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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° 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 ($V_{mCL\text{-}2}$) 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.

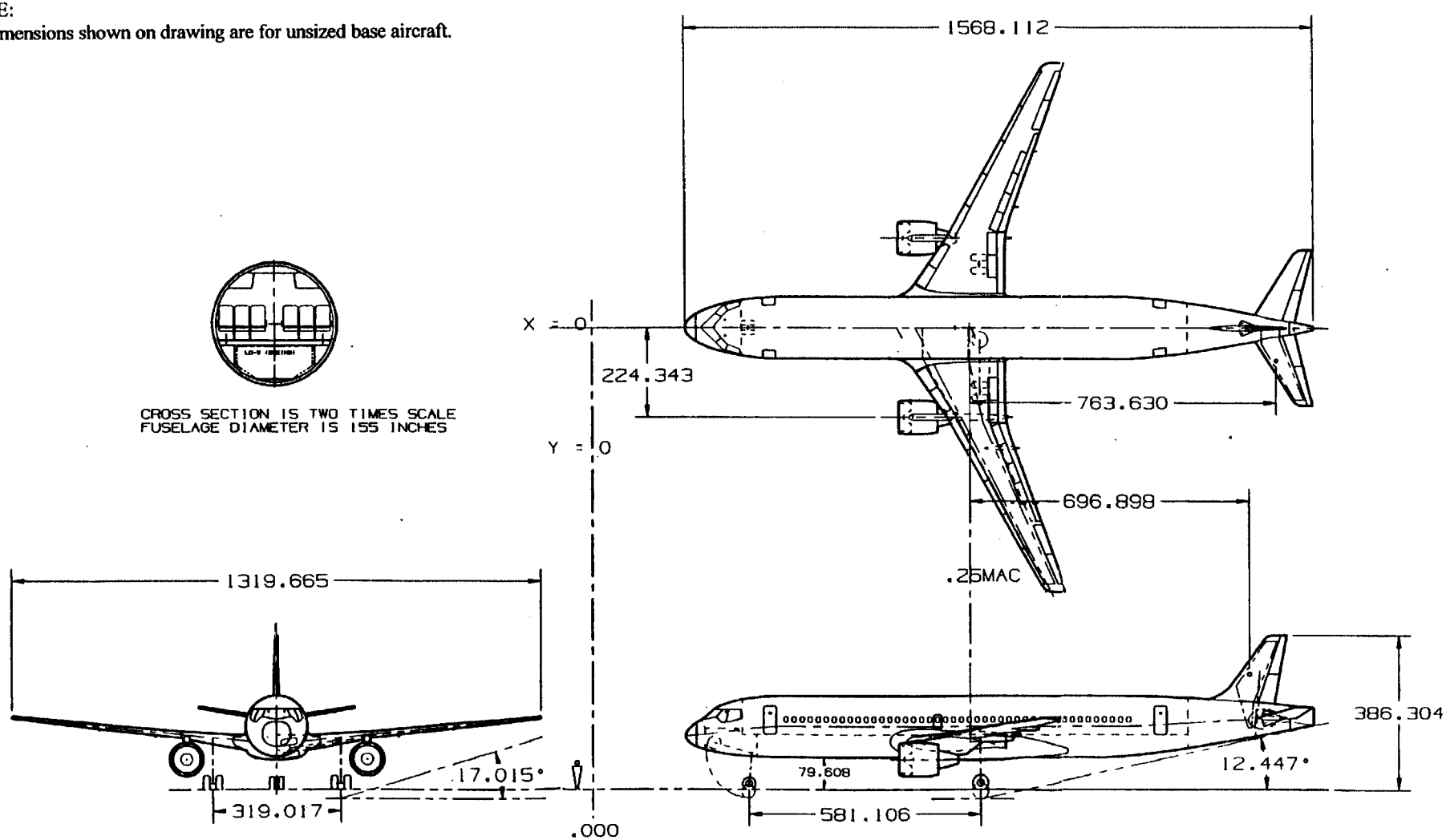

Figure 1. General Arrangement - SR-150

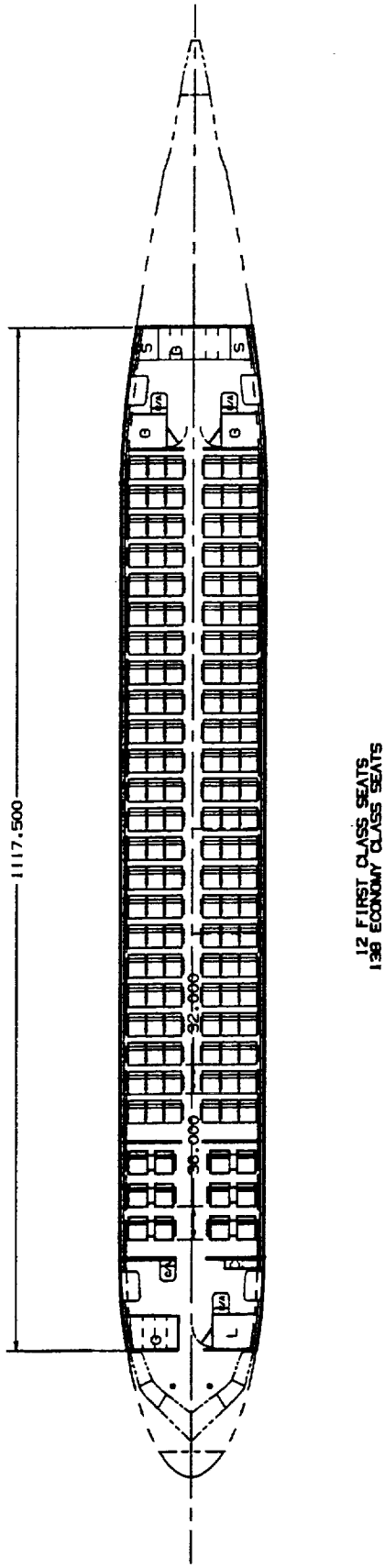

Figure 2. Interior Arrangement - SR-150

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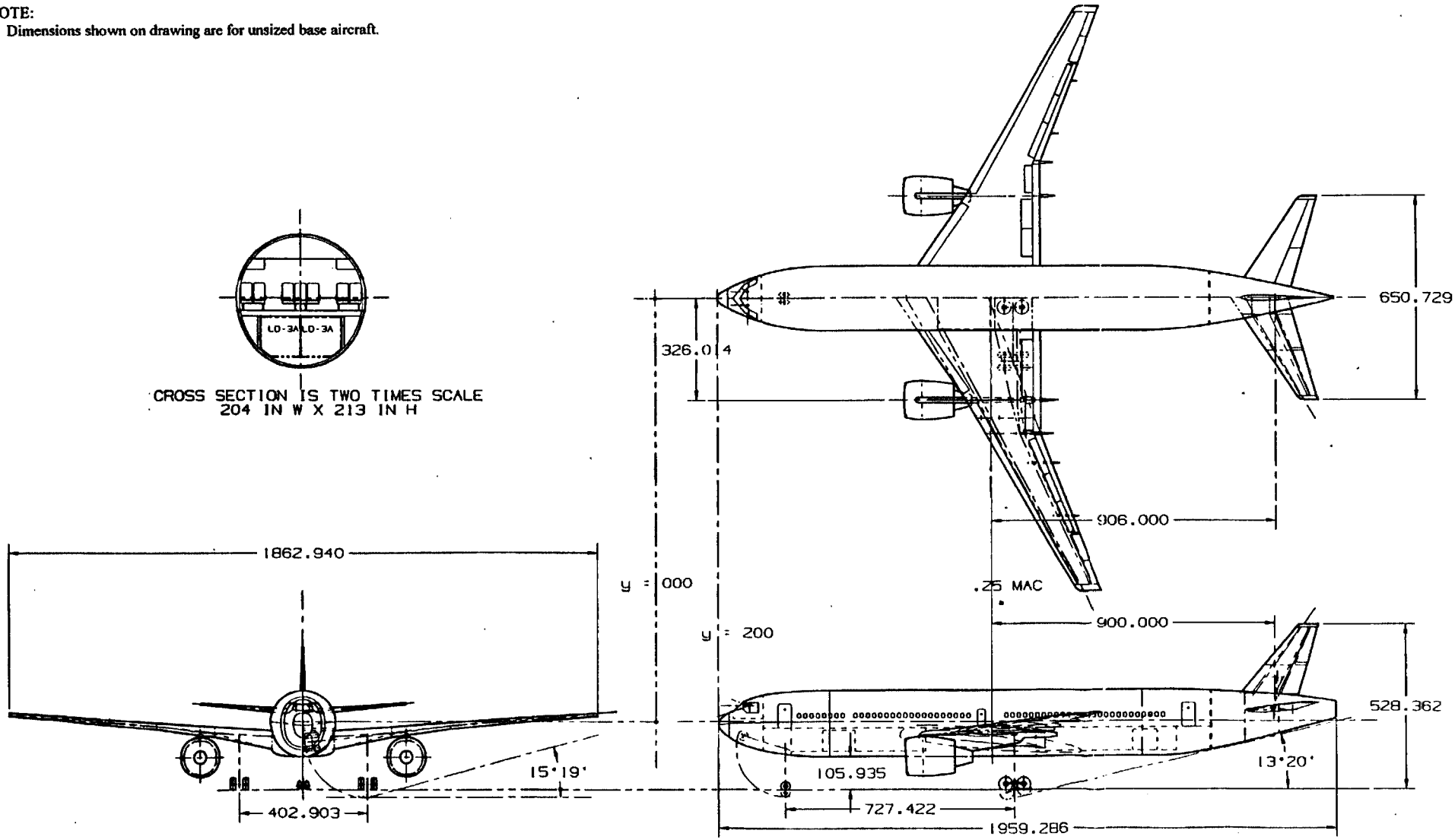

Figure 3. General Arrangement - MR-225

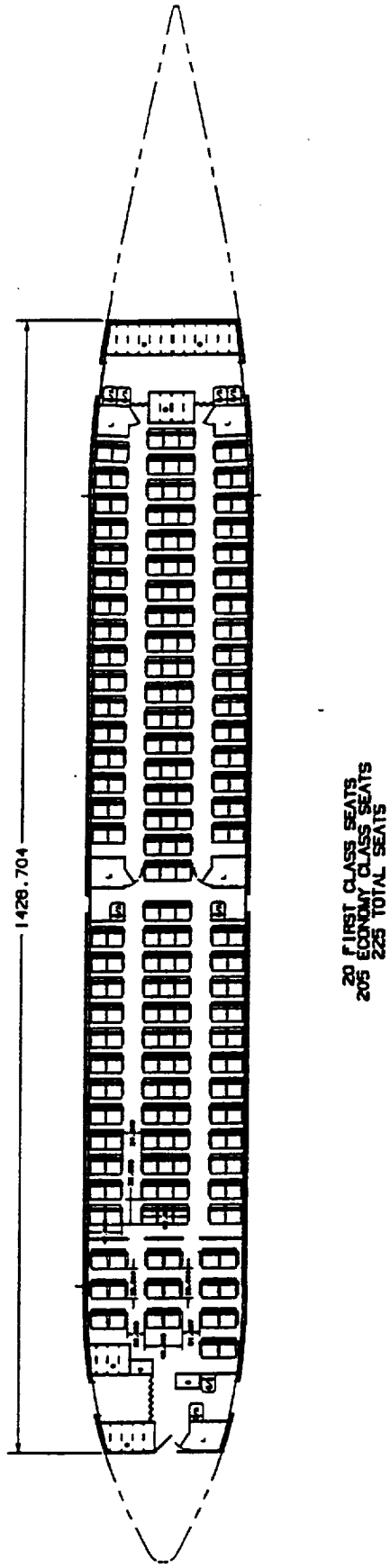

Figure 4. Interior Arrangement - MR-225

NOTE:
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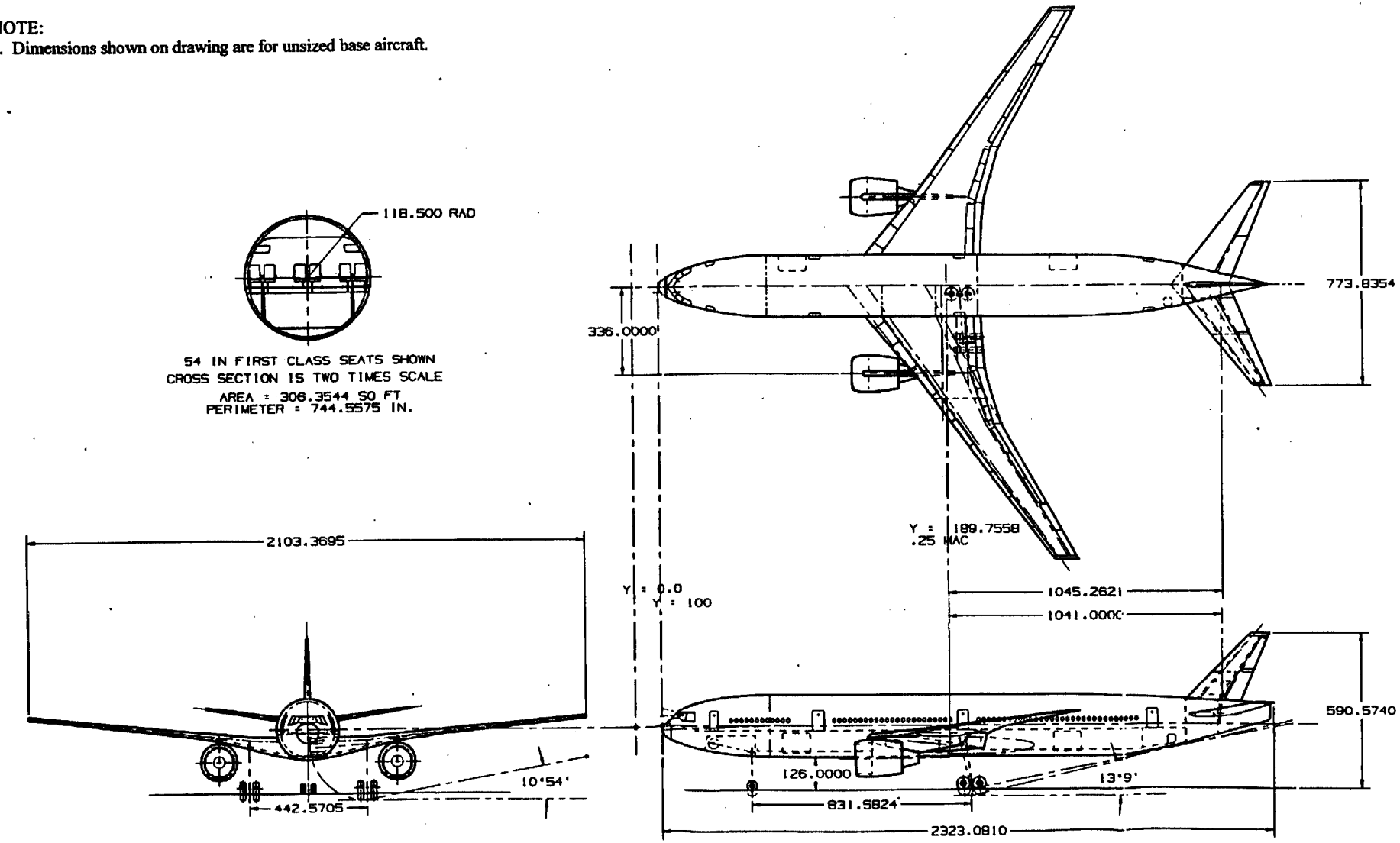

Figure 5. General Arrangement - MR-275

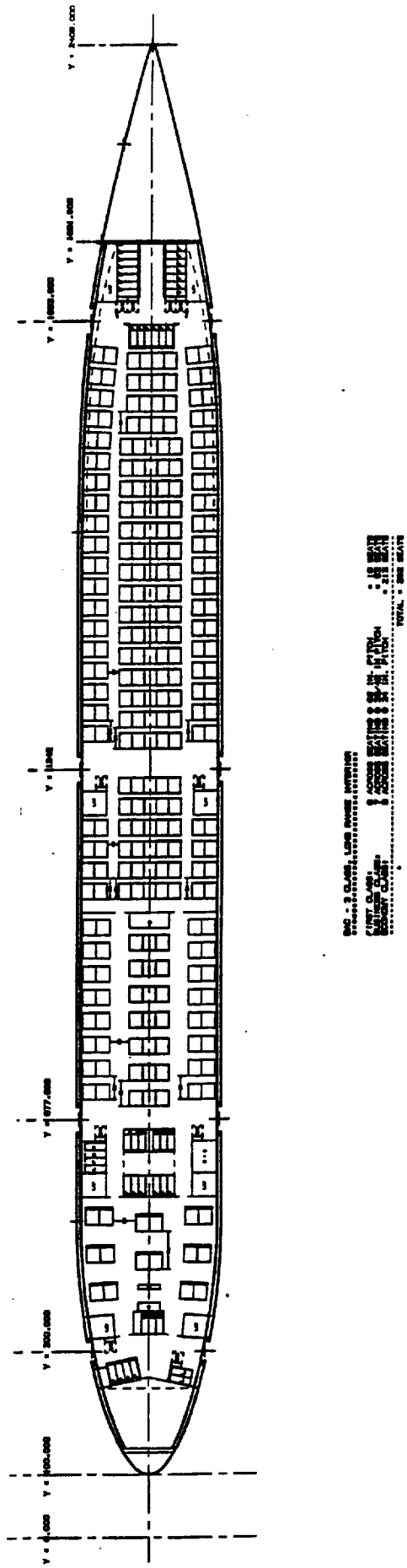

Figure 6. Interior Arrangement - MR-275

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NOTE:
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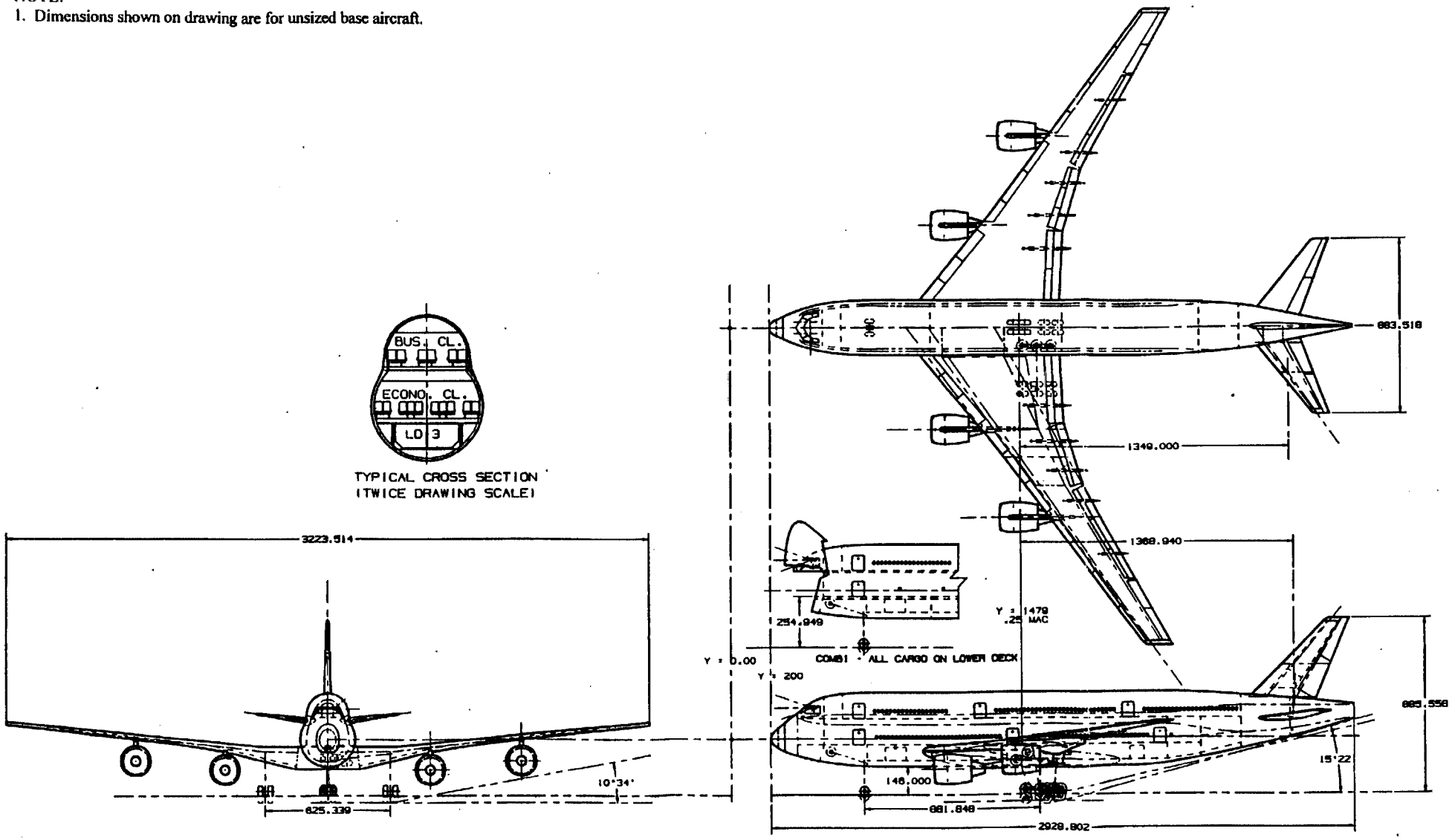

Figure 7. General Arrangement - LR-600

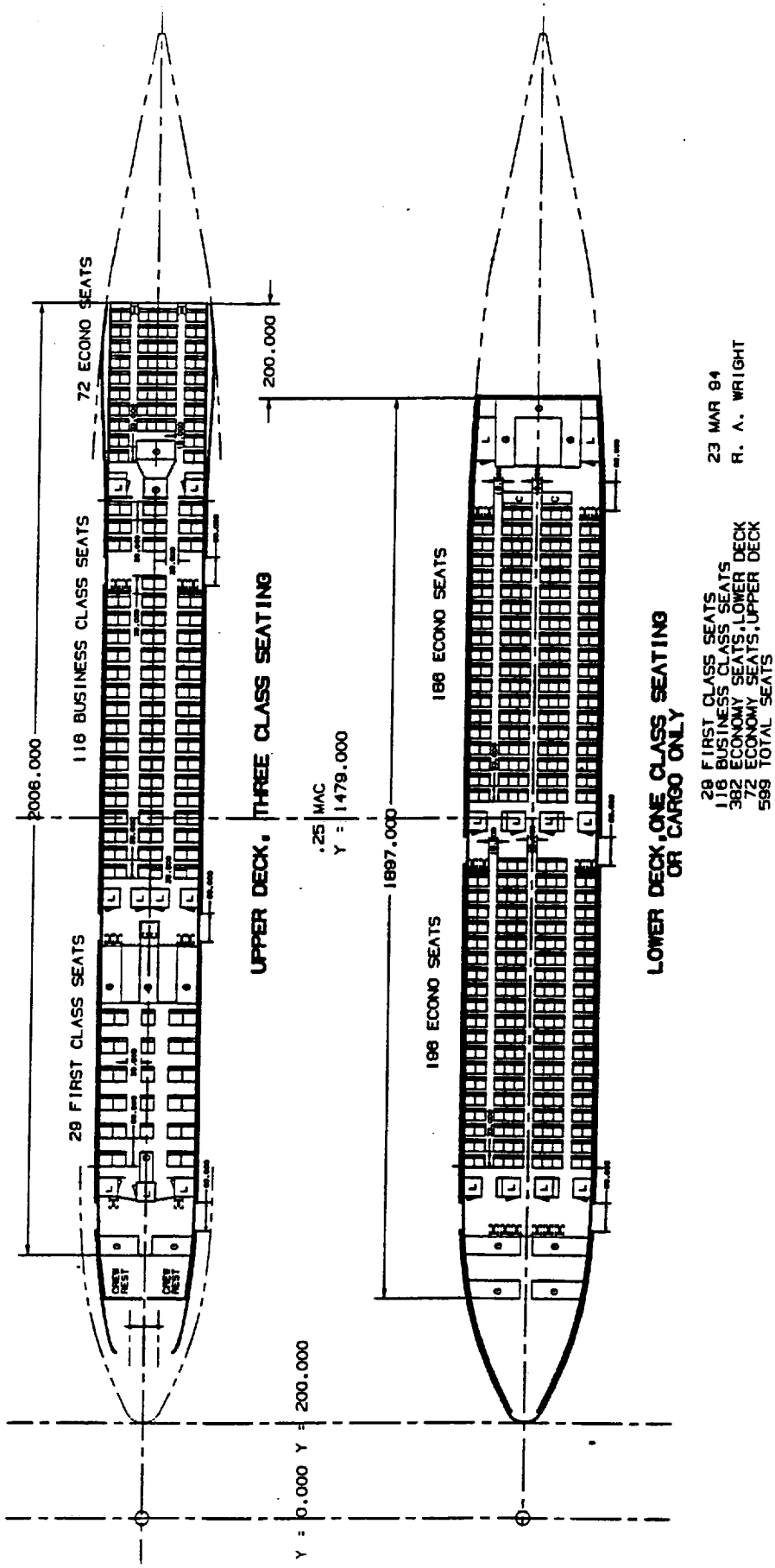

Figure 8. Interior Arrangement - LR-600

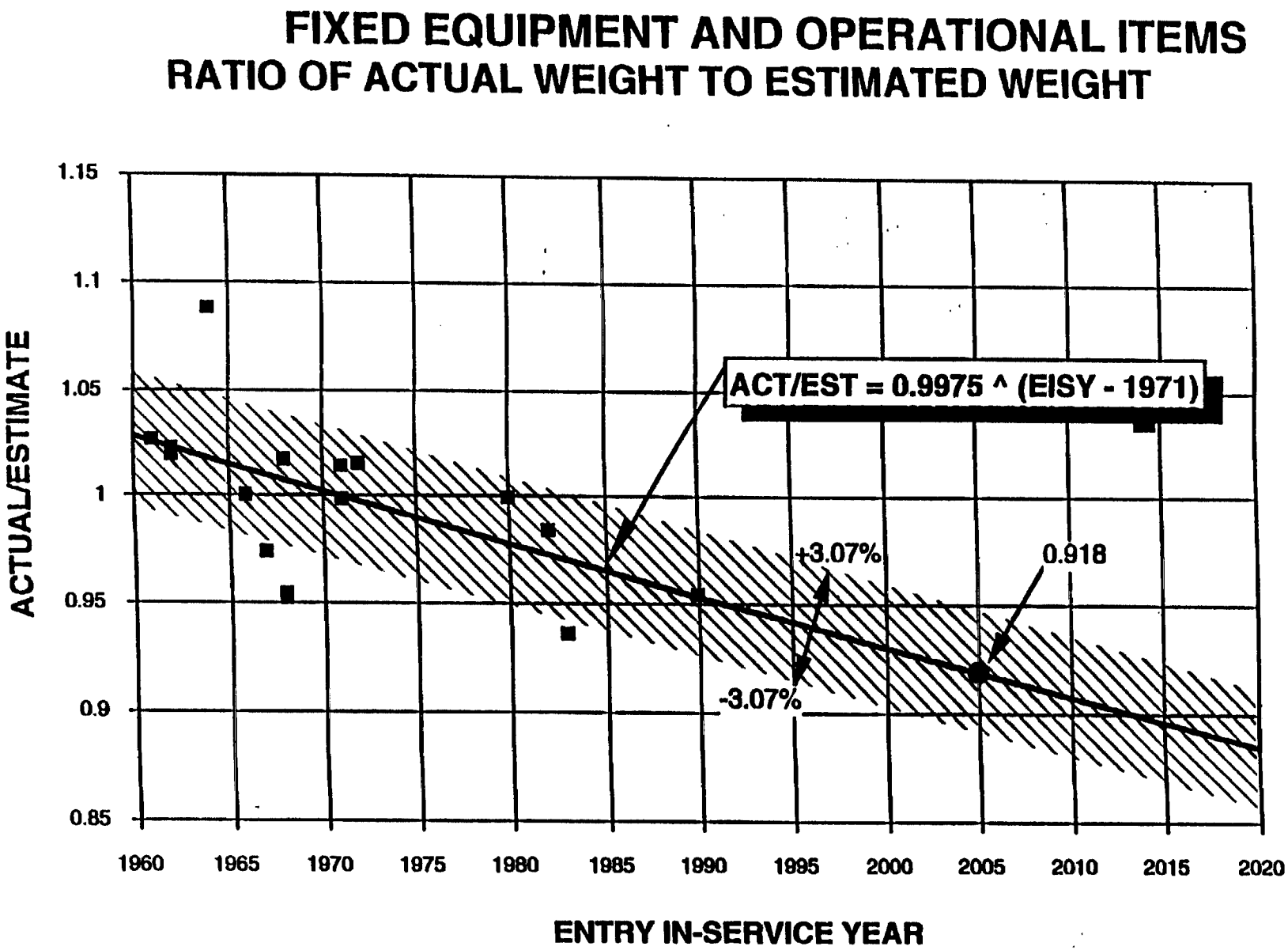

Figure 9. Fixed Equipment and Operational Items Ratio of Actual Weight to Estimated Weights

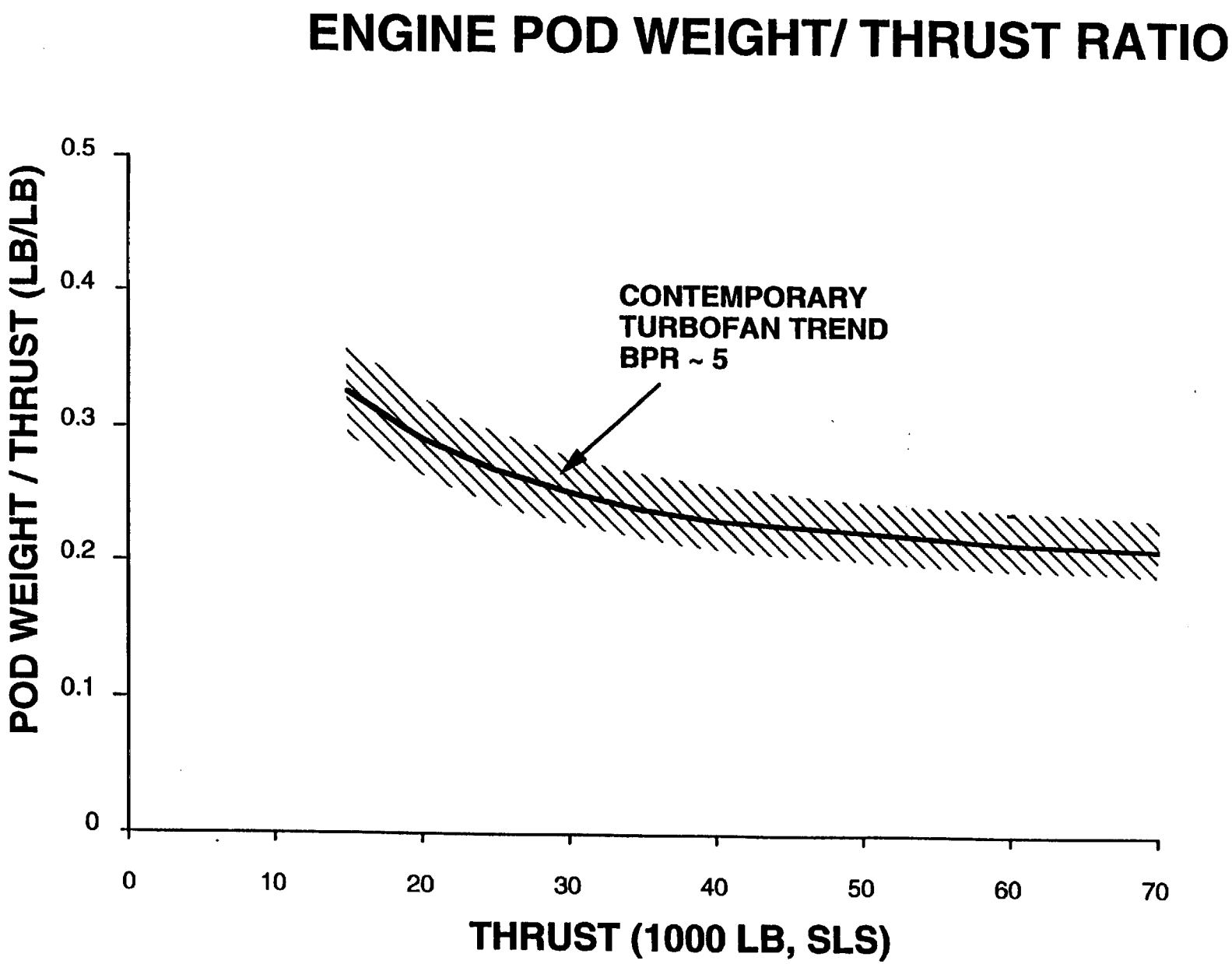

Figure 10. Engine Pod Weight/Thrust Ratio

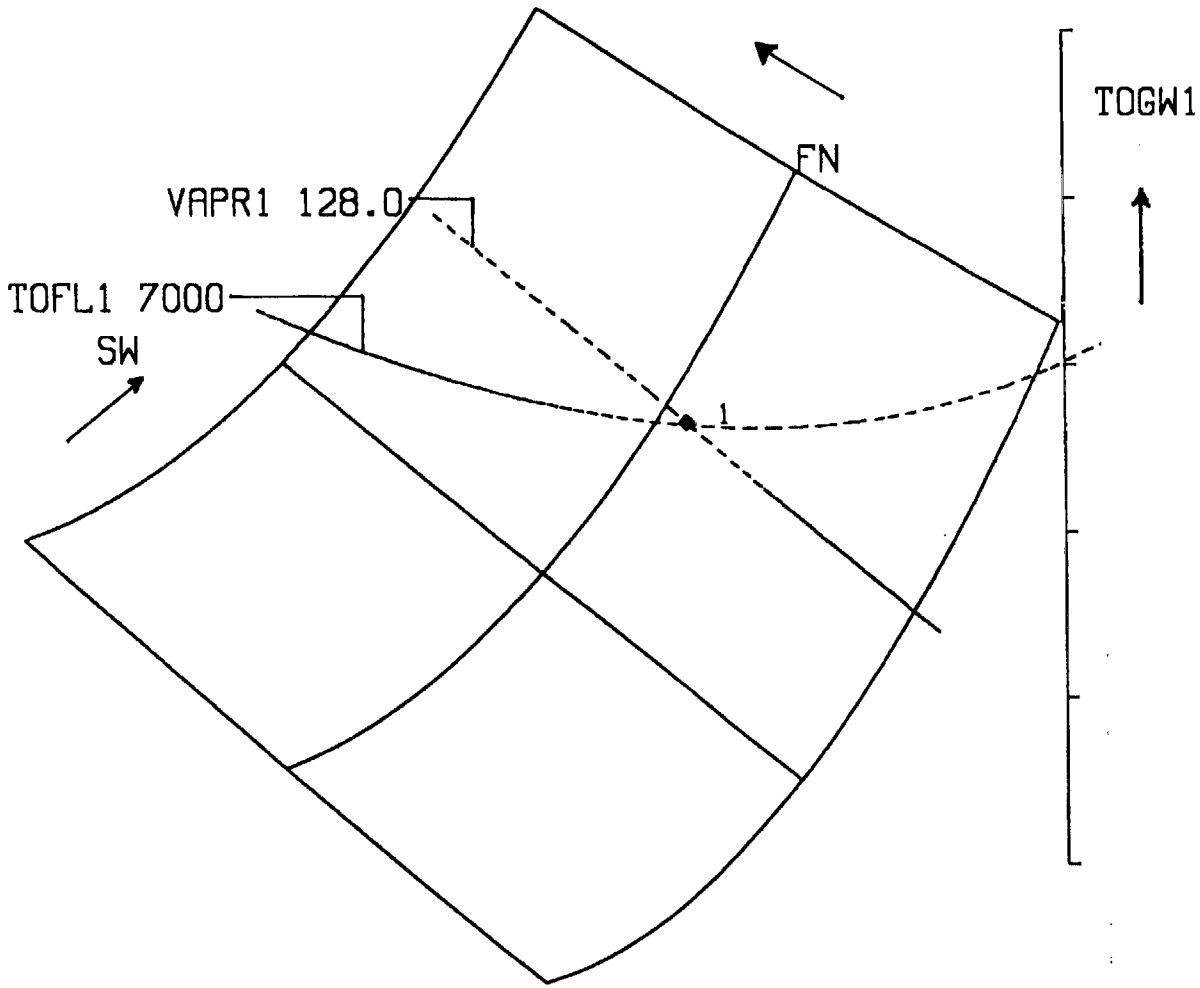

Figure 11. Typical CASES Sizing Carpet Plot

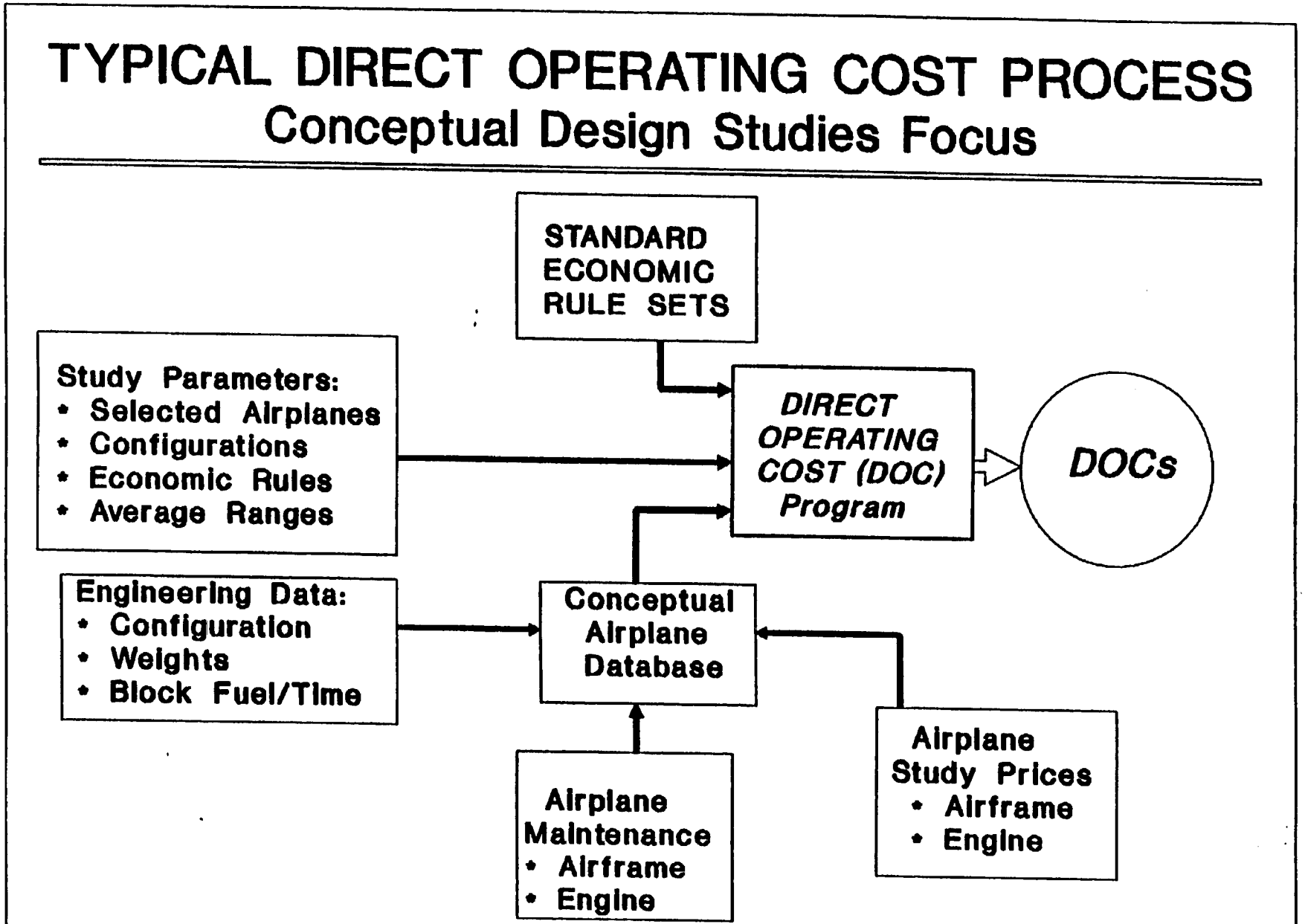

Figure 12. Typical DOC Process

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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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