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PRELIMINARY STUDY OF A VERY LARGE CATAMARAN FREIGHTER AS A DERIVATIVE OF A CURRENT WIDE-BODY AIRCRAFT

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Langley Research Center

SUMMARY

The development of a very large cargo aircraft by combining, in catamaran fashion, two existing wide body transports appears to be feasible. The catamaran derivative should have relatively lighter operational empty weight and increased payload. Cruise speed is unaltered and range increased. The derivative aircraft has greatly improved fuel economy. Direct operating costs should be about 38-percent less than those of the basic aircraft.

INTRODUCTION

Recent studies (refs. 1-4) have indicated that the rapidly increasing air-freight market could expand at an even greater growth rate if aircraft specifically designed for cargo transport were available. Consequent studies (refs. 5-7) indicate that a number of unusual configurations could provide such an aircraft by about 1985.

The actual development of a special containerized cargo aircraft poses substantial financial risks for the manufacturer. First, the large predicted market depends not merely on the currently estimated exponential growth rate but on an anticipated greater exponential rate subsequent to introduction of the new aircraft. Second, the specialized aircraft tend toward unusual configurations (refs. 4-7) which may require protracted development and large development costs. Third, to minimize direct operating cost, the aircraft tends to be extraordinarily large and consequently, expensive. Finally, even at present, the market tends to be absorbed by the large belly-holds of wide-body passenger transports and by very efficient cargo versions of these same wide-body aircraft.

A cheaper alternative to a completely new aircraft is to develop a new cargo carrier as a derivative of a current production aircraft. This approach takes advantage, not only of the manufacturer's current production line, but also of service and maintenance equipment already in the airline's inventory. Both development and service introduction costs are reduced with a resultant decrease in the financial exposure of both the manufacturer and his airline customers.

Most derivative aircraft are merely conservative alterations of wing span and fuselage length. Such simple alterations are unlikely to essentially double the payload to the levels considered in references 4-7. One alternate approach is to double the volumetric capacity by providing two identical fuselages, thereby leading to a twin or "catameran" derivative of a current production aircraft. The technique is not new. The twin-hulled Italian Savoia-Marchetti S-55 flying boats made notable long-distance formation flights in the early 1930's. A larger version, the SM-66, was used in commercial service on the Mediterranean routes prior to World War II. Subsequent to that war, the combination of two P-51's into the F-82 provided the U.S. Air Force with an extremely long-range fighter.

The present paper is a preliminary study of the configuration obtained by combining two current wide-body aircraft into a single catamaran freighter derivative aircraft. The development cost is an order of magnitude less than that of a new aircraft. Simultaneously, the aerodynamic performance, the structural weight fraction, and the payload capability are improved as compared to the basic aircraft. Preliminary economic studies indicate a major reduction in direct operating cost.

RESULTS AND DISCUSSION

Basic Aircraft

Figure 1 shows the basic aircraft from which the new configuration is derived. It is a four-engine wide-body aircraft originally designed as a passenger transport. In one of its recent freighter versions (ref. 8), this aircraft has a gross takeoff weight of 356000 kg (785000 lb) with a maximum gross cargo payload of 107500 kg (237100 lb). Calculations based on reference 9 indicate that one airline operating this aircraft (primarily in North Atlantic service) achieved direct operating costs during the first quarter of 1976 of 3.62 cents per available tonne-km (6.08 cents per ton-n.mi.). Over a hundred such freighter aircraft are already either in operation or on order, with a significant number obtained by conversion of currently excess passenger models.

Derivative Aircraft

General arrangement.- The catamaran derivative is obtained by splicing two of the basic aircraft together with a new center wing panel as shown in figure 2. The wing span is increased by 24.7 m (81 ft) from 59.6 m (195.7 ft) to 84.3 m (276.7 ft). Both fuselages, the outer wings and engines, and the tail assembly are identical to those of the basic aircraft.

Center wing panel.- The center wing panel presents problems of compressibility drag. It can not be a simple continuation of the swept outer panels because the aerodynamic center would be shifted too far forward. Thus, the center panel is unswept; compressibility drag is averted by utilizing a fully supercritical airfoil section with a thickness-chord ratio of only 8.5-percent.

With this airfoil section, the center panel has the same drag rise Mach number ($M = 0.84$) as the basic aircraft.

Because the thickness ratio is small, the center panel must have a large chord to provide structural thickness adequate to provide for the bending loads. The chord used is 16.85 m (55.3 ft). This provides a maximum thickness of 1.43-m (4.7 ft) to accommodate the loads. Torsional loads can be minimized by means of active load alleviation control operating differentially on the ailerons and the two independent horizontal tails. Such a system would probably be less complex than the system considered for the C-5A aircraft (ref. 10).

The central wing panel results in a total wing area of 932 m^2 (10034 ft^2) for the catamaran derivative compared to 511 m^2 (5500 ft^2) for the basic aircraft. The aspect ratio of the derivative is 7.63 about 10-percent greater than the value of 6.96 for the basic aircraft.

Engine placement.- Since the catamaran derivative could be a near-term design, it is assumed to use the same engines, with the total number of engines doubled to eight. The outboard engines and their mountings are identical to those of the basic aircraft. Two of the remaining engines are mounted forward and below the leading edge of the center wing in a manner similar to the outboard engines. The remaining pair of engines is mounted above and well toward the rear of the wing so as to minimize interference with the supersonic flow region on the upper surface of the supercritical wing section.

If engines of substantially greater thrust were available, the aircraft would be more attractive. On the other hand, use of the same engines minimizes the costs of conversion from older aircraft and eliminates engine development costs in the construction of totally new derivative aircraft.

Landing gear.- The wing-mounted main landing gear of the basic aircraft are eliminated and replaced by three main gear mounted from the center wing panel. Local strengthening in the empty wing main-gear wells should be adequate to accommodate any increase in taxi or landing loads at the wing root.

With this main-gear arrangement, the catamaran derivative has a tread width of approximately 29 m (95 ft). This tread may be excessive for certain airports (JF Kennedy in New York has 38 m (125 ft) wide runways); however, it should be acceptable at most international airports where runways generally are from 45 m (150 ft) to 61 m (200 ft) wide. Off-center runway striping would be of material assistance on landing and takeoff since the pilot is asymmetrically located in one of the fuselages.

Runway and taxiway bearing strength would probably be more restrictive than width. Few runways were designed to handle aircraft with the gross weight of the catamaran derivative. Even at present, the load capacity of overpasses limits the maximum takeoff gross weight of the basic aircraft at certain airports. In any event, any aircraft heavier than current types is confronted by problems of bearing strength. The problem is no worse for the catamaran derivative than it is for the large configurations studied in references 4-7.

Weights and Payload

Weight estimates for both the basic aircraft and its catamaran derivative are presented in Table I. The derivative aircraft is significantly lighter than a pair of the basic aircraft.

The largest weight saving is in the wing. The total wing area of the catamaran aircraft is about 93 m^2 (1000 ft^2) less than the wings of two of the basic aircraft. In addition, the center wing panel is unswept and acts as a simply supported (rather than a cantilever) beam. Physically the weight is more evenly distributed across the total wing because the useful load is distributed into two fuselages rather than one. Thus, the catamaran derivative attains much of the advantages of distributed-load configurations (ref. 4-7) while avoiding the aerodynamic penalties of excessive wing area and thickness ratio. Nonduplication of one-per-aircraft equipment results in a major reduction in the weight of both fixed equipment and standard and operational items. The net result is that the operational empty weight of the catamaran derivative is over 18-percent less than the operational empty weight of a pair of the basic aircraft.

Because of the large reduction of weight, a second weight was obtained from a second weight estimator. Using different methods, he obtained an operating empty weight of 253152 kg (558200 lb), only 4700 kg (10300 lb) greater than Table I. Even this difference was traced to the fact that the second weight estimator had considered the weight of a modification rather than new construction. In that case, it was uneconomic to remove certain items of fixed equipment.

The basic aircraft is stressed to accommodate its own greater relative empty weight. Thus, the saving in operating empty may be translated into increased relative payload. Volumetrically, each fuselage can contain approximately 708 m^3 (25000 ft^3) of cargo in assorted container sizes. Assuming a cargo density of 160 kg/m^3 (10 lb/ft^3) with a container tare weight of 24 k/m^3 (1.5 lb/ft^3) yields a payload of 260770 kg (575000 lb) for the catamaran derivative. The aircraft is volume limited. The sum of payload and operational empty weight is still less than the comparable weight of a pair of the basic aircraft.

Aerodynamic Characteristics

The calculated aerodynamic characteristics of the basic aircraft and its catamaran derivative are presented as lift-drag polars in figure 3. Lift-drag ratio as a function of lift coefficient is shown in figure 4.

Because of the somewhat increased aspect ratio, the catamaran derivative has a smaller induced drag coefficient than the basic aircraft. The result is that, at optimum lift-coefficient, the lift-drag ratio of the derivative is about one unit greater than that of the basic aircraft. Because the thickness-ratio of the center wing panel is small, both aircraft have the same critical Mach number and, consequently, will have similar cruise speeds.

Cruise Performance

The range for various takeoff gross weights of both aircraft has been calculated and is presented in figures 5 and 6. The calculations were based on the polars of figure 3, the characteristics of the engines presently used on the basic aircraft, and full ATA international fuel reserve requirements. It was assumed that the maximum fuel capacity of the catamaran derivative was exactly twice the 155966 kg (341700 lb) of the basic aircraft. Cruise Mach number was 0.84 for both aircraft.

The figures present the takeoff gross weight of both aircraft while carrying the maximum possible payload at each range. In addition, the operational empty weight, fuel burned, fuel reserves, and payload are shown. The operational empty weight has already been discussed. The payload and fuel requirements will be discussed subsequently.

Field Length Requirements

Takeoff.- At maximum takeoff gross weight, the wingloading of the catamaran derivative is 4.8-percent greater than that of the basic aircraft; however, its thrust-weight ratio is 4.7-percent greater. Furthermore, with only four engines, the required takeoff field length of the basic aircraft must be obtained from most-critical engine failure considerations; with eight engines, the field length of the catamaran derivative need only be 15-percent greater than the all-engine takeoff distance. An additional factor to be considered is that with the same gear height, the height to span ratio for the catamaran derivative is 40-percent less than for the basic aircraft resulting in an increase in ground effect. Consideration of all these factors leads to the conclusion that any difference in takeoff field length will be in favor of the catamaran deravative.

Landing.- Under landing conditions, the wingloading of the catamaran derivative is about 7-percent greater with full payload to 11-percent less with zero payload. On the average, landing field lengths will be comparable for both aircraft.

Powered lift.- The catamaran derivative offers a uniquely favorable opportunity for the application of powered-lift techniques by over-the-wing blowing, externally blown flap, or a combination of both. In conventional single-fuselage aircraft the benefits of these techniques are limited by consideration of the asymmetric moments created when an engine fails. The four central engines of the catamaran derivative are so close to the centerline that failed-engine moments will be very small. If powered lift is generated using only these four engines, remarkable reductions in field length and approach speed should be obtained. Applying powered lift would seriously increase development time and cost; consequently, it is not considered herein.

Range-Payload Performance

All service.- The payload of the catamaran derivative is compared with both one and two of the basic aircraft in figure 7. The relative decrease in operational empty weight yields an increase in payload at any range for the catamaran derivative as compared with a pair of the basic aircraft. Maximum payload of the derivative is 260771 kg (575000 lb) compared to 215 kg (474200 lb) for two of the basic aircraft.

Because of the increased aspect ratio and lessened induced-drag coefficient, the derivative also has increased range. Full payload may be carried to a distance of 5625 km (2843 n.mi.) whereas the basic aircraft can carry its full payload to only 4963 km (2680 n.mi.). The difference is more pronounced in the extreme ferry range of 15872 km (8570 n.mi.) for the derivative and 13381 km (7225 n.mi.) for the basic aircraft.

Military application.- Ranges in excess of about 5550 km (3000 n.mi.) are of minor significance for most commercial operation; however, long ranges with large payloads are important in military logistics. The M60 main battle tank comprises about 25-percent of weight of equipment required by a current U.S. Army mechanized division (ref 11). Each M60 tank weighs on the order of 50000 kg (110000 lb). The catamaran derivative has the payload capacity to transport four of these tanks for 8000 km (4320 n.mi.) or two tanks for 12700 km (6860 m.mi.) The basic aircraft has the payload capacity to transport two tanks 6220 km (3360 n.mi.) or one tank 10780 km (5820 n.mi.) The difference in range is significant when long stages must be flown and intermediate refueling stops may be denied because of political considerations.

While the payload capacity for the M60 tank is present in these aircraft, neither aircraft has doors adequate to allow the tank to be loaded without major disassembly. Suitable fuselage and door modifications are currently being considered by the manufacturer (ref. 11). The catamaran derivative offers an additional possibility since each of the fuselages has nose gear. Swing noses could be provided to allow loading one fuselage at a time while the gear on the other nose maintained the ground stability of the aircraft. The weight penalties associated with any of these modifications are beyond the scope of the present study.

Burned Fuel

Figure 8 compares the fuel burned by both aircraft while flying the range-payload missions defined in figures 5-7. Because of its improved structural and induced-aerodynamic efficiency, the catamaran derivative burns less fuel than a pair of the basic aircraft at all ranges less than about 12000 km (6500 n.mi.). At greater ranges, the burned fuel is essentially identical since, together with the reserve fuel, it represents the total tankage available in the aircraft.

Fuel Economy

Figure 8 is not a true comparison of the two aircraft since at each range the catamaran derivative carries a greater load than two of the basic aircraft. Define a term, called herein fuel economy, as payload times range divided by fuel burned. At each range, this term represents the average distance that one unit of payload is carried for burning one unit of fuel. This fuel economy is shown for both aircraft in figure 9. Up to ranges of about 11000 km (5900 n.mi.) the catamaran derivative carries a unit of payload 2 km (1.1 n.mi.) further than the basic aircraft per unit of fuel. At greater ranges, the difference increases. The present high price and projected higher prices of fuel place increasing importance on the fuel economy advantage of the catamaran derivative.

Development Cost

A preliminary estimate of the cost of converting a pair of the basic aircraft into a catamaran derivative. This analysis (Table II) indicates that the total development costs (January 1975 dollars) through and including the first aircraft would be about $95,000,000 plus the two aircraft used by the conversion. Although the analysis is crude, it does indicate that development costs for the derivative should be an order of magnitude less than the costs involved in developing a totally new aircraft of similar size and capability.

Aircraft Cost

Table II also presents the production cost of the modification assuming for illustrative purposes a total run of 100 aircraft. This cost is approximately $8,000,000 above the value of the two basic aircraft required for the conversion. The current cost of the used basic aircraft is very low; however, there is no assurance that this trend will continue.

The analysis presented in Table II assumes that the scrap value of the wings and outboard main gear merely covers the cost of their removal. In new construction, where these items are never built, there is a significant saving. A totally new catamaran derivative should cost no more, and possibly less than the cost of two new basic aircraft.

Reference 12 presents a parametric analysis of aircraft price. Formal application of that paper's equations for wide-body aircraft would indicate that the catamaran should cost only 1.5 times the cost of one of the basic aircraft. The equations of reference 12 depend heavily on the type of aircraft and there is great uncertainty that they apply to a configuration so radically different from current wide-body transports.

TABLE I

ESTIMATED WEIGHTS OF THE BASIC AIRCRAFT
AND ITS CATAMARAN DERIVATIVE

	BASIC AIRCRAFT		CATAMARAN DERIVATIVE		FACTOR
	Kg	Lb	Kg	Lb	
WING	42879	94550	51927	114500	1.21
HORIZONTAL TAIL	3673	8100	7347	16200	2.00
VERTICAL TAIL	1814	4000	3628	8000	2.00
BODY	34014	75000	68027	150000	2.00
MAIN LANDING GEAR	13152	29000	23016	50750	1.75
NOISE LANDING GEAR	1497	3300	2993	6600	2.00
NACELLE AND STRUT	4717	10400	9433	20800	2.00
TOTAL STRUCTURE	101746	224350	166371	366850	1.64
ENGINE	16190	35700	32381	71400	2.00
ENGINE ACCESSORIES	204	450	408	900	2.00
ENGINE CONTROLS	159	350	317	700	2.00
STARTING SYSTEM	113	250	277	500	2.00
FUEL SYSTEM	1361	3000	2653	5850	1.95
THRUST REVERSER	2948	6500	5896	13000	2.00
TOTAL PROPULSION SYSTEM	20975	46250	41882	92350	2.00
INSTRUMENTS	748	1650	748	1650	1.00
SURFACE CONTROLS	3311	7300	6621	14600	2.00
HYDRAULICS	1224	2700	2449	5400	2.00
PNEUMATICS	943	2080	1887	4160	2.00
ELECTRICAL	1542	3400	3084	6800	2.00
ELECTRONICS	1061	2340	1061	2340	1.00
FLIGHT PROVISIONS	508	1120	508	1120	1.00
CARGO HANDLING	2095	4620	4190	9240	2.00
EMERGENCY EQUIPMENT	1016	2240	1016	2240	1.00
AIR CONDITIONING	1664	3670	1664	3670	1.00
ANTI-ICING	141	310	172	380	1.23
AUXILIARY POWER UNIT	771	1700	1542	3400	2.00
TOTAL FIXED EQUIPMENT	15024	33130	24942	55000	1.66
EXTERIOR PAINT	327	720	653	1440	2.00
MANUFACTURER'S EMPTY WEIGHT	138072	304450	233848	515640	1.69
STANDARD AND OPERATIONAL ITEMS	14626	32250	14626	32250	1.00
OPERATING WEIGHT EMPTY	152698	336700	248474	547890	1.63
GROSS CARGO	107698	237100	260771	575000	2.43
MAXIMUM ZERO FUEL WEIGHT	260226	573800	509245	1122890	1.96
MAXIMUM TAKEOFF GROSS WEIGHT	356009	785000	680272	1500000	1.91

TABLE II.- ESTIMATED DEVELOPMENT COSTS AND PRICING OF DERIVATIVE MODIFICATION

(January 1975 dollars)

FIRST UNIT COST	
WING	8 375 000
LANDING GEAR	3 570 000
SYSTEMS	5 500 000
ASSEMBLY	3 489 000
	20 934 000
RDT&E COST	
DESIGN	27 000 000
SYSTEMS DEVELOPMENT	22 000 000
TOOLING	19 000 000
FLIGHT TEST	1 000 000
FEE	5 000 000
	74 000 000
UNIT MANUFACTURING COST (100 Units, 85% Long-Linear Unit Curve)	7 110 000
UNIT RDT&E COST	740 000
	7 850 000

TABLE III

DIRECT OPERATING COST

5250 km (2845nmi), 5.5 Flight hours, Maximum Allowable Payload
3-man Crew 11 hr/day Utilization
Cost of Derivative Twice Cost of Basic Aircraft
Fuel price: $.0977/liter ($.37/gallon)
January 1975 ATA International Freighter Coefficients

	Hourly Costs in Dollars		
	Basic Aircraft	Catamaran Derivative	Factor
Crew	395.85	460.93	1.16
Fuel	1598.51	2942.00	1.84
Insurance	77.21	154.42	2.00
Total Flight Operation	2071.57	3557.35	1.72
Airframe	126.71	173.46	1.37
Engines	178.91	357.82	2.00
Total Maintenance	305.62	531.28	1.74
Depreciation	545.35	1090.70	2.00
Total Direct Expense	2922.54	5179.33	1.77
Maintenance Burden	305.62	531.28	1.74
Total Aircraft Expense	3228.16	5710.61	1.77
Payload, kg	90 700	260 770	2.88
lb	200 000	575 000	
Cost/tonne-km	$.0373	$.0229	0.62
/ton-n.mi.	$.0624	$.0384	

Direct Operating Cost

The direct operating cost, calculated by the standard ATA method using January 1975 international freighter coefficients, is presented for both the basic aircraft and its catamaran derivative in Table III. In view of the uncertainty in aircraft cost, the calculations of Table III were based on the assumption that the cost of the catamaran derivative was exactly twice the cost of the basic aircraft. It was further assumed that both aircraft operate with 3-man crews; the actual size of the crew would depend more upon union demands than any other factor.

As indicated in the table, the direct operating cost of the catamaran derivative is 38-percent less than that of the basic aircraft for the mission chosen. There might be some uncertainty as to whether or not the ATA standard estimates of maintenance costs apply to the catamaran; however, even if maintenance costs and burden were fully double for the catamaran derivative, the reduction in direct operating cost would be 37-percent.

The major reasons for the reduction in direct operating cost are the improved flight operation cost and the increased payload. Even if the payload of the catamaran derivative was only twice that of the basic aircraft, direct operation cost would be reduced by 9-percent. On the other hand, for the chosen mission, the payload of the basic aircraft is reduced from the maximum allowable value of almost 108000 kg (237000 lb) to 90700 kg (200000 lb) because of the required fuel. The improved induced efficiency of the catamaran would certainly allow the full payload to be carried at this range. If the increased payload because of improved flight characteristics is credited as an aerodynamic improvement (catamaran payload of 215060 kg (474200 lb), the aerodynamic improvement in direct operating cost is 23-percent. Indeed, payload capability is the key to the improved costs. Even if all costs of the catamaran derivative were twice those of the basic aircraft, the improved payload resulting from an improved structural weight fraction would reduce direct operating cost by 30-percent.

Reference 14 indicates that reductions in direct operating cost on the order of 20- or 30-percent are required to introduce a totally new aircraft into service. Only about half that improvement is necessary to introduce a derivative aircraft. The indicated reductions in direct operating cost for the catamaran derivative appear to exceed these values by a large margin.

Advanced Technology

The large magnitude of the decrease in direct operating cost is remarkable considering that little or no exotic new technology is required. Indeed, new technology has been deliberately avoided throughout since the study was constrained to a derivative version of a current aircraft at minimum development cost.

In the long term, if a new aircraft were being considered, advanced composite structures would further improve the weight and payload fraction of the configuration. An improved specific fuel consumption for the engines would have a similar effect. The same advanced technology would also enhance the performance of the basic aircraft; however, similar relative gains should still be obtained by a catamaran derivative.

Certain modifications to the basic aircraft would be of major importance to the catamaran. If the basic aircraft fuselage were lengthened by means of plugs, the volumetric limitation on payload would be relieved allowing the catamaran to more nearly translate the saved structural weight into payload. If the thrust available from the basic engines was upgraded by 14-percent, only 7 engines would be required; for a 33-percent increase only 6 engines would be needed. A reduction in the number of engines implies a reduction in maintenance and downtime, resulting in an economically more attractive aircraft.

CONCLUSIONS

This preliminary study of a catamaran derivative indicates that:

1. The conversion from an existing four-engine wide-body transport should be feasible.

2. The conversion results in relatively lighter operational empty weight and relatively larger payload while retaining the original cruise speed and increasing the range.

3. The catamaran derivative should have greatly improved fuel economy when compared to the basic aircraft.

4. The derivative has payload and range characteristics such that it should be of great value in military logistics as well as in commercial operation.

5. The development costs and the aircraft price should be modest compared to a new aircraft of the same size and capacity.

6. The indicated reduction in direct operating cost is about 38-percent; an amount normally more than adequate to justify a totally new aircraft.

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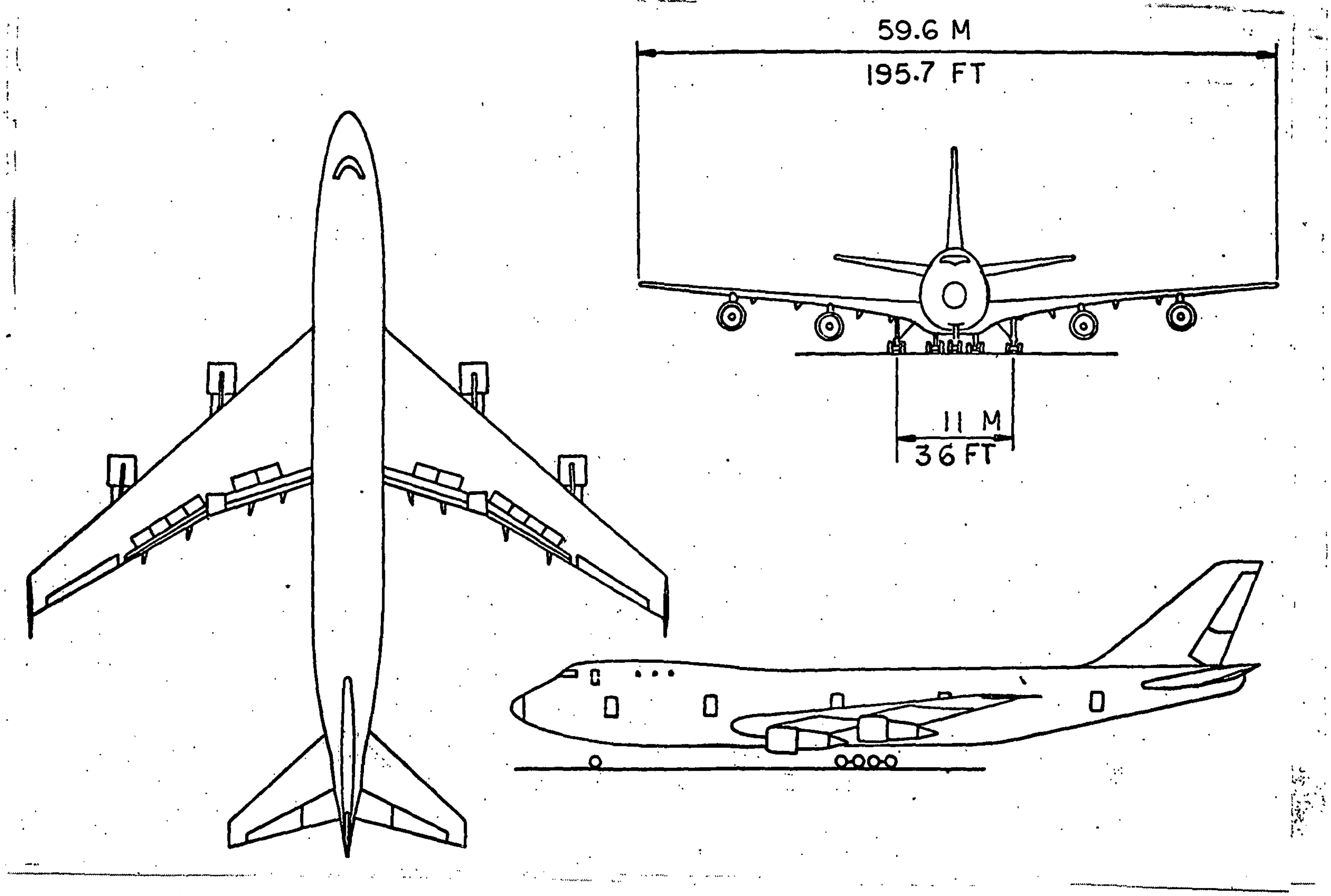

Figure 1. Basic aircraft

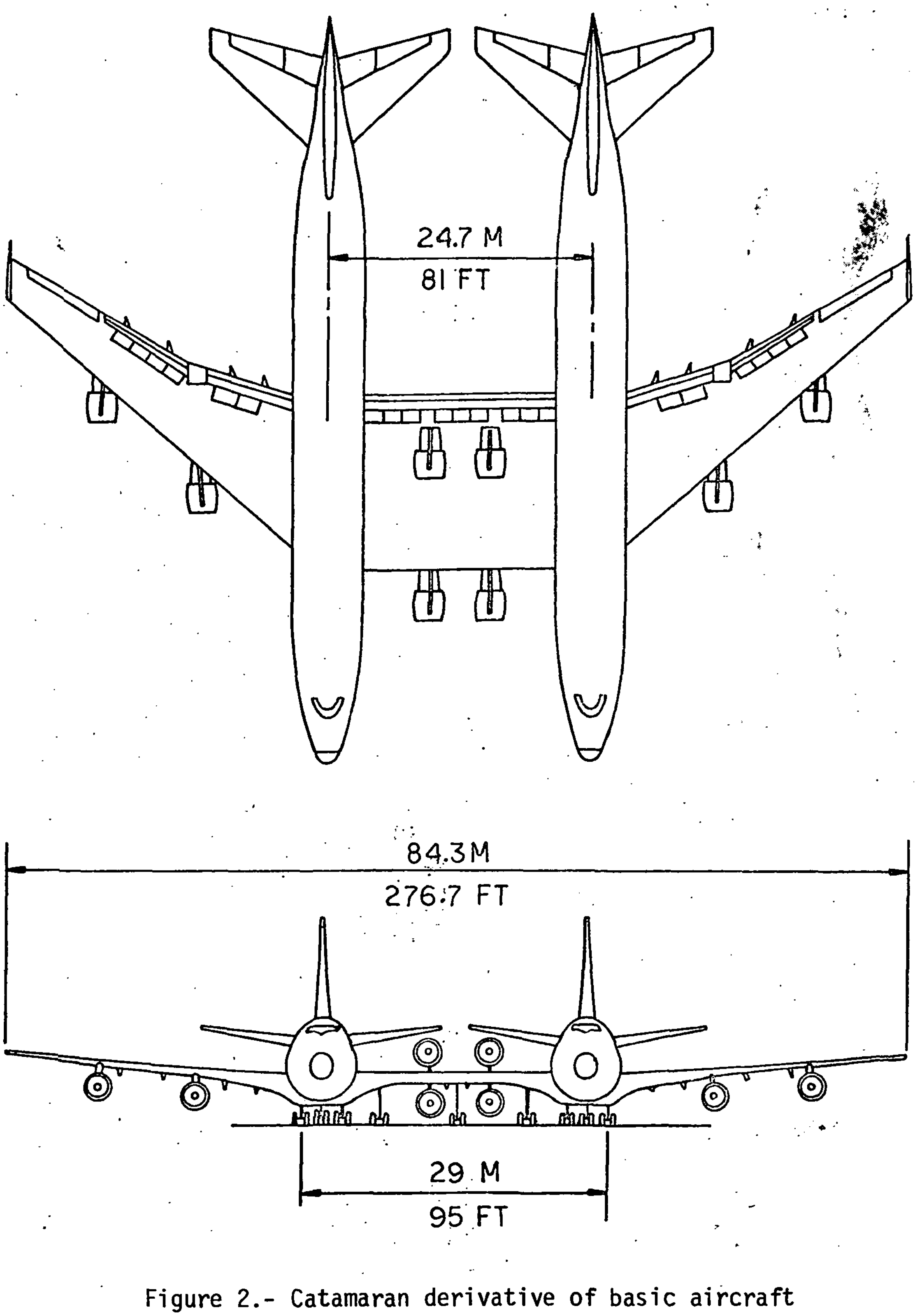

Figure 2.- Catamaran derivative of basic aircraft

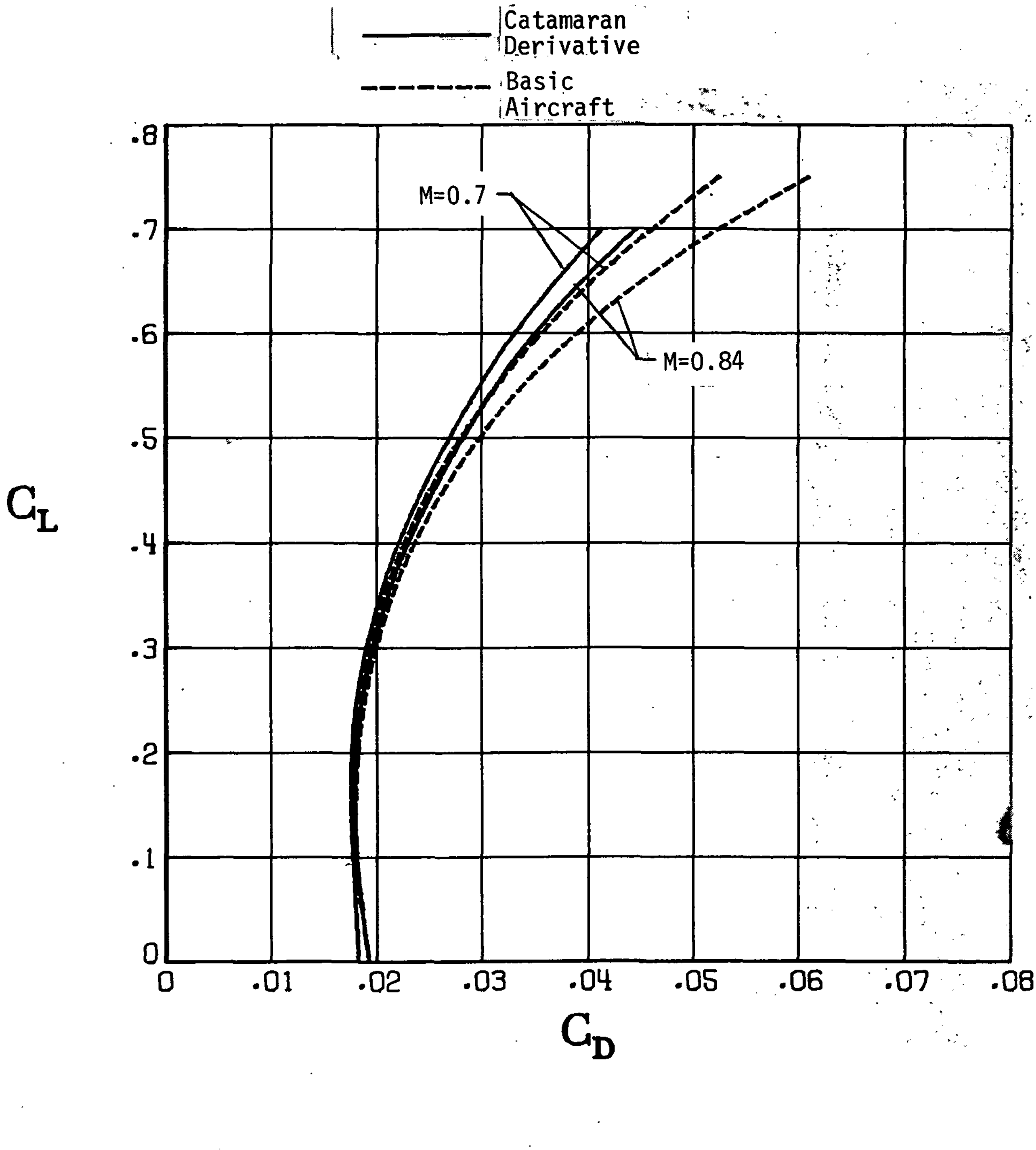

Figure 3. Lift-drag polars for the basic aircraft and its catamaran derivative.

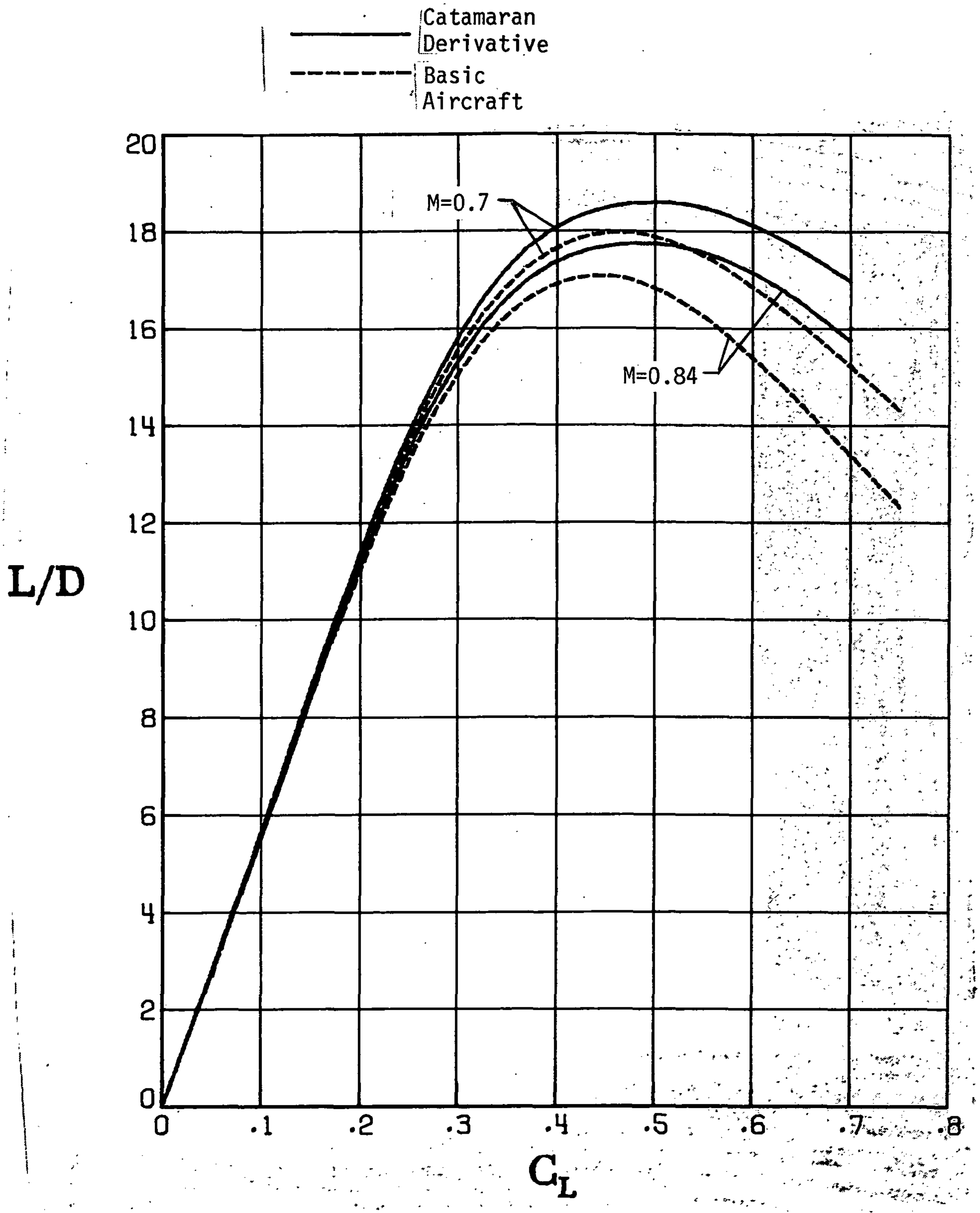

Figure 4. Lift-drag ratio for the basic aircraft and its catamaran derivative.

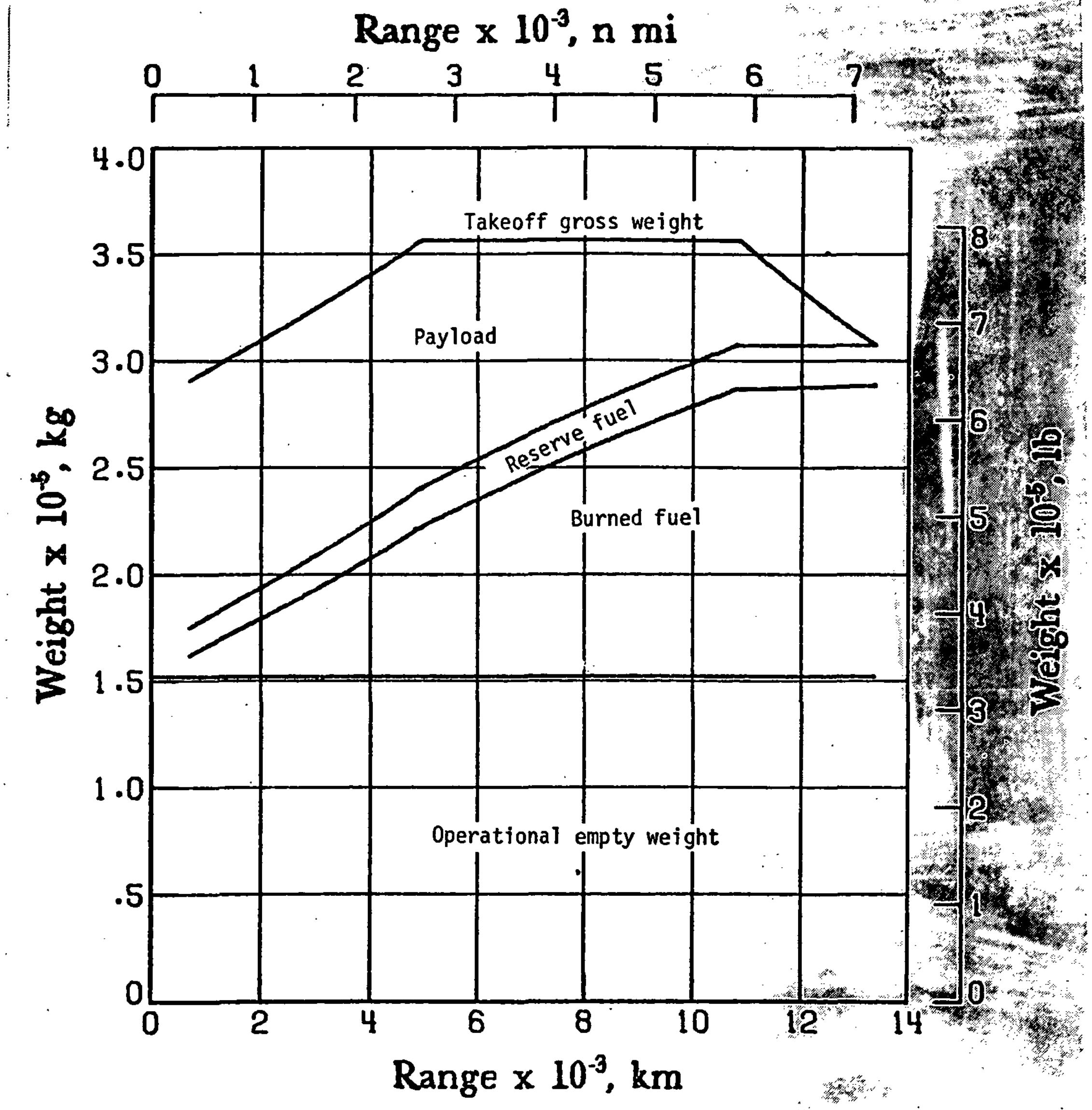

Figure 5. Distribution of take-off gross weight for the basic aircraft as a function of range.

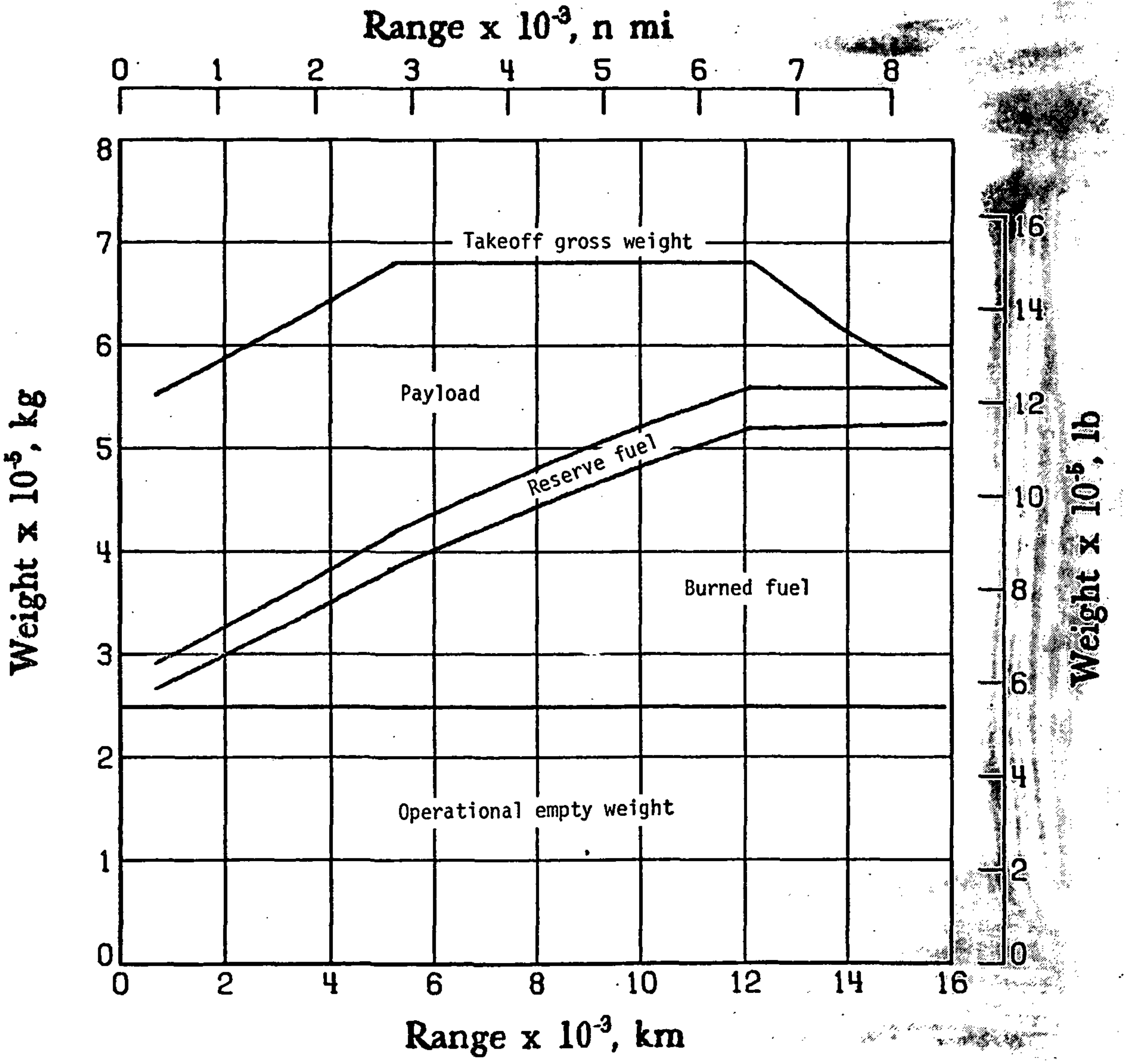

Figure 6. Distribution of take-off gross weight for the catamaran derivative as a function of range.

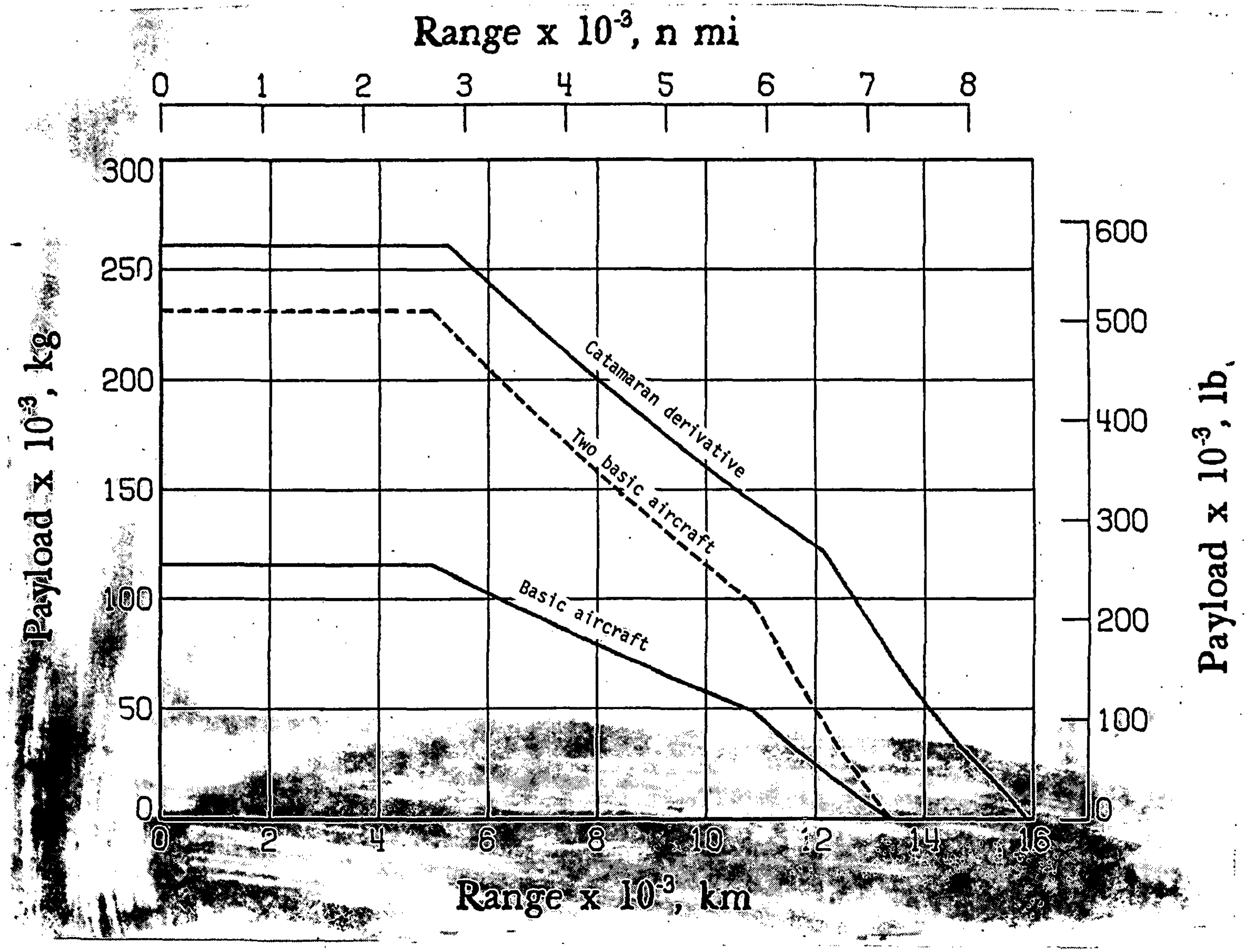

Figure 7. Range-payload performance of the basic aircraft and its catamaran derivative.

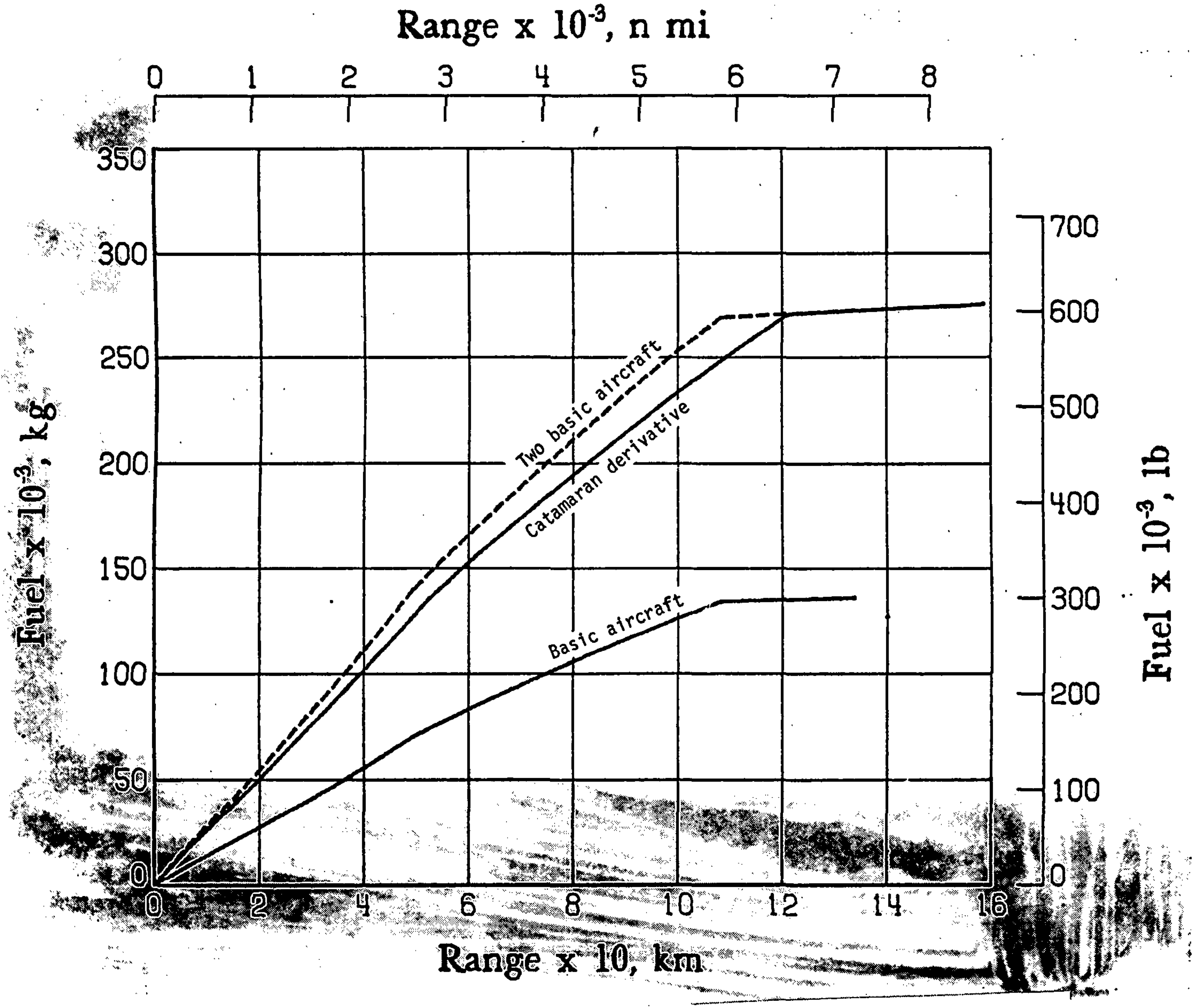

Figure 8. Comparison of fuel burned by the basic aircraft and its catamaran derivative.

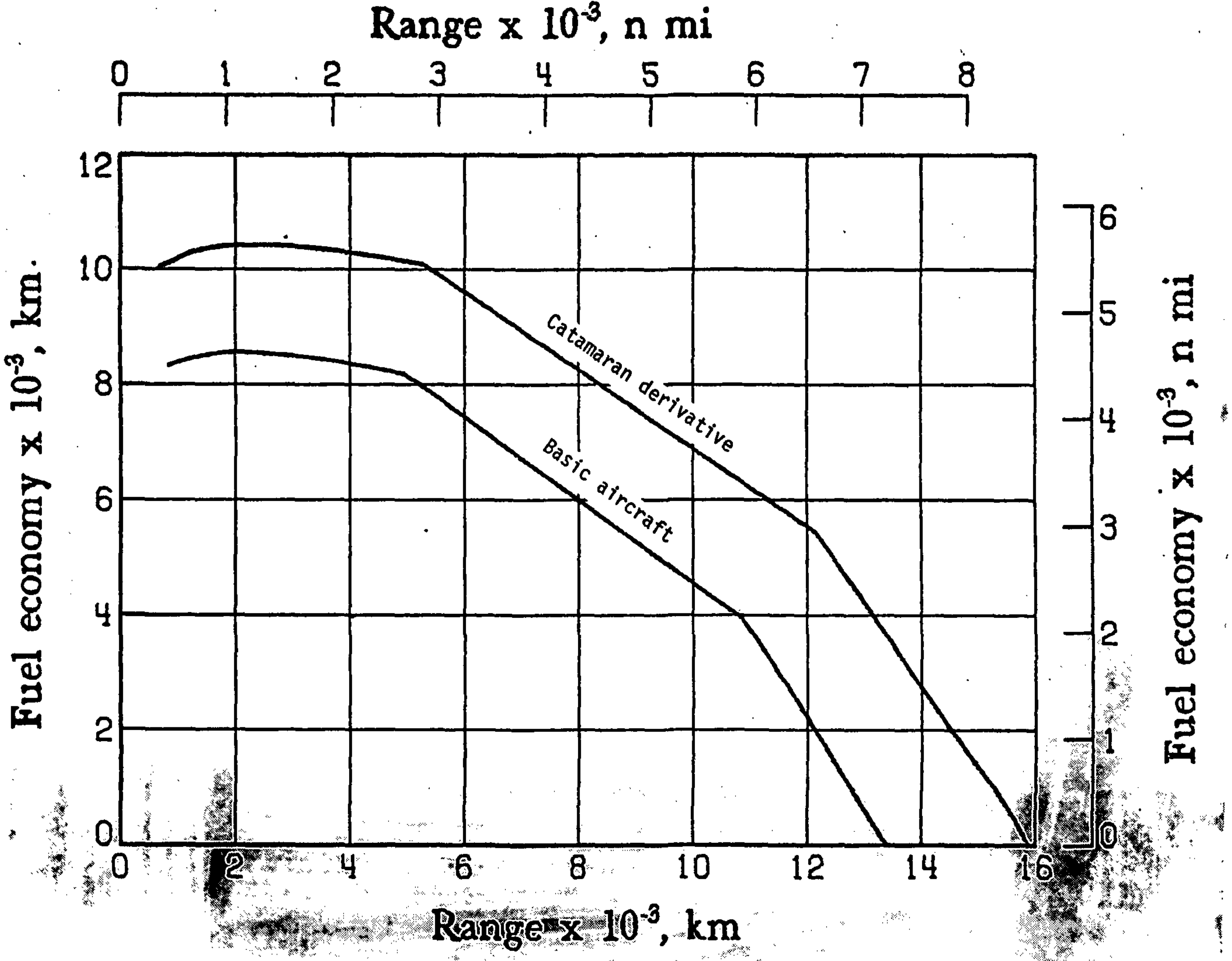

Figure 9. Fuel economy for the basic aircraft and its catamaran derivative. Fuel economy is defined herein as the average distance that a unit of payload is carried for burning a unit of fuel.