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BOEING 747 AIRCRAFT WITH LARGE EXTERNAL POD FOR TRANSPORTING OUTSIZE CARGO

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SUMMARY

A study was conducted to enlarge a previously defined detachable pod that was designed to be mounted to the underside of the fuselage of a Boeing Model 747-200B aircraft to transport either a mobile bridge launcher or the space laboratory module. The effect on structural arrangement, system weight, and range performance was determined. Although no stability, control, or trim analyses were performed, results of recent wind tunnel tests indicate no insurmountable problems.

The results of the study indicated that the increase in pod size was minimal and that the basic 747 structure was adequate to safely absorb the loads induced by ground or air operation while transporting either payload. The 747 with the pod carrying the mobile bridge launcher can attain a range of 7.24 Mm (3 910 n mi), and with the space laboratory module a range of 7.99 Mm (4 315 n mi) is attainable. These ranges are at the military restricted altitude for unpressurized cargo of 5.5 km (18 000 ft). The range attainable with the space laboratory in a pressurized module is 10.75 Mm (5 805 n mi) at an average cruise altitude of 10.6 km (35 000 ft).

INTRODUCTION

In a previous NASA study (ref. 1) the feasibility of transporting outsize cargo, specifically a mobile bridge launcher, in an external cargo pod attached to a Boeing 747 airplane was established. The present study was conducted to determine the effect on structural arrangement, system weight, and range performance of extending the cargo pod payload carrying capability to include either the bridge launcher or a space laboratory (spacelab) module.

The general criteria applied in this study were to minimize modifications to the carrier aircraft and minimize the installation time required to attach the external pod to the 747 (ref. 1). Another criterion used in this study from reference 1 was that the 747, with the bridge-launcher payload, should be capable of achieving a flight distance between the east coast of the United States and Europe without refueling at the military restricted altitude for unpressurized cargo of 5.5 km (18 000 ft).

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The spacelab module has a weight of 178 kN (40 000 lbf), a diameter of 5.48 m (18 ft), and a length of 10.67 m (35 ft). The mobile bridge launcher has a weight of 543 kN (122 000 lbf), a height of 4.11 m (13.5 ft), a width of 4.27 m (14.0 ft), and a length of 9.30 m (30.5 ft). These dimensions for the bridge launcher included the military-specified minimum clearances between vehicle and aircraft structure. Because of the height of the pod, the existing 747 landing gear is unusable. Therefore, the cargo pod was configured with a fully retractable, pod mounted landing gear. Provisions were made for ramp loading the bridge launcher and straight in loading of the spacelab module.

Subsequent to the publication of reference 1, refinements were made to the mold lines of the cargo pod configuration presented in that study, resulting in approximately a seven percent reduction in fuselage-pod wetted area [1895.22 to 1677.83 m^2 (20 400 to 18 060 ft^2)] and hence a reduction of approximately seven counts in parasite drag for the installation. These refined mold lines were used in the development of the larger cargo pod required to accommodate the spacelab module for this study. The aerodynamic data base for this study was developed from performance data of a series of Boeing 747 models (ref. 2). As this data is more conservative than that used in reference 1, and since there is an increase in empty operating weight and pod drag, reductions in range performance are experienced when compared to the results of reference 1.

SYMBOLS AND DEFINITIONS

Values are given in both the International System of Units (S.I.) and U.S. Customary Units. The calculations were made in U.S. Customary Units.

C_D	drag coefficient D/qS
C_L	lift coefficient L/qS
D	drag
L	lift
q	free-stream dynamic pressure

M	Mach number
OWE	operating weight empty
S	wing area, side force
TOGW	take-off gross weight
V	vertical force

DISCUSSION AND RESULTS

Configuration

A study was undertaken to configure a detachable pod which could be mounted to the bottom of the Boeing 747 aircraft for transporting outsize cargo, specifically the spacelab module or a mobile bridge launcher. The internal volume of the pod was configured to accommodate the spacelab module envelope, since it was the larger of the two payloads. A clearance of 15 cm (6 in) was provided between the pod structure and the payload envelope for accessibility to the tie down fittings and other flight or ground crew activity within the cargo area. This clearance was considered adequate to the diameter and curvature of the spacelab module.

This pod (fig. 1), an enlarged version of the externally mounted pod presented in reference 1, was configured utilizing the refined mold lines previously mentioned. The pod width was increased 23 cm (9 in) and the height was increased 91 cm (36 in). The constant slope of the forward pod close-out profile was increased to keep the forward pod/747 fuselage intersection compatible with the 747 nose landing gear mounting at the fuselage station 400 bulkhead. This fuselage station is one of the primary attach points of the pod to the 747 fuselage. The mold lines of the forward pod close-out at different fuselage stations along the constant slope were the same as the refined version of reference 1, except where extensions of the upper mold lines were necessary to intersect with the 747 fuselage (see figure 1 for a view looking rearward). The mold lines beginning at fuselage station 1820 aft along the aft pod close-out were modified to maintain approximately the same aft pod/747 fuselage intersection line (fig. 1, section C-C) as the refined version of the pod of reference 1. The slope of the aft close-out was maintained the same, except for a small increase in the profile slope for the last 5.08 m (200 in) of pod length.

Clamshell doors (similar to the aft doors on the Lockheed C-141) and a ramp that can be lowered to ground level for drive-on loading of the bridge launcher were provided at the rear of the pod, with sufficient clearances to permit straight-in loading of the spacelab module (fig. 1). The clamshell doors are shown in the open position in figure 1.

Due to the height of the pod, the existing 747 main and nose landing gear cannot be used. This landing gear system can either be left on the aircraft in the retracted position (to save conversion time) or removed to save weight. The replacement gear consists of a retractable four strut main landing gear and single strut nose landing gear mounted to the pod. All taxi, take-off, and landing loads were considered to be borne by this gear system. The main gear, when retracted, is enclosed within blisters on each side of the pod. The nose gear, when retracted, is enclosed within the forward pod close-out without requiring protruberances (fig. 1).

The 91 cm (36 in) increase in pod height, and accompanying increase in vertical center-of-gravity position above the ground plane level, required an increase of the semi-track width of 4.93 m (194 in) (ref. 1) to 5.33 m (210 in) in order to maintain a tipover angle less than the maximum allowable of 63 degrees. The main landing gear blister external mold lines were maintained with the increased track.

The forward pod close-out was extended forward to the 747 fuselage station 400 bulkhead; shaped to keep the longitudinal and transverse external curvature rate of change to a minimum; and designed to provide a mount for the nose gear to the pod. This resulted in moving the pod mounted nose gear from fuselage station 390 to fuselage station 764 in order to keep the strut to an acceptable length. This relocation necessitated changing from a two-wheel truck to a four-wheel truck to accommodate the increased tire loads.

The five primary structural attachments of the pod to the 747 aircraft of reference 1 were maintained at fuselage station 400 (nose-landing-gear bulkhead); station 1000 (center-wing-box front spar); station 1241 (center-wing-box rear spar); station 1350 (forward landing-gear-beam bulkhead); and station 1480 (aft-landing-gear bulkhead). The nose landing gear vertical loads would be reacted by shear in the 747 fuselage station 400 bulkhead and in the center-wing-box front spar at fuselage station 1000. For this purpose a truss type construction was incorporated at the forward end of the pod in the shape of a triangle with the base corner points fastened to the station 400 bulkhead and to the front spar, respectively. The forward main landing gear vertical loads would be reacted by shear in the center-wing-box rear spar at fuselage station 1241 and the landing-gear-beam bulkhead at fuselage station 1350. The aft main landing gear vertical loads were considered to be absorbed by shear in the fuselage bulkhead at station 1480. Transfer of these loads from the landing gear to the 747 structure would be through heavy bulkheads in the pod. Transfer of horizontal drag loads between the pod and 747 fuselage would be by means of shear and would occur mainly in the region of the main-landing-gear attachments.

To achieve a snug mating of the pod to the 747 carrier, secondary attachment points will be necessary at certain intervals along the length of the pod. These points were not defined in this study.

Structural Analysis

A preliminary strength analysis was performed on the 747/pod configuration shown in figure 1. This analysis was more refined than that presented in reference 1. Computer aided methods were utilized in the pod configuration development and weight evaluation. The criteria adapted for the strength and weight analysis included: utilization of the existing 747 wing and fuselage hardpoints; minimum impact on the basic 747 airframe; simple pod attachments; and an unpressurized pod. The limit load factors were 2.5 g down (positive maneuver), 1.0 g side (maneuver), ten feet per second sink rate at landing, and 6.0 g forward (crash). A safety factor of 1.5 was applied.

Aluminum was selected as the material for the pod. Forgings of 2014-T6 aluminum alloy were used for the landing gear support frames and their attachments to the 747 fuselage. The pod skin, formed frames, and built-up floor beams were made of 7075-T6 aluminum alloy. The wheel fairings and all doors were also made of 7075-T6 aluminum alloy with 064 mm (.025 in) as a minimum gauge. The landing gear utilizes primarily high heat-treated steels; namely 4340 alloy with a strength of 1.930 GPa (280 000 lbf/in^2). In tension applications, the strength allowables were reduced to provide satisfactory fatigue life. In all other applications room temperature "A" (ref. 3) values were utilized.

The critical loading conditions for the 747/pod attachment points, pod structure, and main and nose landing gear occur during ground rather than flight operations. The criteria of reference 4 were used to determine the critical ground loads. The braked roll condition was critical for both the main and nose landing gear and their attachment structure. The main gear is critical for an aft center-of-gravity condition while the nose gear is critical for a forward c.g. condition. A finite element structural analysis was conducted, using the SPAR Structural Analysis System (ref. 5), to determine the internal loads in the main landing gear region and the wing-body intersection of the 747. The main gear loads (ultimate) are shown in figures 2 and 3. The critical nose gear load of 1 068 kN (240 000 lbf) (ultimate) is much larger than the 547 kN (123 000 lbf) (ultimate) load for the basic 747 aircraft. This increased load was caused by the shorter distance between the nose and main gear for the pod configuration than for the basic aircraft.

The results of the analysis show that the pod tends to distribute the concentrated landing gear loads throughout the pod structure before reaching the 747/pod interface. The basic 747 gear loads result in higher internal loads in the region of the 747 wing and fuselage than the pod mounted gear loads. From this preliminary analysis, it appears that there are no attachment loads that exceed the capability of the basic 747 structure.

The internal loads calculated by the SPAR computer program were utilized to size the pod landing gear struts, pod frames, and skins. The nose gear frame was analyzed as a simple truss. The pod skin and formed frames carry the gear drag and crash loads, along with the relatively small airloads. The pod drag loads were sheared into the 747 structure primarily in the region of the main gear attachments. Concentrated crash loads induced by the payload (bridge launcher) determined the floor beam sizes.

Weight Analysis

A weight analysis was conducted for the pod and 747/pod configuration shown in figure 1. The analysis reflects the results of the strength analysis, previously discussed, which resulted in a lighter weight pod and landing gear structural concept than that presented in reference 1. The pod and pod-mounted landing gear weights (Table I) were determined using the prediction methods of reference 6 and a mass properties computer program developed by the Vought Corporation Hampton Technical Center.

The 747-200B aircraft was selected as the carrier in this study because of the availability of weight data for the this aircraft. It was assumed that certain furnishings (seats) and the majority of the operational items (galleys, food, etc.) would be removed prior to or during the pod attachment operation. The wall and floor coverings, which were removed in the study of reference 1 would remain. It was further assumed that the 747 landing gear would be removed (if adequate time was available) to save weight, since it becomes unusable. Weight breakdowns of the basic 747 and of the aircraft with the pod attached are presented in Table II. If the original landing gear remained on the airplane, the empty weight values for the configuration with the pod would be 144 kN (32 300 lbf) higher than shown.

The 747-200B can carry a full fuel load of 193 056 liters (51 000 gal) and the spacelab-module payload without exceeding the 747 take-off gross weight capability of 3 447 kN (775 000 lbf). The 747 can only carry 184 168 liters (48 652 gal) of fuel with the bridge-launcher payload.

Aerodynamic Drag

The minimum parasite drag of the 747-200B transport with the external cargo pod and retractable landing gear was determined assuming that the pod was a lower-lobe enlargement of the 747 fuselage. Essentially, the drag calculations accounted for the increased wetted area, a fuselage fineness-ratio correction, and a non-optimum shape correction. The drag increment between the present configuration and the basic 747 was added to the drag polar for the 747.

The 747 drag polar was determined by using the specific range (nautical-miles-per-pound-of-fuel) data of reference 2 in conjunction with the fuel consumption curves for the Pratt and Whitney JT9D-7 engine. The resulting polar for the 747 plus external cargo pod, assuming no compressibility drag at a cruise Mach number of .68 and altitude of 5.5 km (18 000 ft), is presented in figure 4. Lift-drag ratios for the aircraft are presented in figure 5.

Stability and Control

There was no stability, contorl, or trim analysis conducted on this study configuration. However, the results of recent wind tunnel tests (ref. 7) on the configuration of reference 1 indicate no insurmountable problems. The wind tunnel tests indicated that the pod produces a significant decrease in directional stability; however, the addition of horizontal tail tip fins restores some of the stability, particularly at the lower angles of attack. The present study did not include the addition of the fins.

Mission Analysis

Reference 1 has shown that maximum range was attained at a Mach number of .68 for flight at an altitude of 5.5 km (18 000 ft) when transporting the bridge launcher in the cargo pod with retractable landing gear, and with the original 747 landing gear removed. For this reason the majority of mission ranges in the present study were computed at M = .68 and 5.5 km (18 000 ft) altitude.

The 747-200B airplane equipped with the external cargo pod specifically designed to transport the 177.9 kN (40 000 lbf) spacelab module has a take-off weight of 3152.5 kN (708 700 lbf) with a maximum fuel capacity of 1520.0 kN (341 700 lbf), (Table II). The operating weight empty is increased by 77.8 kN (17 500 lbf) when compared to the weight statement of reference 1 (Table III). This configuration attains a range of 7.99 Mm (4 315 n mi). Replacing the spacelab module with the 524.7 kN (122 000 lbf) bridge launcher brings the configuration up to the maximum take-off weight of 3447.4 kN (775 000 lbf) with only 1450.1 kN (326 000 lbf) of fuel. The range of this configuration is 7.24 Mm (3 910 n mi), a 750 km (405 n mi) penalty. Had it been possible to take off with full fuel capacity, the take-off weight would have increased to 3517.2 kN (790 700 lbf) and the achieved range would have been 7.59 Mm (4 100 n mi), a 400 km (215 n mi) penalty. The climb and descent distances, and the take-off, climb, and descent fuel consumptions were derived from the data in reference 2. The domestic Air Transport Association (ATA) fuel reserves were used when computing the mission range capability.

In the event that the spacelab module is packaged in a pre-pressurized container, the cruise altitude restriction of 5.5 km (18 000 ft) will not apply. Assuming initial and final cruise altitudes of 9.1 to 12.2 km (30 000 to 40 000 ft) the maximum range is 10.75 Mm (5 805 n mi) at M = .805. This range value was computed using a derived drag polar based on data from reference 2 with no additional compressibility drag due to the external cargo pod. Table III presents a summary of mission capability.

CONCLUSIONS

A study was conducted to determine the effect on structural arrangement, system weight, and range performance of extending the 747/cargo pod payload capability of a previous study to transport the space laboratory module or the mobile bridge launcher. The principle results of this study were as follows:

1. The increase in pod size required to accommodate the space laboratory module was minimal, 91 cm (36 in) in height and 23 cm (9 in) in width. These dimensional increases occurred in the area of the payload envelope.
2. The basic 747 structure is adequate to safely absorb the loads induced by ground or air operation while transporting either payload.
3. The 747/pod with the bridge launcher payload can attain a range of 7.24 Mm (3 910 n mi) and with the space laboratory module it can attain a range of a range of 7.99 Mm (4 315 n mi). These ranges are at the military restricted altitude for unpressurized cargo of 5.5 km (18 000 ft). The range attainable with the space laboratory in a prepressurized module is 10.75 Mm (5 805 n mi).

4. The 747/pod with the bridge launcher payload cannot carry a full load of fuel because of the basic 747 take-off gross weight limitation of 3460.7 kN (778 000 lbf).

5. Although no stability, control, or trim analysis was conducted, results of recent wind tunnel tests indicate no insurmountable problems.

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TABLE I. - POD STRUCTURAL WEIGHT BREAKDOWN

Item	Pod Configuration with Retractable Gear	
	kN	lbf
Landing Gear Support Frames		
Station 770 (Nose Gear)	4.0	900
Station 1342.5	9.3	2 100
Station 1463.5	5.0	1 120
Floor Beams	8.0	1 800
Pod Skins and Frames	21.2	4 760
Landing Gear Fairings	3.6	810
TOTAL POD	51.1	11 490
Main Gear (Pod Mounted)	123.2	27 700
Nose Gear (Pod Mounted)	25.4	5 710
TOTAL GEAR	148.6	33 410
TOTAL POD AND GEAR	199.7	44 900

TABLE II. - WEIGHT BREAKDOWN OF AIRCRAFT WITH EXTERNAL POD

	Basic 747-200B (1)		Aircraft Plus Pod w/ Bridge Launcher		Aircraft Plus Pod w/ Spacelab	
	kN	lbf	kN	lbf	kN	lbf
STRUCTURE	845.6	190 100	845.6	190 100	845.6	190 100
LANDING GEAR	143.7	32 300	0	0	0	0
PROPULSION	205.5	46 200	205.5	46 200	205.5	46 200
SYSTEMS	111.7	25 100	111.7	25 100	111.7	25 100
FURNISHINGS	181.0	40 700	77.8	17 500	77.8	17 500
PAINT	3.1	700	3.1	700	3.1	700
MANU. EMPTY WEIGHT	1490.6	335 100	1243.7	279 600	1243.7	279 600
STD. & OPERATIONAL ITEMS	151.2	34 000	11.1	2 500	11.1	2 500
OPERATING WEIGHT EMPTY (O.W.E., - AIRCRAFT ONLY)	1641.8	369 100	1254.8	282 100	1254.8	282 100
PASSENGERS	351.1	78 925	0	0	0	0
CARGO	348.9	78 475	0	0	0	0
POD + GEAR	0	0	199.7	44 900	199.7	44 900
O.W.E. OF A/C + POD	-	-	1454.5	327 000	1454.5	327 000
POD PAYLOAD	0	0	542.7	122 000	177.9	40 000
ZERO FUEL WEIGHT	2342.0	526 500	1997.3	449 000	1632.4	367 000
FUEL	1105.4	248 500	1450.1	326 000 (3)	1520.1	341 700 (2)
TAKE-OFF GROSS WEIGHT	3447.4	775 000	3447.4	775 000	3152.5	708 700
MAX. LANDING	2508.7	564 000	2508.7	564 000	2508.7	564 000
MAX. RAMP WEIGHT	3460.7	778 000	3460.7	778 000	3460.7	778 000

(1) Boeing weight statement; (2) 193 056 liter (51 000 gal) @ 7.87 N/liter (6.7 lbf/gal) (max. capacity);
(3) 184 168 liter (48 652 gal) @ 7.87 N/liter (6.7 lbf/gal).

TABLE III. - MISSION RANGE CAPABILITY

TOGW, kN (lbf)	3447.4 (775 000)	3447.4 (775 000)	3447.4 (775 000)	3447.4 (775 000)	3152.5 (708 700)	3152.5 (708 700)
OWE, kN (lbf)	1177.0 (264 600)	1177.0 (264 600)	1177.0 (264 600)	1254.8 (282 100)	1254.8 (282 100)	1254.8 (282 100)
Mission Fuel, kN (lbf)	1515.5 (340 700)	1515.5 (340 700)	1515.5 (340 700)	1450.1 (326 000)	1520.0 (341 700)	1520.0 (341 700)
Payload	Bridge Launcher	Bridge Launcher	Bridge Launcher	Bridge Launcher	Spacelab Module	Spacelab Module
Cruise Altitude, km (ft)	5.5 (18 000)	5.5 (18 000)	5.5 (18 000)	5.5 (18 000)	5.5 (18 000)	9.1 to 12.2 (30 000 to 40 000)
M	.68	.68	.68	.68	.68	.805
Range, Mm (n.mi.)	8.70 (4 700)	8.50 (4 460)	8.59 (4 560)	7.24 (3 910)	7.99 (4 315)	10.75 (5 805)
	(1)	(2)	(3)	(4)	(4)	(4)

NOTES:
(1) Range based on ref. 1 drag estimate of B-747 plus ref. 1 pod.
(2) Range based on ref. 2 drag estimate of B-747 plus ref. 1 pod.
(3) Range based on ref. 2 drag estimate of B-747 plus modified ref. 1 pod.
(4) Range based on ref. 2 drag estimate of B-747 plus present pod.

} with domestic ATA fuel reserves

B-747 fuselage and ref. 1 pod wetted area = 1895.22 m^2 (20 400 ft^2)
B-747 fuselage and modified ref. 1 pod wetted area = 1677.83 m^2 (18 060 ft^2)
B-747 fuselage and present study pod wetted area = 1755.87 m^2 (18 900 ft^2)

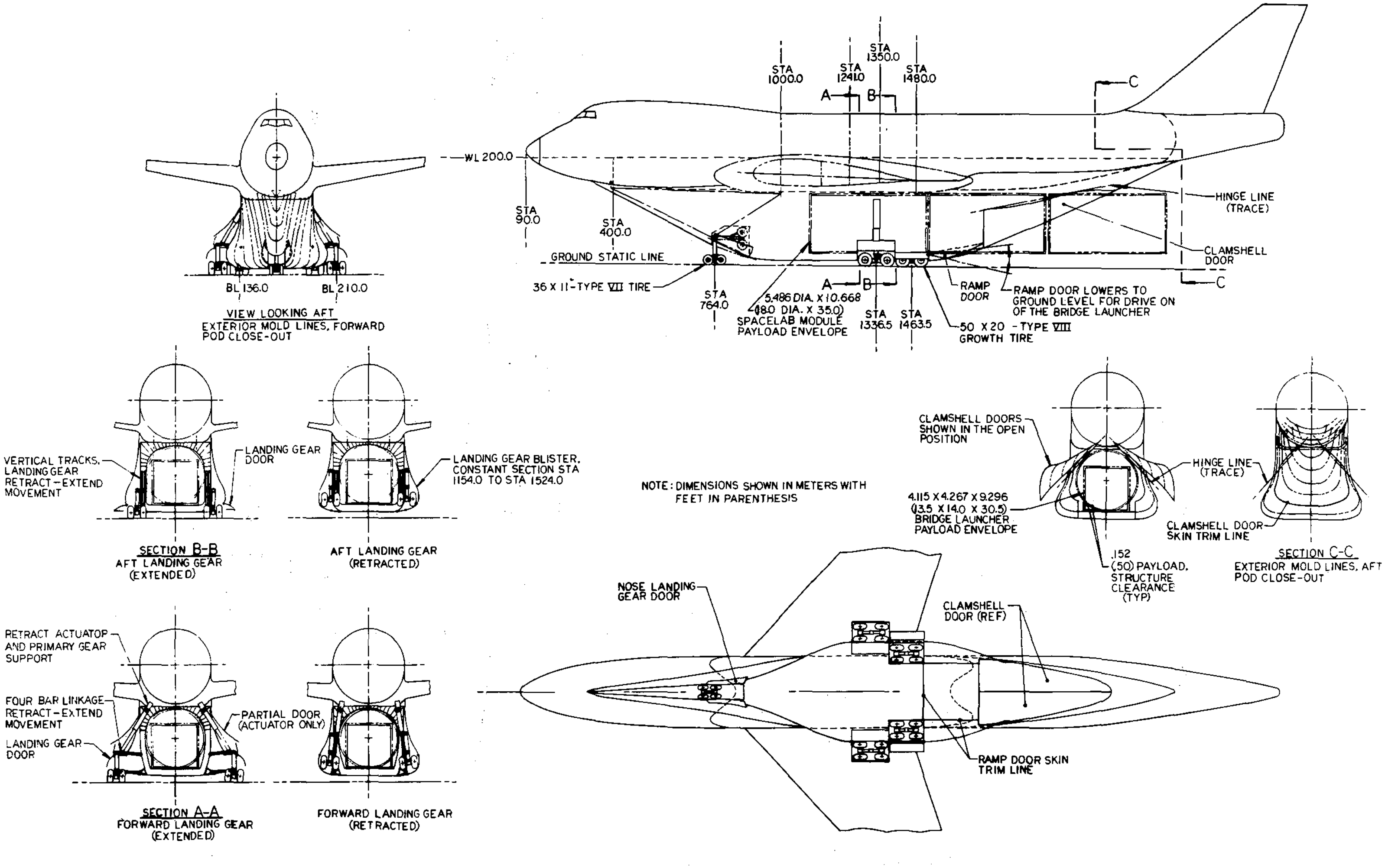
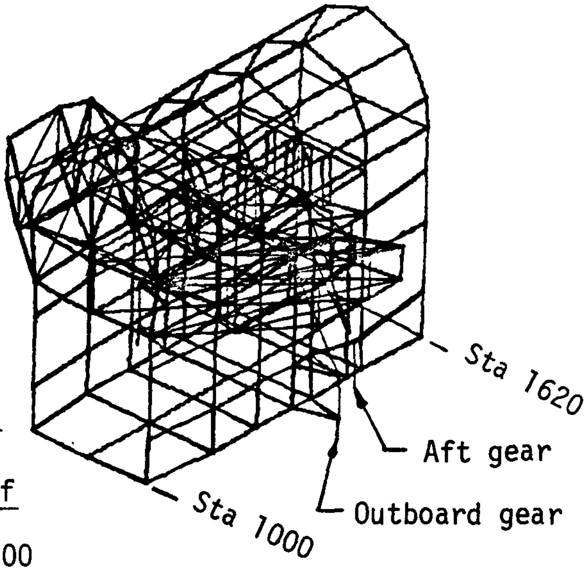
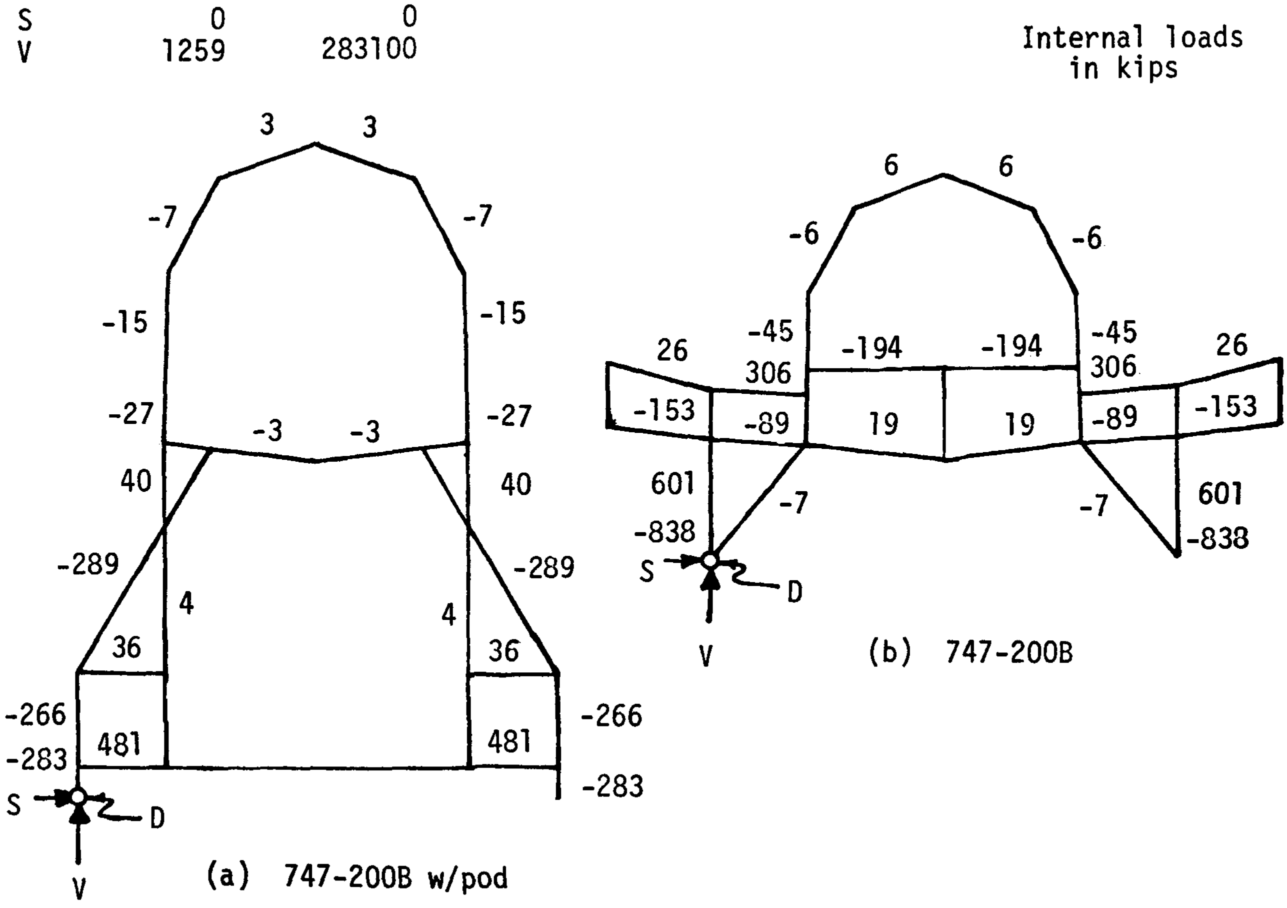


Figure 1. - Boeing 747 with external spacelab module/bridge launcher cargo pod - fully retractable landing gear.



External loads per gear

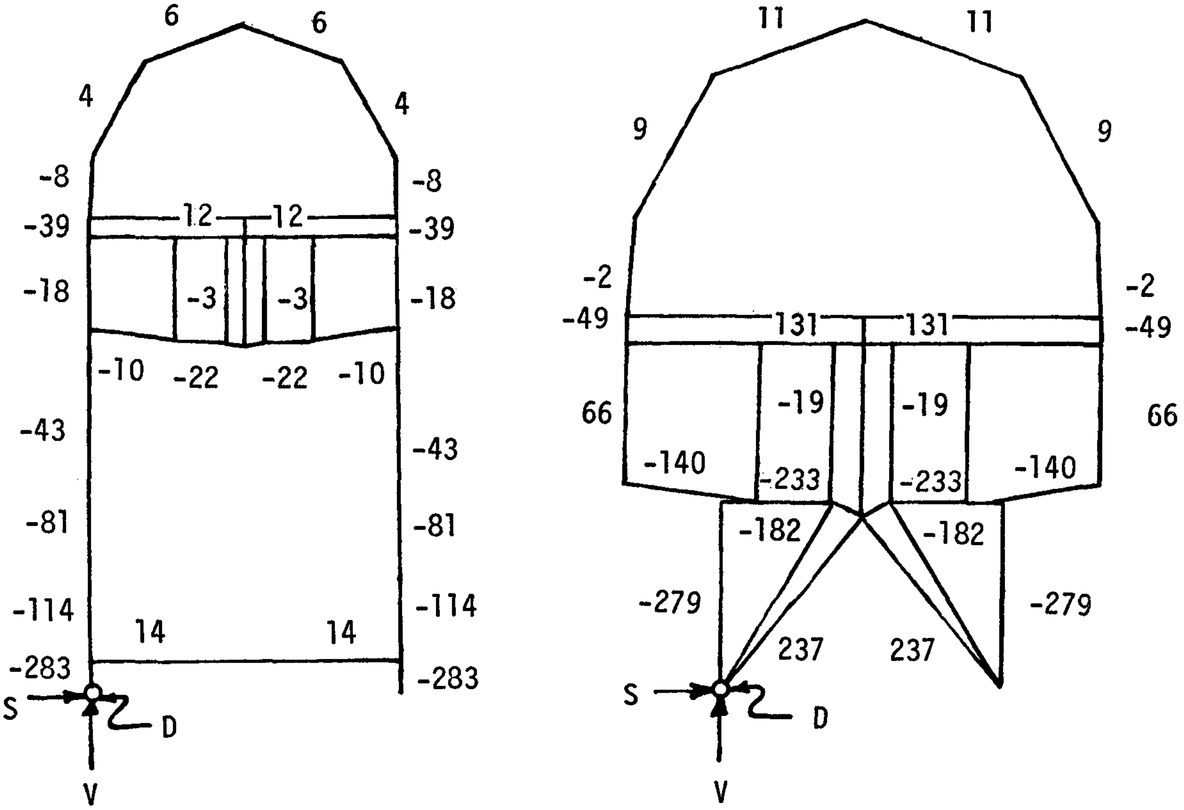
	kN	lbf
D	1008	226500
S	0	0
V	1259	283100



(a) 747-200B w/pod

(b) 747-200B

Figure 2. - Outboard gear bulkhead axial loads - braked roll condition.



(a) 747-200B w/pod

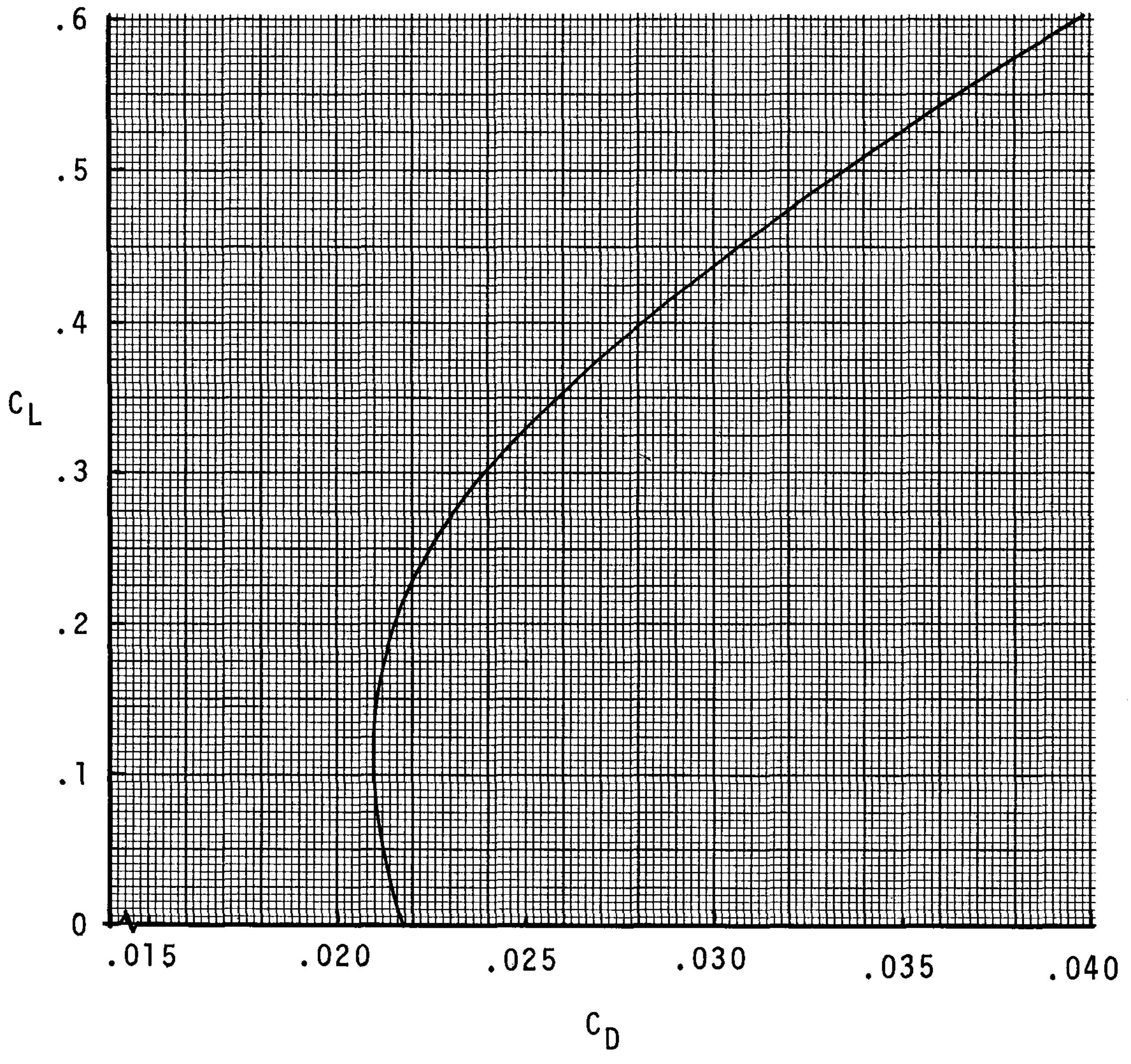
(b) 747-200B

External loads per gear

	kN	lbf
D	1008	226500
S	0	0
V	1259	283100

Internal loads
in kips

Figure 3. - Aft gear bulkhead axial loads - braked roll condition.



747-200B WITH POD AND RETRACTABLE LANDING GEAR

M ≈ .72

Figure 4.- Cruise drag polar.

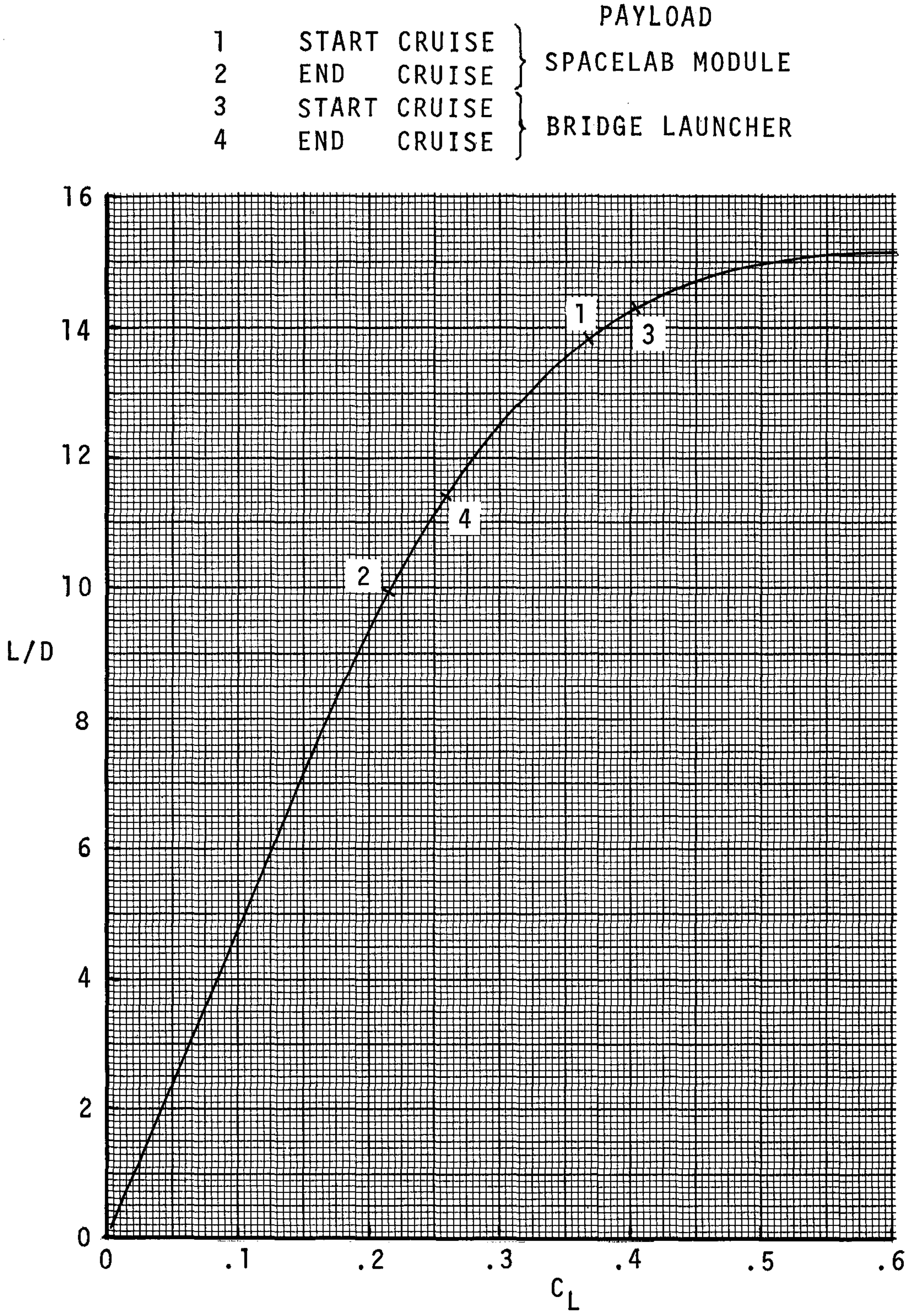


Figure 5.- Lift-Drag ratio as a function of C_L for 747 with pod. Operating points are shown by tic marks. M =.68 at an altitude of 5.5 km (18000 ft).

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16. Abstract

A study was conducted to enlarge a previously defined detachable pod that was designed to be mounted to the underside of the fuselage of a Boeing Model 747-200B aircraft to transport either a mobile bridge launcher or the space laboratory module. The effect on structural arrangement, system weight, and range performance was determined. Although no stability, control, or trim analyses were performed, results of recent wind tunnel tests indicate no insurmountable problems.

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