframe is priced on an airframe-weight basis and the advanced-technology engine is priced on a delta-cost basis, the DOC+I advantage increases from 4.8% to 7.1%.

The details behind the DOC+Is for the SR-150 concept are shown in Tables 12, 13, and 14. In each table, the advanced-technology propulsion system is compared to the conventional-technology propulsion system, with percentage differences shown for the technical and operational characteristics that drive the DOC+I values as well as for each of the DOC+I cost elements. In addition, each cost element is shown as a percentage of the total DOC+I, so as to indicate the relative impact of the change in each cost element to the total DOC+I change.

Table 12 details the case where the airframe is priced on a payload-range basis and both engines are priced on a market basis. The cash operating cost of the airplane configured with the advanced technology PD577-2A6 engine was 4.4% lower than the airplane configured with the current-technology PD577-1A6 engine. Of the cost components directly affected by the engine itself, the block fuel and fuel cost were reduced 17.1% using the advanced-technology engine, while the engine maintenance cost increased 12.5%. However, the engine maintenance cost increase was offset by its relatively small contribution to the total DOC+I. With the airframe price (based on PRI) unchanged between airplanes and the advanced-technology engine priced 7.4% less than the current-technology engine, partly because of reduced size (thrust), the ownership cost of the SR-150 with the advanced-technology engine is 1.4% lower than that of the SR-150 with the current-technology engine. The combination of the 4.4% reduction in cash costs and the 1.4% reduction in ownership cost afforded by the advanced-technology engine produced an overall reduction in DOC+I of 3.1%.

When the advanced-technology PD577-2A6 engine is priced on a delta-cost basis as opposed to being priced on a market basis (Table 13), its price difference relative to the -1A6 increases to 23.8%. Airframe price, still PRI-based, remains unchanged. The cash cost reduction remains unchanged at 4.4%. The further reduction in engine price produced an ownership cost reduction of 5.2%, and a total DOC+I reduction of 4.8%.

The alternate airframe and engine pricing case shown in Table 14, where the airframe price is airframe-weight based and the advanced-technology engine is priced on a delta-cost basis, essentially doubles the reduction in ownership cost, compared to the case just described and shown in Table 13. The 10.7% reduction in ownership afforded by the advanced-technology engine produced a total DOC+I reduction of 7.1%.

Table 12. SR−150 AIRCRAFT DOC SUMMARY & COMPARISON

[Baseline Case]

DOMESTIC RULES, $1993

ENGINE: TYPE : ENTRY−INTO−SERVICE [EIS]		PD577−1A6 1995	PD577−2A6 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] PD577−1A6	DOC+I DISTRIBUTION [% TOTAL] PD577−2A6
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	158,000	144,000	−8.9%		
MLGW	lbm	146,448	137,592	−6.0%		
OEW	lbm	92,600	84,400	−8.9%		
Airframe Weight	lbm	76,587	69,518	−9.2%		
Airframe Price	$M	$33.7	$33.7	0.0%		
Engine Thrust	lbf	26,610	24,640	−7.4%		
Engine Price	$M	$4.10	$3.84	−6.3%		
No. of Engines/Acft	−	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	500	500			
Block Time	hr	1.622	1.618	−0.2%		
Block Fuel	lbm	7,061	5,857	−17.1%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/Trip	[None]	[None]			
COCKPIT CREW	"	850	836	−1.7%	16.0%	16.2%
CABIN CREW	"	417	416	−0.2%	7.9%	8.1%
LANDING FEE	"	220	206	−6.0%	4.1%	4.0%
MAINT − AIRFRAME	"	573	545	−4.7%	10.8%	10.6%
MAINT − ENGINE	"	308	346	12.5%	5.8%	6.7%
FUEL	"	685	568	−17.1%	12.9%	11.0%
CASH DOC ==>	$/Trip	3,052	2,918	−4.4%	57.5%	56.7%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/Trip	1,296	1,278	−1.4%	24.4%	24.8%
INTEREST	"	893	881	−1.4%	16.8%	17.1%
INSURANCE	"	69	68	−1.2%	1.3%	1.3%
OWNERSHIP DOC ==>	$/Trip	2,258	2,227	−1.4%	42.5%	43.3%
TOTAL DOC ==>	$/TRIP	5,311	5,145	−3.1%	100.0%	100.0%

NOTES:
(1) Engine prices are market based.
(2) Airframe prices are based on payload−range index.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

Table 13. SR-150 AIRCRAFT DOC SUMMARY & COMPARISON
[Alternate Engine Pricing Case]

DOMESTIC RULES, $1993

ENGINE: TYPE / : ENGINE EIS DATE		PD577-1A6 1995	PD577-2A6 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% Total] PD577-1A6	PD577-2A6
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	158,000	144,000	-8.9%		
MLGW	lbm	146,448	137,592	-6.0%		
OEW	lbm	92,600	84,400	-8.9%		
Airframe Weight	lbm	76,587	69,518	-9.2%		
Airframe Price	$M	33.7	33.7	0.0%		
Engine Thrust	lbf	26,610	24,640	-7.4%		
Engine Price	$M	4.1	3.1	-23.8%		
No. of Engines/Acft	-	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	500	500			
Block Time	hr	1.622	1.618	-0.2%		
Block Fuel	lbm	7,061	5,857	-17.1%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/Trip	[None]	[None]			
COCKPIT CREW	"	850	836	-1.7%	16.0%	16.5%
CABIN CREW	"	417	416	-0.2%	7.9%	8.2%
LANDING FEE	"	220	206	-6.0%	4.1%	4.1%
MAINT - AIRFRAME	"	573	545	-4.7%	10.8%	10.8%
MAINT - ENGINE	"	308	346	12.5%	5.8%	6.8%
FUEL	"	685	568	-17.1%	12.9%	11.2%
CASH DOC ==>	$/Trip	3,052	2,918	-4.4%	57.5%	57.7%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/Trip	1,296	1,228	-5.3%	24.4%	24.3%
INTEREST	"	893	846	-5.3%	16.8%	16.7%
INSURANCE	"	69	66	-4.7%	1.3%	1.3%
OWNERSHIP DOC ==>	$/Trip	2,258	2,140	-5.2%	42.5%	42.3%
TOTAL DOC ==>	$/TRIP	5,311	5,058	-4.8%	100.0%	100.0%

NOTES:
(1) Engine prices are market based (-1A6) and delta-cost based (-2A6).
(2) Airframe prices are based on payload-range index.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

ALLISON PROPRIETARY INFORMATION

Table 14. SR–150 AIRCRAFT DOC SUMMARY & COMPARISON

[Alternate Airframe and Engine Pricing Case]

DOMESTIC RULES, $1993

ENGINE: TYPE / : ENTRY–INTO–SERVICE [EIS]		PD577–1A6 (1995)	PD577–2A6 (2005)	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] PD577–1A6	DOC+I DISTRIBUTION [% TOTAL] PD577–2A6
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	158,000	144,000	–8.9%		
MLGW	lbm	146,448	137,592	–6.0%		
OEW	lbm	92,600	84,400	–8.9%		
Airframe Weight	lbm	76,587	69,518	–9.2%		
Airframe Price	$M	34.0	31.6	–7.0%		
Engine Thrust	lbf	26,610	24,640	–7.4%		
Engine Price	$M	4.1	3.1	–23.8%		
No. of Engines/Acft	–	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	500	500			
Block Time	hr	1.622	1.618	–0.2%		
Block Fuel	lbm	7,061	5,857	–17.1%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	[None]	[None]			
COCKPIT CREW	"	850	836	–1.7%	16.0%	16.9%
CABIN CREW	"	417	416	–0.2%	7.9%	8.4%
LANDING FEE	"	220	206	–6.0%	4.1%	4.2%
MAINT – AIRFRAME	"	573	545	–4.7%	10.8%	11.0%
MAINT – ENGINE	"	308	346	12.5%	5.8%	7.0%
FUEL	"	685	568	–17.1%	12.9%	11.5%
CASH DOC ==>	$/trip	3,052	2,918	–4.4%	57.5%	59.1%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	1,304	1,165	–10.7%	24.6%	23.6%
INTEREST	"	898	803	–10.7%	16.9%	16.3%
INSURANCE	"	56	52	–7.0%	1.1%	1.1%
OWNERSHIP DOC ==>	$/trip	2,259	2,020	–10.6%	42.5%	40.9%
TOTAL DOC ==>	$/TRIP	5,311	4,938	–7.0%	100.0%	100.0%

NOTES:

(1) Engine prices are market based (–1A6) and delta–cost based (–2A6).

(2) Airframe price is based on airframe weight.

(3) Trip costs are rounded to the nearest $1/trip.

(4) Engine thrust is shown on a sized, uninstalled basis.

IV. SUMMARY

A study to examine the sole effect of advanced technology engines on the performance and DOC+I of a 150-passenger subsonic transport airplane has been completed. Two airplanes were designed and sized: one using the current technology (1995) Allison engine PD577-1A6 as a baseline, and one using the advanced technology (2005) Allison engine PD577-2A6. All other aircraft technologies were kept constant. The year 2005 was selected as the entry-into-service date for the airframe/engine combinations.

The advanced technology engine provided significant reductions in fuel burn, weight, and wing area as follows:

reduction in fuel burn	=	17%
reduction in wing area	=	10%
reduction in TOGW	=	9%

These corresponded to a range of DOC+I reductions from 3.1% to 7.1% depending on the airframe/engine pricing models used. The DOC+I reduction of 7.1% was obtained using the airframe price based on airframe weight and the advanced technology engine price based on delta-cost relative to the baseline engine.

It is recommended that the results of this study be viewed from more than a single perspective: the physical characteristics of the airplanes themselves (TOGW, OEW, Sw, Fn, etc.), and the corresponding DOC+I figures. The economic analyses have been defined in two forms: 1. airframe cost based on the mission (number of passengers and range), which result in the airframe cost being invariant between the current and advanced technology airplanes, and 2. airframe cost varying with airframe weight. The first method forces the DOC+I increment between the current and advanced technology airplanes to become dependent solely on engine price, maintenance cost, and fuel burn. No specific reward is offered for the reduction in airplane size and weight provided by the advanced technology powerplants. Alternatively, the second method provides a more direct reward for the advanced technology in both engines and airframe. These two economic algorithms may be regarded as bounding the problem, and the true economic benefit probably lies somewhere in between their DOC+I predictions.

Finally, it should be understood that the scope of the present study did not allow for an optimization of the matching of engines to the airplanes and the design mission. A careful iterative analysis should yield an increase in the performance benefits offered by the advanced technology engines.

APPENDIX

SR-150 Detailed Weight Summaries

PROGRAM **PAIT #9** CONFIGURATIC **SR-150/ALSN VHBR PD-577-1A6** DATE & TIME : 12/16/94 14:29

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	14,463	
BENDING MATERIAL		6,333
SPAR WEB		675
RIBS AND BULKHEADS		728
AERODYNAMIC SURFACES		4,899
SECONDARY STRUCTURE		1,828
TAIL	3,631	
FUSELAGE	16,574	
LANDING GEAR	5,516	
NACELLE & PYLON	3,782	
AIR INDUCTION	1,029	
PROPULSION	18,660	
ENGINES		12,524
ENGINES SYSTEM		2,017
EXHAUST SYSTEM		224
THRUST REVERSER		3,125
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		770
FLIGHT CONTROLS	1,749	
COCKPIT CONTROLS		122
SYSTEM CONTROL		1,627
POWER SYSTEMS	4,532	
AUXILIARY POWER PLANT		990
HYDRAULICS		772
PNEUMATICS		470
ELECTRICAL		2,300
INSTRUMENTS	840	
AVIONICS & AUTOPILOT	1,550	
FURNISHINGS & EQUIPMENT	12,970	
AIR CONDITIONING	1,680	
ANTI-ICING	596	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	87,571	
OPERATIONAL ITEMS	5,030	
OPERATING EMPTY WEIGHT	92,601	
USABLE FUEL	33,768	
PAYLOAD	31,500	
TAKEOFF GROSS WEIGHT	157869	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 1,147	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 22,995	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 137.6
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2913
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.2139
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 31,500	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 43,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	33,180	33,180	= 0.1575 SWT^ 1.74
CENTER WING	588	17,062	= 3.9009 SWT^ 1.19
FUSELAGE			
TOTAL	33,768	50,242	

SIZING DERIVATIVES

dOEW/dWG = 0.12489

dOEW/dSW = 10.07467

dOEW/dT OR dP = 0.65082

Wconstant = 46,364

PAGE 2
SR-150 /PD-577-1A6-DDN

Table A1. Base engine SR-150 Aircraft Group Weight Statement

Table A2. Advanced engine SR-150 Aircraft Group Weight Statement

PROGRAM **PAIT #9** CONFIGURATION **SR-150/ALSN VHBR PD-577-2A6** DATE & TIME : 12/16/94 14:31

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	12,889	
BENDING MATERIAL		5,680
SPAR WEB		600
RIBS AND BULKHEADS		625
AERODYNAMIC SURFACES		4,357
SECONDARY STRUCTURE		1,628
TAIL	3,357	
FUSELAGE	16,370	
LANDING GEAR	4,985	
NACELLE & PYLON	3,073	
AIR INDUCTION	992	
PROPULSION	14,050	
ENGINES		8,511
ENGINES SYSTEM		1,809
EXHAUST SYSTEM		112
THRUST REVERSER		2,913
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		705
FLIGHT CONTROLS	1,611	
COCKPIT CONTROLS		122
SYSTEM CONTROL		1,489
POWER SYSTEMS	4,467	
AUXILIARY POWER PLANT		990
HYDRAULICS		707
PNEUMATICS		470
ELECTRICAL		2,300
INSTRUMENTS	840	
AVIONICS & AUTOPILOT	1,550	
FURNISHINGS & EQUIPMENT	12,970	
AIR CONDITIONING	1,680	
ANTI-ICING	536	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	79,369	
OPERATIONAL ITEMS	5,030	
OPERATING EMPTY WEIGHT	84,399	
USABLE FUEL	28,082	
PAYLOAD	31,500	
TAKEOFF GROSS WEIGHT	143981	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 1,030	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)		= 21,266
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 139.8
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2954
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.1950
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 31,500	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 43,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	27,515	27,515	= 0.1575 SWT^ 1.74
CENTER WING	567	15,012	= 3.9009 SWT^ 1.19
FUSELAGE			
TOTAL	28,082	42,527	

SIZING DERIVATIVES

dOEW/dWG = 0.12441

dOEW/dSW = 10.00485

dOEW/dT OR dP = 0.53684

Wconstant = 44,765

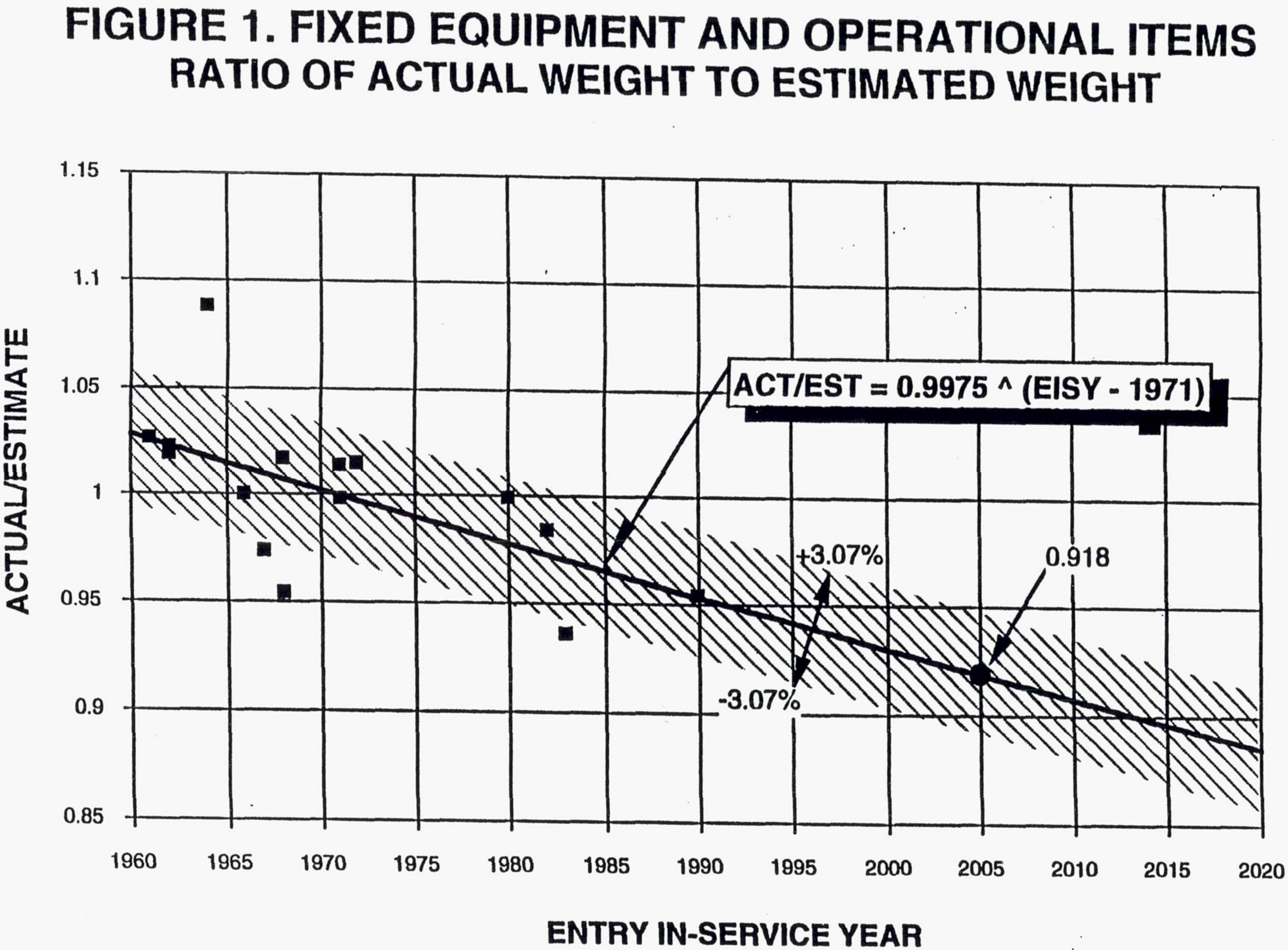

Figure 1. Fixed Equipment and Operational Items Ratio of Actual Weight to Estimated Weight

FIGURE 2. ENGINE POD WEIGHT/ THRUST RATIO

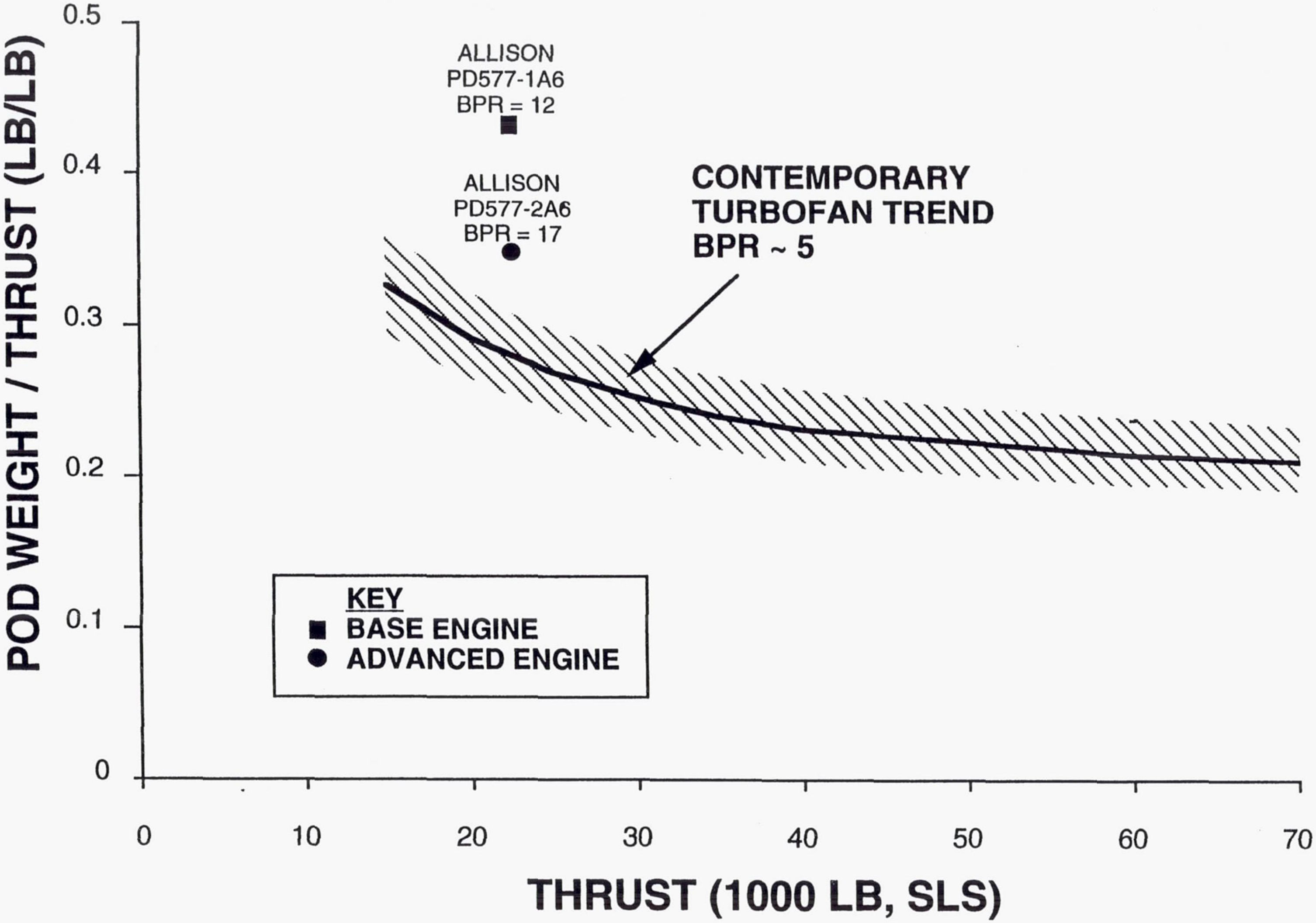

Figure 2. Engine Pod Weight/Thrust Ratio

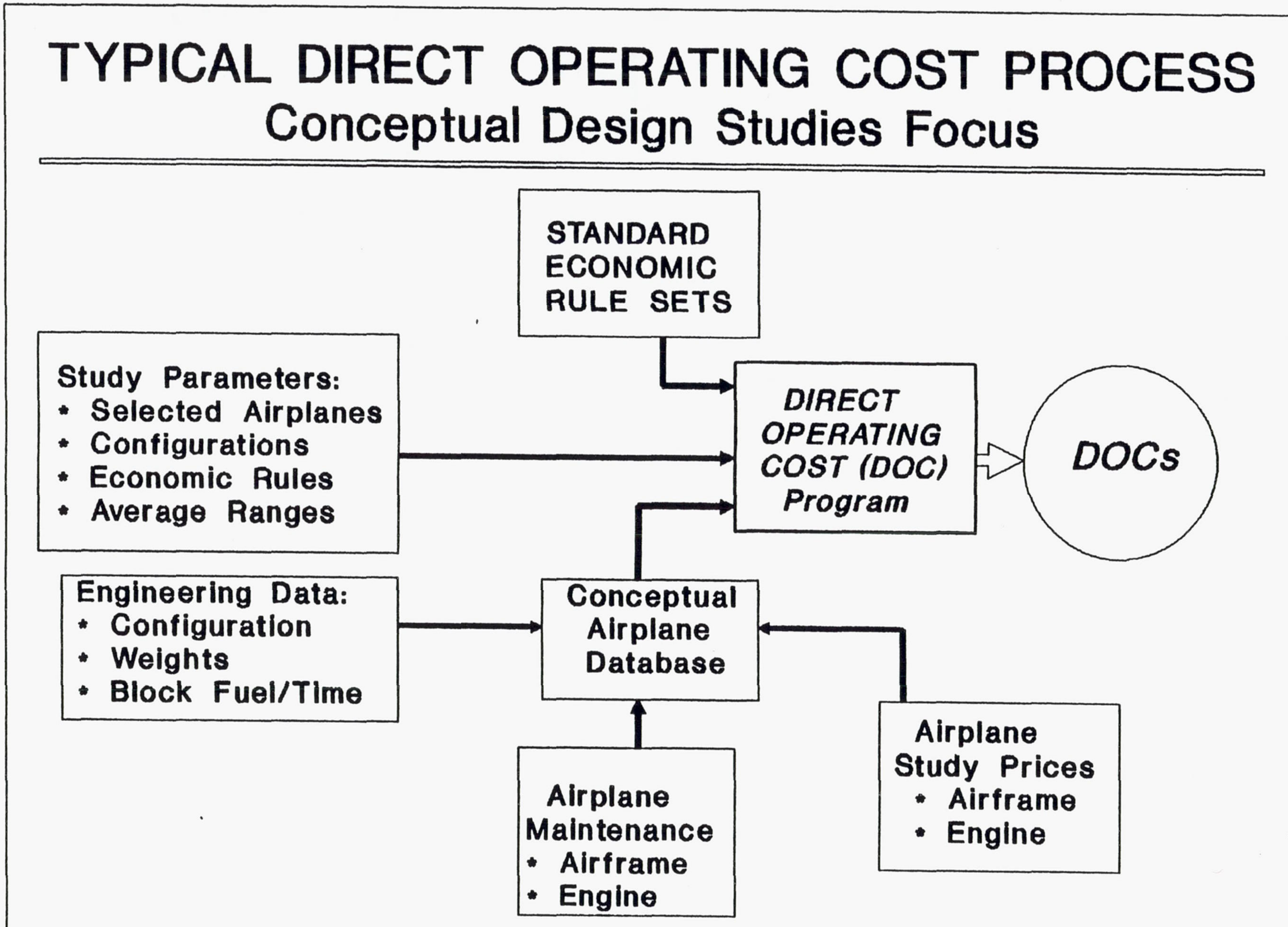

Figure 4. Typical DOC Process

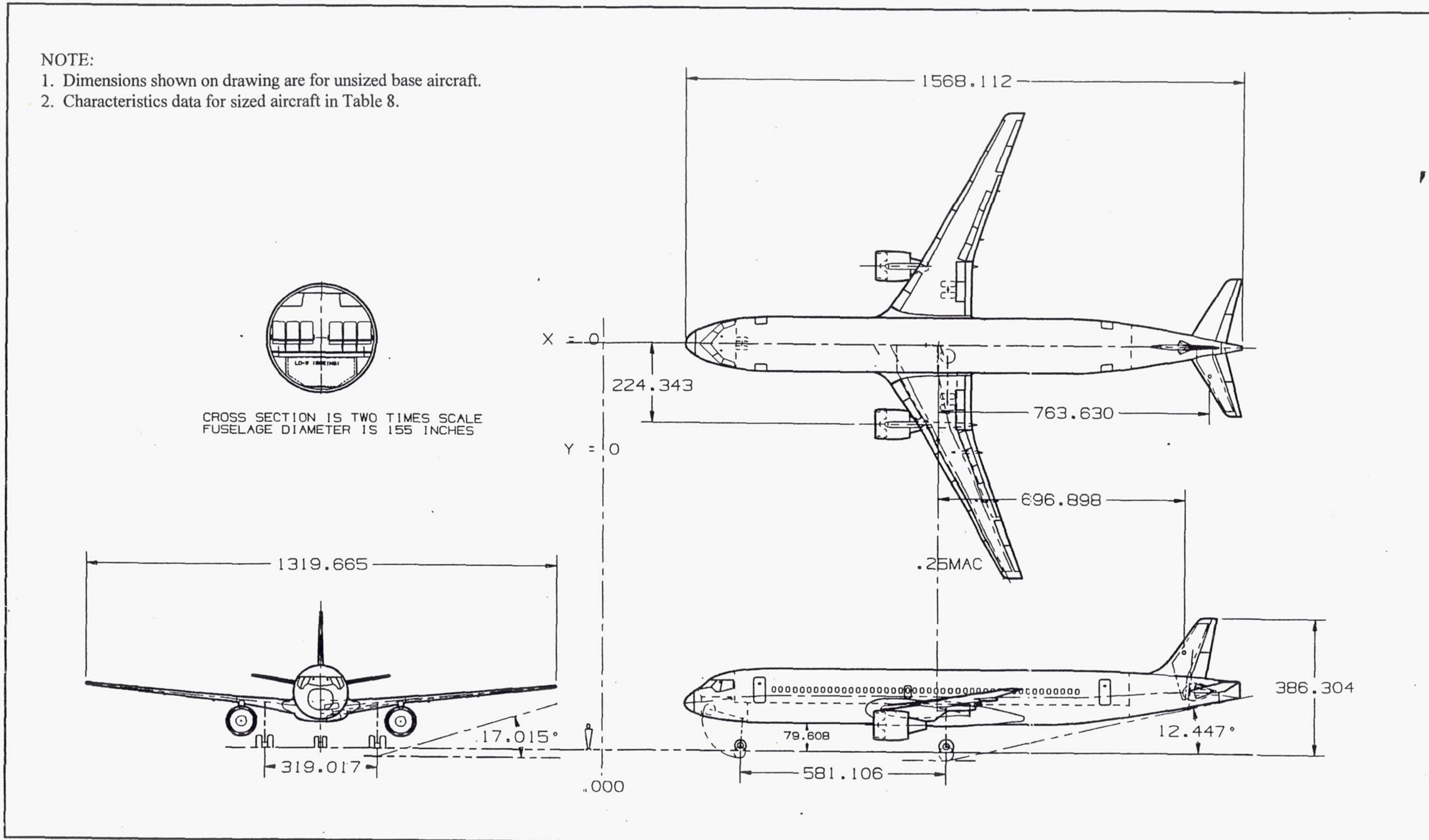

Figure 5. General Arrangement - SR-150

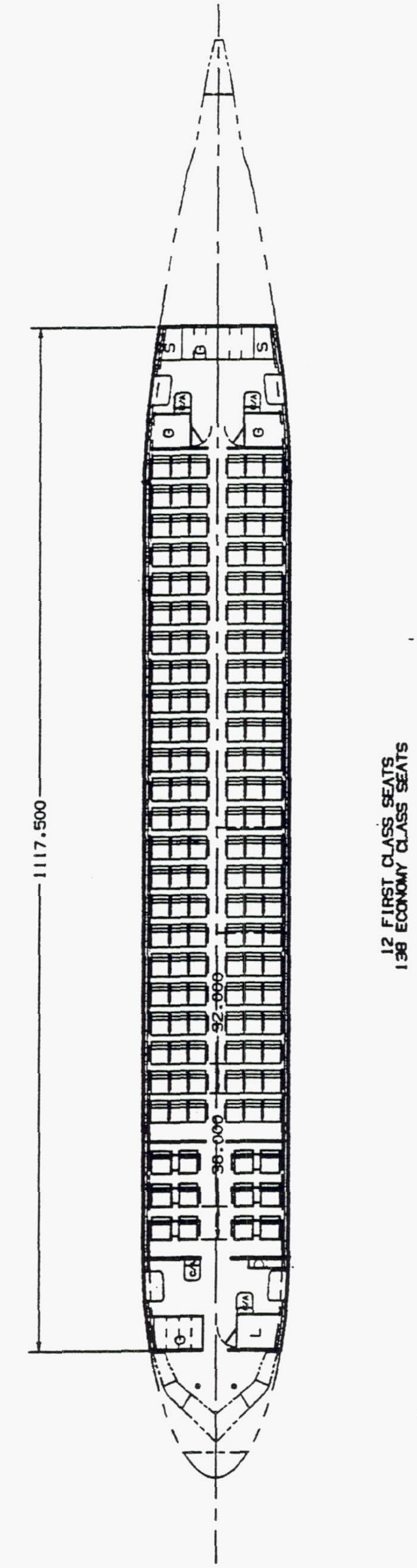

Figure 6. Interior Arrangement - SR-150

UNCLASSIFIED

Advanced Subsonic Technologies Evaluation Analysis

NASA Contract NAS3-25459-Task 7

SELECTED BASELINE ENGINE

PD577-1A6 Performance and Configuration

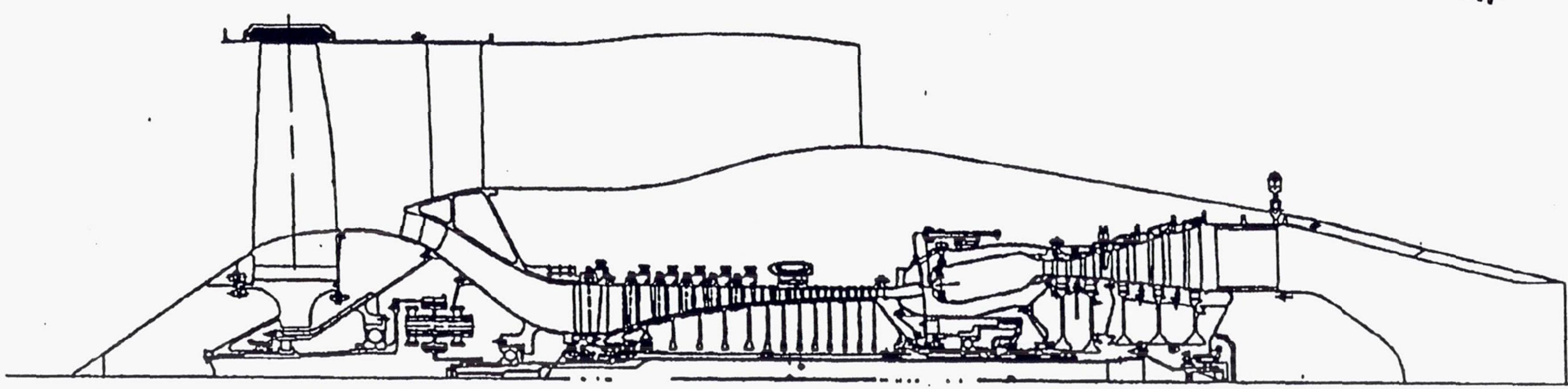

Figure 7. Allison Baseline Engine PD577-1A6 Configuration

Allison
UNCLASSIFIED

Advanced Subsonic Technologies Evaluation Analysis

NASA Contract NAS3-25459-Task 7

SELECTED ADVANCED ENGINE
PD577-2A6 Performance and Configuration

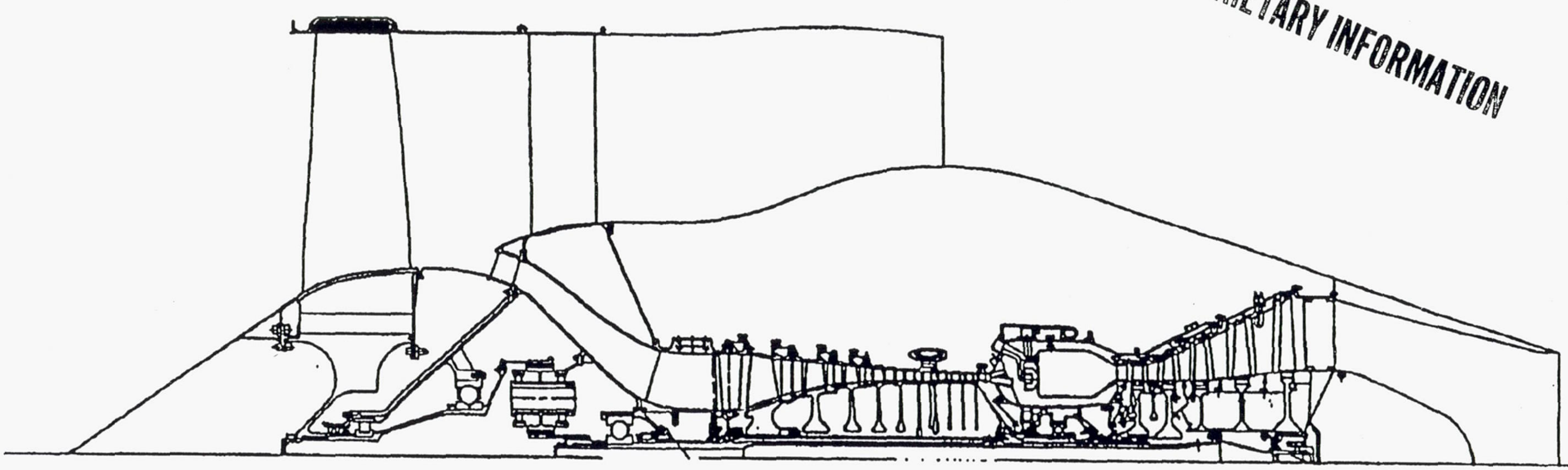

Figure 8. Allison Advanced Engine PD577-2A6 Configuration

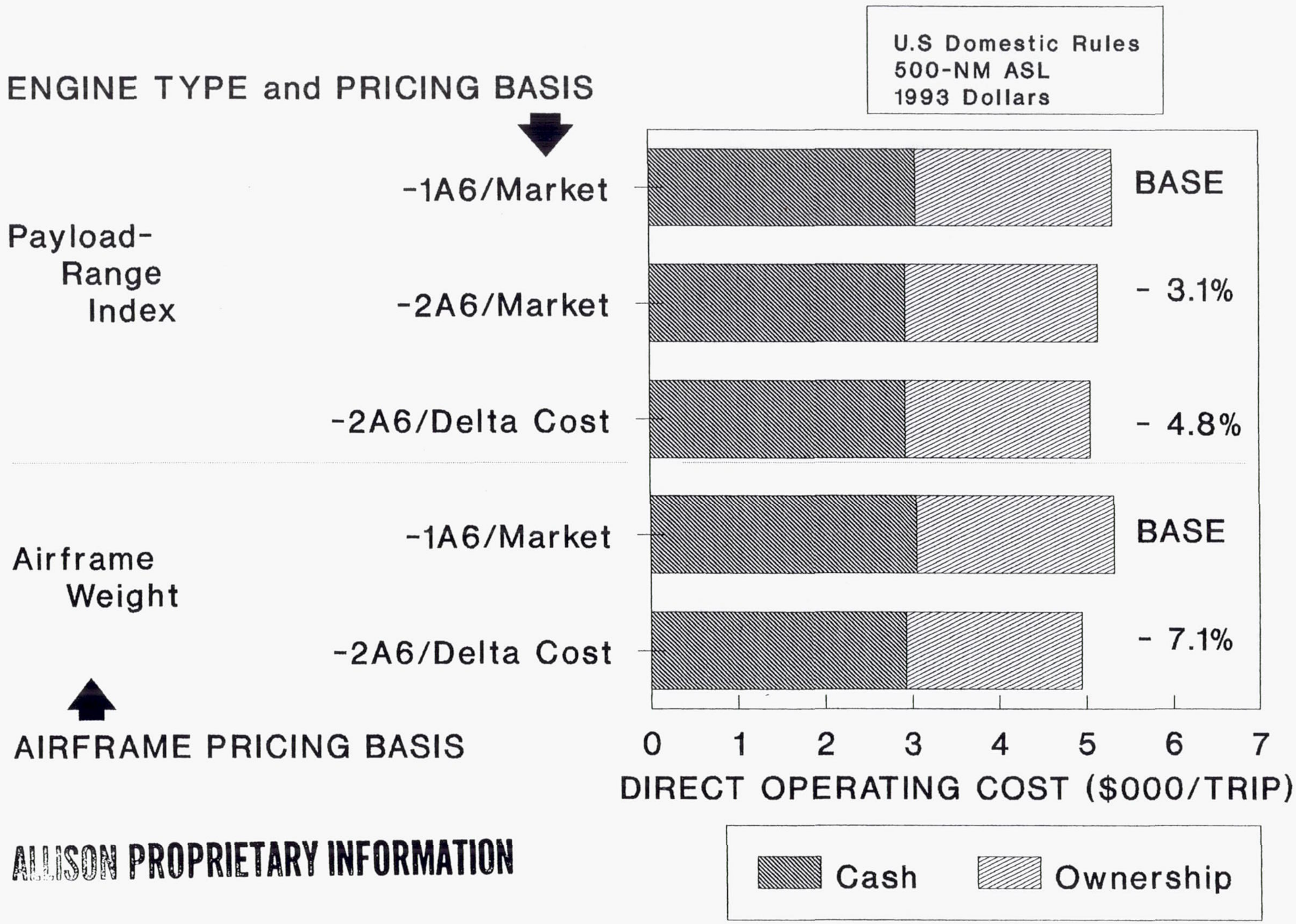

Figure 9. SR-150 DOC+I RESULTS

ADVANCED SUBSONIC AIRPLANE DESIGN & ECONOMIC STUDIES

APPENDIX B: 225-PASSENGER AIRPLANES WITH GE ENGINES

Robert H. Liebeck, Donald A. Andrastek, Johnny Chau, Raquel Girvin, Roger Lyon, Blaine K. Rawdon, Paul W. Scott, Robert A. Wright
MCDONNELL DOUGLAS AEROSPACE, LONG BEACH, CALIFORNIA

Contract NAS3-25965, Task 9

April 1995

National Aeronautics and
Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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PREFACE

This report was prepared by McDonnell Douglas Corporation under Task Assignment 9 of contract NAS3-25965 for NASA Lewis Research Center as an appendix to NASA CR-195443. This report contains GE Aircraft Engines proprietary data.

The NASA technical monitors were Joseph D. Eisenberg and Felix R. Torres. The McDonnell Douglas Program Manager was Robert H. Liebeck. The members of McDonnell Douglas team that participated in this task order and deserve recognition for their contributions are as follows:

Aerodynamics	Robert S. Bird, Johnny Chau, Roger Lyon
Configuration	Robert A. Wright, Blaine K. Rawdon
Economics	Donald A. Andrastek, Madeline Ellis
Propulsion	Raquel Girvin, Susan M. Koval, James K. Wechsler
Secondary Power	Kenneth R. Williams
Weights	Dennis Nguyen, Paul W. Scott

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I. INTRODUCTION

The purpose of this study is to examine the effect of advanced technology engines on the performance of subsonic transport airplanes and provide a vision of the potential which these advanced engines offer. The year 2005 has been set as the entry-into-service (EIS) date for the engine/airframe combination. A set of four transport airplane classes (passenger and design range) that are envisioned to span the needs for the 2005 EIS period have been defined. This problem could be approached utilizing existing airframes with advanced technology engines, however, since the origin of some the existing (and currently produced) airframes dates back more than two decades, a consistent framework for evaluation becomes difficult. Consequently, 2005 EIS advanced technology airframes have been designed and sized for all classes.

Two airplanes have been designed and sized for each class: one using current technology (1995) engines to provide a baseline, and one using advanced technology (2005 EIS) engines. The resulting engine/airframe combinations have then been compared and evaluated on the basis of sensitivity to the basic engine performance parameters (e.g. SFC and engine weight) as well as DOC+I. Noise and emissions have not been considered in the present study.

Participants in this study include: McDonnell Douglas Aerospace for the design, sizing and evaluation of the airplanes, and the three engine companies; Allison, GE Aircraft Engines, and Pratt and Whitney who have provided the engine data for their current and advanced technology engines. Proprietary considerations preclude the documentation of this study in single report, and therefore a separate report has been prepared for each engine company. General discussions pertaining to all airplanes are common to all reports.

II. APPROACH

A. Mission Definition

Four airplane design missions have been defined and are summarized in Table 1; the designations SR-150, MR-225, MR-275, and LR-600 are used in these reports to refer to these four airplane types respectively. These were selected to represent the complete spectrum of subsonic transport requirements envisioned for the year 2005 and beyond. Commuter missions have not been considered in this study. To claim that these missions accurately and precisely define air transportation's needs in 2005 would of course be naive, however, they represent the best judgment at this writing.

Of the four missions, the long range (600 passenger, 7500 n.mi.) is the most speculative, particularly with respect to the payload. The 7500 n mi range is regarded as serving all

meaningful city-pair requirements. Very large aircraft (VLA's) are defined as 500 to 1000 passengers, so the choice for this study is somewhat near the lower bound. Increasing the payload would be straightforward, however, the 800-1000 level could begin to deteriorate the accuracy and resolution of existing data bases for weights.

Table 1. Subsonic Airframe/Propulsion Integration
Airplane Design Specifications
2005 EIS

Category	Seats	Rules	Range (N.Mi.)	Cruise Mach No.	ICA (Ft)	VAP (Kts)	TOFL (Ft)
Short Range	150	2 Class Narrow Body	2500	.78	31,000	130	7,000
Medium Range	225	2 Class Twin Aisle	4500	.80	35,000	135	7,500
Medium Range	275	3 Class Interna-tional	6000	.83	35,000	140	9,000
Long Range	600	3 Class Interna-tional	7,500	.85	31,000	150	11,000

B. Airframe Technology Definition

Technology for all airframes is based on a 2005 entry-into-service date. The philosophy used in selecting technology levels was to lean to the optimistic but maintain reality. The resulting airplanes thus show measurable reductions in size and weight over those which would be obtained from simple derivatives of existing airframes. Specific technologies are described below.

1. Aerodynamics

All wing designs are based on advanced supercritical divergent trailing edge airfoils which are highly loaded to minimize wetted area. Selection of a composite wing structure allows a relatively high aspect ratio limit of 11. High-lift system design and performance is based on the technology developed for the MD-12. This utilizes a full-span leading edge slat and a track motion flap system with two segments inboard and a single segment outboard. The system provides high values of C_{Lmax} and L/D for both takeoff and landing configurations.

2. Structure

Advanced composites are used for the entire wing and empennage structure. Fuselage structure utilizes aluminum-lithium longerons with the skins made from GLARE, an aluminum and fiberglass laminate. This combination of materials and structural design yields structural weight reductions which are shown in Table 6.

3. Stability and Control

The Stability & Control terms that strongly affect the aircraft performance are vertical and horizontal tail size, and cruise center-of-gravity (C.G.). The lateral controls affect the available flap span and therefore C_{Lmax}. Further, if the outboard ailerons suffer from aeroelastic reversal, then it is necessary to add inboard ailerons in the stiff mid-span region. Unfortunately, these inboard ailerons also reduce flap area and distort the takeoff and landing spanloads which hurts low-speed L/D. For these reasons the wing structure is sized to preclude aileron reversal in the operational speed range and therefore no inboard aileron is required.

The horizontal tail sizes are based on an advanced high-lift tail with a slotted elevator that can deflect -35° for low-speed takeoff rotation. The slot door is articulated to provide a sealed aerodynamically smooth surface at low elevator deflections. The unaugmented static stability of the airplanes is set to -15%MAC at aft C.G. for the critical V_{FC}/M_{FC} condition where aeroelastic losses are greatest. This static stability level places the C.G. at the Maneuver Point which represents neutral stability from a load-factor standpoint.

The vertical tail is sized for minimum ground control speed (V_{mCG}) on the twin engine airplanes, and two engine-out landing speed (V_{mCL-2}) for the four engine airplanes. In all cases, the all-flying tail concept is used to minimize tail area. This feature requires larger actuators, a pivot shaft, and additional supporting structure, but reduces the tail size by nearly 50% since the fin can be deflected in addition to the rudder.

4. Systems

This arrangement, chosen for the baseline study aircraft, yields weight and complexity reductions, as well as robustness for both the signalling and the power systems.

It should be noted that the secondary power system arrangement chosen for the baseline study aircraft represents the anticipated 2005 EIS technology, which integrates the conventional pneumatic, electrical and hydraulic systems into one electrically powered system. This Power-by-Wire (PBW) system requires only shaft power extraction from the engine. An allowance has been made in this study for other airframe applications which would require engine bleed air, but this has been limited to 1% of the engine core airflow.

This type of secondary power system makes possible the consideration of future very high bypass engines, whose smaller core airflow would not allow the use of conventional bleed air utilization. These PBW secondary power systems are compatible with the present engines used in the study, and therefore provide for a generic evaluation of the results, with respect to engine type verus secondary power system installation. Table 2 shows the actual anticipated engine extraction expected for each of the study aircraft types.

Table 2. Power Extraction versus Aircraft Type

AIRCRAFT TYPE		POWER EXTRACTION	PER ENGINE
Short Range 150 Passengers	Shaft	225 hp Norm. (167.6 Kva)	281 hp Max. (209.5 Kva)
	Air	1% core flow max;	30 hp
Medium Range 225 Passengers	Shaft	379 hp Norm. (282.7 Kva)	474 hp Max. (353.4 (Kva)
	Air	1% core flow max;	70 hp
Medium Range 275 Passengers	Shaft	394 hp Norm. (293.7 Kva)	492 hp Max. (367.2 Kva)
	Air	1% core flow max;	85 hp
Long Range 600 Passengers	Shaft	559 hp Norm. (416.8 Kva)	698 hp Max. (521.0 Kva)
	Air	1% core flow max;	120 hp

C. Engine Definition

Each of the three engine companies defined their current and advanced technology engines according to each company's design philosophy and technology base. Relative to the current engines, the advanced technology engines incorporate cycle, materials, and turbomachinery efficiency and design improvements.

The three pairs of current and advanced technology engines used in this study are listed below in Table 3. The Allison engines were used for the short-range/150-passenger airplanes, the GE engines were used for the medium-range/225-passenger airplanes, and the P&W engines were used for both the medium-range/275-passenger and long-range/600-passenger airplanes. The short and medium-range airplanes were configured with two engines; the long-range airplanes had four engines.

Table 3. Baseline and Advanced Engine Model Designations

Engine Company	Baseline Engine (1995 EIS)	Advanced Engine (2005 EIS)
Allison	PD577-1A6	PD577-2A5/6
GE Aircraft Engines	Baseline ASTEA	Advanced ASTEA
Pratt & Whitney	PW4484	STS1046

D. Configuration Definition and Rules

A conventional configuration with pylon-mounted wing engines was selected. This arrangement isolates the engine inlets from the airframe so that engine technology changes can be analyzed without airflow complications. Interior accommodations are set for 225 passengers using Douglas Aircraft Company (DAC) rules for a two class seating arrangement with two aisles for short/medium range flights with 9 percent first class, and the remainder economy class with a 32 inch seat pitch. Flight crew requirements are derived from the FAR Part 121, subpart R, paragraph 121.480.

Once sized, the fuselage is considered a constant, while the engine technology level used will re-size the wing, empennage, landing gear, engine size (thrust), and fuel requirement.

E. Airplane Sizing and Performance

1. Propulsion model

The airplanes were sized using engine performance data provided by GE for the baseline and advanced ASTEA engines. Data were provided for a large matrix of takeoff and climb/cruise flight conditions. Thrust and fuel flow were extracted from the GE engine datapacks and loaded into the McDonnell Douglas airplane sizing program which in turn interpolated and scaled the engine data according to the airplane mission requirements.

2. Weight Estimation Model

MDC's proprietary Conceptual Weight Estimation Program (CWEP) requires inputs such as geometrical parameters, design criteria, and advanced technology multipliers. CWEP uses a series of weight estimating relationships (WERs) and a modified Breguet range equation to develop the initial aircraft sizing parameters, which are then processed by the more sophisticated CASES sizing code. The sizing parameters (shown in Table 4) consist of the partial derivatives of Operational Empty Weight (OEW) with respect to gross weight, wing area, and thrust plus a constant weight. To obtain the final aircraft weight, the CASES wing area, thrust, and gross weight are input to CWEP. The resulting group weight statement is used for cost estimation. Both the sizing derivatives and the group weight statements are shown in the tables at the end of this section.

TABLE 4. Aircraft Sizing Derivatives

$$OEW = W_c + \frac{\partial OEW}{\partial W_g}(W_g - W_{g_o}) + \frac{\partial OEW}{\partial S_W}(S_W - S_{W_o}) + \frac{\partial OEW}{\partial T}(T - T_o)$$

$$W_g = OEW + W_{pl} + W_{fuel}$$

OEW = Operational Empty Weight (lb)

$\frac{\partial OEW}{\partial S_W}$ = Partial derivative of OEW with respect to wing area (lb / ft^2)

$\frac{\partial OEW}{\partial T}$ = Partial derivative of OEW with respect to Thrust (lb / lb)

$\frac{\partial OEW}{\partial W_g}$ = Partial derivative of OEW with respect to MTOGW (lb / lb)

S_W = Wing area (ft^2)

S_{W_o} = Base wing area (ft^2)

T = Thrust per engine, sea level static rated (lbf)

T_o = Base thrust per engine, sea level static rated (lbf)

W_c = Base constant weight (lb)

W_g = Maximum Takeoff Gross Weight (lb)

W_{g_o} = Base Maximum Takeoff Gross Weight (lb)

W_{fuel} = Fuel Weight (lb)

W_{pl} = Payload weight (lb)

Design Criteria

The aircraft's maximum takeoff gross weight (MTOGW) is defined by the requirement to transport the maximum design passenger capacity over the design range. The full complement of passengers and bags at 210 lb each defines the performance payload (WPPL), which is shown in Table 5. The maximum payload (WMPL) reflects the heaviest payload that the aircraft must carry and influences the structural weight. As is typical for commercial aircraft, the configurations for this study are designed for a 2.5 limit load factor and a 10 ft/sec limit landing sink rate.

The MR-225 is designed to provide an 8000 ft cabin pressure at 43,000 ft. This results in a limit differential cabin pressure (PD) of 8.6 psig for this aircraft. The maximum speeds in a dive (VD) for the aircraft are also presented in Table 5.

TABLE 5. Design Criteria

CONFIGURATION	WPPL (lb)	RANGE (nm)	WMPL (lb)	PD (psig)	VD (KEAS)
MR-225	47,250	4,500	77,000	8.6	410

Advanced Technology Weight Impacts

CWEP utilizes advanced technology multipliers (ATMs) to reflect the technology level. The ATMs of Table 6 are based on an entry into service date (EIS) of 2005 as referenced to the database of operational aircraft. The structural weight increments of advanced composites in newer operational transports have been factored out in order to normalize the database.

The wing and tail incorporate maximum use of advanced composites, but metallics are assumed for leading edges, aerodynamic surface hinges, and at critical joints. More dramatic weight reductions may be feasible, but commercial transports must emphasize low cost of manufacturing and maintenance. The fuselage uses GLARE skins, Aluminum-Lithium longerons, and advanced composite secondary structure. The landing gear utilizes carbon brakes, radial tires and steel struts with a moderate improvement material properties.

The fixed equipment ATM's are empirically derived trends that reflect numerous weight reductions due to technology improvements, many of which are offset by increased capabilities and improved functionality. The term "fixed equipment" refers to those items whose weight is insensitive to changes in MTOGW and includes furnishings, APU, pneumatics, air conditioning, electrical, instruments and avionics. The weight of fixed equipment items tend to scale with fuselage size. Dividing the sum of actual aircraft fixed equipment weights plus operational item weights by the value estimated by a WER and plotting this versus the EIS date of each aircraft determines the ATM trend versus EIS date. This trend curve, shown in Figure 1, estimates an ATM of 0.918 for a 2005 EIS. However, this factor is not distributed evenly across all of the components.

Table 6. Advanced Technology Multipliers for 2005 EIS

FUNCTIONAL GROUP	ATM	COMMENTS
Wing		
Bending material	0.75	
Spar webs	0.75	
Ribs and bulkheads	0.75	
Aerodynamic surfaces	0.92	
Secondary structure	0.83	
Tail	0.80	
Fuselage	0.95	
Landing gear	0.91	
Nacelle and Propulsion	NA	By engine manufacturer
Flight controls & Hydraulics	0.95	
APU, Pneumatics, Air Conditioning Electrical, Instruments & Avionics	0.976	
Furnishings & Equipment	0.869	
Operational items	0.976	

Although a EIS 2005 transport may be all-electric, there is scant empirical data on such systems and no reliable rational for identifying related weight increments, therefore none are assumed.

GE Aircraft Engines
Proprietary Information

Propulsion System Weights

All engine pod weights are provided by the engine manufacturers. The ratio of these pod weights to their rated thrust is presented in Figure 2. Both GE baseline and advanced engines fall within the trend curves.

When adequate detail is provided by the manufacturer, MDC uses a MIL-STD-1374A functional weight reporting format for the propulsion related weights. MIL-STD-1374A allocates the inlet cowl to the Air Induction Group, and the fan cowl doors plus the pylon are charged to the Nacelle Group. The fan exhaust duct, core cowl and nozzle are allocated to the exhaust system, which is part of the Propulsion Group. In some instances, the fan exhaust duct and the thrust reverser weights are reported as an assembly and cannot be separately identified.

MDC estimates the propulsion related items that are external to the pod, such as the engine pylons and the aircraft's fuel system. Lacking detailed engine pylon drawings, all pylons are estimated to weigh 16 % of the pod weight, a value that is typical of the highly cantilevered pylons on modern commercial transport aircraft. All of the PAIT aircraft are assumed to carry fuel in their outer and center wings. With the exception of the SR-150, all configurations are assumed to have a trim tank in their horizontal stabilizer.

Detailed Weight Summaries

Tables A1 and A2 present the group weight statements for the base engine and advanced engine MR-225 configurations respectively. The weight sizing derivatives and maximum fuel capacities are also reported in each table.

3. Aerodynamic model

High Lift System

The high lift system is composed of a slat plus Fowler-motion flap. At takeoff, the slat is sealed, and it is fully open at landing. An "auto-slat" system is utilized to reduce takeoff speed by automatically opening the slats from the sealed takeoff position to the open landing position if stall is approached. This makes available the high C_{Lmax} of the open slat with the high L/D of the sealed slat. The trailing edge system is composed of two spanwise flap segments plus drooped ailerons. Inboard, the flap has two elements with the auxiliary element remaining stowed at takeoff. Midspan and outboard flaps are single element. Maximum flap setting is 30°.

Low speed aerodynamic characteristics were estimated using a combination of flight and wind tunnel test data as well as conceptual handbook methods. Lift and drag data were assembled and trimmed using the MDA CASES aircraft sizing program. All takeoff data and C_{Lmax} were trimmed at the forward CG limit, and all landing data was trimmed at the mid CG position.

Transonic

High speed aerodynamic data were based on a combination of MDA advanced design methodology and empirical data which has been substantiated by wind tunnel tests of advanced technology transport aircraft. Wing design and performance is based on the latest advanced technology supercritical airfoils with divergent trailing edges.

4. Sizing Procedures (CASES)

MDC's proprietary Configuration Aircraft Sizing and Evaluation System (CASES) was used for the evaluation and optimization of the aircraft in this report. The program is designed to facilitate the sizing of aircraft to meet specific mission requirements for payload, range, takeoff field length, approach speed, initial cruise altitude, and other requirements. The program requires inputs from Aerodynamics, Propulsion, Stability & Control and Weights. The sizing parameters require inputs such as wing area (S_W), TOFL, and thrust. The design optimization is accomplished with interactive plotting routines which provide visual relationships between the geometric variables, design constraints, and optimization criteria used. Figure 3 shows the sizing carpet plot created in CASES with varying wing areas (S_W) and thrusts. From the plot, the minimum TOGW or fuel burned to meet the initial cruise altitude can be obtained.

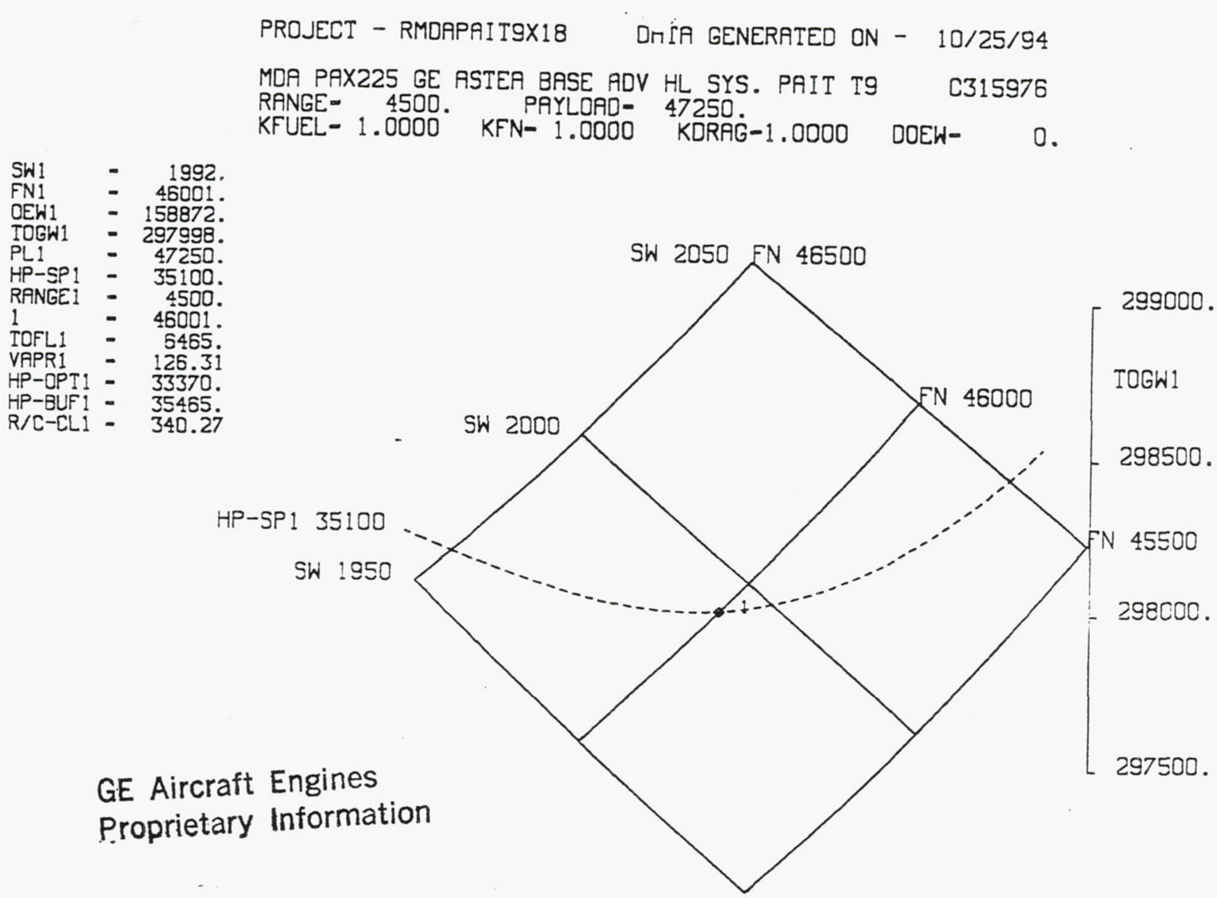

Figure 3. Typical CASES Sizing Carpet Plot

F. Sensitivity Analysis

Sensitivity studies have been conducted to estimate the effect on maximum takeoff gross weight of increases in engine weight and SFC relative to target at entry into service. Both the baseline (1995) and advanced technology (2005 EIS) engined airplanes have been analyzed. Increments of plus 5 percent in engine + pod + pylon weight and SFC have been applied, and the resulting airplanes have then been re-sized to meet the design criteria of Table 1.

G. DOC+I Method and Rules

1. Introduction

This section presents the direct operating cost rules and calculation process used to evaluate and compare the MR-225 airplane concept with current-technology and advanced-technology General Electric (GE) turbofan engines. The economic analysis focus was on the first-level effects of advanced propulsion system technology with respect to airplane performance (block time, block fuel) and airplane economics (DOC for a typical average stage length (ASL) of 3,000 NM , using international rules).

The economic criterion used for evaluating and comparing the effect of advanced propulsion systems on airplane design and operation was Direct Operating Cost (DOC). The Air Transportation Association of America, in 1944, published the first universally recognized method for estimating direct operating costs of airplanes. That ATA method was progressively updated through the years with inputs from ATA member airlines and prime airframe and engine manufacturers. The ATA standard method of estimating comparative direct operating costs of turbine powered transport airplanes, last published in December 1967, formed the basis for the method and approach used for this study.

The DOC method used for this study was based on the combination of ground rules and assumptions developed collectively by McDonnell Douglas Corporation (MDC) and its commercial aircraft component, Douglas Aircraft Company (DAC), the Boeing Commercial Airplane Group (BCAG), and NASA's Lewis Research Center (LeRC). The method was referred to as the "DOC+I" method, since the interest cost element was added. In addition, cabin crew costs, landing fees and navigation fees, usually considered to be indirect operating costs by the former Civil Aeronautics Board (CAB), were also added to the original ATA DOC cost element structure. Using DOC+I to describe this method affords a way to discriminate from the basic ATA DOC method.

With the aforementioned additions to the basic ATA DOC method, the DOC+I cost element structure for this study included the following cost elements:

(1) Flight Crew
(2) Cabin Crew
(3) Landing Fees
(4) Navigation Fees

(5) Maintenance - Airframe
(6) Maintenance - Engine
(7) Fuel
(8) Depreciation - Aircraft and Spares
(9) Insurance
(10) Interest

Elements (1) through (7) are commonly referred to as "cash costs"; whereas elements (8) through (10) are referred to as "ownership costs".

For purposes of this study, the terms "DOC" and "DOC+I" may be used interchangeably as they will both mean the same thing.

2. DOC Process

The DOC process shown in Figure 4 is typical of the process used for this study. The block 'standard economic rules sets' includes the ten cost elements just discussed and the specific ground rules and assumptions to calculate each one. The blocks 'Study Parameters' and 'Engineering Data' provide the airplane descriptions for each airplane concept under study, which would include configuration geometry data, design weights, engine description, technology level, and performance data.

Airplane study prices, consisting of separate airframe and engine prices, were calculated using parametric methods. Engine company data for each conventional technology and advanced technology engine design were combined with parametrically-determined scaling factors to derive engine study prices for each sized airplane concept. Airplane (airframe and engine) maintenance values were also parametrically determined from DAC's historical database and engine company data for each specific engine concept.

The DOC process is the last part of a generalized aircraft concept study process employed by MDC. Part of that process involves aircraft sizing, which was done using MDC's internally-developed 'Computer-Aided Sizing and Evaluation System [CASES] already described in Section II. The CASES results include the design mission configuration, weight, and performance data, as well as the performance data for the economic mission used for DOC evaluation.

3. DOC Groundrules, Assumptions and Element Descriptions

The DOC ground rules and assumptions used for the study are summarized in Table 7. Listed are the various factors for each of the DOC elements, either in narrative or quantitative form. Domestic and international equations are so identified. The DOC values are calculated in mid-1993 dollars.

Following are detailed descriptions of each DOC element. Note that the cost units of any element may differ from one to the next, e.g., $/block hour, $/flight hour, $/trip.

COCKPIT CREW. Based on the aircraft maximum takeoff gross weight [MTOGW].

[Domestic] $/Block Hour = 440 + 0.532*(MTOGW/1000)
[International] $/Block Hour = 482 + 0.590*(MTOGW/1000)

CABIN CREW. Based on the number of seats in the aircraft and a cost-per-block hour rate for each crew member.

[Domestic] $/Block Hour = (Number of Seats/35)*60
[International] $/Block Hour = (Number of Seats/30)*78

LANDING FEE. Based on either the maximum landing gross weight (MLGW) or the maximum take-off gross weight MTOGW.

[Domestic] $/Trip = $1.50 * (MLGW/1000)
[International] $/Trip = $4.25 * (MTOGW/1000)

NAVIGATION FEE. Based on the first 500NM of a trip and the MTOGW, and used only for international DOC cases.

[International] $/Trip = $0.136 * 500NM * (Square Root of MTOGW/1000)

FUEL. Based on the economic mission block fuel, at a density of 6.7 pounds per US gallon, and a price per gallon of either $0.65 (US Domestic) or $0.70 (International).

MAINTENANCE. Total airplane maintenance cost includes the cost of direct maintenance labor, maintenance material, and applied maintenance burden for both the airframe and engines. The airframe direct maintenance labor and maintenance material costs are based on parametric equations developed by the Boeing Commercial Airplane Group (BCAG).

The engine maintenance costs are based on data provided by the engine companies. This data was augmented, where appropriate, by cost data from the McDonnell Douglas Corporation (MDC) commercial transport engine maintenance database. Since the engine company maintenance cost data was for a fixed reference thrust level, the Boeing engine maintenance cost equations were used as general scaling equations based on sea-level static thrust.

Airframe Maintenance Labor [AFLAB]. Based on airframe weight [AFW], defined as manufacturer's empty weight (MEW) less the dry weight of the engines. AFLAB has both a flight-cycle (FC) and a flight-hour (FH) component. The equations produce either maintenance-man-hour-per-flight-cycle (MMH/FC) or maintenance-man-hour-per-flight-hour (MMH/FH) values. Each trip consists of one flight cycle and a variable number of flight hours.

AFLAB:MMH/FH = 1.260+(1.774*AFW)/10^5)-.1071*(AFW/10^5)^2
AFLAB:MMH/FC = 1.614+(.7227*AFW)/10^5)+.1024*(AFW/10^5)^2
AFLAB:MMH/TRIP = ((MMH/FH)*(FH/TRIP)) + MMH/FC

Total maintenance man-hours per trip are converted to direct labor dollars per trip by multiplying by the direct maintenance labor rate ($25/MMH).

Airframe Maintenance Materials [AFMAT]. Same basis as airframe maintenance labor, with both a cyclic and flight-hour component.

AFMAT:$MAT/FH = 12.39+(29.80*AFW)/10^5)+.1806*(AFW/10^5)^2
AFMAT:$MAT/FC = 15.20+(97.33*AFW)/10^5)-2.862*(AFW/10^5)^2
AFMAT: $MAT/TRIP = (($MAT/FH)*(FH/TRIP)) + $MAT/FC

Airframe Applied Maintenance Burden [AAMB]. The airframe maintenance overhead cost is calculated as a function of airframe direct maintenance labor cost.

AAMB = 2.0 * Airframe Direct Labor Cost

All three airframe maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get total airframe maintenance cost.

Engine Maintenance Labor [ENGLAB]. The scaling equation for engine direct maintenance labor is based on the maximum rated uninstalled sea-level static thrust (SLST) per engine, in pounds force (lbf), the flight hours (FH) per trip, and the number of engines per aircraft (NE). In contrast to the airframe, the engine maintenance labor cost is not separated into flight-cycle and flight-hour components.

ENGLAB: MMH/TRIP = (.645+(.05*SLST/10^4))*(.566+.434/FH))*
FH * NE

The engine direct maintenance labor cost is calculated by multiplying the MMH/TRIP by the direct maintenance labor rate ($25/MMH).

Engine Maintenance Material [ENGMAT]. The scaling equation for engine maintenance material cost is based on the same parameters as the engine direct maintenance labor. In contrast to the airframe, the engine maintenance material cost is not separated into flight-cycle and flight-hour components.

ENGMAT: $MAT/TRIP = (25+(18*SLST/10^4))*((.62+(.38/FH))*
FH * NE

Engine Applied Maintenance Burden [EAMB]. The engine maintenance overhead cost is calculated as a function of the engine direct maintenance cost.

EAMB = 2.0 * Engine Direct Maintenance Labor Cost

All three engine maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get the total engine maintenance cost.

Depreciation, interest and insurance are annual costs. Reducing these annual costs to trip costs are accomplished by dividing the annual cost by the number of trips flown per year. As noted in Table 7, the international mission of 3,000 NM will generate 625 trips per year.

DEPRECIATION. Depreciation is based on the total airplane (airframe + engines) price and its associated spares price. The airframe and engine spares factors, the depreciation period and the residual value are noted in Table 7.

INTEREST. Most aircraft purchases are financed through the use of long-term debt and a down payment from company funds. To account for the total interest cost to the airline, interest is computed on the total price of the airplane plus spares less the down payment. Although interest payments will decline each year, an average annual interest cost is used in aircraft comparisons to reflect the average effect over the airplane's depreciable life. The interest method assumes a 15-year loan period, two loan payments per year, and equal principle payments. The factors defining the amount financed, the depreciation period, and the interest rate are noted in Table 7.

INSURANCE. The annual hull insurance cost is based on the total airplane price. The insurance rate is 0.35% of the total airplane price.

AIRFRAME AND ENGINE STUDY PRICES. Airframe study price for the MR-225 concept was based on a parametric relationship between airframe study price and either payload-range index or airframe weight. Payload-range index (PRI) was selected as the primary independent variable, since the MR-225 concept was chosen as a possible replacement airplane for this particular market sector (225 seats, 4,500-NM design range). Airframe weight, the secondary independent variable, was also evaluated as an airframe price generator in order to assess the impact of airframe downsizing afforded by advanced engine technology.

However, it should be understood that commercial transport aircraft are not sold on a price-per-pound basis. Its selling price in essence represents a market-based price (without relationship to cost). The commercial product relies on a fixed price based on an end item specification, performance guarantees, service life policies, and warranties. This would apply to airframe as well as to engines.

The airframe payload-range index for the MR-225 was statistically determined from a adjusted database of U.S. and non-U.S. commercial transports with two-class international seating capacities ranging from 211 to 523 and design ranges varying from 3,665 to 6,580 NM (International rules), and is dimensioned in (seat-NM) /1000. For the 225-seat, 4,500-NM design, the payload-range index would be 1,012.5 (225*4500/1000). A payload-range adjustment was required since the current MDC database represented current three-class interiors for intercontinental aircraft and the MR-225 was configured with a two-class intercontinental interior of the type that was prevalent when the original wide-body airliners such as the B747-200, DC-10-30, and L-1011 began flying in the late 1960s and early 1970s. It was also assumed that, for any given airplane in the database, the OWE for the two-class airplane would be essentially identical to the three-class airplane. All payload-range adjustments further assumed equal-MTOGW conditions.

The airframe prices for two-class intercontinental airplanes were derived from MDC's current three-class intercontinental commercial transport database, and, for purposes of this study, were assumed to be identical to those of those of the three-class airplane. For the 225-seat airplane, a linear regression of airframe price and PRI produced the following airframe study price equation:

$$\text{Airframe Study Price (\$M)} = 45.9721 + 0.0239 * \text{PRI}$$

A power curve fit of airframe study price (in millions of dollars) versus airframe weight (in pounds, and denoted by AW) produced the following airframe study price equation:

$$\text{Airframe Study Price (\$M)} = 0.7822 * (\text{AW}/1000) \wedge 0.8937$$

Engine study prices were developed from MDC's historical database and from engine manufacturer's data. These engine prices represent only the bare engine, as the remainder of the propulsion system price is assumed to be part of the airframe price (e.g., nacelles and thrust reversers). This is in keeping with the original ATA DOC methodology. The parametric trend of engine price versus engine thrust (i.e., engine price scaling) was derived from the MDC database for current technology engines, and was segregated into two engine classes: 15,000 to 40,000 lbf for the SR-150 concept discussed in another report in this series, and 50,000 to 90,000 lbf for the twin-aisle airplane concepts evaluated in this study. For the 225-seat concept, it was assumed that the engine study price trend for engines in the 50,000-90,000 lbf thrust class could be extrapolated into the 44,000-48,000 lbf region, the likely engine thrust region for twin-engine transports of that payload-range class.

General Electric provided engine study prices based on two pricing scenarios. The baseline scenario assumed that the advanced-technology GE ASTEA 2005-EIS engine was 8% higher in bare-engine study price than the current-technology 1995-EIS engine. The alternate GE pricing scenario was that both the 1995-EIS and 2005-EIS engines had identical prices for the same thrust level. The GE-submitted study prices were for the whole propulsion system, and were not separated into bare engine, nacelle, thrust reverser, and other components. A bare-engine-to-total-propulsion-pod factor was derived by MDC from its GE engine price database and was used to convert the GE 1995-EIS base propulsion system price to a bare-engine basis.

The variation of bare engine price with engine thrust is assumed to be identical for both the current- and advanced-technology engines. Fitting a power curve of the form y=aX^b to the engine data, and calibrating that curve to the GE 1995-EIS baseline ASTEA engine at its reference thrust and associated price produced characteristics of the engine price scaling equations as shown below.

Engine	Constant	Exponent
ASTEA Baseline	0.0028709	0.739423
ASTEA Advanced	0.0031005	0.739423

GE Aircraft Engines
Proprietary Information

The difference in the constant term is the 8% factor in GE's baseline pricing scenario, as previously discussed.

The impact of different airframe and engine pricing scenarios on DOC+I will be evaluated and discussed in Section III.

Table 7. DOC+I Ground Rules And Assumptions
MR-225 Concept

Item	Parameter
DOC+I Basis	International rules
Design Mission	4,500 NM
Economic Mission	3,000 NM
Utilization	625 trips per year
Dollar Year	1993
Fuel Price	$0.70 per US gallon
Maintenance Labor Rate	$25.00 per man-hour
Maintenance Burden Rate	200% of direct labor
Number of Cockpit Crew	2
Number of Cabin Crew	1 per 30 seats
Landing Fees	Function of MTOGW
Navigation Fees	Function of MTOGW, first 500 NM
Hull Insurance Rate	0.35% of airplane price
Depreciation:Period	15 Years
Depreciation:Residual Value	10% of price (Including spares)
Investment Spares:Airframe	6% of airframe price
Investment Spares:Engine	23% of engine price
Interest:Amount Financed	100% of aircraft & spares
Interest:Period	15 Years
Interest:Rate	8%

III. RESULTS

A. Description of Configuration

Figure 5 is a general arrangement drawing of the 225 passenger airplane. This is a conventional twin engine configuration whose advanced concept features include an aspect ratio 11 wing and an all-flying vertical tail. The fuselage has a near circular cross section and will accommodate two LD-3A (LD-2) containers below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 225 seat two class, as shown in the drawing of Figure 6. It should be noted that the wing and empennage sizes shown on the general arrangement drawing of Figure 5 are not to exact scale of the final sized airplanes. The actual dimensions are given in the Characteristics Data below (Table 8) for both airplanes; current technology (1995) engined, and advanced technology (2005 EIS) engined.

Table 8. MR-225 Geometric Characteristics Table

		WING	HORIZONTAL	VERTICAL
SREF (BASE ENG.)	FT^2	2000	362.06	168.50
SREF (ADV. ENG.)	FT^2	1845	320.80	149.29
SPAN (BASE ENG.)	FT	148.32	42.55	17.42
SPAN (ADV. ENG.)	FT	142.46	40.05	16.39
MAC (BASE ENG.)	FT	14.79	9.17	10.49
MAC (ADV. ENG.)	FT	14.20	8.63	9.88
COMMON GEOMETRIC CHARACTERISTICS				
ASPECT RATIO		11.00	5.00	1.80
C/4SWEEP ANGLE	DEG	28.00	30.00	35.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	98.09	50.00	0.00
TAIL ARM	IN	N/A	906.00	900.00
VOLUME RATIO		N/A	0.9243	0.0426
DIHERAL ANGLE	DEG	5.00	4.00	0.00
THICKNESS, % CHORD	Average	0.125	0.095	0.11
		AIRCRAFT		
OVERALL LENGTH	FT	163.27		
HEIGHT BASE	FT	42.81		
HEIGHT ADVANCED	FT	41.78		

B. Engine Selections

In the NASA sponsored Advanced Subsonic Technologies Evaluation Analysis (ASTEA) GEAE designed a baseline engine, service entry 1995, and an advanced engine, service entry 2005. Both were sized for a nominal 45000 lb thrust, sea level static take off.

The base engine is a similar design to GEAE's most advanced commercial engine and has the proven two shaft configuration with a large pressure ratio HP compressor, and a two stage HP turbine. The fan is wide chord, composite, shroudless, 0.3 radius ratio with a two stage booster and a 4 stage LP turbine.

The advanced engine has a similar configuration but uses 4 highly loaded booster stages to raise the overall pressure ratio. The HP pressure ratio is maintained but there are considerable redesign changes to allow the core of the engine to operate with compressor exit temperatures 115°F hotter. Turbine inlet temperature increases by up to 270°F.

The fan duty and dimensions are similar for both engines, they differ principally in the higher efficiency projected for the advanced engine.

Major cycle parameters are as follows:

Parameter		Baseline	Advanced
FNINI T/0.25M SL		35200	35200
BPR	Cruise	7.87	10.61
OPR	0.8M	34.5	43.9
FPR	35K	1.50	1.50
W41R	(pps)	16.8	10.5
Fan tip diameter (inches)		84.07	84.1
Power plant weights (lbs)		11047	9290
Max nacelle diam (inches)		116.2	111.7
Mean cowl length (inches)		165.2	115.0

The base engine was designed for the McDonnell Douglas MDXX, an advanced medium range, twin, 225 passenger, commercial aircraft. The MDXX required a thrust of around 30000 lbs which was the thrust size at which the baseline engine was originally designed. Later versions of the MDXX required around 45000 lbs thrust so the base engine was scaled up by 1.5. The advanced engine was also designed for the higher thrust. Engine takeoff and top of climb thrusts are designed to suit the MDXX which has an unusually high T/O thrust requirement and consequently, the engines have a relatively modest thrust lapse rate with altitude. The high T/O thrust is more compatible with a growth than a new engine application and for best economy we have run the fan faster at T/O. This results in a higher jet velocity which causes a slight increase in sideline and takeoff noise levels.

The advanced engine employs a wide range of the most cost effective mix of technologies to raise the operating efficiency which is around 8% higher than the base engine. Many other technology concepts are used to reduce engine costs, weight to improve reliability and to extend engine life. All these factors will contribute towards a lower aircraft direct operating cost.

Cross sectional drawings of both engines, together with conceptual nacelles are shown on Figures 7 & 8. Baseline and advanced engines are separate flow and use conventional translating cowl, cascade thrust reversers.

C. Final Sized Airplanes

1. Primary sizing constraints

The primary sizing criteria used in this report are shown in Table 1. In all cases, the critical sizing parameters are payload, range and initial cruise altitude (ICA). Takeoff field length (TOFL) and approach speed (Vappr) are less critical. Takeoff field length is computed at sea level and 84 ^{o}F. The aircraft are sized by the combination of Fn and Sw to meet the takeoff field length requirement at a minimum MTOGW.

2. Effects of engine technology improvements

Table 9 summarizes the results of the final sized aircraft with the GE ASTEA base and GE ASTEA adanced engines. In comparing the aircraft characteristics of these two airplanes, the advanced airplane has an overall better performance. The sized operating empty weight (OEW) is 9,000 lbs lighter than the base. The specific fuel consumption (SFC) is 9% better than the base. The effects of engine change from base to advanced engines are a reduction in wing area (Sw), thrust (Fn) and fuel burned. As a result, the aircraft sized with the advanced engines resulted in a lighter maximum takeoff gross weight (MTOGW) compared to the base engine.

Table 9. MR-225 Aircraft Sizing Results

Engine	GE ASTEA BASE	GE ASTEA ADV
Bypass Ratio	7	10
MTOW (LB)	298,000	278,000
OEW (LB)	159,000	150,000
Sw (SQ FT)	2,000	1,845
Fn (LB)	46,000	44,500
Block Fuel (LB)	79,900	70,500
Block Time (Hr)	10.26	10.25
Wt/Sw (LB/SQ FT)	149.04	150.67
Fn/Wt	0.309	0.320
ICA (FT)	35,000	35,000
TOFL (FT)	6,400	6,200
Vappr (KEAS)	126.08	128.02
1st Seg Grad (%)	1.79	1.85
2nd Seg Grad (%)	2.40	2.47
V2 (KEAS)	142.38	141.15
CL Avg @ 35000	0.59	0.60
L/D Avg@ 35000	18.70	18.38
SFC Avg @ 35000	0.5660	0.5212

D. Sensitivity Results

Tables 10 & 11 below show the sensitivity of aircraft sizing to increases in SFC and pod & pylon weights for the MR-225 base and advanced GE engines. Increasing SFC has greater impact on TOGW, Fn and S_W than increasing engine weight. The aircraft sized with a 5% SFC increase have heavier MTOGW compared to the aircraft sized with a 5% engine weight increase. The overall effect of SFC on TOGW is about 2.0% greater than in the engine weights case. Since the aircraft are sized to meet the sizing criteria stated in Table 1, an increase in either SFC or engine weights would also result in an increase in S_W and Fn. Takeoff thrust (Fn) and wing area (S_W) for the SFC case increased by 1.0% and 1-3% respectively relative to the aircraft sized with engine weight. In general, the aircraft sized with advanced engines have a smaller effect in TOGW compared to the base engines because of the better performance of the advanced engines relative to the base engines..

Table 10. Sizing Effects of 5% SFC Increase

	GE ASTEA Base	GE ASTEA Advanced
Δ TOGW (lb)	2.8%	2.4%
Δ OEW (lb)	1.4%	1.0%
Δ Fn (lb)	2.1%	2.6%
Δ S_W (ft^2)	3.3%	0.9%

Table 11. Sizing Effects of 5% Engine Weight Increase

	GE ASTEA Base	GE ASTEA Advanced
Δ TOGW (lb)	0.8%	0.7%
Δ OEW (lb)	0.3.%	0.3%
Δ Fn (lb)	0.9%	0.8%
Δ S_W ft^2)	0.1%	0.0%

E. Direct Operating Cost Analysis And Comparison

The direct operating cost method described in Section II was used to evaluate and compare the impact of propulsion system technology on the DOC+I of the MR-225 concept at an average stage length of 3,000 NM using international rules.

The results for the MR-225 concept with both the GE conventional ASTEA and advanced ASTEA propulsion systems are shown in Figure 9 and in Tables 12 and 13, and 14. In the tables, the current-technology engine is referred to as the GE/BASE/7 while the advanced-technology engine is identified as GE/ADV./10.

The summary results, shown in Figure 9, are for two engine pricing and maintenance scenarios and two airframe pricing scenarios. The results from the baseline scenario indicate that, when the airplane is configured with the advanced-technology GE ASTEA engine and that engine is priced 8% higher than the current-technology engine on an equivalent-thrust basis, its maintenance cost is 8% greater on that same basis, and the airframe is priced on a payload-range basis, its DOC+I is 1.6% less than the airplane configured with the current-technology ASTEA engine. In the alternate engine pricing and maintenance scenario where the advanced-technology engine price and maintenance cost are identical to the current-technology engine on an equal-thrust basis, the DOC+I difference increases 1.1 percentage points to 2.7%.

When the airframe study price is based on airframe weight, and there is no difference in relative engine price or maintenance cost at the same thrust level between the current-technology and advanced-technology engines, the DOC+I difference increased to 3.4% in favor of the advanced technology engine.

The details of the three DOC+I case studies for the MR-225 concept are shown in Tables 12, 13, and 14. The baseline case is shown in Table 12 for the scenario where the advanced ASTEA engine is 8% higher in price and 8% greater in maintenance cost on an equivalent-thrust basis, and the airframe price is based on the payload-range index. Table 13 illustrates the case when both engines have the same basis for price and maintenance cost, and the airframe is still priced on a PRI-basis. The alternate airframe pricing case (based on airframe weight), coupled with the alternate engine pricing and maintenance case, is shown in Table 14.

In each table, the aircraft with the advanced-technology propulsion system is compared to the aircraft with the conventional-technology propulsion system, with percentage differences shown for the technical and operational characteristics that drive the DOC+I values as well as for each of the DOC+I cost elements. In addition, each cost element is shown as a percentage of the total DOC+I, so as to indicate the relative impact of the change in each cost element to the total DOC+I change.

Referring to Table 12 (the baseline case), the cash operating cost of the airplane configured with the advanced technology ASTEA engine was 3.6% lower than the airplane configured with the current-technology ASTEA engine. Of the cost components directly affected by the engine itself, the block fuel and fuel cost was reduced 11.6% using the advanced-technology engine. However, the engine maintenance cost increased 5.8% when the advanced-technology engine was used, but the impact of this increase in maintenance cost was offset by its relatively small contribution to the total DOC+I.

The variations in ownership cost afforded by the advanced-technology engine ranged from an increase of 1.1% when the 2005-EIS engine was assumed to have a 8%-higher equivalent-thrust price than the 1995-EIS engine (Table 12) to a decrease of 0.5% when the advanced-technology and current-technology engines were priced on the same basis (Table 13). As can be seen from Table 12, when the 2005-EIS engine has an 8% price disadvantage, the study price of the advanced-technology engine is 5.3% greater than the study price of the current-technology engine when both engines are compared on a sized, uninstalled SLST basis.

When the advanced-technology engine is priced on an equal basis relative to its current-technology counterpart (Table 13), its price difference relative to the current-technology engine changes from +5.3% to -2.5%. As shown in the table, the total cost is reduced by 0.5%, and the total DOC+I is reduced by 2.7%.

The alternate airframe pricing scenario, where the airframe price is related to airframe weight, indicates the impact of airframe downsizing afforded by the advanced-technology engine. As shown in Table 14 for the MR-225, the impact was relatively small, with the airframe weight reduction being 2%. Based on the airframe price equation shown in Section II, the airframe study price dropped from $60.1M (current-technology engine) to

$59.1M (advanced-technology engine), a reduction of 1.7%. This in turn, increased the ownership difference to 1.9% and the total DOC+I difference to 3.4%.

It should be noted that, when the MR-225 airframe price is weight-based instead of payload-range-based, the difference in price is relatively large, compared to the other airplane concepts evaluated in the overall study and described in other reports. For the current-technology-engine airplanes, the payload-range-based airframe study price was $70.1M, whereas the airframe-weight-based study price was $60.1M. This had some impact on the absolute values of the ownership cost components as well as their relationship to one another. The unusual payload-range design point of this particular aircraft concept, coupled with the derived nature of the two-class international payload-range points for the current airliner database, most likely contributed to the wider-than-expected difference in airframe study prices, but, for purposes of this study, this difference in airframe prices did not radically influence the conclusions drawn.

Table 12. MR-225 AIRCRAFT DOC+I SUMMARY & COMPARISON
[Baseline Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE :ENTRY-INTO-SERVICE [EIS]		GE/BASE/7 1995	GE/ADV/10 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] GE/BASE/7	 GE/ADV/10
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	298,000	278,000	-6.7%		
OEW	lbm	159,000	150,000	-5.7%		
Airframe Weight	lbm	128,845	126,328	-2.0%		
Airframe Price	$M	$70.2	$70.2	0.0%		
Engine Thrust	lbf	47,400	45,800	-3.4%		
Engine Price	$M	$8.2	$8.7	5.3%		
No. of Engines/Acft	-	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	3,000	3,000			
Block Time	hr	6.997	6.992	-0.1%		
Block Fuel	lbm	51,736	45,756	-11.6%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	1,191	1,150	-3.4%	3.2%	3.2%
COCKPIT CREW	"	4,603	4,517	-1.9%	12.5%	12.5%
CABIN CREW	"	4,093	4,090	-0.1%	11.1%	11.3%
LANDING FEE	"	1,267	1,182	-6.7%	3.4%	3.3%
MAINT - AIRFRAME	"	2,408	2,378	-1.3%	6.6%	6.6%
MAINT - ENGINE	"	1,952	2,065	5.8%	5.3%	5.7%
FUEL	"	5,405	4,780	-11.6%	14.7%	13.2%
CASH DOC ==>	$/trip	20,919	20,163	-3.6%	56.9%	55.7%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	9,083	9,186	1.1%	24.7%	25.4%
INTEREST	"	6,257	6,328	1.1%	17.0%	17.5%
INSURANCE	"	485	490	1.0%	1.3%	1.4%
OWNERSHIP DOC ==>	$/trip	15,825	16,004	1.1%	43.1%	44.3%
TOTAL DOC ==>	$/TRIP	36,745	36,167	-1.6%	100.0%	100.0%

NOTE:
(1) Engine price and maintenance cost ratio - 2005 EIS/1995 EIS=1.08
(2) Airframe price is based on payload-range index.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

Table 13. MR−225 AIRCRAFT DOC+I SUMMARY & COMPARISON
[Alternate Engine Pricing & Maintenance Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE : ENTRY−INTO−SERVICE [EIS]		GE/BASE/7 1995	GE/ADV/10 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] GE/BASE/7	 GE/ADV/10
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	298,000	278,000	−6.7%		
OEW	lbm	159,000	150,000	−5.7%		
Airframe Weight	lbm	128,845	126,328	−2.0%		
Airframe Price	$M	$70.2	$70.2	0.0%		
Engine Thrust	lbf	47,400	45,800	−3.4%		
Engine Price	$M	$8.2	$8.0	−2.5%		
No. of Engines/Acft	−	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	3,000	3,000			
Block Time	hr	6.997	6.992	−0.1%		
Block Fuel	lbm	51,736	45,756	−11.6%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	1,191	1,150	−3.4%	3.2%	3.2%
COCKPIT CREW	"	4,603	4,517	−1.9%	12.5%	12.6%
CABIN CREW	"	4,093	4,090	−0.1%	11.1%	11.4%
LANDING FEE	"	1,267	1,182	−6.7%	3.4%	3.3%
MAINT − AIRFRAME	"	2,408	2,378	−1.3%	6.6%	6.7%
MAINT − ENGINE	"	1,952	1,912	−2.1%	5.3%	5.3%
FUEL	"	5,405	4,780	−11.6%	14.7%	13.4%
CASH DOC ==>	$/trip	20,919	20,010	−4.3%	56.9%	56.0%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	9,083	9,034	−0.5%	24.7%	25.3%
INTEREST	"	6,257	6,224	−0.5%	17.0%	17.4%
INSURANCE	"	485	483	−0.5%	1.3%	1.4%
OWNERSHIP DOC ==>	$/trip	15,825	15,741	−0.5%	43.1%	44.0%
TOTAL DOC ==>	$/TRIP	36,745	35,751	−2.7%	100.0%	100.0%

NOTE:
(1) Engine price and maintenance ratio − 2005EIS/1995EIS=1.00.
(2) Airframe price based on payload−range index.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

Table 14. MR–225 AIRCRAFT DOC+I SUMMARY & COMPARISON
[Alternate Airframe Pricing & Engine Pricing/Maintenance Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE : ENTRY–INTO–SERVICE EIS]		GE/BASE/7 1995	GE/ADV/10 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] GE/BASE//7	 GE/ADV/10
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	298,000	278,000	–6.7%		
OEW	lbm	159,000	150,000	–5.7%		
Airframe Weight	lbm	128,845	126,328	–2.0%		
Airframe Price	$M	$60.1	$59.1	–1.7%		
Engine Thrust	lbf	47,400	45,800	–3.4%		
Engine Price	$M	$8.2	$8.0	–2.5%		
No. of Engines/Acft	–	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	3,000	3,000			
Block Time	hr	6.997	6.992	–0.1%		
Block Fuel	lbm	51,736	45,756	–11.6%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	1,191	1,150	–3.4%	3.4%	3.4%
COCKPIT CREW	"	4,603	4,517	–1.9%	13.2%	13.4%
CABIN CREW	"	4,093	4,090	–0.1%	11.7%	12.1%
LANDING FEE	"	1,267	1,182	–6.7%	3.6%	3.5%
MAINT – AIRFRAME	"	2,408	2,378	–1.3%	6.9%	7.0%
MAINT – ENGINE	"	1,952	1,912	–2.1%	5.6%	5.7%
FUEL	"	5,405	4,780	–11.6%	15.5%	14.2%
CASH DOC ==>	$/trip	20,919	20,010	–4.3%	59.8%	59.2%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	8,062	7,907	–1.9%	23.1%	23.4%
INTEREST	"	5,554	5,447	–1.9%	15.9%	16.1%
INSURANCE	"	429	421	–1.9%	1.2%	1.2%
OWNERSHIP DOC ==>	$/trip	14,045	13,774	–1.9%	40.2%	40.8%
TOTAL DOC ==>	$/TRIP	34,965	33,784	–3.4%	100.0%	100.0%

NOTE:
(1) Engine price and maintenance cost ratio – 2005 EIS/1995 EIS=1.00
(2) Airframe price is based on airframe weight.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

IV. SUMMARY

A study to examine the sole effect of advanced technology engines on the performance and DOC+I of a 225-passenger subsonic transport airplane has been completed. Two airplanes were designed and sized: one using the current technology (1995) GE Base ASTEA engine as a baseline, and one using the advanced technology (2005) GE Advanced ASTEA engine. All other aircraft technologies were kept constant. The year 2005 was selected as the entry-into-service date for the airframe/engine combinations.

The advanced technology engine provided significant reductions in fuel burn, weight, and wing area as follows:

reduction in fuel burn	=	12%
reduction in wing area	=	8%
reduction in TOGW	=	7%

These corresponded to a range of DOC+I reductions from 1.6% to 3.4% depending on the airframe/engine pricing models used. The DOC+I reduction of 3.4% was obtained using the airframe price based on airframe weight and the advanced technology engine priced on the same basis as the baseline engine.

It is recommended that the results of this study be viewed from more than a single perspective: the physical characteristics of the airplanes themselves (TOGW, OEW, Sw, Fn, etc.), and the corresponding DOC+I figures. The economic analyses have been defined in two forms: 1. airframe cost based on the mission (number of passengers and range), which result in the airframe cost being invariant between the current and advanced technology airplanes, and 2. airframe cost varying with airframe weight. The first method forces the DOC+I increment between the current and advanced technology airplanes to become dependent solely on engine price, maintenance cost, and fuel burn. No specific reward is offered for the reduction in airplane size and weight provided by the advanced technology powerplants. Alternatively, the second method provides a more direct reward for the advanced technology in both engines and airframe. These two economic algorithms may be regarded as bounding the problem, and the true economic benefit probably lies somewhere in between their DOC+I predictions.

Finally, it should be understood that the scope of the present study did not allow for an optimization of the matching of engines to the airplanes and the design mission. A careful iterative analysis should yield an increase in the performance benefits offered by the advanced technology engines.

APPENDIX

MR-225 Detailed Weight Summaries

Table A1. Base engine MR-225 Aircraft Group Weight Statement

CT/CWEP VERSION 3.0

PROGRAM **PAIT#9** CONFIGURATION **MR-225/GE ASTEA 45K BASE** DATE & TIME : ###########

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	30,408	
BENDING MATERIAL		13,819
SPAR WEB		1,431
RIBS AND BULKHEADS		1,504
AERODYNAMIC SURFACES		10,098
SECONDARY STRUCTURE		3,556
TAIL	5,419	
FUSELAGE	31,494	
LANDING GEAR	11,095	
NACELLE & PYLON	4,113	
AIR INDUCTION	634	
PROPULSION	22,376	
ENGINES		15,548
ENGINES SYSTEM		1,588
EXHAUST SYSTEM		811
THRUST REVERSER		3,104
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		1,323
FLIGHT CONTROLS	2,956	
COCKPIT CONTROLS		126
SYSTEM CONTROL		2,830
POWER SYSTEMS	6,933	
AUXILIARY POWER PLANT		1,260
HYDRAULICS		1,343
PNEUMATICS		1,030
ELECTRICAL		3,300
INSTRUMENTS	1,210	
AVIONICS & AUTOPILOT	2,220	
FURNISHINGS & EQUIPMENT	24,850	
AIR CONDITIONING	2,840	
ANTI-ICING	478	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	147,027	
OPERATIONAL ITEMS	11,850	
OPERATING EMPTY WEIGHT	158,877	
USABLE FUEL	91,871	
PAYLOAD	47,250	
TAKEOFF GROSS WEIGHT	297,998	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 1,992	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 46,000	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 149.6
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.3680
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.3083
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 47,250	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 77,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)	= 4,500	
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		= 0.100
MISSION FUEL (LB)		= 83,519
TAKEOFF FIELD LENGTH (FT)	= 7,500	
APROACH SPEED (KNOT)	= 135	= 135

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	85,414	85,414	= 0.1674 SWT^ 1.73
CENTER WING	6,457	43,768	= 6.0393 SWT^ 1.17
FUSELAGE			
TOTAL	91,871	129,182	

SIZING DERIVATIVES

dOEW/dWG = 0.12342

dOEW/dSW = 11.77218

dOEW/dT OR dP = 0.43874

Wconstant = 78,465

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MR-225/GE ASTEA 45K-DDN

Table A2. Advanced engine MR-225 Aircraft Group Weight Statement

CT/CWEP VERSION 3.0

PROGRAM **PAIT#9** CONFIGURATION **MR-225/GE ASTEA ADV ENG** DATE & TIME : ###########

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	27,992	
BENDING MATERIAL		12,784
SPAR WEB		1,312
RIBS AND BULKHEADS		1,349
AERODYNAMIC SURFACES		9,278
SECONDARY STRUCTURE		3,269
TAIL	5,076	
FUSELAGE	31,206	
LANDING GEAR	10,278	
NACELLE & PYLON	3,262	
AIR INDUCTION	758	
PROPULSION	18,392	
ENGINES		11,830
ENGINES SYSTEM		1,271
EXHAUST SYSTEM		570
THRUST REVERSER		3,480
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		1,242
FLIGHT CONTROLS	2,782	
COCKPIT CONTROLS		126
SYSTEM CONTROL		2,656
POWER SYSTEMS	6,850	
AUXILIARY POWER PLANT		1,260
HYDRAULICS		1,260
PNEUMATICS		1,030
ELECTRICAL		3,300
INSTRUMENTS	1,210	
AVIONICS & AUTOPILOT	2,220	
FURNISHINGS & EQUIPMENT	24,850	
AIR CONDITIONING	2,840	
ANTI-ICING	443	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	138,158	
OPERATIONAL ITEMS	11,850	
OPERATING EMPTY WEIGHT	150,008	
USABLE FUEL	80,707	
PAYLOAD	47,250	
TAKEOFF GROSS WEIGHT	277,965	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 1,845	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 44,526	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 150.7
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.3709
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.2903
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 47,250	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 77,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)	= 4,500	
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		= 0.100
MISSION FUEL (LB)		= 73,370
TAKEOFF FIELD LENGTH (FT)	= 7,500	
APROACH SPEED (KNOT)	= 135	= 135

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	74,806	74,806	= 0.1674 SWT^ 1.73
CENTER WING	5,901	40,013	= 6.0393 SWT^ 1.17
FUSELAGE			
TOTAL	80,707	114,819	

SIZING DERIVATIVES

dOEW/dWG = 0.12269

dOEW/dSW = 11.95114

dOEW/dT OR dP = 0.37042

Wconstant = 77,362

PAGE 2
MR-225/GE ADV ASTEA-DDN

FIGURE 1. FIXED EQUIPMENT AND OPERATIONAL ITEMS RATIO OF ACTUAL WEIGHT TO ESTIMATED WEIGHT

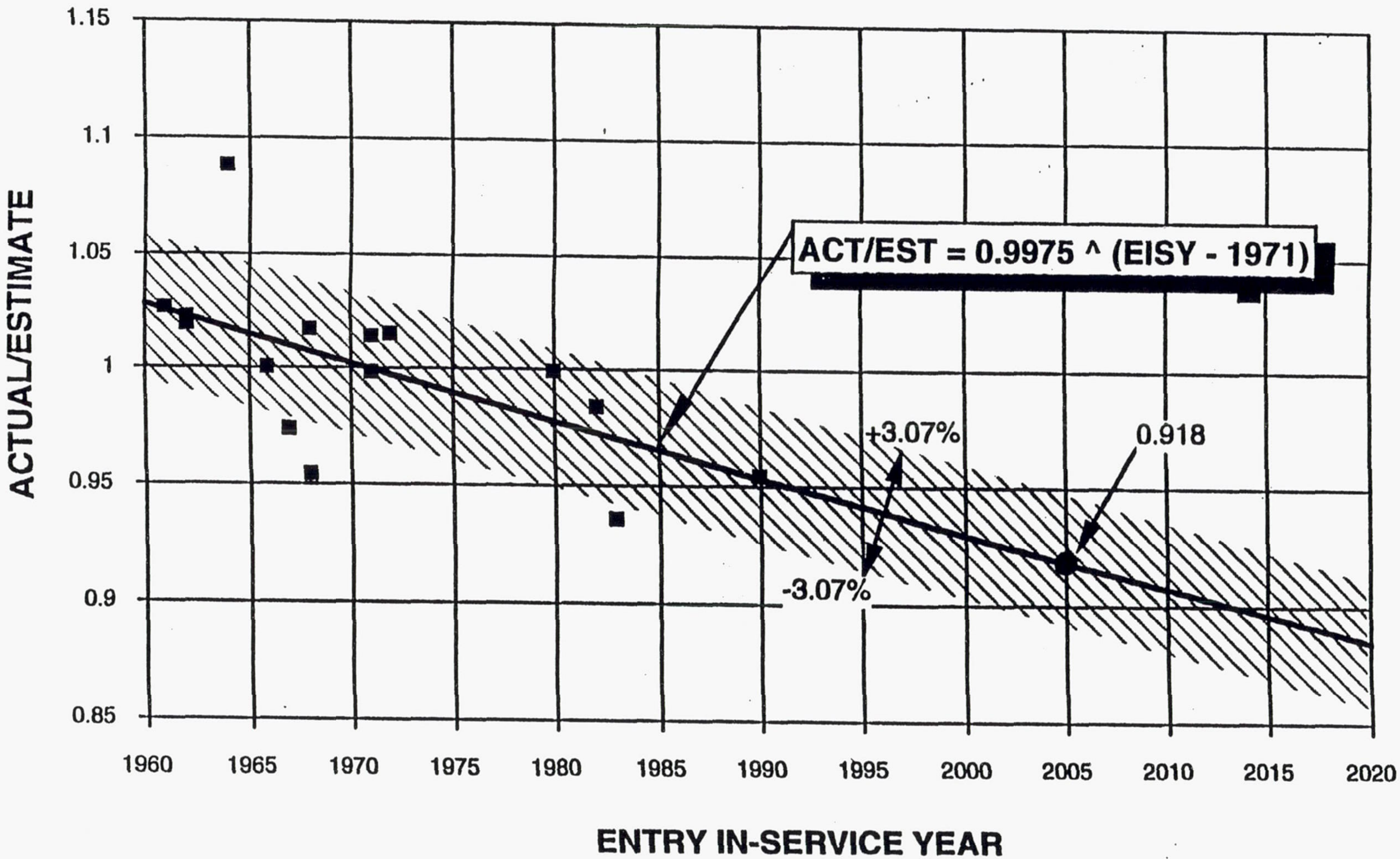


Figure 1. Fixed Equipment and Operational Items Ratio of Actual Weight to Estimated Weight

FIGURE 2. ENGINE POD WEIGHT/ THRUST RATIO

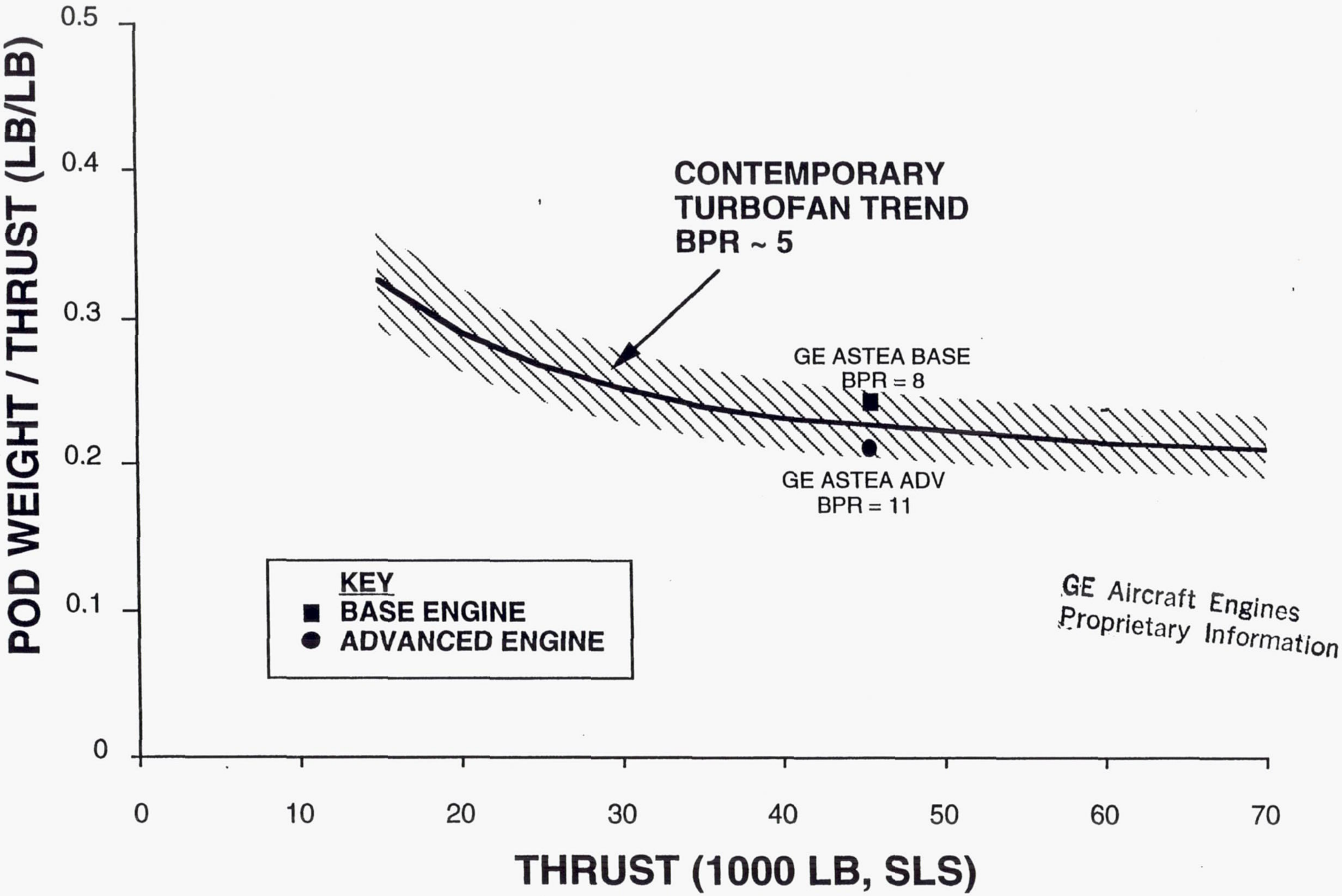


Figure 2. Engine Pod Weight/Thrust Ratio

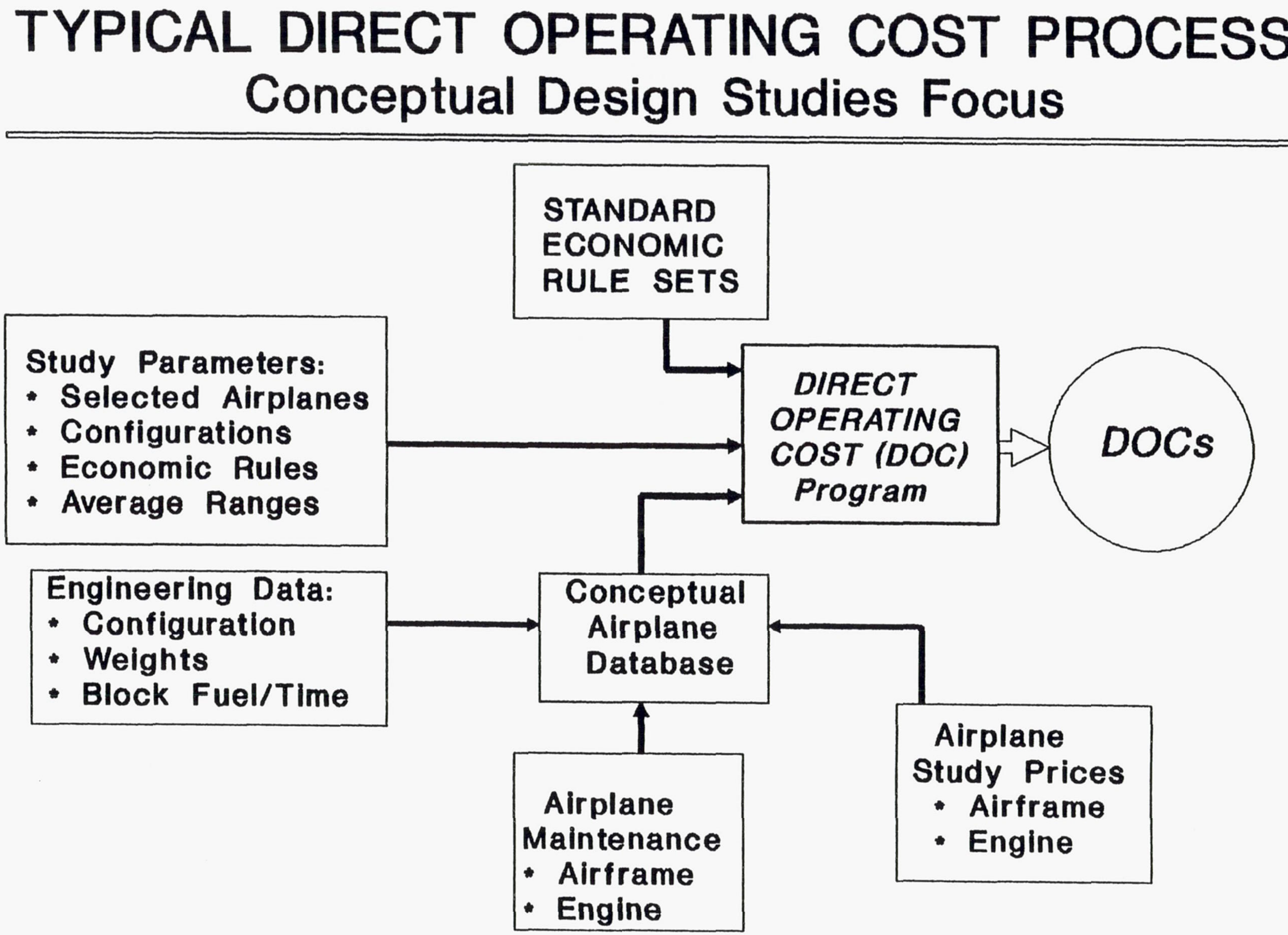


Figure 4. Typical DOC Process

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.
2. Characteristics data for sized aircraft in Table 8.

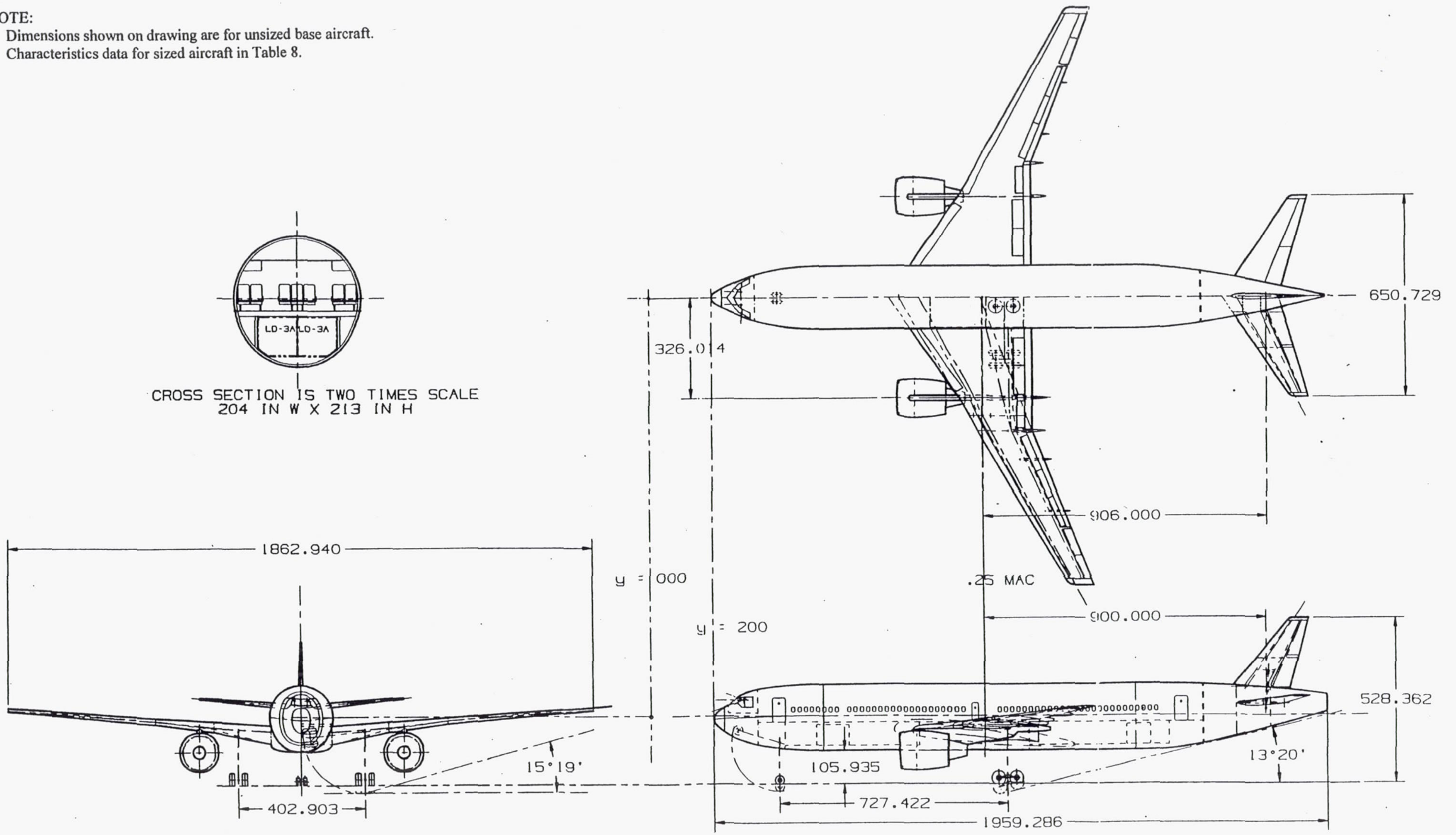


Figure 5. General Arrangement - MR-225

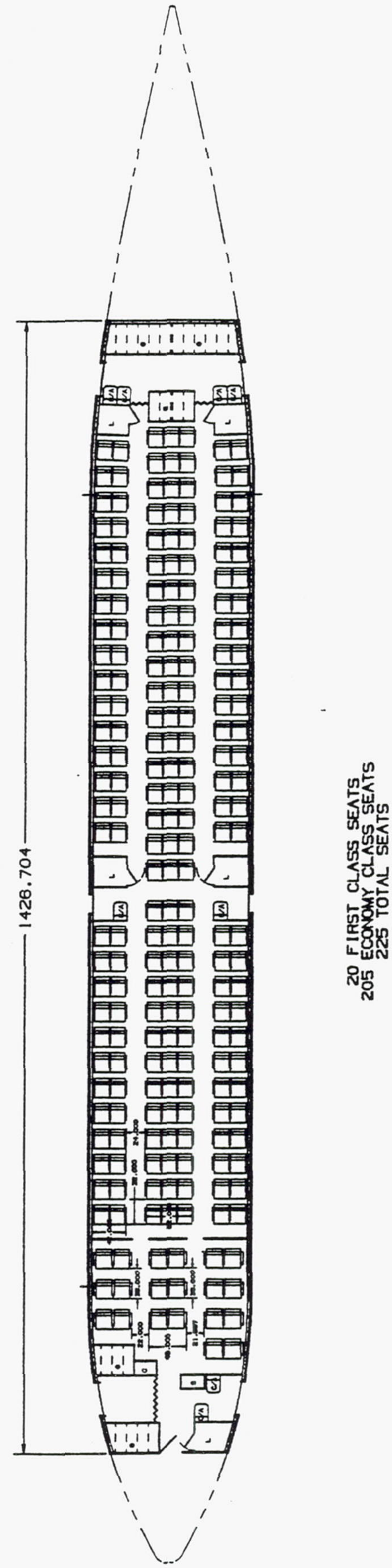


Figure 6. Interior Arrangement - MR-225

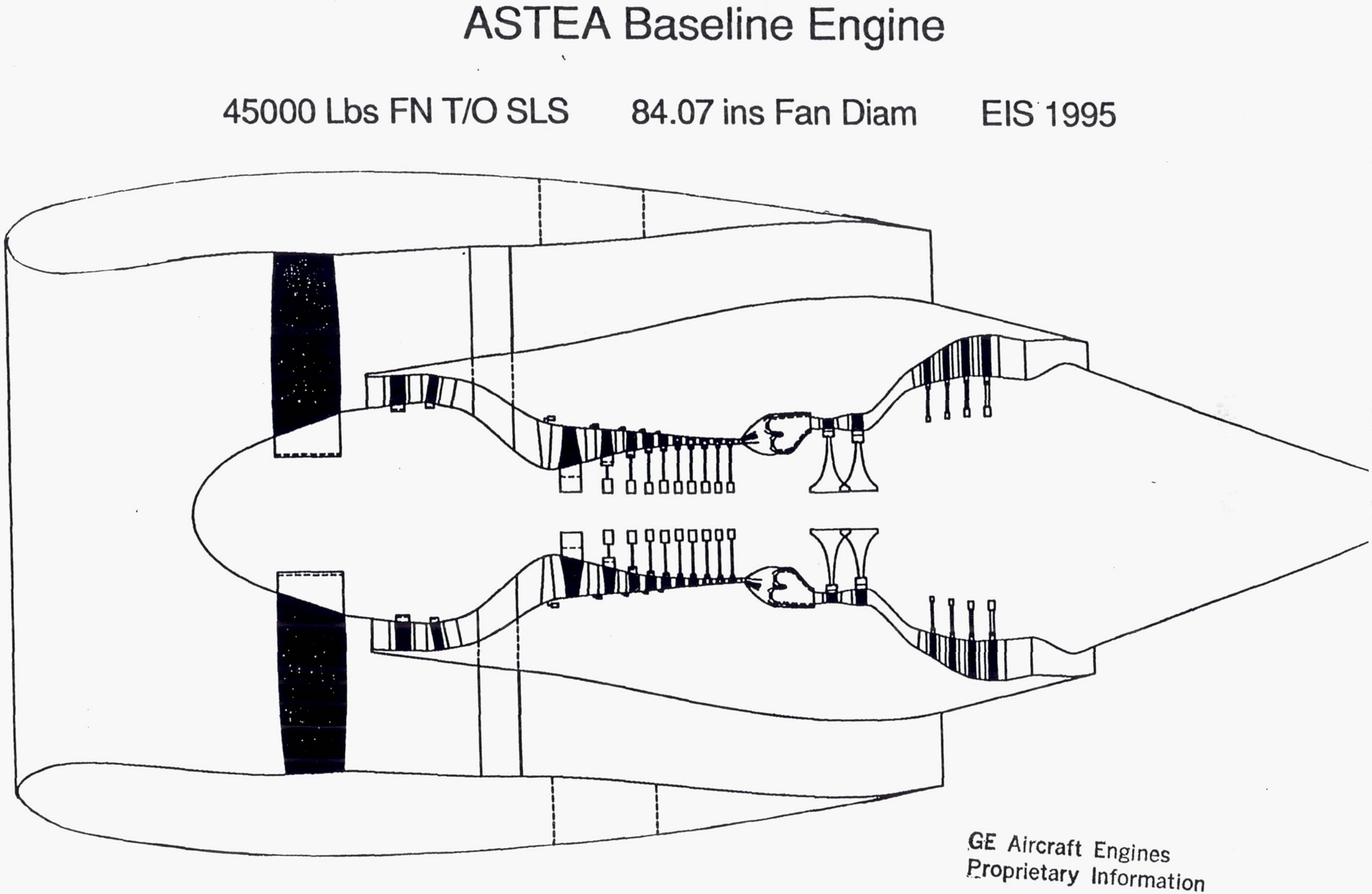


Figure 7. GE Baseline ASTEA Engine Configuration

ASTEA Advanced Direct Drive Engine

45,000 Lbs FN T/O SLS 84.1 ins Fan Dia EIS 2005

GE Aircraft Engines
Proprietary Information

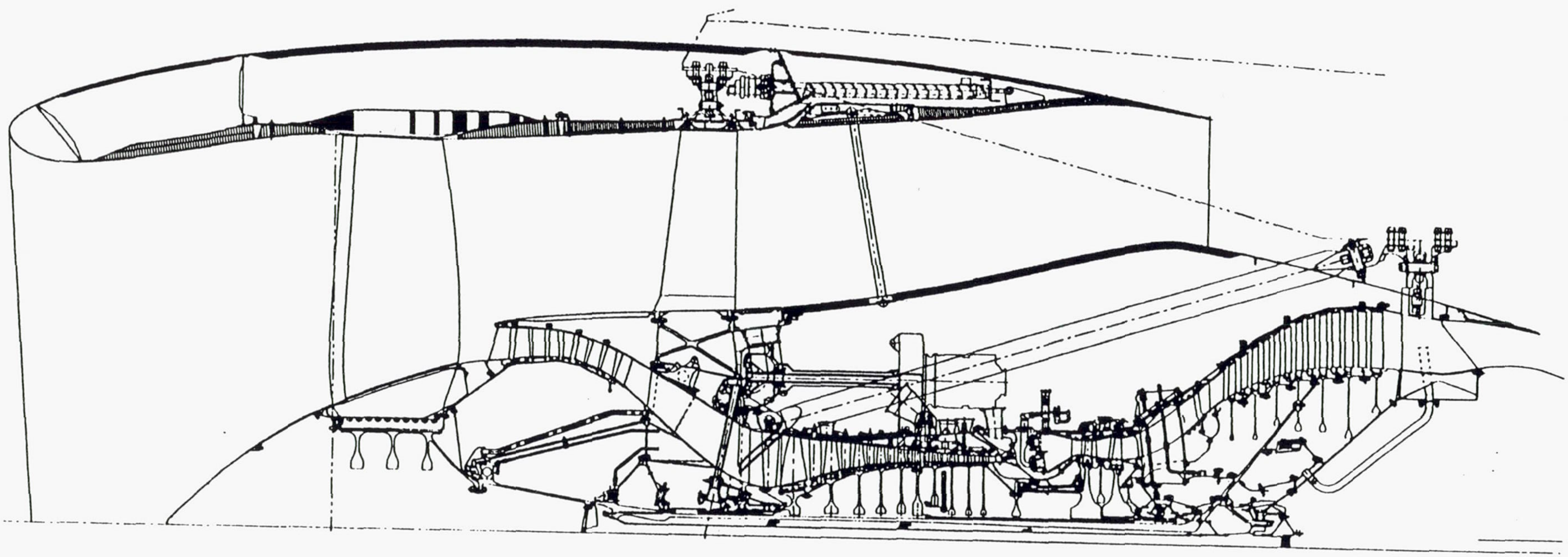
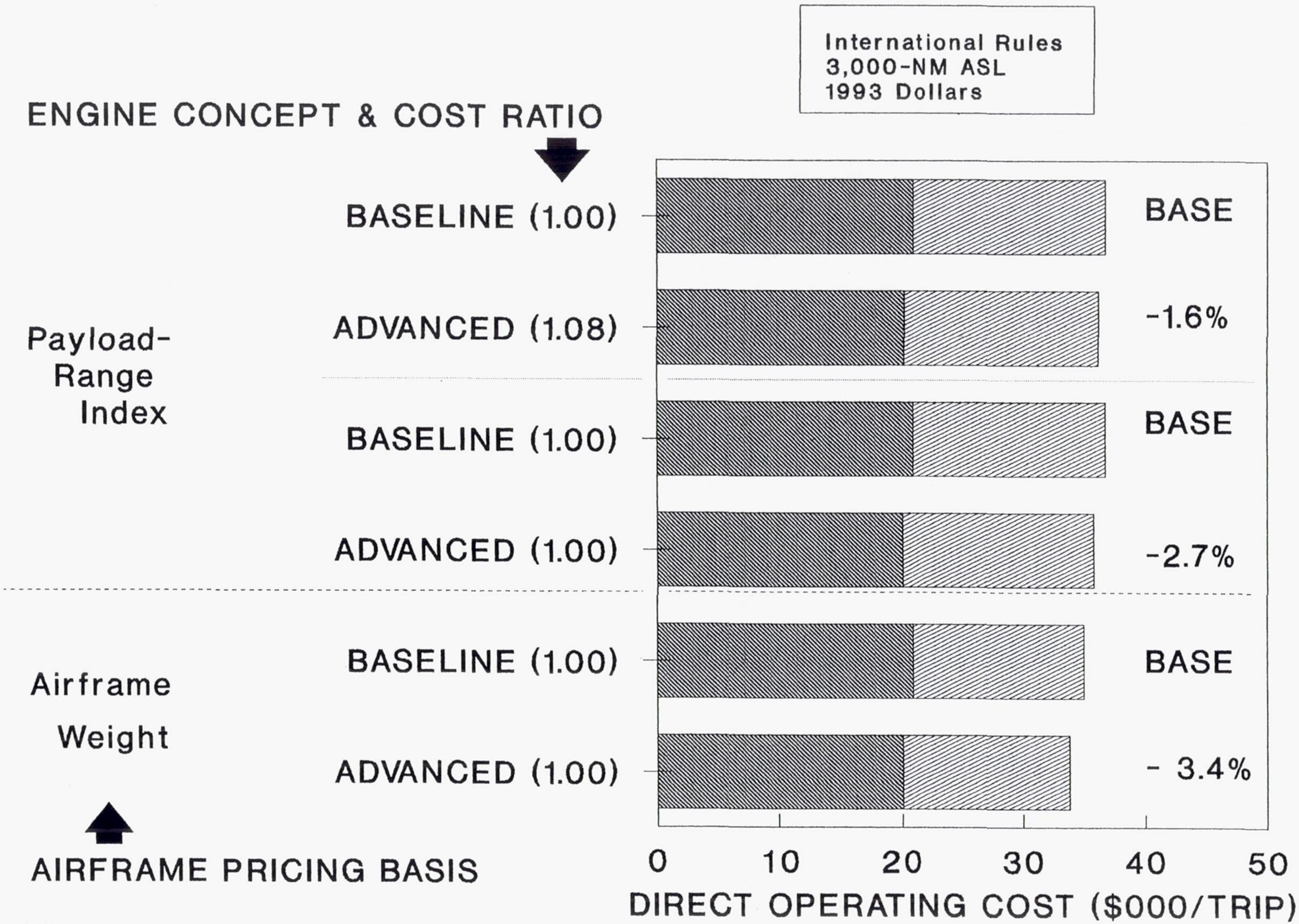


Figure 8. GE Advanced ASTEA Engine Configuration



GE Aircraft Engines
Proprietary Information

Figure 9. MR-225 DOC+I Results

ADVANCED SUBSONIC AIRPLANE DESIGN & ECONOMIC STUDY

APPENDIX C: 275- AND 600-PASSENGER AIRPLANES WITH PRATT & WHITNEY ENGINES

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MCDONNELL DOUGLAS AEROSPACE, LONG BEACH, CALIFORNIA

Contract NAS3-25965, Task 9

April 1995

National Aeronautics and
Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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PREFACE

This report was prepared by McDonnell Douglas Corporation under Task Assignment 9 of contract NAS3-25965 for NASA Lewis Research Center as an appendix to NASA CR-195443. This report contains Pratt and Whitney/United Technologies Corporation proprietary data.

The NASA technical monitors were Joseph D. Eisenberg and Felix R. Torres. The McDonnell Douglas Program Manager was Robert H. Liebeck. The members of McDonnell Douglas team that participated in this task order and deserve recognition for their contributions are as follows:

Aerodynamics	Robert S. Bird, Johnny Chau, Roger Lyon
Configuration	Robert A. Wright, Blaine K. Rawdon
Economics	Donald A. Andrastek, Madeline Ellis
Propulsion	Raquel Girvin, Susan M. Koval, James K. Wechsler
Secondary Power	Kenneth R. Williams
Weights	Dennis Nguyen, Paul W. Scott

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I. INTRODUCTION

The purpose of this study is to examine the effect of advanced technology engines on the performance of subsonic transport airplanes and provide a vision of the potential which these advanced engines offer. The year 2005 has been set as the entry-into-service (EIS) date for the engine/airframe combination. A set of four transport airplane classes (passenger and design range) that are envisioned to span the needs for the 2005 EIS period have been defined. This problem could be approached utilizing existing airframes with advanced technology engines, however, since the origin of some the existing (and currently produced) airframes dates back more than two decades, a consistent framework for evaluation becomes difficult. Consequently, 2005 EIS advanced technology airframes have been designed and sized for all classes.

Two airplanes have been designed and sized for each class: one using current technology (1995) engines to provide a baseline, and one using advanced technology (2005 EIS) engines. The resulting engine/airframe combinations have then been compared and evaluated on the basis of sensitivity to the basic engine performance parameters (e.g. SFC and engine weight) as well as DOC+I. Noise and emissions have not been considered in the present study.

Participants in this study include: McDonnell Douglas Aerospace for the design, sizing and evaluation of the airplanes, and the three engine companies; Allison, GE Aircraft Engines, and Pratt and Whitney who have provided the engine data for their current and advanced technology engines. Proprietary considerations preclude the documentation of this study in single report, and therefore a separate report has been prepared for each engine company. General discussions pertaining to all airplanes are common to all reports.

II. APPROACH

A. Mission Definition

Four airplane design missions have been defined and are summarized in Table 1; the designations SR0-150, MR-225, MR-275, and LR-600 are used in these reports to refer to these four airplane types respectively. These were selected to represent the complete spectrum of subsonic transport requirements envisioned for the year 2005 and beyond. Commuter missions have not been considered in this study. To claim that these missions accurately and precisely define air transportation's needs in 2005 would of course be naive, however, they represent the best judgment at this writing.

Of the four missions, the long range (600 passenger, 7500 n.mi.) is the most speculative, particularly with respect to the payload. The 7500 n mi range is regarded as serving all

meaningful city-pair requirements. Very large aircraft (VLA's) are defined as 500 to 1000 passengers, so the choice for this study is somewhat near the lower bound. Increasing the payload would be straightforward, however, the 800-1000 level could begin to deteriorate the accuracy and resolution of existing data bases for weights.

Table 1. Subsonic Airframe/Propulsion Integration
Airplane Design Specifications
2005 EIS

Category	Seats	Rules	Range (N.Mi.)	Cruise Mach No.	ICA (Ft)	VAP (Kts)	TOFL (Ft)
Short Range	150	2 Class Narrow Body	2500	.78	31,000	130	7,000
Medium Range	225	2 Class Twin Aisle	4500	.80	35,000	135	7,500
Medium Range	275	3 Class International	6000	.83	35,000	140	9,000
Long Range	600	3 Class International	7,500	.85	31,000	150	11,000

B. Airframe Technology Definition

Technology for all airframes is based on a 2005 entry-into-service date. The philosophy used in selecting technology levels was to lean to the optimistic but maintain reality. The resulting airplanes thus show measurable reductions in size and weight over those which would be obtained from simple derivatives of existing airframes. Specific technologies are described below.

1. Aerodynamics

All wing designs are based on advanced supercritical divergent trailing edge airfoils which are highly loaded to minimize wetted area. Selection of a composite wing structure allows a relatively high aspect ratio limit of 11. High-lift system design and performance is based on the technology developed for the MD-12. This utilizes a full-span leading edge slat and a track motion flap system with two segments inboard and a single segment outboard. The system provides high values of C_{Lmax} and L/D for both takeoff and landing configurations.

2. Structure

Advanced composites are used for the entire wing and empennage structure. Fuselage structure utilizes aluminum-lithium longerons with the skins made from GLARE, an aluminum and fiberglass laminate. This combination of materials and structural design yields structural weight reductions which are shown in Table 6.

3. Stability and Control

The Stability & Control terms that strongly affect the aircraft performance are vertical and horizontal tail size, and cruise center-of-gravity (C.G.). The lateral controls affect the available flap span and therefore $C_{L_{max}}$. Further, if the outboard ailerons suffer from aeroelastic reversal, then it is necessary to add inboard ailerons in the stiff mid-span region. Unfortunately, these inboard ailerons also reduce flap area and distort the takeoff and landing spanloads which hurts low-speed L/D. For these reasons the wing structure is sized to preclude aileron reversal in the operational speed range and therefore no inboard aileron is required.

The horizontal tail sizes are based on an advanced high-lift tail with a slotted elevator that can deflect -35° for low-speed takeoff rotation. The slot door is articulated to provide a sealed aerodynamically smooth surface at low elevator deflections. The unaugmented static stability of the airplanes is set to -15%MAC at aft C.G. for the critical V_{FC}/M_{FC} condition where aeroelastic losses are greatest. This static stability level places the C.G. at the Maneuver Point which represents neutral stability from a load-factor standpoint.

The vertical tail is sized for minimum ground control speed (V_{mCG}) on the twin engine airplanes, and two engine-out landing speed (V_{mCL-2}) for the four engine airplanes. In all cases, the all-flying tail concept is used to minimize tail area. This feature requires larger actuators, a pivot shaft, and additional supporting structure, but reduces the tail size by nearly 50% since the fin can be deflected in addition to the rudder.

4. Systems

This arrangement, chosen for the baseline study aircraft, yields weight and complexity reductions, as well as robustness for both the signalling and the power systems.

It should be noted that the secondary power system arrangement chosen for the baseline study aircraft represents the anticipated 2005 EIS technology, which integrates the conventional pneumatic, electrical and hydraulic systems into one electrically powered system. This Power-by-Wire (PBW) system rquires only shaft power extraction from the engine. An allowance has been made in this study for other airframe applications which would require engine bleed air, but this has been limited to 1% of the engine core airflow.

This type of secondary power system makes possible the consideration of future very high bypass engines, whose smaller core airflow would not allow the use of conventional bleed air utilization. These PBW secondary power systems are compatible with the present engines used in the study, and therefore provide for a generic evaluation of the results, with respect to engine type versus secondary power system installation. Table 2 shows the actual anticipated engine extraction expected for each of the study aircraft types.

Table 2. Power Extraction versus Aircraft Type

AIRCRAFT TYPE		POWER EXTRACTION	PER ENGINE
Short Range 150 Passengers	Shaft	225 hp Norm. (167.6 Kva)	281 hp Max. (209.5 Kva)
	Air	1% core flow max;	30 hp
Medium Range 225 Passengers	Shaft	379 hp Norm. (282.7 Kva)	474 hp Max. (353.4 (Kva)
	Air	1% core flow max;	70 hp
Medium Range 275 Passengers	Shaft	394 hp Norm. (293.7 Kva)	492 hp Max. (367.2 Kva)
	Air	1% core flow max;	85 hp
Long Range 600 Passengers	Shaft	559 hp Norm. (416.8 Kva)	698 hp Max. (521.0 Kva)
	Air	1% core flow max;	120 hp

C. Engine Definition

Each of the three engine companies defined their current and advanced technology engines according to each company's design philosophy and technology base. Relative to the current engines, the advanced technology engines incorporate cycle, materials, and turbomachinery efficiency and design improvements.

The three pairs of current and advanced technology engines used in this study are listed below in Table 3. The Allison engines were used for the short-range/150-passenger airplanes, the GE engines were used for the medium-range/225-passenger airplanes, and the P&W engines were used for both the medium-range/275-passenger and long-range/600-passenger airplanes. The short and medium-range airplanes were configured with two engines; the long-range airplanes had four engines.

Table 3. Baseline and Advanced Engine Model Designations

Engine Company	Baseline Engine (1995 EIS)	Advanced Engine (2005 EIS)
Allison	PD577-1A6	PD577-2A5/6
GE Aircraft Engines	Baseline ASTEA	Advanced ASTEA
Pratt & Whitney	PW4484	STS1046

D. Configuration Definition and Rules

Conventional configurations with pylon-mounted wing engines have been selected for the MR-275 and LR-600 airplanes. This arrangement isolates the engine inlets from the airframe so that engine technology changes can be analyzed without airflow complications. Interior accommodations are set for 275 and 600 passengers using Douglas Aircraft Company (DAC) rules for a three class seating arrangement with two aisles. The 275 passenger airplane is configured for medium/long range flights with 6 percent first class, 19 percent business class, and the remainder economy class with a 33 inch seat pitch. The 600 passenger airplane is configured with a double-lobe, two-floor arrangement for long range flights with 5 percent first class, 19 percent business class and the remainder economy class with 33 inch seat pitch. Flight crew requirements are derived from the FAR Part 121, subpart R, paragraph 121.480.

Once sized, the fuselage is considered a constant, while the engine technology level used will re-size the wing, empennage, landing gear, engine size (thrust), and fuel requirement.

E. Airplane Sizing and Performance

1. **Propulsion model**

The MR-275 and LR-600 airplanes were sized using engine performance data provided by Pratt and Whitney. Data for the baseline engine, PW4484, were obtained from P&W engine cycle deck CCD 733-01.1 originally intended for MD-12 airplane studies. The baseline engine is also referred to in the report as the PW44XX, PW4084, and PW4000. Data for the advanced engine, STS1046, were obtained by applying a 1.063 fuel flow factor to the STS1045 datapack previously transmitted by Pratt & Whitney. (The STS1045 was an earlier vintage engine design.) Thrust and fuel flow were extracted from the P&W engine datapacks and loaded into the McDonnell Douglas airplane sizing program which in turn interpolated and scaled the engine data according to the airplane mission requirements.

2. Weight Estimation Model

MDC's proprietary Conceptual Weight Estimation Program (CWEP) requires inputs such as geometrical parameters, design criteria, and advanced technology multipliers. CWEP uses a series of weight estimating relationships (WERs) and a modified Breguet range equation to develop the initial aircraft sizing parameters, which are then processed by the more sophisticated CASES sizing code. The sizing parameters (shown in Table 4) consist of the partial derivatives of Operational Empty Weight (OEW) with respect to gross weight, wing area, and thrust plus a constant weight. To obtain the final aircraft weight, the CASES wing area, thrust, and gross weight are input to CWEP. The resulting group weight statement is used for cost estimation. Both the sizing derivatives and the group weight statements are shown in the tables at the end of this section.

TABLE 4. Aircraft Sizing Derivatives

$$OEW = W_c + \frac{\partial OEW}{\partial W_g}(W_g - W_{g_o}) + \frac{\partial OEW}{\partial S_w}(S_w - S_{w_o}) + \frac{\partial OEW}{\partial T}(T - T_o)$$

$$W_g = OEW + W_{pl} + W_{fuel}$$

OEW = Operational Empty Weight (lb)

$\frac{\partial OEW}{\partial S_w}$ = Partial derivative of OEW with respect to wing area (lb / ft^2)

$\frac{\partial OEW}{\partial T}$ = Partial derivative of OEW with respect to Thrust (lb / lb)

$\frac{\partial OEW}{\partial W_g}$ = Partial derivative of OEW with respect to MTOGW (lb / lb)

S_w = Wing area (ft^2)

S_{w_o} = Base wing area (ft^2)

T = Thrust per engine, sea level static rated (lbf)

T_o = Base thrust per engine, sea level static rated (lbf)

W_c = Base constant weight (lb)

W_g = Maximum Takeoff Gross Weight (lb)

W_{g_o} = Base Maximum Takeoff Gross Weight (lb)

W_{fuel} = Fuel Weight (lb)

W_{pl} = Payload weight (lb)

Design Criteria

The aircraft's maximum takeoff gross weight (MTOGW) is defined by the requirement to transport the maximum design passenger capacity over the design range. The full complement of passengers and bags at 210 lb each defines the performance payload (WPPL), which is shown in Table 5. The maximum payload (WMPL) reflects the heaviest payload that the aircraft must carry and influences the structural weight. As is typical for commercial aircraft, the configurations for this study are designed for a 2.5 limit load factor and a 10 ft/sec limit landing sink rate.

The MR-275 and LR-600 configurations provide an 8000 ft cabin pressure at 43,000 ft. This results in a limit differential cabin pressure (PD) of 8.6 psig. The maximum speeds in a dive (VD) for the aircraft are also presented in Table 5.

TABLE 5. Design Criteria

CONFIGURATION	WPPL (lb)	RANGE (nm)	WMPL (lb)	PD (psig)	VD (KEAS)
MR-275	57,750	6,000	100,000	8.6	415
LR-600	126,000	7,500	200,000	8.6	420

Advanced Technology Weight Impacts

CWEP utilizes advanced technology multipliers (ATMs) to reflect the technology level. The ATMs of Table 6 are based on an entry into service date (EIS) of 2005 as referenced to the database of operational aircraft. The structural weight increments of advanced composites in newer operational transports have been factored out in order to normalize the database.

The wing and tail incorporate maximum use of advanced composites, but metallics are assumed for leading edges, aerodynamic surface hinges, and at critical joints. More dramatic weight reductions may be feasible, but commercial transports must emphasize low cost of manufacturing and maintenance. The fuselage uses GLARE skins, Aluminum-Lithium longerons, and advanced composite secondary structure. The landing gear utilizes carbon brakes, radial tires and steel struts with a moderate improvement material properties.

The fixed equipment ATM's are empirically derived trends that reflect numerous weight reductions due to technology improvements, many of which are offset by increased capabilities and improved functionality. The term "fixed equipment" refers to those items whose weight is insensitive to changes in MTOGW and includes furnishings, APU, pneumatics, air conditioning, electrical, instruments and avionics. The weight of fixed equipment items tend to scale with fuselage size. Dividing the sum of actual aircraft fixed equipment weights plus operational item weights by the value estimated by a WER and plotting this versus the EIS date of each aircraft determines the ATM trend versus EIS date. This trend curve, shown in Figure 1, estimates an ATM of 0.918 for a 2005 EIS. However, this factor is not distributed evenly across all of the components.

Table 6. Advanced Technology Multipliers for 2005 EIS

FUNCTIONAL GROUP	ATM	COMMENTS
Wing		
Bending material	0.75	
Spar webs	0.75	
Ribs and bulkheads	0.75	
Aerodynamic surfaces	0.92	
Secondary structure	0.83	
Tail	0.80	
Fuselage	0.95	LR-600 ATM is 0.94
Landing gear	0.91	
Nacelle and Propulsion	NA	By engine manufacturer
Flight controls & Hydraulics	0.95	
APU, Pneumatics, Air conditioning Electrical, Instruments & Avionics	0.976	
Furnishings & Equipment	0.869	
Operational items	0.976	

Although an EIS 2005 transport may be all-electric, there is scant empirical data on such systems and no reliable rational for identifying related weight increments, therefore none are assumed.

Propulsion System Weights

All engine pod weights are provided by the engine manufacturers. The ratio of these pod weights to their rated thrust is presented in Figure 2. The very high bypass ratio of the advanced Pratt & Whitney engine more than offsets the weight savings due to advanced technologies and materials, thus causing its weight fraction to fall above the trend curves. For the purpose of estimating weights, the base Pratt & Whitney engine is the PW4460, since its thrust level is very close to that required by the MR-275 and LR-600. However, performance analyses use a PW4484 engine deck.

When adequate detail is provided by the manufacturer, MDC uses a MIL-STD-1374A functional weight reporting format for the propulsion related weights. MIL-STD-1374A allocates the inlet cowl to the Air Induction Group, and the fan cowl doors plus the pylon are charged to the Nacelle Group. The fan exhaust duct, core cowl and nozzle are allocated to the exhaust system, which is part of the Propulsion Group. In some instances, the fan exhaust duct and the thrust reverser weights are reported as an assembly and cannot be separately identified. The ADP engine does not require a thrust reverser, as it can reverse the pitch of its blades.

MDC estimates the propulsion related items that are external to the pod, such as the engine pylons and the aircraft's fuel system. Lacking detailed engine pylon drawings, all pylons are estimated to weigh 16 % of the pod weight, a value that is typical of the highly cantilevered pylons on modern commercial transport aircraft. All of the study aircraft are assumed to carry fuel in their outer and center wings. With the exception of the SR-150, all configurations are assumed to have a trim tank in their horizontal stabilizer.

Detailed Weight Summaries

Tables A1 and A2 present the group weight statements for the base engine and advanced engine MR-275 configurations respectively. Similarly, tables A3 and A4 present the group weight statements for the LR-600 configurations. The weight sizing derivatives and maximum fuel capacities are also reported in each table.

3. **Aerodynamic model**

High Lift System

The high lift system is composed of a slat plus Fowler-motion flap. At takeoff, the slat is sealed, and it is fully open at landing. An "auto-slat" system is utilized to reduce takeoff speed by automatically opening the slats from the sealed takeoff position to the open landing position if stall is approached. This makes available the higher C_{Lmax} of the open slat with the higher L/D of the sealed slat. The trailing edge system is composed of two spanwise flap segments plus drooped ailerons. Inboard, the flap has two elements with the auxiliary element remaining stowed at takeoff. Midspan and outboard flaps are single element. Maximum flap setting is 30°.

Low speed aerodynamic characteristics were estimated using a combination of flight and wind tunnel test data as well as conceptual handbook methods. Lift and drag data were assembled and trimmed using the MDA CASES aircraft sizing program. All takeoff data and C_{Lmax} were trimmed at the forward CG limit, and all landing data was trimmed at the mid CG position.

Transonic

High speed aerodynamic data were based on a combination of MDA advanced design methodology and empirical data which has been substantiated by wind tunnel tests of advanced technology transport aircraft. Wing design and performance is based on the latest advanced technology supercritical airfoils with divergent trailing edges. Design Mach numbers were 0.82 and 0.85 for the 275 and 600 passenger airplanes respectively. The airplanes were trimmed in cruise at a CG location of 30-percent mean aerodynamic chord.

4. Sizing Procedures (CASES)

MDC's proprietary Configuration Aircraft Sizing and Evaluation System (CASES) was used for the evaluation and optimization of the aircraft in this report. The program is designed to facilitate the sizing of aircraft to meet specific mission requirements for payload, range, takeoff field length, approach speed, initial cruise altitude, and other requirements. The program requires inputs from Aerodynamics, Propulsion, Stability & Control and Weights. The sizing parameters require inputs such as wing area (S_W), TOFL and thrust. The design optimization is accomplished with interactive plotting routines which provide visual relationships between the geometric variables, design constraints, and optimization criteria used. Figure 3 shows the sizing carpet plot created in CASES with varying wing areas (S_W) and thrusts. From the plot, the minimum TOGW or fuel burned to meet the initial cruise altitude can be obtained.

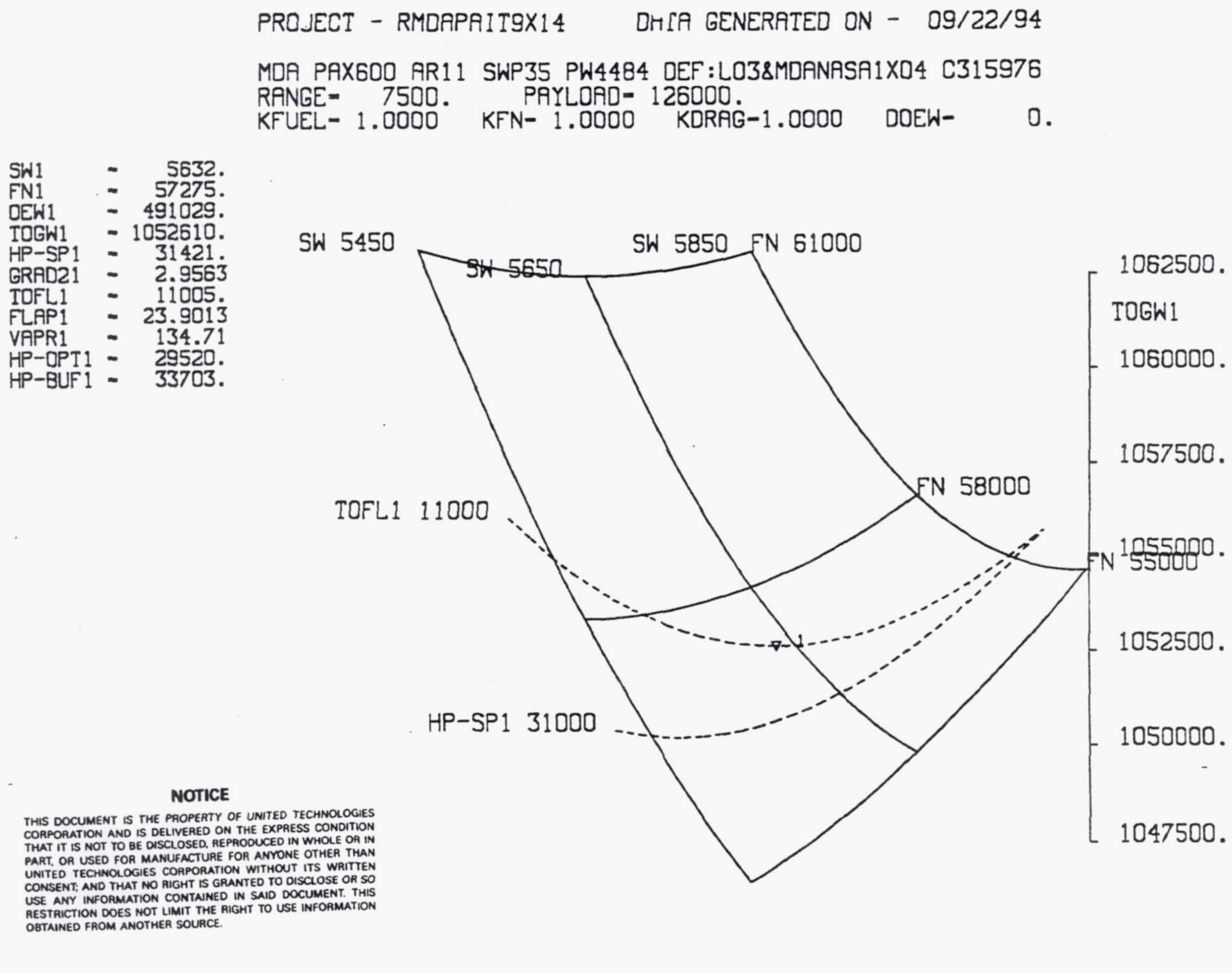

Figure 3. Typical CASES Sizing Carpet Plot

F. Sensitivity Analysis

Sensitivity studies have been conducted to estimate the effect on maximum takeoff gross weight of increases in engine weight and SFC relative to target at entry into service. Both the baseline (1995) and advanced technology (2005 EIS) engined airplanes have been analyzed. Increments of plus 5 percent in engine + pod + pylon weight and SFC have been applied, and the resulting airplanes have then been re-sized to meet the design criteria of Table 1.

G. DOC+I Method and Rules

1. Introduction

This section presents the direct operating cost rules and calculation process used to evaluate and compare the MR-275 and LR-600 airplane concepts with current-technology and advanced-technology Pratt & Whitney (P&W) turbofan engines. The economic analysis focus was on the first-level effects of advanced propulsion system technology with respect to airplane performance (block time, block fuel) and airplane economics (DOC for a typical average stage length (ASL) of 3,000 NM for the MR-275 concept, and 4,000 NM for the LR-600 concept, using international rules].

The economic criterion used for evaluating and comparing the effect of advanced propulsion systems on airplane design and operation was Direct Operating Cost (DOC). The Air Transportation Association of America, in 1944, published the first universally recognized method for estimating direct operating costs of airplanes. That ATA method was progressively updated through the years with inputs from ATA member airlines and prime airframe and engine manufacturers. The ATA standard method of estimating comparative direct operating costs of turbine powered transport airplanes, last published in December 1967, formed the basis for the method and approach used for this study.

The DOC method used for this study was based on the combination of ground rules and assumptions developed collectively by McDonnell Douglas Corporation (MDC) and its commercial aircraft component, Douglas Aircraft Company (DAC), the Boeing Commercial Airplane Group (BCAG), and NASA's Lewis Research Center (LeRC). The method was referred to as the "DOC+I" method, since the interest cost element was added. In addition, cabin crew costs, landing fees and navigation fees, usually considered to be indirect operating costs by the former Civil Aeronautics Board (CAB), were also added to the original ATA DOC cost element structure. Using DOC+I to describe this method affords a way to discriminate from the basic ATA DOC method.

With the aforementioned additions to the basic ATA DOC method, the DOC+I cost element structure for this study included the following cost elements:

(1) Flight Crew
(2) Cabin Crew

(3) Landing Fees
(4) Navigation Fees
(5) Maintenance - Airframe
(6) Maintenance - Engine
(7) Fuel
(8) Depreciation - Aircraft and Spares
(9) Insurance
(10 Interest

Elements (1) through (7) are commonly referred to as "cash costs"; whereas elements (8) through (10) are referred to as "ownership costs".

For purposes of this study, the terms "DOC" and "DOC+I" may be used interchangeably as they will both mean the same thing.

2. DOC Process

The DOC process shown in Figure 4 is typical of the process used for this study. The block 'standard economic rules sets' includes the ten cost elements just discussed and the specific ground rules and assumptions to calculate each one. The blocks 'Study Parameters' and 'Engineering Data' provide the airplane descriptions for each airplane concept under study, which would include configuration geometry data, design weights, engine description, technology level, and performance data. Airplane study prices, consisting of separate airframe and engine prices, were calculated using parametric methods. Engine company data for each conventional technology and advanced technology engine design were combined with parametrically-determined scaling factors to derive engine study prices for each sized airplane concept. Airplane (airframe and engine) maintenance values were also parametrically determined from DAC's historical database and engine company data for each specific engine concept.

The DOC process is the last part of a generalized aircraft concept study process employed by MDC. Part of that process involves aircraft sizing, which was done using MDC's internally-developed 'Computer-Aided Sizing and Evaluation System [CASES] already described in Section II. The CASES results include the design mission configuration, weight, and performance data, as well as the performance data for the economic mission used for DOC evaluation.

3. DOC Groundrules, Assumptions and Element Descriptions

The DOC ground rules and assumptions used for the study are summarized in Table 7. Listed are the various factors for each of the DOC elements, either in narrative or quantitative form. Domestic and international equations are so identified. The DOC values are calculated in mid-1993 dollars.

Following are detailed descriptions of each DOC element. Note that the cost units of any element may differ from one to the next, e.g., $/block hour, $/flight hour, $/trip.

COCKPIT CREW. Based on the aircraft maximum takeoff gross weight [MTOGW].

[Domestic] $/Block Hour = 440 + 0.532*(MTOGW/1000)
[International] $/Block Hour = 482 + 0.590*(MTOGW/1000)

CABIN CREW. Based on the number of seats in the aircraft and a cost-per-block hour rate for each crew member.

[Domestic] $/Block Hour = (Number of Seats/35)*60
[International] $/Block Hour = (Number of Seats/30)*78

LANDING FEE. Based on either the maximum landing gross weight (MLGW) or the maximum take-off gross weight MTOGW.

[Domestic] $/Trip = $1.50 * (MLGW/1000)
[International] $/Trip = $4.25 * (MTOGW/1000)

NAVIGATION FEE. Based on the first 500NM of a trip and the MTOGW, and used only for international DOC cases.

[International] $/Trip = $0.136 * 500NM * (Square Root of MTOGW/1000)

FUEL. Based on the economic mission block fuel, at a density of 6.7 pounds per US gallon, and a price per gallon of either $0.65 (US Domestic) or $0.70 (International).

MAINTENANCE. Total airplane maintenance cost includes the cost of direct maintenance labor, maintenance material, and applied maintenance burden for both the airframe and the engines. The airframe direct maintenance labor and maintenance material costs are based on parametric equations developed by the Boeing Commercial Airplane Group (BCAG).

The engine maintenance costs are based on data provided by the engine companies. This data was augmented, where appropriate, by cost data from the McDonnell Douglas Corporation (MDC) commercial transport engine maintenance cost database. Since the engine company maintenance cost data was for a fixed reference thrust level for each engine concept, the Boeing engine maintenance cost equations were used as general scaling equations based on sea-level static thrust.

Airframe Maintenance Labor [AFLAB]. Based on airframe weight [AFW], defined as manufacturer's empty weight (MEW) less the dry weight of the engines. AFLAB has both a flight-cycle (FC) and a flight-hour (FH) component. The equations produce either maintenance-man-hour-per-flight-hour (MMH/FH) values. Each trip consists of one flight cycle and a variable number of flight hours.

$$\text{AFLAB:MMH/FH} = 1.260+(1.774*\text{AFW}/10^5)-.1071*(\text{AFW}/10^5)^2$$
$$\text{AFLAB:MMH/FC} = 1.614+(.7227*\text{AFW}/10^5)+.1024*(\text{AFW}/10^5)^2$$
$$\text{AFLAB:MMH/TRIP} = ((\text{MMH/FH})*(\text{FH/Trip})) + \text{MMH/FC}$$

Total maintenance man-hours per trip are converted to direct labor dollars per trip by multiplying by the direct labor rate ($25/MMH).

Airframe Maintenance Materials [AFMAT]. Same basis as airframe maintenance labor, with both a cyclic and flight-hour component.

$$\text{AFMAT:\$MAT/FH} = 12.39+(29.80*\text{AFW}/10^5)+.1806*(\text{AFW}/10^5)^2$$
$$\text{AFMAT:\$MAT/FC} = 15.20+(97.33*\text{AFW}/10^5)-2.862*(\text{AFW}/10^5)^2$$
$$\text{AFMAT:\$MAT/TRIP} = ((\text{\$MAT/FH})*(\text{FH/Trip})) + \text{\$MAT/FC}$$

Airframe Applied Maintenance Burden [AAMB]. The airframe maintenance overhead cost is calculated as a function of airframe direct maintenance labor cost.

$$\text{AAMB} = 2.0 * \text{Airframe Direct Labor Cost}$$

All three airframe maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get total airframe maintenance cost.

Engine Maintenance Labor [ENGLAB]. The scaling equation for engine direct maintenance labor is based on the maximum rated sea-level static thrust (SLST) per engine, in pounds force (lbf), flight hours (FH) per trip, and the number of engines per aircraft (NE). In contrast to the airframe, the engine maintenance labor cost is not separated into flight-cycle and flight-hour components.

$$\text{ENGLAB: MMH/TRIP} = (.645+(.05*\text{SLST}/10^4))*(.566+.434/\text{FH})* \\ \text{FH} * \text{NE}$$

The engine direct maintenance labor cost is calculated by multiplying the MMH/Trip by the direct maintenance labor rate ($25/MMH).

Engine Maintenance Material [ENGMAT]. The scaling equation for engine maintenance material cost is based on the same parameters as the engine direct maintenance labor. In contrast to the airframe, the engine maintenance material cost is not separated into flight-cycle and flight-hour components.

$$\text{ENGMAT: \$MAT/TRIP} = (25+(18*\text{SLST}/10^4))*(.62+(.38/\text{FH}))* \\ \text{FH} * \text{NE}$$

Engine Applied Maintenance Burden [EAMB]. The engine maintenance overhead cost is calculated as a function of the engine direct maintenance labor cost.

EAMB = 2.0 * Direct Engine Maintenance Labor Cost

All three engine maintenance cost elements (direct labor, materials, and burden) are calculated on a per-trip basis and summed to get the total engine maintenance cost.

Depreciation, interest and insurance are annual costs. Reducing these annual costs to trip costs are accomplished by dividing the annual cost by the number of trips flown per year. As noted in Table 7, the international mission of 3,000 NM will generate 625 trips per year; the 4,000-NM mission will generate 480 trips per year.

DEPRECIATION. Depreciation is based on the total airplane (airframe + engines) price and its associated spares price. The airframe and engine spares factors, the depreciation period and the residual value are noted in Table 7.

INTEREST. Most aircraft purchases are financed through the use of long-term debt and a down payment from company funds. To account for the total interest cost to the airline, interest is computed on the total price of the airplane plus spares less the down payment. Although interest payments will decline each year, an average annual interest cost is used in aircraft comparisons to reflect the average effect over the airplane's depreciable life. The interest method assumes a 15-year loan period, two loan payments per year, and equal principle payments. The factors defining the amount financed, the depreciation period, and the interest rate are noted in Table 7.

INSURANCE. The annual hull insurance cost is based on the total airplane price. The insurance rate is 0.35% of the total airplane price.

AIRFRAME AND ENGINE STUDY PRICES. Airframe study price for the MR-275 and LR-600 concepts was based on a parametric relationship between airframe study price and either payload-range index or airframe weight. Payload-range index (PRI) was selected as the primary independent variable since the MR-275 concept was chosen as a possible replacement airplane for this market sector (275 seats, 6,000-NM design range). The LR-600 concept was chosen since that airplane could define a new market sector (600 seats, 7,500-NM design range). Airframe weight, the secondary independent variable, was also evaluated as an airframe price generator in order to assess the impact of airframe downsizing afforded by advanced engine technology.

However, it should be understood that a commercial transport aircraft is not sold on a price-per-pound basis. Its selling price in essence represents a market-based price (without relationship to cost). The commercial product relies on a fixed price based on an end item specification, performance guarantees, service life policies, and warranties. This would apply to airframes as well as to engines.

The airframe payload-range index for the MR-275 and LR-600 concepts was determined from a database of commercial transports with three-class international seating capacities ranging from 181 to 421, and ranges varying from 3,920 to 7,007 NM (International rules), and is dimensioned in (seat-NM)/1000. For the 275-seat 6000-NM design, the payload-range index would be 1,650 (275*6000/1000). The PRI for the 600-seat 7500-NM concept would be 4,500. The airframe prices were derived from MDC's commercial transport database. For both the 275- and 600-seat airplanes in a three-class intercontinental configuration, the airframe study price equation is

Airframe Study Price ($M) = 43.553 + 0.282 * PRI

A power curve fit of airframe study price (in millions of dollars) versus airframe weight (in pounds and denoted by AFW) produced the following study price equation:

Airframe Study Price ($M) = 0.7822 * (AFW/1000) ^ 0.8937

The above equation was developed from an expanded MDC database of 11 current-generation twin-aisle U.S. and non-U.S. commercial transports.

Engine study prices were developed from MDC's historical database and from engine manufacturer's data. These engine prices represent only the bare engine, as the remainder of the propulsion system price (e.g., nacelles and thrust reversers) is assumed to be part of the airframe price. This is in keeping with the original ATA DOC methodology. The parametric trend of engine price vs. engine thrust (i.e., engine price scaling) was derived from the MDC database for current-technology engines, and was segregated into two engine classes: 15,000 to 40,000 lbf for the SR-150 concepts discussed in another report in this series, and 50,000 to 90,000 lbf for the MR-275 and LR-600 intercontinental airplane concepts studied. The current technology engines for the MR-275 and LR-600 concepts were the PW4000 series, and formed the basis for the current-technology 1995-EIS HBR engines. The advanced-technology 2005-EIS VHBR engines were priced 10% higher than the 1995-EIS HBR engines for the same thrust level, based on P&W information.

The engine study price equations were in log-linear format and are based on uninstalled maximum sea-level static thrust (SLST), dimensioned in pounds-force. The engine price dimension in millions of dollars per engine. The variation of bare engine price with engine thrust is assumed to be identical for both the current- and advanced-technology engines. The characteristics of the engine price equations, which take on the form y=ax^b, are as follows:

Engine	Constant	Exponent
PW 4XXX (HBR)	0.0021915	0.739423
PW STS1046 (BHBR)	0.0024106	0.739423

The difference in the constant term between the 1995-EIS HBR engine and the 2005-EIS VHBR engine is the 10% factor suggested by P&W.

The impact of different airframe and engine pricing scenarios on DOC+I will be evaluated and discussed in Section III.

Table 7. DOC+I Ground Rules And Assumptions
MR-275 and LR-600 Concepts

Item	Parameter
DOC+I Basis	International rules
Design Mission [MR-275/LR-600]	6,000 NM/7,500 NM
Economic Mission [MR-275/LR-600]	3,000 NM/4,000 NM
Utilization	625/480 trips per year
Dollar Year	1993
Fuel Price	$0.70 per US gallon
Maintenance Labor Rate	$25.00 per man-hour
Maintenance Burden Rate	200% of direct labor
Number of Cockpit Crew	2
Number of Cabin Crew	1 per 30 seats
Landing Fees	Function of MTOGW
Navigation Fees	Function of MTOGW, first 500 NM
Hull Insurance Rate	0.35% of airplane price
Depreciation:Period	15 Years
Depreciation:Residual Value	10% of price (Including spares)
Investment Spares:Airframe	6% of airframe price
Investment Spares:Engine	23% of engine price
Interest:Amount Financed	100% of aircraft & spares
Interest:Period	15 Years
Interest:Rate	8%

III. RESULTS

A. Description of Configurations

Figure 5 is a general arrangement drawing of the 275 passenger airplane. This is a conventional twin engine configuration whose advanced concept features include an aspect ratio 11 wing and an all-flying vertical tail. The fuselage has a circular cross section and will accommodate two LD-3 containers below the floor forward and aft of the wing box and main landing gear bay. Interior arrangement is 278 seats (not the target of 275 seats) three class, as shown in the drawing of Figure 6. Economy class seat spacing is slightly greater than that specified by Douglas interior rules, and a flight crew rest area is provided due to the long duration of the design flight range. (Note that in the costing analysis, only a two person flight crew is used.) It should also be noted that the wing and empennage sizes shown on the general arrangement drawing of Figure 5 are not to exact scale of the final sized airplanes. The actual dimensions are given in the Characteristics Data below (Table 8) for both current technology (1995) and advanced technology (2005 EIS) engined airplanes.

Table 8. MR-275 Geometric Characteristics Table

		WING	HORIZONTAL	VERTICAL
SREF (PW-4484)	FT^2	3000	709.56	283.08
SREF (STS-1046)	FT^2	2935	686.62	273.93
SPAN (PW-4484)	FT	181.91	59.56	22.57
SPAN (STS-1046)	FT	179.93	58.59	22.21
MAC (PW-4484)	FT	15.16	4.96	1.88
MAC (STS-1046)	FT	17.91	12.62	13.38
COMMON GEOMETRIC CHARACTERISTICS				
ASPECT RATIO		11.03	5.00	1.80
C/4SWEEP ANGLE	DEG	34.95	35.00	40.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	115.00	50.00	0.00
TAIL ARM	IN	N/A	1045.00	1041.00
VOMUME RATIO		N/A	1.1376	0.0450
DIHERAL ANGLE	DEG	6.00	8.00	0.00
THICKNESS, % CHORD	Average	0.12	0.10	0.10
		AIRCRAFT		
OVERALL LENGTH	FT	195.21		
HEIGHT PW4484	FT	50.43		
HEIGHT STS1046	FT	50.07		

Figure 7 is a general arrangement drawing of the 600 passenger airplane. This is a conventional four engine configuration whose advanced concept features include an aspect ratio 11 wing and an all-flying vertical tail. The fuselage has a double lobed cross section with seating on both floors; 217 seats on the upper deck and 382 on the lower deck. The upper deck has three class seating (first class, business, and economy) with two aisles. Seat count on the upper deck can be increased substantially to approximately 317 with economy only seating. Passenger arrangement on the lower deck for the basic 600 seat airplane is one class economy with three aisles and a seat pitch of 33 and 32 inches. A rest area is provided for the flight crew due to the long duration of the design mission. (Note that only a two person crew is used in the costing analysis.) Provisions to accommodate two LD-3 containers or commercial pallets are below the lower floor, forward and aft of the wing box and main landing gear bay. Figure 8 shows the interior arrangement. It should also be noted that the wing and empennage sizes shown on the general arrangement drawing of Figure R3 are not to exact scale of the final sized airplanes. The actual dimensions are given in the Characteristics Data below (Table 9) for both current technology (1995) and advanced technology (2005 EIS) engined airplanes.

Table 9. LR-600 Geometric Characteristics Table

		WING	HORIZONTAL	VERTICAL
SREF (PW-4484)	FT^2	5625	625.00	850.70
SREF (STS-1046)	FT^2	5130	544.34	740.91
SPAN (PW-4484)	FT	248.75	53.03	39.13
SPAN (STS-1046)	FT	237.55	49.49	36.52
MAC (PW-4484)	FT	24.80	12.70	23.58
MAC (STS-1046)	FT	23.68	11.85	22.00
COMMON GEOMETRIC CHARACTERISTICS				
ASPECT RATIO		11.00	4.50	1.80
C/4SWEEP ANGLE	DEG	35.00	35.00	40.00
TRAP TAPER		0.30	0.35	0.33
Y SIDE OF BODY	IN	136.00	84.00	0.00
TAIL ARM	IN	N/A	1382.00	1352.00
VOLUME RATIO		N/A	0.5160	0.0685
DIHERAL ANGLE	DEG	6.00	8.00	0.00
THICKNESS, % CHORD	Average	0.103	0.093	0.10
		AIRCRAFT		
OVERALL LENGTH	FT	244.07		
HEIGHT PW4484	FT	79.20		
HEIGHT STS1046	FT	76.59		

The lower deck can be configured for passengers or cargo. When the lower deck is to be used for cargo, the floor and cabin area will accommodate two 88 x 108 inch pallets side by side with a height of 8 feet. A visor type nose door is shown in Figure R3 as an option for the lower cargo floor arrangement, however, this was not analyzed in the weight and cost calculations.

B. Engine Selections

For both the MR-275 and LR-600 airplanes, the base engine representing 1995 entry into service (EIS) is indicative of the PW4000 engine family (Figure 9). The level of performance is representative of that of the PW4084 scheduled to enter into service on the Boeing 777 in May of 1995 and lower thrust versions certified earlier and incorporating performance improvements bringing them to 1995 equivalency. The PW4000 family covers a thrust range from 50,000 lbs. to 84,000 lbs. plus, thereby providing a broad base upon which to represent performance for a 1995 EIS engine. The PW4000 engine incorporates such technology features as controlled diffusion airfoils, advanced floatwall combustor, single crystal turbine blades, radial gradient turbine airfoils and a full authority digital electronic control. The performance represents a bypass ratio of 5.0 to 6.5 (fan pressure of about 1.75) and a cycle pressure ratio in the 30-35 range. Noise and emission levels meet or exceed current or anticipated regulations.

For both the MR-275 and LR-600 airplanes, the year 2005 EIS advanced technology advanced ducted propulsor (ADP) engine designated the STS1046 (Figure 10), employs advanced aerodynamics for high component performance, a high pressure ratio (55 OPR) and high temperature (3100°F) cycle and a geared low pressure ratio (1.32) fan for improved propulsive efficiency. The bypass ratio at top of climb is 16.7 compared with the base engine ratio of 4.6. The improvement in uninstalled bucket TSFC at cruise was 14.6%.

The high spool was based on the P&W advanced technology common core ATCC-D (commercialized military IHPTET gas generator) which incorporates a high speed/high pressure ratio per stage compressor (six stages, pressure ratio = 9) and a high speed single stage turbine. This allows for a significant parts count reduction compared with the base engine resulting in reduced gas generator acquisition and maintenance costs. This is consistent with long term trends toward increased compressor and turbine speeds. The ADP concept incorporates a geared (4.2 gear ratio) variable pitch low speed fan. The reduced 850 ft/sec tip speed fan and advanced acoustic design provides noise characteristics that are anticipated to meet or exceed all projected future noise reduction requirements. Performance, weight and cost estimates also included allowances for a reduced emissions staged combustor which would meet or exceed projected emission requirements. Both the low noise and reduced emission designs reflect advances being developed under the NASA Advanced Subsonic Technology (AST) program.

C. Final Sized Airplanes

1. Primary sizing constraints

The primary sizing criteria used in this report are shown in Table 1. For the 275-passenger aircraft, the critical sizing parameters are payload, range and takeoff field length (TOFL). Initial cruise altitude (ICA) and approach speed (Vappr) are less critical. For the 600-passenger aircraft, the critical sizing parameters are payload, range, takeoff field length, and initial cruise altitude. Approach speed (Vappr) is not critical. Climb speed of Mach 0.83 was used in order to achieve an initial climb altitude of 31,000 ft.

For all configurations, takeoff field length is computed at sea level and 84 ^{O}F. The aircraft are sized by the combination of Fn and Sw to meet the takeoff field length requirement at a minimum MTOGW.

2. Effects of engine technology improvements

MR-275

Table 10 summarizes the results of the final sized MR-275 aircraft with the PW4484 and STS1046 engines. In comparing the aircraft characteristics of these two airplanes, the STS1046 airplane has an overall better performance. The operating empty weight (OEW) is 4,100 lbs lighter than the PW4484. The specific fuel consumption (SFC) is about 20% better than the PW4484. The effects of engine change from PW4484 to STS1046 are a reduction in wing area (Sw), thrust (Fn) and fuel burned. As a result, the aircraft sized with the STS1046 engines resulted in a lighter maximum takeoff gross weight (MTOGW) compared to the base engine.

Table 10. MR-275 Sized Aicraft

Engine	PW4484	STS1046
Bypass Ratio	6	23
Sw (Sq Ft)	3,000	2,935
Fn (Lb SLS)	62,450	56,800
MTOW (Lb)	456,589	420,143
OEW (Lb)	232,638	228,533
Block Fuel (Lb)	149,158	119,331
Block Time (Hr)	13.09	13.095
Wt/Sw (Lb/Sq Ft)	152.2	143.15
Fn/Wt	0.273	0.27
ICA (Ft)	35K+(Cl Ceil)	36K+(Cl Ceil)
Vappr (KEAS)	125	125
TOFL (Ft)	9,000	9,000
1st Seg Grad (%)	0.81	0.72
2nd Seg Grad (%)	2.4	2.4
V2 (KEAS)	160.1	158.6
CL Avg @ 35000	0.563	0.547
L/D Avg @ 35000	19.68	19.35
SFC Avg @ 35000	0.5934	0.4949

LR-600

Table 11 summarizes the results of the final sized LR-600 aircraft with the PW4484 and STS1046 engines. In comparing the aircraft characteristics of these two airplanes, the STS1046 airplane has an overall better performance. The maximum takeoff gross weight (MTOGW) is 120,000 lb less than the PW4484 airplane. The specific fuel consumption (SFC) is about 21% better than the PW4484. The effects of engine change from PW4484 to STS1046 are a reduction in wing area (Sw), thrust (Fn) and fuel burned. As a result, the aircraft sized with the STS1046 engines resulted in a lighter maximum takeoff gross weight (MTOGW) compared to the base engine.

Table 11. LR-600 Sized Aicraft

Engine	PW4484	STS1046
Bypass Ratio	6	23
MTOW (LB)	1,052,204	931,690
OEW (LB)	490,752	465,162
Sw (SQ FT)	5,625	5,130
Fn (LB)	57,150	50,800
Block Fuel (LB)	395,683	308,813
Block Time (Hr)	15.790	15.796
Wt/Sw (LB/SQ FT)	187.06	181.62
Fn/Wt	0.217	0.218
ICA (FT)	31K + (Climb Ceil)	31K + (Cruise Ceil)
TOFL (FT)	11,000	11,000
Vappr (KEAS)	134.8	137.5
1st Seg Grad (%)	2.40	2.27
2nd Seg Grad (%)	3.05	3.00
V2 (KEAS)	163.1	163.2
CL Avg @ 35000	0.556	0.562
L/D Avg @ 35000	20.04	19.46
SFC Avg @ 35000	0.600	0.500

D. Sensitivity Results

MR-275

Tables 12 and 13 show the sensitivity of aircraft sizing to increases in SFC and pod & pylon weights for the MR-275 with the base and advanced P&W engines. Increasing SFC has greater impact on TOGW, Fn and S_W than increasing engine weight. The aircraft sized with a 5% SFC increase have heavier MTOGW compared to the aircraft sized with a 5% engine weight increase. The overall effect of SFC on TOGW is about 3.0% greater than in the engine weight case. Since the aircraft are sized to meet the sizing criteria stated in Table 1, an increase in either SFC or engine weights would also result in an increase in S_W and Fn. In general, the aircraft sized with advanced engines have a smaller effect in TOGW compared to the base engines because of the better performance of the advanced engines relative to the base engines.

Table 12. Sizing Effects of 5% SFC Increase

	PW4484	STS1046
Δ TOGW (lb)	3.6%	3.1%
Δ OEW (lb)	1.8%	1.3%
Δ Fn (lb)	3.6%	4.1%
Δ S_W (sq. ft.)	2.6%	0.4%

Table 13. Sizing Effects of 5% Engine Weight Increase

	PW4484	STS1046
Δ TOGW (lb)	0.7%	0.7%
Δ OEW (lb)	0.3%	0.2%
Δ Fn (lb)	0.9%	0.8%
Δ S_W (sq. ft.)	0.0%	0.0%

LR-600

Tables 14 and 15 show the sensitivity of aircraft sizing to increases in SFC and pod & pylon weights for the LR-600 with the base and advanced P&W engines. Increasing SFC has greater impact on TOGW, Fn and S_W than increasing engine weight. The aircraft sized with a 5% SFC increase have heavier MTOGW compared to the aircraft sized with a 5% engine weight increase. The overall effect of SFC on TOGW is about 3-4% greater than in the engine weight case. Since the aircraft are sized to meet the sizing criteria stated in Table 1, an increase in either SFC or engine weight would also result in an increase in S_W and Fn. Takeoff thrust (Fn) and wing area (S_W) were increased by 3% and 4% respectively relative to aircraft sized with engine weights. In general, the aircraft sized with advanced engines have a smaller effect in TOGW compared to the base engines because of the better performance of the advanced engines relative to the base engines.

Table 14. Sizing Effects of 5% SFC Increase

	PW4484	STS1046
Δ TOGW (lb)	4.5%	3.8%
Δ OEW (lb)	2.7%	2.4%
Δ Fn (lb)	4.0%	3.3%
Δ S_W (sq. ft.)	4.9%	5.2%

Table 15. Sizing Effects of 5% Engine Weight Increase

	PW4484	STS1046
Δ TOGW (lb)	0.7%	0.7%
Δ OEW (lb)	0.4%	0.5%
Δ Fn (lb)	1.0%	0.4%
Δ S_W (sq. ft.)	0.4%	1.3%

E. Direct Operating Cost Analysis and Comparison

The direct operating cost method described in Section II was used to evaluate and compare the impact of propulsion system technology on the DOC+I of the MR-275 concept at a stage length of 3000 NM and of the LR-600 concept at a stage length of 4000 NM, with both concepts evaluated using international rules.

The results for both P&W-powered concepts are shown graphically in Figures 11 (MR-275) and 12 (LR-600), and individually in Tables 16 and 17 (MR-275) and 18 and 19 (LR-600). The DOC+I results are based on two airframe pricing scenarios [payload-range index (PRI) and airframe weight (AFW)] and one engine pricing and maintenance cost scenario where, per P&W, the advanced-technology engine is 10% higher in study price and 5% higher in maintenance cost than its current-technology counterpart at identical thrust levels. Tables 16 and 18 depict the baseline case where the airframe price is PRI-based and Tables 17 and 19 the alternate case where the airframe price is AFW-based.

The MR-275 summary results, shown in Figure 11, indicate that when that concept is configured with the advanced-technology ADP/VHBR STS1046 engine and the airframe is priced on a PRI basis, the DOC+I is 3.6% less than the airplane configured with the current-technology HBR PW4000-series engine. When the airframe is priced on an AFW basis, the DOC+I advantage of the advanced-technology engine widens to 3.9%.

On a similar basis, the LR-600 concept powered by the advanced-technology engine generates a DOC+I that is 5.1% lower than its current-technology-powered counterpart when the airframe price is PRI-based (Figure 12). When the airframe price is airframe-weight based, the DOC+I difference widens to 6.8%.

The percentage differences shown for the LR-600 are greater than those shown for the MR-275 with the same engines. For the LR-600 concept relative to the MR-275, the advanced-technology engine produces greater percentage reductions in MTOGW, OEW, airframe weight, engine thrust, and block fuel. Another contributor is the longer stage length (4,000 NM vs. 3,000 NM) at which the DOC+I is evaluated.

The details behind the DOC+Is for the MR-275 and LR-600 concepts are shown in Tables 16 and 17 and Tables 18 and 19, respectively. In each table, the advanced-technology propulsion system is compared to the conventional-technology propulsion system, with percentage differences shown for the technical and operational characteristics that drive the DOC+I values as well as for each of the DOC+I cost elements. In addition, each cost element is shown as a percentage of the total DOC+I, so as to indicate the relative impact of the change in each cost element to the total DOC+I change.

Referring to Tables 16 and 17, the cash operating cost of the MR-275 concept configured with the advanced technology STS1046 engine was 7.0% lower than that of the airplane configured with the current-technology PW44xx engine. Of the operating cost components directly affected by the engine itself, the block fuel and fuel cost was reduced 18.5% using the advanced-technology engine. The engine maintenance cost decreased 1.2% when the advanced-technology engine was used, based on the sized engines and including a 5% equivalent-thrust maintenance cost penalty for the advanced engine. The 5.9% reduction is sized, uninstalled engine thrust afforded by the advanced-technology engine tended to offset the aforementioned 5% maintenance cost penalty.

The advanced-technology engine increased the ownership cost of the MR-275 concept by 0.9% with the airframe priced on a PRI basis and 0.3% with the airframe priced on an airframe-weight basis. This difference was caused by shifts in the relative impact of the airframe and engine study prices in the three cost components of ownership cost when the airframe is priced either of two ways. As noted in the tables, the sized STS1046 engine was priced 5.2% higher than the sized PW44xx engine for their respective sized thrust levels.

Tables 18 and 19 detail the DOC+I results for the LR-600 concept in the same format. As noted previously, the advanced-technology STS1046 engine provided greater reductions in airplane design and operational elements and thus generated larger reductions in DOC+I. The cash operating cost reduction was 9.5%, influenced primarily by the 20.2% reduction in block fuel. The ownership cost difference was heavily influenced by the choice of airframe pricing parameter. When the airframe was priced on a PRI basis, the ownership cost difference was 0.6%. In contrast, when the airframe was priced on an AFW basis, that difference changed to -3.4%, thus contributing to the widening of the total DOC+I difference from 5.1% to 6.8%.

Table 16. MR−275 AIRCRAFT DOC SUMMARY & COMPARISON
[Baseline Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE / ENTRY−INTO−SERVICE (EIS)		PW44xx/6 1995	STS1046/23 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] PW44xx/6	DOC+I DISTRIBUTION [% TOTAL] STS1046/23
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	456,589	420,143	−8.0%		
OEW	lbm	232,638	228,533	−1.8%		
Airframe Weight	lbm	196,215	193,559	−1.4%		
Airframe Price	$M	$90.1	$90.1	0.0%		
Engine Thrust	lbf	64,300	60,500	−5.9%		
Engine Price	$M	$7.9	$8.3	5.2%		
No. of Engines/Acft	−	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	3,000	3,000			
Block Time	hr	6.799	6.799	0.0%		
Block Fuel	lbm	69,248	56,412	−18.5%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	1,474	1,414	−4.1%	3.3%	3.3%
COCKPIT CREW	"	5,109	4,962	−2.9%	11.5%	11.6%
CABIN CREW	"	4,861	4,861	0.0%	11.0%	11.4%
LANDING FEE	"	1,941	1,786	−8.0%	4.4%	4.2%
MAINT − AIRFRAME	"	3,073	3,045	−0.9%	6.9%	7.1%
MAINT − ENGINE	"	1,321	1,306	−1.2%	3.0%	3.1%
FUEL	"	7,235	5,894	−18.5%	16.4%	13.8%
CASH DOC ==>	$/trip	25,014	23,269	−7.0%	56.5%	54.5%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	11,030	11,126	0.9%	24.9%	26.1%
INTEREST	"	7,598	7,664	0.9%	17.2%	18.0%
INSURANCE	"	593	597	0.8%	1.3%	1.4%
OWNERSHIP DOC ==>	$/trip	19,221	19,387	0.9%	43.5%	45.5%
TOTAL DOC ==>	$/TRIP	44,235	42,656	−3.6%	100.0%	100.0%

NOTE:
(1) Engine 2005EIS/1995EIS ratios: study price − 1.10; maintenance cost − 1.05.
(2) Airframe price is based on payload−range index.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

Table 17 . MR−275 AIRCRAFT DOC SUMMARY & COMPARISON

[Alternate Airframe Pricing Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE : ENTRY−INTO−SERVICE (EIS)		PW44xx/6 1995	STS1046/23 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] PW44xx/6	DOC+I DISTRIBUTION [% TOTAL] STS1046/23
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	456,589	420,143	−8.0%		
OEW	lbm	232,638	228,533	−1.8%		
Airframe Weight	lbm	196,215	193,559	−1.4%		
Airframe Price	$M	$84.5	$84.0	−0.7%		
Engine Thrust	lbf	64,300	60,500	−5.9%		
Engine Price	$M	$7.9	$8.3	5.2%		
No. of Engines/Acft	−	2	2			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	3,000	3,000			
Block Time	hr	6.799	6.799	0.0%		
Block Fuel	lbm	69,248	56,412	−18.5%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	1,474	1,414	−4.1%	3.4%	3.4%
COCKPIT CREW	"	5,109	4,962	−2.9%	11.8%	11.9%
CABIN CREW	"	4,861	4,861	0.0%	11.2%	11.7%
LANDING FEE	"	1,941	1,786	−8.0%	4.5%	4.3%
MAINT − AIRFRAME	"	3,073	3,045	−0.9%	7.1%	7.3%
MAINT − ENGINE	"	1,321	1,306	−1.2%	3.1%	3.1%
FUEL	"	7,235	5,894	−18.5%	16.7%	14.2%
CASH DOC ==>	$/trip	25,014	23,269	−7.0%	57.8%	56.0%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	10,462	10,498	0.3%	24.2%	25.3%
INTERETS	"	7,207	7,232	0.3%	16.7%	17.4%
INSURANCE	"	562	563	0.2%	1.3%	1.4%
OWNERSHIP DOC ==>	$/trip	18,231	18,293	0.3%	42.2%	44.0%
TOTAL DOC ==>	$/TRIP	43,245	41,562	−3.9%	100.0%	100.0%

NOTE:

(1) Engine 2005EIS/1995EIS ratios: study price − 1.10; maintenance cost − 1.05.

(2) Airframe price is based on airframe weight.

(3) Trip costs are rounded to the nearest $1/trip.

(4) Engine thrust is shown on a sized, uninstalled basis.

Table 18. LR–600 AIRCRAFT DOC+I SUMMARY & COMPARISON

[Baseline Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE		PW44xx/6	STS1046/23	COMPARISON	DOC+I DISTRIBUTION [% TOTAL] PW44xx/6	DOC+I DISTRIBUTION [% TOTAL] STS1046/23
ENTRY–INTO–SERVICE (EIS)		1995	2005	2005:1995 [% DIFF.]		
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	1,052,204	931,690	–11.5%		
OEW	lbm	490,752	465,162	–5.2%		
Airframe Weight	lbm	402,250	381,040	–5.3%		
Airframe Price	$M	$170.4	$170.4	0.0%		
Engine Thrust	lbf	58,900	54,100	–8.1%		
Engine Price	$M	$7.4	$7.6	3.3%		
No. of Engines/Acft	–	4	4			
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	4,000	4,000			
Block Time	hr	8.71	8.71	0.0%		
Block Fuel	lbm	191,105	152,455	–20.2%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	2,238	2,106	–5.9%	2.1%	2.1%
COCKPIT CREW	"	9,606	8,989	–6.4%	9.1%	9.0%
CABIN CREW	"	13,589	13,592	0.0%	12.9%	13.6%
LANDING FEE	"	4,472	3,960	–11.5%	4.2%	4.0%
MAINT – AIRFRAME	"	6,255	6,031	–3.6%	5.9%	6.0%
MAINT – ENGINE	"	3,127	3,018	–3.5%	3.0%	3.0%
FUEL	"	19,966	15,928	–20.2%	18.9%	15.9%
CASH DOC ==>	$/trip	59,253	53,624	–9.5%	56.1%	53.5%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	26,557	26,704	0.6%	25.2%	26.7%
INTEREST	"	18,295	18,396	0.6%	17.3%	18.4%
INSURANCE	"	1,428	1,435	0.5%	1.4%	1.4%
OWNERSHIP DOC ==>	$/trip	46,280	46,534	0.6%	43.9%	46.5%
TOTAL DOC ==>	$/TRIP	105,533	100,158	–5.1%	100.0%	100.0%

NOTE:

(1) Engine 2005EIS/1995EIS Ratios: study price – 1.10; maintenance cost – 1.05

(2) Airframe price is based on payload–range index.

(3) Trip costs are rounded to the nearest dollar.

(4) Engine thrust is shown on a sized, uninstalled basis.

Table 19. LR−600 AIRCRAFT DOC+I SUMMARY & COMPARISON
[Alternate Airframe Pricing Case]

INTERNATIONAL RULES, $1993

ENGINE: TYPE : ENTRY−INTO−SERVICE (EIS)		PW44xx/6 1995	STS1046/23 2005	COMPARISON 2005:1995 [% DIFF.]	DOC+I DISTRIBUTION [% TOTAL] PW44xx/6	STS1046/23
SELECTED DOC+I PARAMETERS						
MTOGW	lbm	1,052,204	931,690	−11.5%		
OEW	lbm	490,752	465,162	−5.2%		
Airframe Weight	lbm	402,250	381,040	−5.3%		
Airframe Price	$M	$166.4	$158.5	−4.7%		
Engine Thrust	lbf	58,900	54,100	−8.1%		
Engine Price	$m	$7.4	$7.6	3.3%		
AVERAGE TRIP PERFORMANCE						
Average Trip Distance	NM	4,000	4,000			
Block Time	hr	8.71	8.71	0.0%		
Block Fuel	lbm	191,105	152,455	−20.2%		
CASH COSTS/TRIP						
NAVIGATION FEE	$/trip	2,238	2,106	−5.9%	2.1%	2.2%
COCKPIT CREW	"	9,606	8,989	−6.4%	9.2%	9.2%
CABIN CREW	"	13,589	13,592	0.0%	13.0%	13.9%
LANDING FEE	"	4,472	3,960	−11.5%	4.3%	4.1%
MAINT − AIRFRAME	"	6,255	6,031	−3.6%	6.0%	6.2%
MAINT − ENGINE	"	3,127	3,018	−3.5%	3.0%	3.1%
FUEL	"	19,966	15,928	−20.2%	19.1%	16.3%
CASH DOC ==>	$/trip	59,253	53,624	−9.5%	56.6%	55.0%
OWNERSHIP COSTS/TRIP						
DEPRECIATION	$/trip	26,039	25,165	−3.4%	24.9%	25.8%
INTEREST	"	17,938	17,336	−3.4%	17.1%	17.8%
INSURANCE	"	1,399	1,350	−3.5%	1.3%	1.4%
OWNERSHIP DOC ==>	$/trip	45,375	43,850	−3.4%	43.4%	45.0%
TOTAL DOC ==>	$/TRIP	104,629	97,474	−6.8%	100.0%	100.0%

NOTE:
(1) Engine 2005EIS/1995EIS ratios: study price − 1.10; maintenance − 1.05
(2) Airframe price is based on airframe weight.
(3) Trip costs are rounded to the nearest $1/trip.
(4) Engine thrust is shown on a sized, uninstalled basis.

IV. SUMMARY

A study to examine the sole effect of advanced technology engines on the performance and DOC+I of 275- and 600-passenger subsonic transport airplanes has been completed. Two airplanes were designed and sized for each class: one using the current technology (1995) P&W engine PW4084 as a baseline, and one using the advanced technology (2005) P&W ADP engine STS1046. All other aircraft technologies were kept constant. The year 2005 was selected as the entry-into-service date for the airframe/engine combinations.

The advanced technology engine provided significant reductions in fuel burn, weight, and wing area as follows:

		275-passenger	600-passenger
reduction in fuel burn	=	20%	22%
reduction in wing area	=	2%	9%
reduction in TOGW	=	8%	11%.

These corresponded to a range of DOC+I reductions from 3.6% to 3.9% for the 275-passenger airplane, and 5.1% to 6.8% for the 600-passenger airplane depending on the airframe/engine pricing models used. In both cases, more DOC+I reduction was obtained using the airframe price based on airframe weight.

It is recommended that the results of this study be viewed from more than a single perspective: the physical characteristics of the airplanes themselves (TOGW, OEW, Sw, Fn, etc.), and the corresponding DOC+I figures. The economic analyses have been defined in two forms: 1. airframe cost based on the mission (number of passengers and range), which result in the airframe cost being invariant between the current and advanced technology airplanes, and 2. airframe cost varying with airframe weight. The first method forces the DOC+I increment between the current and advanced technology airplanes to become dependent solely on engine price, maintenance cost, and fuel burn. No specific reward is offered for the reduction in airplane size and weight provided by the advanced technology powerplants. Alternatively, the second method provides a more direct reward for the advanced technology in both engines and airframe. These two economic algorithms may be regarded as bounding the problem, and the true economic benefit probably lies somewhere in between their DOC+I predictions.

Finally, it should be understood that the scope of the present study did not allow for an optimization of the matching of engines to the airplanes and the design mission. A careful iterative analysis should yield an increase in the performance benefits offered by the advanced technology engines.

APPENDIX

MR-275 and LR-600 Detailed Weight Summaries

Table A1. Base engine MR-275 Aircraft Group Weight Statement

PROGRAM **PAIT #9** CONFIGURATION **MR-275/PW4460** DATE & TIME : 6/29/94 12:37

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	53,038	
BENDING MATERIAL		25,266
SPAR WEB		2,508
RIBS AND BULKHEADS		2,847
AERODYNAMIC SURFACES		17,203
SECONDARY STRUCTURE		5,214
TAIL	10,350	
FUSELAGE	45,920	
LANDING GEAR	17,741	
NACELLE & PYLON	4,528	
AIR INDUCTION	1,224	
PROPULSION	26,326	
ENGINES		19,661
ENGINES SYSTEM		1,370
EXHAUST SYSTEM		495
THRUST REVERSER		3,112
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		1,688
FLIGHT CONTROLS	4,381	
COCKPIT CONTROLS		128
SYSTEM CONTROL		4,252
POWER SYSTEMS	8,968	
AUXILIARY POWER PLANT		1,490
HYDRAULICS		2,018
PNEUMATICS		1,560
ELECTRICAL		3,900
INSTRUMENTS	1,430	
AVIONICS & AUTOPILOT	2,620	
FURNISHINGS & EQUIPMENT	34,900	
AIR CONDITIONING	3,730	
ANTI-ICING	720	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	215,876	
OPERATIONAL ITEMS	16,760	
OPERATING EMPTY WEIGHT	232,636	
USABLE FUEL	166,203	
PAYLOAD	57,750	
TAKEOFF GROSS WEIGHT	456589	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 3,000	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 62,450	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 152.2
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2736
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.3640
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 57,750	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 100,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	166,202	173,328	= 0.1812 SWT^ 1.72
CENTER WING		83,502	= 7.7310 SWT^ 1.16
FUSELAGE			
TOTAL	166,202	256,830	

SIZING DERIVATIVES

dOEW/dWG = 0.11855

dOEW/dSW = 14.54546

dOEW/dT OR dP = 0.51007

Wconstant = 103,020

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MR275/PW4460-DDN

Table A2. Advanced engine MR-275 Aircraft Group Weight Statement

PROGRAM **PAIT #9** CONFIGURATION **MR-275 / STS 1046 ADP** DATE & TIME : 7/21/94 8:43

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	50,651	
BENDING MATERIAL		24,068
SPAR WEB		2,283
RIBS AND BULKHEADS		2,760
AERODYNAMIC SURFACES		16,561
SECONDARY STRUCTURE		4,979
TAIL	9,685	
FUSELAGE	45,451	
LANDING GEAR	16,190	
NACELLE & PYLON	8,217	
AIR INDUCTION		
PROPULSION	24,100	
ENGINES		18,176
ENGINES SYSTEM		2,272
EXHAUST SYSTEM		2,083
THRUST REVERSER		
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		1,569
FLIGHT CONTROLS	4,304	
COCKPIT CONTROLS		128
SYSTEM CONTROL		4,175
POWER SYSTEMS	8,932	
AUXILIARY POWER PLANT		1,490
HYDRAULICS		1,982
PNEUMATICS		1,560
ELECTRICAL		3,900
INSTRUMENTS	1,430	
AVIONICS & AUTOPILOT	2,620	
FURNISHINGS & EQUIPMENT	34,900	
AIR CONDITIONING	3,730	
ANTI-ICING	1,526	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	211,735	
OPERATIONAL ITEMS	16,760	
OPERATING EMPTY WEIGHT	228,495	
USABLE FUEL	133,898	
PAYLOAD	57,750	
TAKEOFF GROSS WEIGHT	420143	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 2,935	
NUMBER OF ENGINES	= 2	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 56,800	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 143.1
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2704
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.3187
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 57,750	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 100,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)

DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	133,898	166,919	= 0.1812 SWT^ 1.72
CENTER WING		81,407	= 7.7310 SWT^ 1.16
FUSELAGE			
TOTAL	133,898	248,326	

SIZING DERIVATIVES

dOEW/dWG = 0.12055
dOEW/dSW = 14.58400
dOEW/dT OR dP = 0.56599
Wconstant = 102,894

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MR275/STS1045 ADP-DDN

Table A3. Base engine LR-600 Aircraft Group Weight Statement

PROGRAM **PAIT #9** CONFIGURATION **LR-600-PW4460/PW4484** DATE & TIME : 9/22/94 9:23

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	134,802	
BENDING MATERIAL		73,438
SPAR WEB		7,925
RIBS AND BULKHEADS		6,294
AERODYNAMIC SURFACES		36,684
SECONDARY STRUCTURE		10,460
TAIL	22,398	
FUSELAGE	93,966	
LANDING GEAR	44,444	
NACELLE & PYLON	8,287	
AIR INDUCTION	2,240	
PROPULSION	48,278	
ENGINES		35,985
ENGINES SYSTEM		2,507
EXHAUST SYSTEM		907
THRUST REVERSER		5,696
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		3,183
FLIGHT CONTROLS	7,485	
COCKPIT CONTROLS		133
SYSTEM CONTROL		7,352
POWER SYSTEMS	13,439	
AUXILIARY POWER PLANT		1,600
HYDRAULICS		3,489
PNEUMATICS		3,200
ELECTRICAL		5,150
INSTRUMENTS	1,900	
AVIONICS & AUTOPILOT	3,450	
FURNISHINGS & EQUIPMENT	65,000	
AIR CONDITIONING	5,000	
ANTI-ICING	1,350	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	452,038	
OPERATIONAL ITEMS	38,700	
OPERATING EMPTY WEIGHT	490,738	
USABLE FUEL	435,466	
PAYLOAD	126,000	
TAKEOFF GROSS WEIGHT	1,052,204	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 5,625	
NUMBER OF ENGINES	= 4	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 57,150	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 187.1
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2173
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.4139
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 126,000	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 200,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)
DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	374,864	374,864	= 0.2047 SWT^ 1.67
CENTER WING	60,602	163,237	= 8.6632 SWT^ 1.14
FUSELAGE			
TOTAL	435,466	538,101	

SIZING DERIVATIVES

dOEW/dWG = 0.17043
dOEW/dSW = 11.48558
dOEW/dT OR dP = 0.97961
Wconstant = 190,823

PROGRAM **PAIT #9** CONFIGURATIC **LR-600-ADV ENGINE STS1046** DATE & TIME : #########

COMMERCIAL AIRCRAFT - GROUP WEIGHT STATEMENT

WING	119,052	
BENDING MATERIAL		64,527
SPAR WEB		6,704
RIBS AND BULKHEADS		5,530
AERODYNAMIC SURFACES		32,938
SECONDARY STRUCTURE		9,353
TAIL	20,085	
FUSELAGE	92,510	
LANDING GEAR	38,873	
NACELLE & PYLON	14,693	
AIR INDUCTION		
PROPULSION	43,103	
ENGINES		32,500
ENGINES SYSTEM		4,062
EXHAUST SYSTEM		3,724
THRUST REVERSER		
PROPELLERS		
SPEED REDUCTION GEARBOXES		
FUEL SYSTEM		2,817
FLIGHT CONTROLS	6,948	
COCKPIT CONTROLS		133
SYSTEM CONTROL		6,815
POWER SYSTEMS	13,184	
AUXILIARY POWER PLANT		1,600
HYDRAULICS		3,234
PNEUMATICS		3,200
ELECTRICAL		5,150
INSTRUMENTS	1,900	
AVIONICS & AUTOPILOT	3,450	
FURNISHINGS & EQUIPMENT	65,000	
AIR CONDITIONING	5,000	
ANTI-ICING	2,670	
AUXILIARY GEAR		
MANUFACTURER'S EMPTY WEIGHT	426,468	
OPERATIONAL ITEMS	38,700	
OPERATING EMPTY WEIGHT	465,168	
USABLE FUEL	340,425	
PAYLOAD	126,000	
TAKEOFF GROSS WEIGHT	931,593	

	INPUT	OUTPUT
TRAPEZOIDAL WING AREA (SQFT)	= 5,134	
NUMBER OF ENGINES	= 4	
THRUST PER ENGINE @ SEA LEVEL STATIC CONDITION (LB)	= 50,781	
MAX. POWER PER ENGINE @ SL RATED CONDITION (SHP)		
WING LOADING BASED ON TRAPEZOIDAL WING AREA (PSF)		= 181.5
TAKEOFF THRUST OR POWER TO WEIGHT RATIO (LBF OR SHP / LBM)		= 0.2180
FUEL FRACTION = USABLE FUEL WEIGHT / GROSS WEIGHT		= 0.3654
PERFORMANCE PAYLOAD @ DESIGN RANGE (LB)	= 126,000	
MAXIMUM PAYLOAD @ LIMIT LOAD FACTOR (LB)	= 200,000	
LIMIT LOAD FACTOR	= 2.50	
DESIGN RANGE (NM)		
AVERAGE LIFT TO DRAG RATIO		
AVERAGE CRUISE SPEED (KT)		
AVERAGE INSTALLED TSFC (LBM/LBF-HR)		
AVG. SFC DIVIDED BY PROP EFFICIENCY (LBM/HP-HR)		
CORR'N FACTOR: EXTRA FUEL BURNED FOR CLIMB & ACCELERATION		
RESERVE FUEL FRACTION = RESERVE FUEL / MISSION FUEL		

FUEL (LB)
DENSITY = 6.7 LB/GAL

	REQ'D	CAPACITY	FUEL EQN
OUTER WING	321,848	321,848	= 0.2047 SWT^ 1.67
CENTER WING	18,577	147,096	= 8.6632 SWT^ 1.14
FUSELAGE			
TOTAL	340,425	468,944	

SIZING DERIVATIVES

dOEW/dWG = 0.17112
dOEW/dSW = 11.50278
dOEW/dT OR dP = 1.08867
Wconstant = 191,418

Table A4. Advanced engine LR-600 Aircraft Group Weight Statement

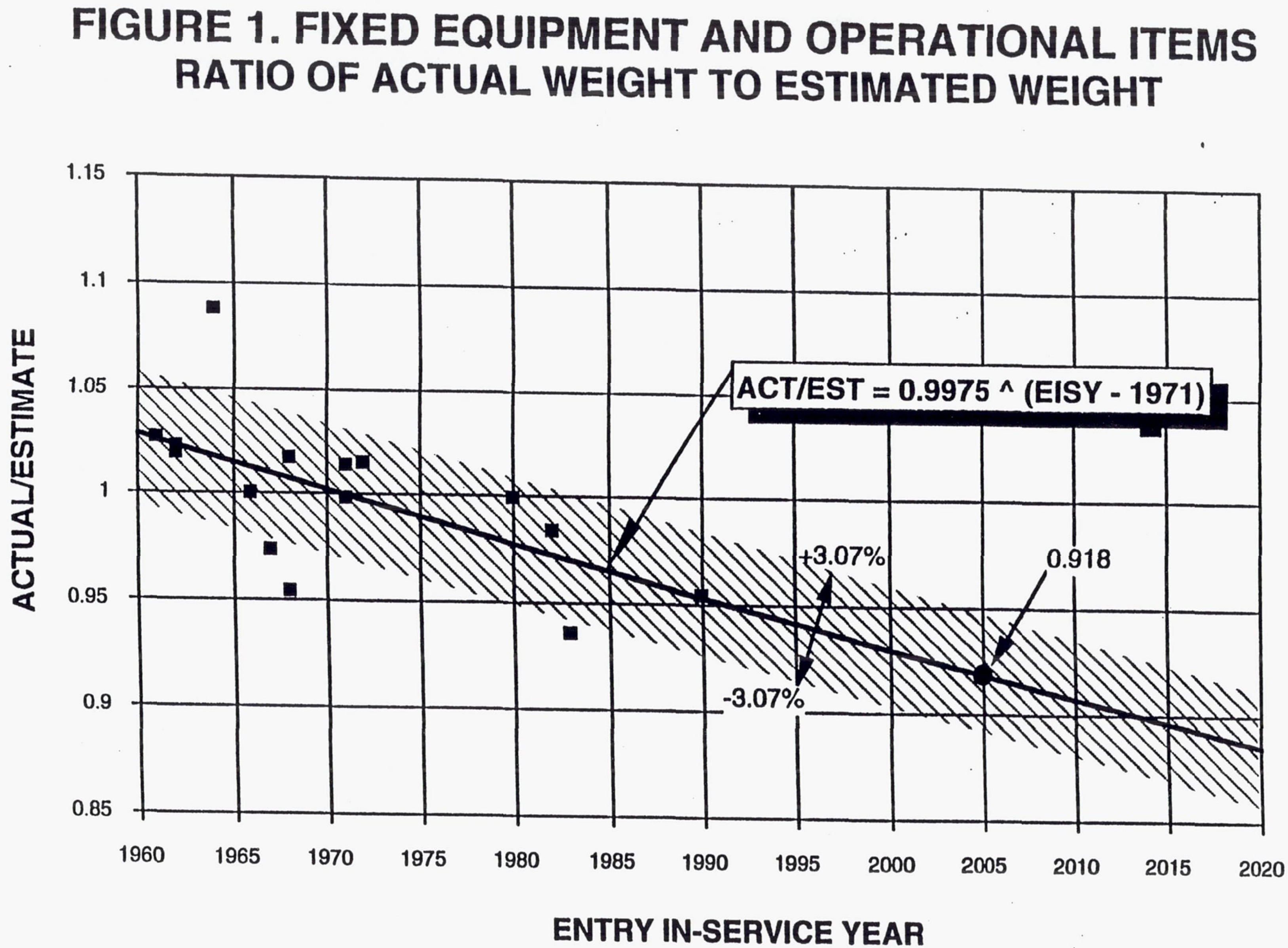

Figure 1. Fixed Equipment and Operational Items Ratio of Actual Weight to Estimated Weight

FIGURE 2. ENGINE POD WEIGHT/ THRUST RATIO

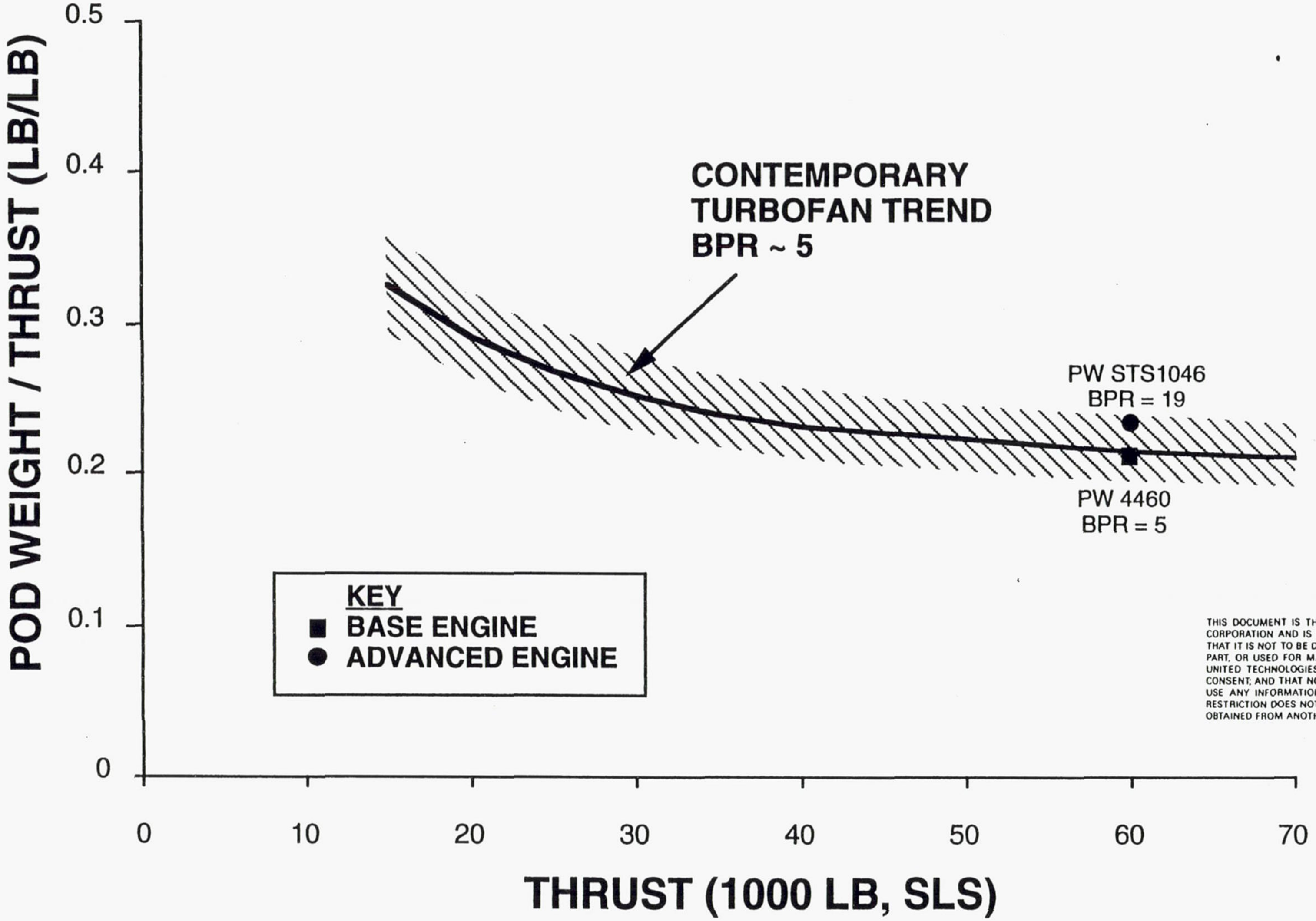

Figure 2. Engine Pod Weight/Thrust Ratio

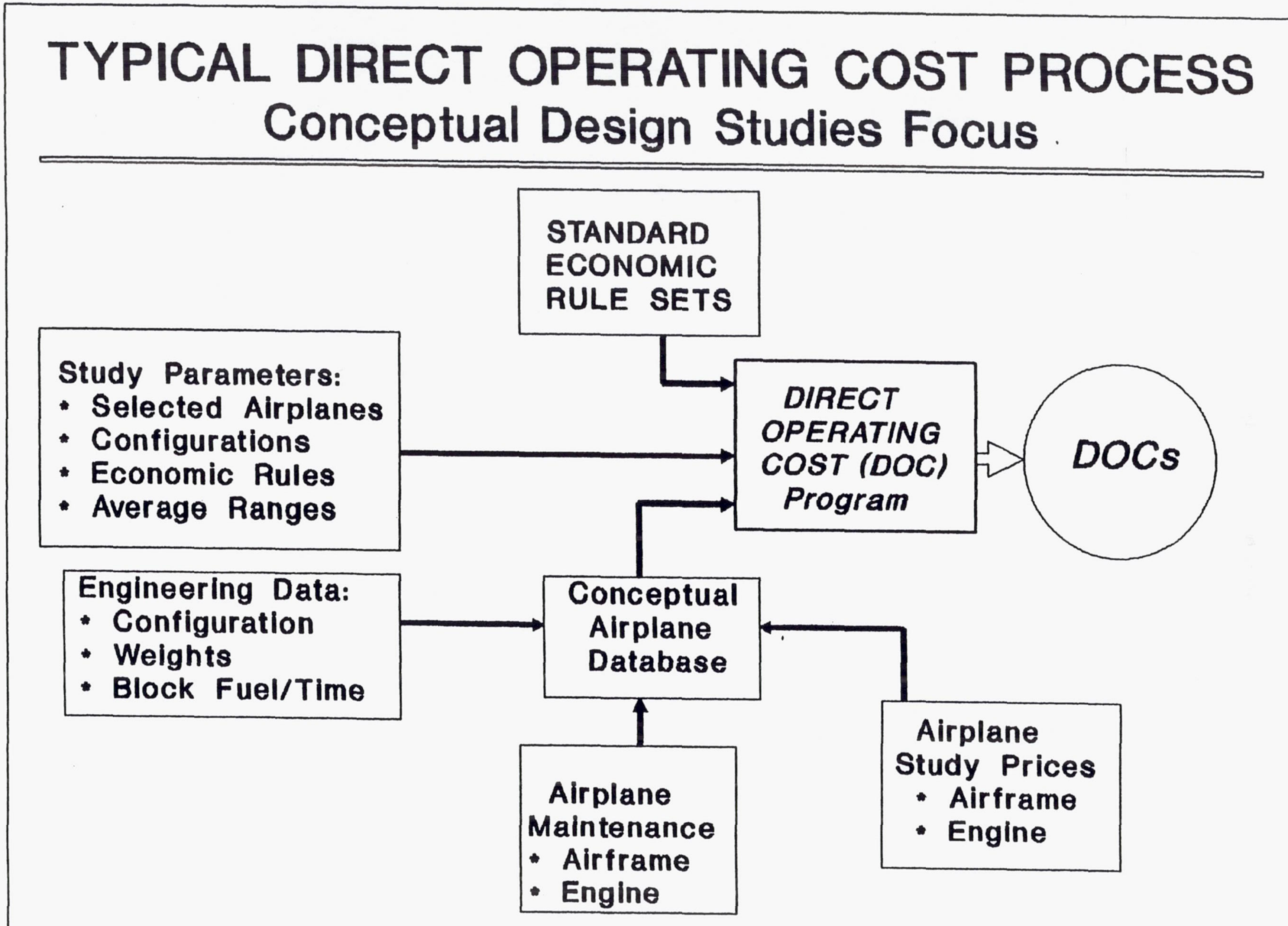

Figure 4. Typical DOC Process

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.
2. Characteristics data for sized aircraft in Table 8.

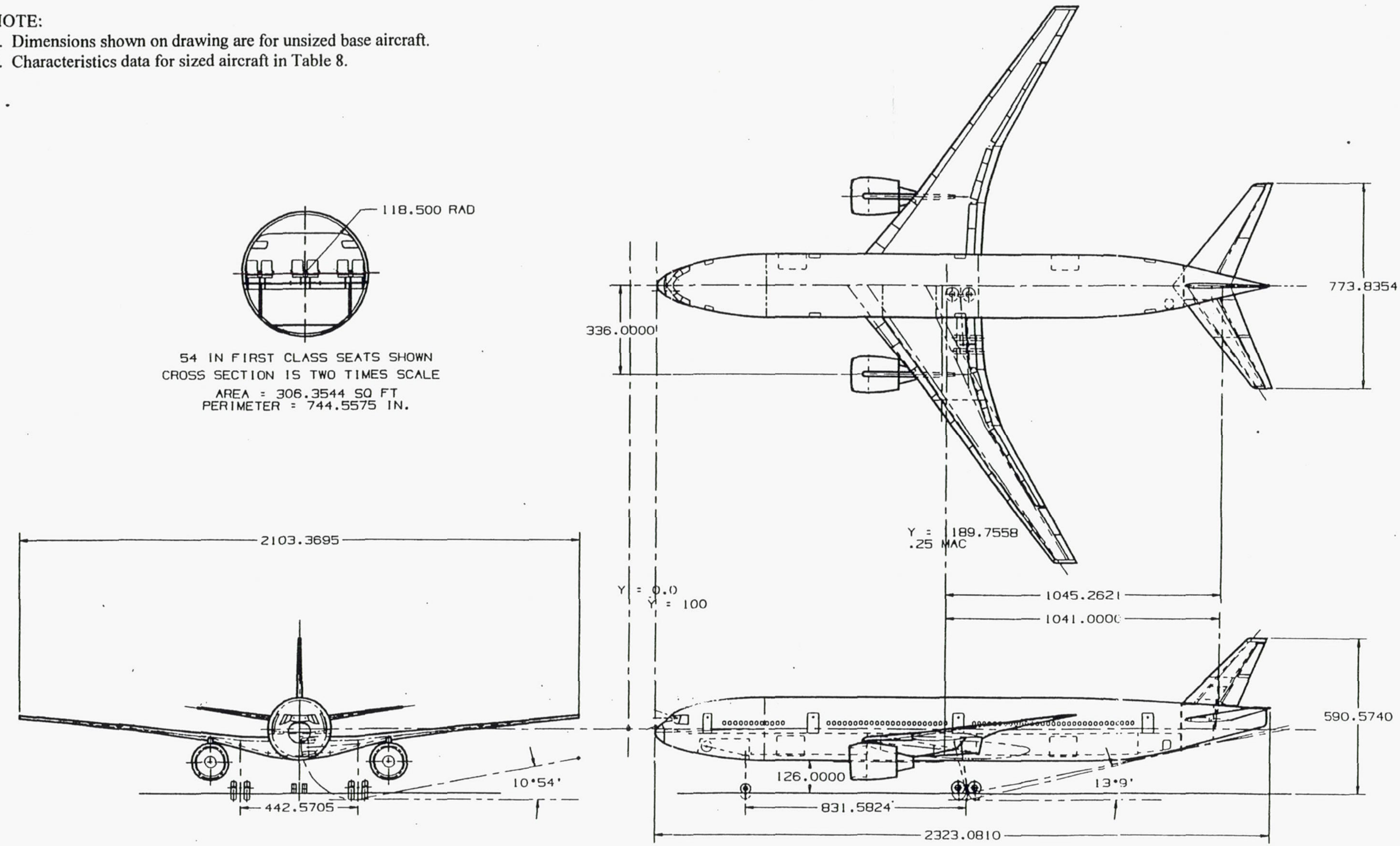

Figure 5. General Arrangement - MR-275

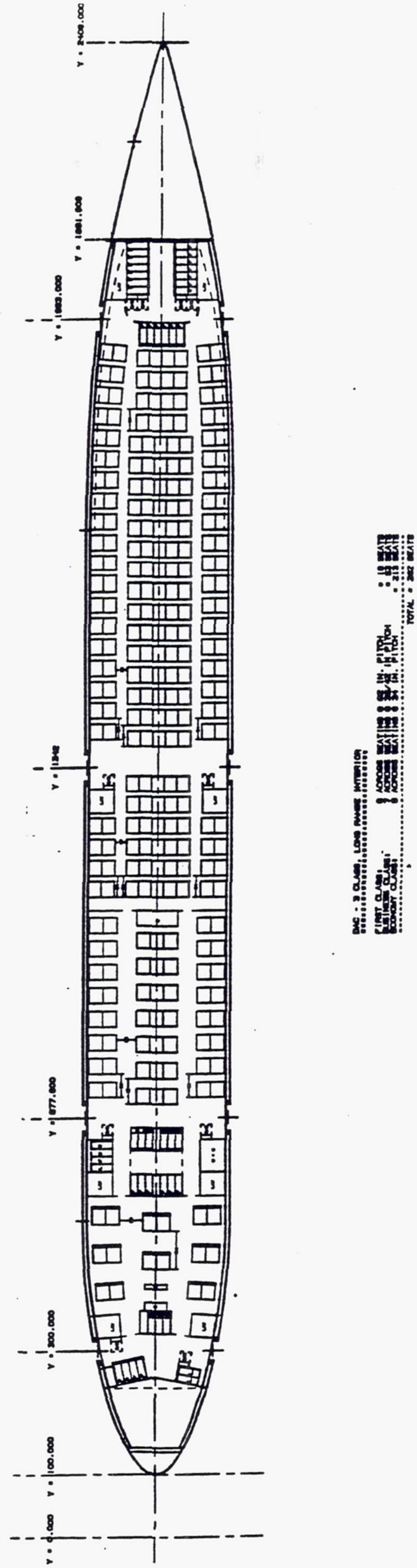

Figure 6. Interior Arrangement - MR-275

NOTE:
1. Dimensions shown on drawing are for unsized base aircraft.
2. Characteristics data for sized aircraft in Table 9.

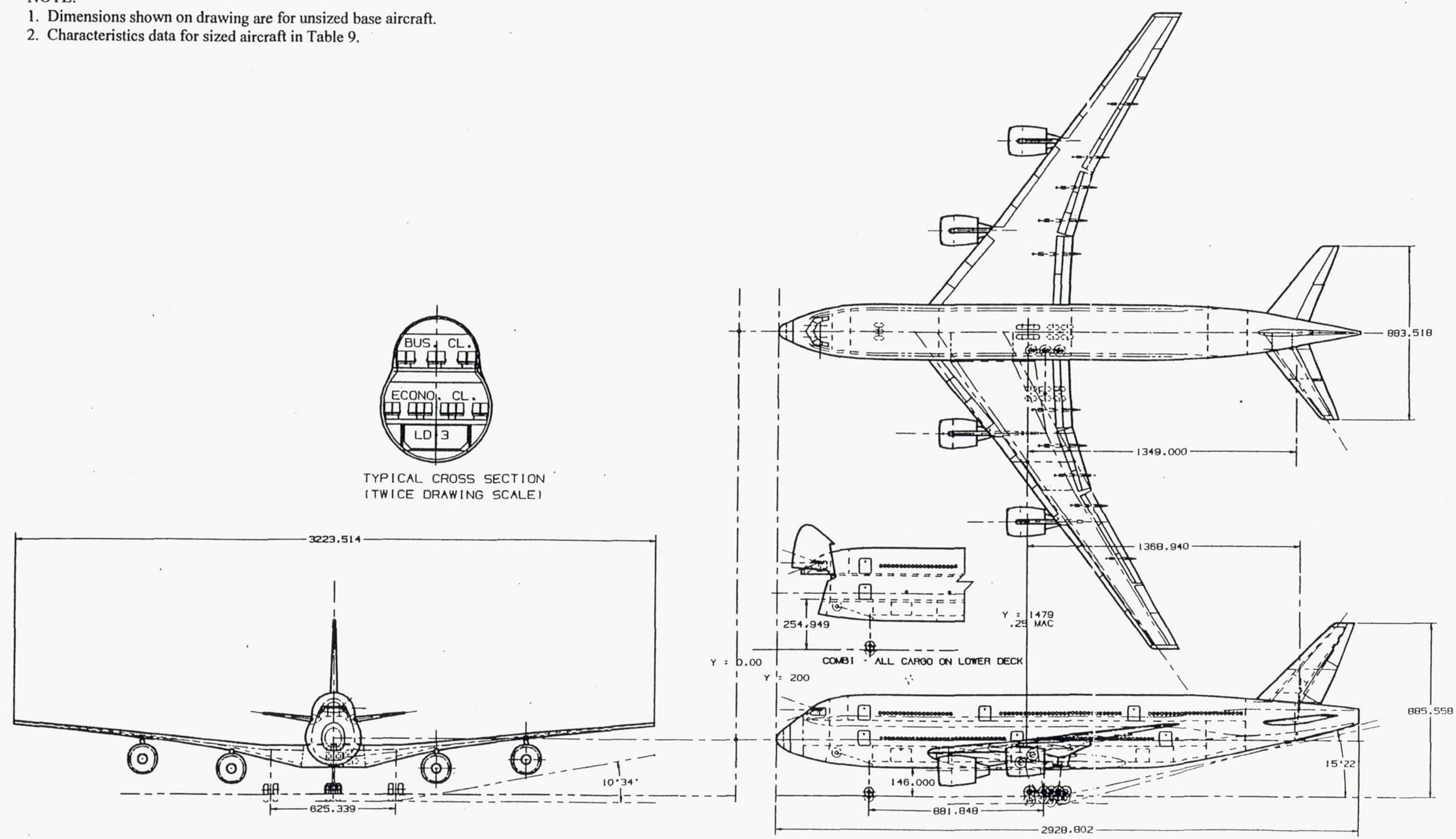

Figure 7. General Arrangement - LR-600

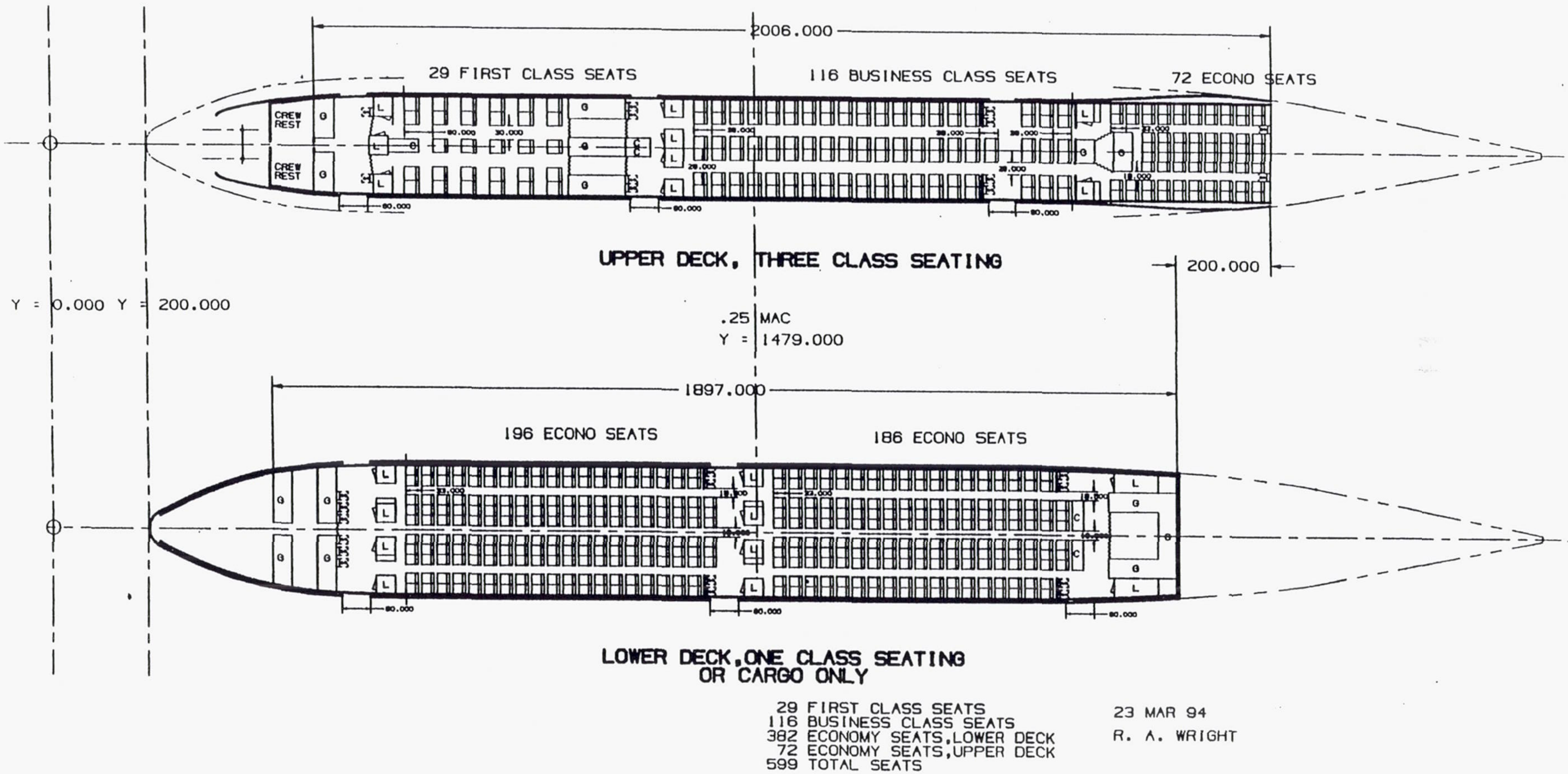

Figure 8. Interior Arrangement - LR-600

PW4074/84 BASELINE CONFIGURATION

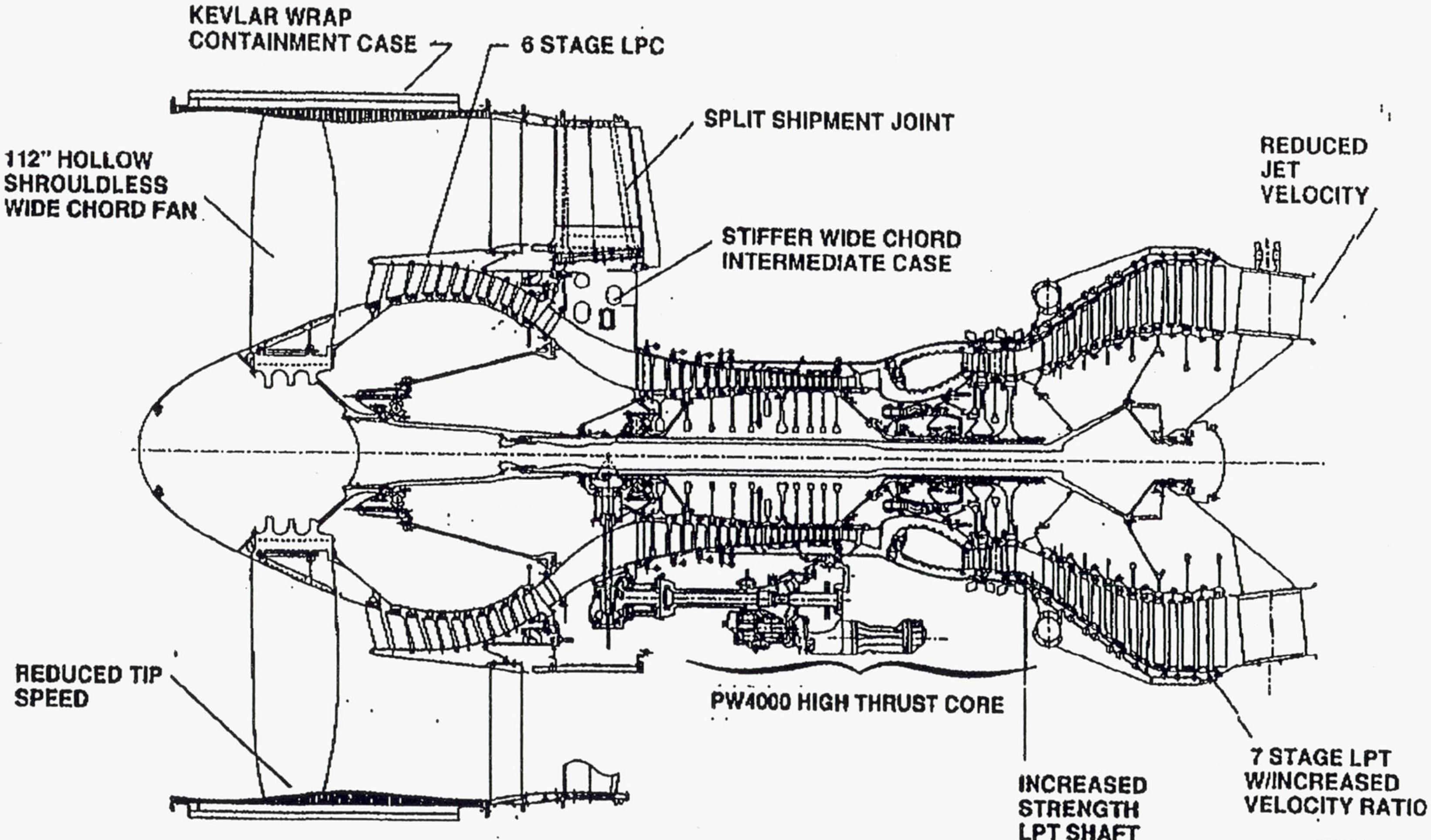

Figure 9. P&W Baseline Engine PW4000 Configuration

P&W APPROACH TO ACHIEVING AST GOALS

Scaled ATCC Powered ADP

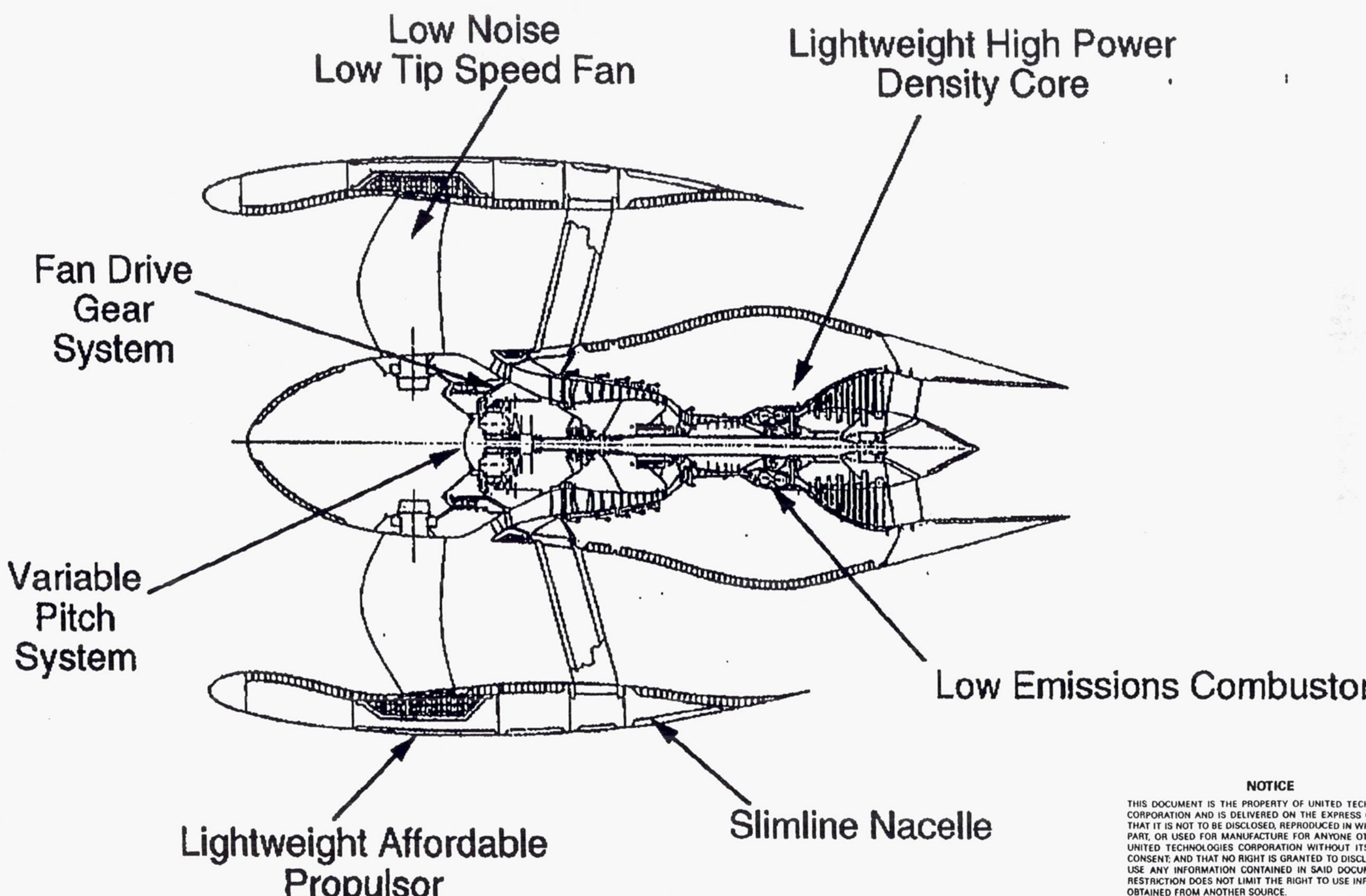

Figure 10. P&W Advanced Engine ADP/STS1046 Configuration

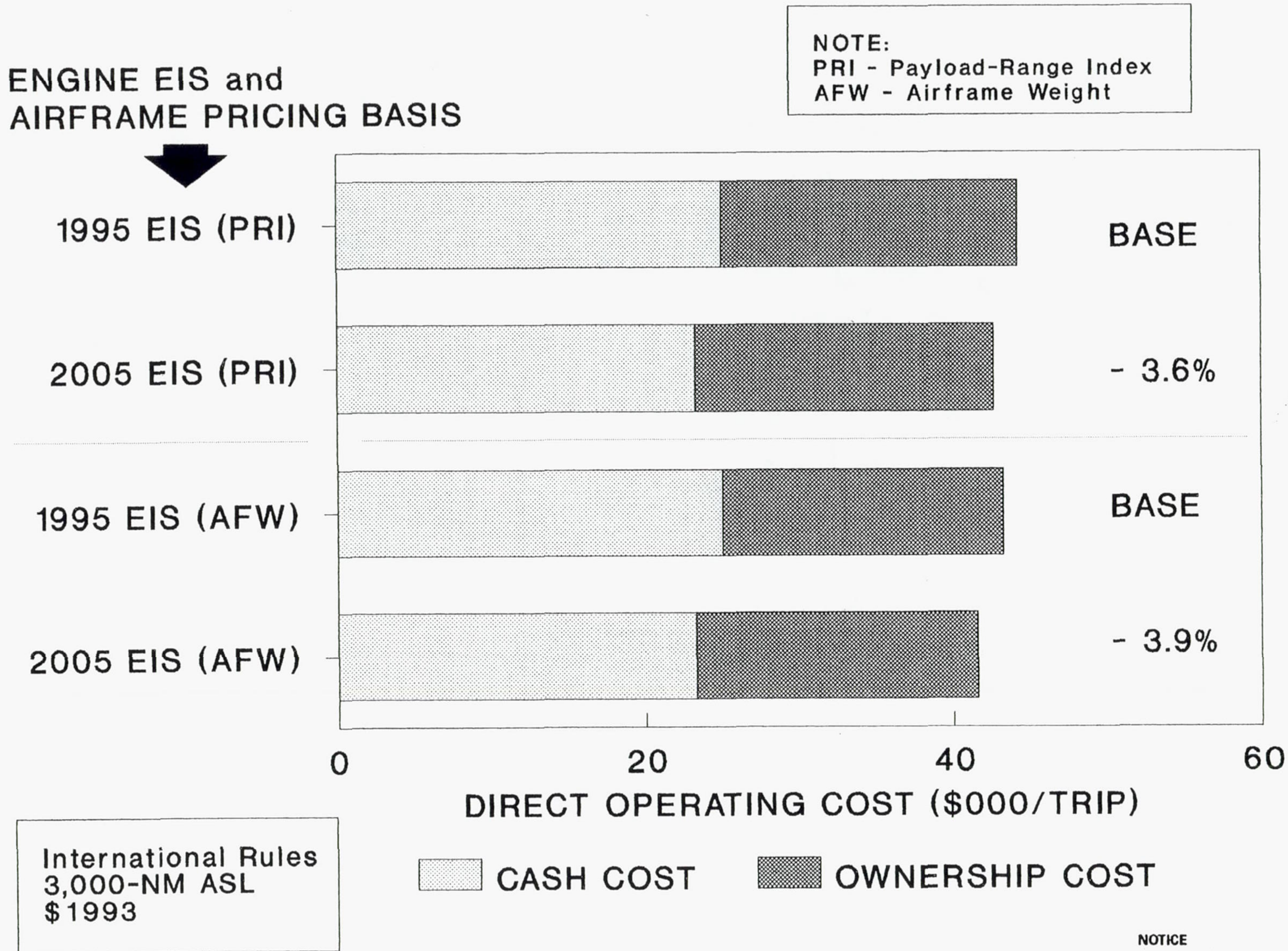

Figure 11. MR-275 DOC+I Results

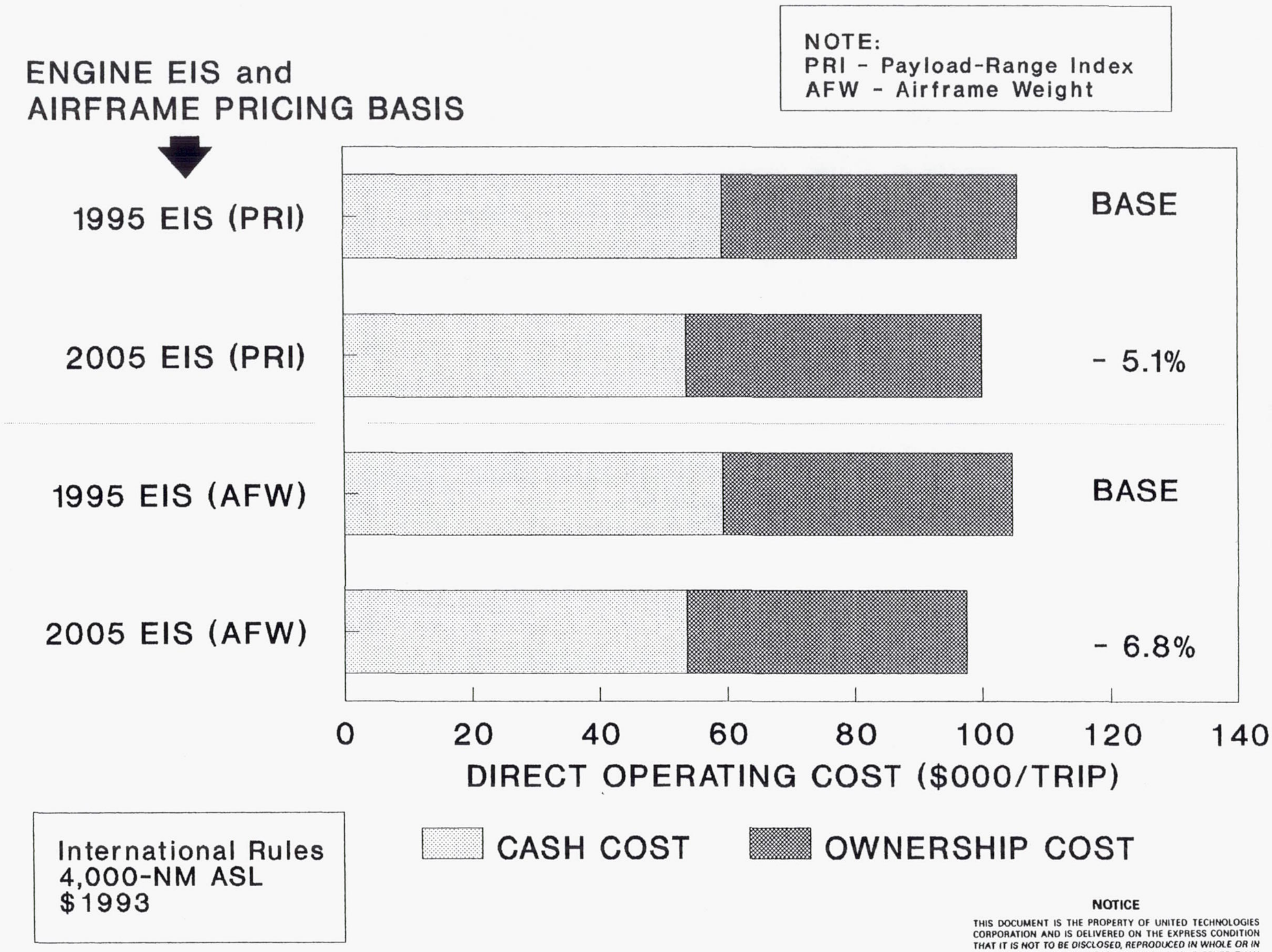

Figure 12. LR-600 DOC+I Results