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SPACE SHUTTLE WITH EXTERNAL HYDROGEN DROP TANKS

By Herman E. Thomason
Preliminary Design Office
Program Development

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This report presents the guidelines and study results of an investigation into the fully-reusable Space Shuttle configuration to determine the effect of carrying the ascent liquid hydrogen (LH_2) propellant in external tanks. The concept chosen for comparison carried 100 percent of the ascent LH_2 in external tanks; after the orbiter is inserted into the transfer orbit, the tanks are separated from the vehicle. The concept allows extensive use of heat sink materials on the Booster, rather than thermal protection materials. Weight and cost differences from the base-line vehicle are evaluated by a normalization procedure which includes a set of weight-scaling equations, vehicle sizing programs, and cost estimating relations (CER).

Results indicate that for the low cross-range configuration a reduction in vehicle gross lift-off weight (GLOW) of 362 874 kg (800 000 lb) can be achieved with a program cost savings of approximately $0.6 billion, whereas the high cross-range configuration shows a 680 389-kg (1 500 000-lb) reduction in GLOW, with a $1 billion program cost saving. The RD&TE cost reduction would be on the order of $1.4 billion with reductions in the peak and early program years' funding.

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TECHNICAL MEMORANDUM X- 64579

SPACE SHUTTLE WITH EXTERNAL HYDROGEN DROP TANKS

SUMMARY

This report presents the guidelines and study results of an investigation into the fully-reusable Space Shuttle configuration to determine the effect of carrying the ascent liquid hydrogen (LH_2) propellant in external tanks. The concept chosen for comparison carried 100 percent of the ascent LH_2 in external tanks; after the Orbiter is inserted into the transfer orbit, the tanks are separated from the vehicle. The concept allows extensive use of heat sink materials on the Booster, rather than thermal protection materials. Weight and cost differences from the base-line vehicle are evaluated by a normalization procedure which includes a set of weight-scaling equations, vehicle sizing programs, and cost estimating relations (CER).

Results indicate that for the low cross-range configuration a reduction in vehicle gross lift-off weight (GLOW) of 362 874 kg (800 000 lb) can be achieved with a program cost savings of approximately $0.6 billion, whereas the high cross-range configuration shows a 680 389-kg (1 500 000-lb) reduction in GLOW, with a $1 billion program cost saving. The RD&TE cost reduction would be on the order of $1.4 billion with reductions in the peak and early program years' funding.

INTRODUCTION

The purpose of the study was to explore system alternatives for the fully-reusable Space Shuttle in an attempt to reduce program costs without imposing large compromises in desired design characteristics. The study guidelines specified that the base-line Shuttle system was to be a fully-reusable two-stage launch vehicle capable of delivering a 11 340-kg (25 000-lb) payload, housed in the 4.57- by 18.29-m (15- by 60-ft) cargo bay, into a 500-km (270-n.mi.) orbit inclined 55 deg to the equator. The vehicle was to have the base-line operational performance characteristics consistent with present NASA/DOD guidelines. The aim was to investigate configurations that would carry the liquid hydrogen (LH_2) ascent propellant in expendable drop tanks and to evaluate the cost and weight differences associated with this modification. Consequently, the configurations identified in the NASA Phase B studies have been chosen, and the technologies have been factored in through a derived set of weight-scaling relationships to produce vehicle stage weights. By means of a normalization process and cost computer program, gross lift-off weights and total program costs for the different configurations are provided so that a comparison can be made on a consistent basis.

The Orbiter and Booster configurations selected for the study are shown in Figures 1 and 2. They represent the primary competitive fully-reusable low cross-range vehicle candidates; the high cross-range vehicles are also considered and the results included. The base-line assumptions involved in defining the size and performance of the configurations are given in Table 1. The assumptions represent the common ground rules as currently defined in NASA Phase B studies. The decision to use JP-4 fuel in lieu of LH_2 fuel for the airbreathing propulsion system was made after the study was underway; therefore, the earlier results considered LH_2 airbreathing engine fuel, whereas the later results reflect the use of the JP-4 fuel. The individual subsystem and propellant weight items that make up the total weight of the reusable vehicle, along with the vehicle characteristics of the reusable vehicle, are listed in Table 2. A contingency allowance of 10 percent was chosen for these subsystem weights to be consistent with the basic ground rules. The guidelines for the study were, initially, to vary the amount of LH_2 ascent propellant in external drop tanks to the Booster from 0 to 75 percent in 25-percent increments and resize the Orbiter for optimum performance; this exercise resulted in four configurations. The next step was to vary in 25-percent increments the amount of LH_2 ascent propellant in external drop tanks from 0 to 100 percent for the low cross-range Orbiter, thus resulting in five configurations. In addition, the delta Orbiter base-line configuration was compared with a 100-percent LH_2 external tank delta configuration, resulting in two additional configurations.

TABLE 1. STUDY GROUND RULES

Phase B Shuttle Requirements

- 11 340-kg (25 000-lb) Payload to Reference Orbit
- 4.57- by 18.29-m (15- by 60-ft) Payload Bay
- Orbiter Go-Around
- Booster Flyback
- LH_2 Airbreathing Fuel
- ICD Main Engines
- 10 Percent Dry Weight Contingency
- 457-m/sec (1500-ft/sec) Orbit Maneuvering System
- 83.3- by 185-km (45- by 100-n.mi.) Transfer Orbit

Orbiter and Booster resized in all cases without changing the base-line vehicle shape or reentry aerodynamic configuration.

The Booster was resized for optimum performance (considered throughout this analysis to be minimum GLOW) for each configuration. The Orbiter and Booster were resized in all cases, but the base-line vehicle shape or reentry aerodynamic configuration were not changed. The Booster staging velocity at which the external LH_2 tank Orbiter configuration optimizes permits extensive use of heat sink material on the Booster.

TABLE 2. REUSABLE VEHICLE SUBSYSTEMS, PROPELLANT, AND VEHICLE CHARACTERISTICS

Subsystem Weight Items

Body Structure/Aerodynamic Surface/Thermal Protection
Landing Gear
Thrust Structure
Launch Gear/Docking System
Main Tankage, Integral (Bulkheads and Insulation)
Main Tankage, Nonintegral
Tankage On-Orbit Propellant
Tankage Airbreathing Engines
Main Engines/Accessories
On-Orbit Propulsion System
Propulsion System Accessories
Airbreathing Engine/Accessories
Main Gimbal Control System Contained in Main Engine
Aerodynamic Controls
Reaction Control System
Avionics (Guidance and Control/Instrumentation) (Communications/Control)
Separation System Interface
Primary Power System
Power Conversion/Distribution
Environmental Control System
Personnel Provisions
Range Safety Abort
Contingency
Personnel
Cargo

Propellants

Residuals and Service Items
Reaction Control Propellants
Thrust Decay Propellants
Airbreathing Engine Fuel
On-Orbit Propellants
Main Stage Propellants

TABLE 2. (Concluded)

Vehicle Characteristics
Mass Fraction
Number of Main Engines
Vacuum Thrust
Number of Jet Engines
Fly-Back Range
Area Wetted
Planform Area
Vehicle Length
Planform Loading Activity

RESULTS

Comparison of Configurations with Booster Drop Tanks

The inert weights were computed by weight-scaling equations for the delta canard Booster and straight-wing Orbiter vehicle, and vehicle performance computation runs were made optimizing staging velocity. From these results propellant loadings for each stage were determined. A scaled layout was then made to accommodate the required propellant into the vehicle tankage and to determine that the resulting configuration had sufficient volume to contain the main engine and the auxiliary systems. The four configurations investigated, along with the resulting propellant loading, Booster inert weights, and drop tank size, are shown in Figure 3.

Comparisons of vehicle performance capabilities are shown in Table 3. The comparisons presented in the first column are made for GLOW for the referenced 11 340-kg (25 000-lb) payload in the 4.57- by 18.29-m (15- by 60-ft) Orbiter cargo bay inserted into the referenced mission; whereas the second column shows payload gains by maintaining GLOWs constant. The advantages are minimal when one considers the operational complexity that would be encountered. Figure 4 shows the vehicle dynamic pressure as a function of the percentage of total LH_2 in the Booster's drop tanks. Because of the high dynamic pressure, the separation of the drop tanks from the Booster would be extremely complex for LH_2 tanks which contain from 20 to 80 percent of the Booster's hydrogen. The gains below 20 percent liquid hydrogen were not considered large enough to be explored further, and separation of the tanks resulting from a 100-percent liquid hydrogen loading would be quite undesirable since tank separation would be occurring simultaneously with Orbiter separation. Later separation of the tanks from the Booster would be restricted because of the critical reentry maneuvers being conducted. The disposal of Booster drop tanks would be limited by range safety, and the all-azimuth launch requirement would be forfeited. Therefore, further consideration of Booster drop tanks was terminated.

TABLE 3. VEHICLE PERFORMANCE WITH DROP TANKS ON BOOSTER

Tank Size (%)	GLOW for Reference Payload 11 340 kg (25 000 lb)	Payload at Fixed GLOW 1 587 573 kg (3 500 000 lb)
0	1 632 933 kg (3 600 000 lb)	10 569 kg (23 300 lb)
25	1 587 573 kg (3 500 000 lb)	11 431 kg (25 200 lb)
50	1 551 286 kg (3 420 000 lb)	12 383 kg (27 300 lb)
75	1 533 142 kg (3 380 000 lb)	12 927 kg (28 500 lb)

Comparison of Configurations with Orbiter Drop Tanks

The effect of external LH_2 drop tanks upon the straight-wing Orbiter is presented in Figure 5, which shows the vehicle GLOW sensitivity with respect to varying the quantity of liquid hydrogen in the external tanks. The inert weights are computed and both the Booster and Orbiter are sized by optimization of the relative staging velocity. A scaled layout of the Orbiter with its LH_2 drop tanks and the remainder of the propulsion system was made to determine whether the configuration had sufficient volume to contain the 4.57-m dia by 18.29-m long (15- by 60-ft) payload, the orbiting maneuvering system, and the auxiliary systems. Figure 5 also shows that, with the ground rule of not changing the vehicle's aerodynamic shape, the total gains that were theoretically possible above the 50-percent LH_2 tanks could not be attained because the configuration volume would not contain all the required systems. If the vehicle were allowed to change aerodynamically, a more efficient packaging arrangement could be made and most of the theoretical gains could be realized. It should be noted, however, that this is not to infer that benefits above the 50-percent level are not attainable, but rather only slightly less than those expected theoretically.

Figure 6 shows a comparison of vehicle performance results of the base-line vehicle with 50- and 100-percent external LH_2 tanks on the Orbiter. The Orbiter configurations investigated are shown in Figure 7. Table 4 summarizes data of the five configurations; the data are for the base-line 11 340-kg (25 000-lb) payload in the 4.57- by 18.29-m (15- by 60-ft) cargo bay delivered into the reference orbit. A review of these data shows that the configurations with 100 percent LH_2 in the external tanks results in the greatest gain in the reduction of the GLOW. Additionally, from an operational consideration (i.e., propellant feed system, tank separation, hydrogen tank purge before landing, tank insulation, etc.) it is the simplest system. Therefore the remainder of the investigation considered only this design (Figure 8). A comparison of the 100-percent LH_2 drop tanks with the base-line vehicle shows for the same payload a possible reduction of 362 874 kg (800 000 lb) in the GLOW is attainable, or conversely, for a fixed GLOW a possible payload gain of 12 701 kg (28 000 lb) may be achieved.

The LH_2 tanks considered for the Orbiter are shown in Figure 9 in comparison with the drop tanks that are being proposed for the stage and one-half vehicle. The important feature of the LH_2 drop tanks is their simple cylindrical construction, with only the loads pertaining to the internal LH_2 [13 608 kg (30 000 lb)] being the major factor in sizing the structure and separation device. Loads associated with the heavy liquid oxygen (LOX) are carried in the main vehicle structure; therefore manufacturing and shipping problems should be simplified. The mass fraction of the drop tanks (i.e., ratio of propellant to that of total weight $\frac{W_P}{W_P + W_I}$, where W_P is total hydrogen propellant and W_I is total inert weight) as a function of the external hydrogen weight is shown in Figure 10. With the 100-percent LH_2 drop tank [13 608 kg (30 000 lb) of propellant], the resulting mass fraction is 0.79, and, as shown in the figure, the mass fraction is relatively insensitive at this point. If this drop tank mass fraction is used in the design of the fixed-wing Orbiter, the Orbiter mass fraction improves at the 100-percent point. This is depicted in Figure 11 for both the fixed [11 340-kg (25 000-lb)] payload (decreasing GLOW) as well as for fixed GLOW (increasing payload).

Of primary concern is the disposal of the drop tanks upon achieving the 92.6- by 185-km (50- by 100-n.mi.) injection orbit. Several methods have been proposed, including: (1) destruction, which is not considered to be desirable because of the resulting orbital debris; (2) collection into a given orbit, which could serve as an orbital propellant depot; and (3) using the same size drop tank in both the Tug and lunar Shuttle designs. The tanks are approximately the size of the Shuttle Orbiter payload bay, and therefore could be moved within the cargo bay. For such an application the drop tanks would be fitted to the core vehicle in low earth orbit. Perhaps the most attractive disposal mode would be to stage the tanks during the 92.6- by 185-km (50- by 100-n.mi.) injection orbit such that the earth impact point could be controlled. This potential disposal management technique is developed as shown in Figures 12 and 13. Figure 12 is the normal flight profile injecting the Orbiter at perigee [92.6 km (50 n.mi.)] with a relative velocity of 7885 m/sec (25 869 ft/sec) and with a 90-deg path angle. The Orbiter is circularized after coasting to the 185-km (100-n.mi.) apogee with the orbit maneuvering system (OMS). A rotation of the transfer orbit allowing Orbiter insertion after perigee would result in a slightly higher injection altitude with a lower velocity and a path angle slightly less than 90 deg as compared to the basic transfer orbit. The 185-km (100-n.mi.) circular orbit would still be obtained by the OMS burn at apogee. The drop tanks would be separated after injection, but before apogee, and their impact point would be controlled to within an acceptable circular error probability (CEP). More detailed analysis of this tank disposal technique is required to verify that the impact can be adequately predicted if destruction does not occur during reentry. This method would result in approximately a 454-kg (1000-lb) payload penalty and is illustrated in Figure 13.

The cost to develop the 100-percent external LH_2 tanks has been estimated to be \$96 million. The total Space Shuttle development and test program costs which include the first five Orbiters and five Boosters would be reduced by \$640 million through use of the 100-percent LH_2 drop tanks. The costs that were included for fabrication of the tanks were taken directly from the results of the stage and one-half task study. This is an average cost of \$134/kg (\$61/lb) and is probably excessive for the simpler, less load-carrying LH_2 tank considered in this analysis. The total operational cost increase for the addition of the drop tanks for a 10-year flight mission model of 445 flights is \$209 million. Thus a total 10-year program savings of \$430 million could be realized for the drop tank Shuttle vehicle defined here. The cost models used were from CER as defined by Aerospace Corporation.

The remainder of the study was devoted to a delta-wing Orbiter configuration, which is inherently more sensitive to inert weight changes than the fixed-wing Orbiter. The results of this phase of the study will be defined and discussed in the following paragraphs.

The change to JP-4 airbreathing fuel instead of LH_2 for both the Orbiter and Booster jet engines has also been included. Figures 14 and 15 show the configuration which was used as the basis for comparison. The comparison is made in Table 5; the first column gives the base-line vehicle weight and size data for a 11 340-kg (25 000-lb) payload in the 4.57- by 18.29-m (15- by 60-ft) cargo bay and delivered into the 55-deg, 500-km (270-n.mi.) reference orbit. The second column depicts comparative data with the delta Orbiter designed with 100 percent LH_2 drop tanks. This comparison shows a GLOW reduction from the basic two-stage vehicle for some payload of approximately 680 388 kg (1 500 000 lb) when LH_2 drop tanks are utilized with the delta Orbiter, both stages with JP-4 fuel for the airbreathing engines. Cost comparison shows a total program cost saving of \$941 million with an RD&TE cost reduction of \$1.4 billion. This basic vehicle, because of required changes including the JP-4 fuel for the airbreathing engines, has grown; thus, the staging velocity optimizes at a lower value when compared with earlier configurations sized with LH_2 airbreathing propulsion engines. Because of the higher velocity requirements for the Orbiter, it has a more efficient mass fraction; therefore, the advantages of this more efficient Orbiter are realized. As the amount of LH_2 in the Orbiter increases, the drop tank design will become more attractive, resulting in greater savings in both GLOW and costs. The Booster staging velocity [2286 m/sec (7500 ft/sec)] at which the external LH_2 tank Orbiter configuration optimizes is 912 m/sec (3000 ft/sec) lower than the present vehicle configuration. This allows extensive use of heat sink materials with the Booster, in lieu of the complicated thermal protection systems now being designed. The amount of heat sink materials that can be used at this staging velocity is approximately 80 percent of the Booster exterior surface area. Lower staging velocities would result in lower GLOW, with still greater amounts of heat sink material used for the Booster; but the increased size of the Orbiter results in the loss of cost benefits realized with the initial staging velocity of 2286 m/sec (7500 ft/sec).

Figure 16 shows the relative sensitivities of the Shuttle vehicle concepts and two of the Saturn derivative vehicles. The primary point made here is that the Orbiter gets smaller with 100-percent LH_2 drop tanks, and, therefore, the sensitivity fraction decreases (i.e., ratio of change in payload to a change in inert weight).

An investigation of putting all Orbiter ascent fuels, LOX and LH_2, in external drop tanks has also been made; but since the internal fuel tanks are also load-carrying structures, an approximate 3628-kg (8000-lb) payload penalty would result when compared to the configuration having only LH_2, (100 percent) external.

CONCLUSIONS

This analysis has emphasized internal consistency in comparing vehicle configurations and characteristics. The use of LH_2 external tanks on the Orbiter offers a feasible and attractive low-cost configuration. The program cost saving, approaching $1 billion, is directly proportional to the decrease in total vehicle GLOW [approximately 680 388 kg (1 500 000 lb)]. The early year peak funding would be impacted significantly with the $1.5-billion RD&TE cost reduction that can be obtained using the LH_2 drop tanks.

The advantages, in addition to lower development, refurbishment, and maintenance costs, are as follow: elimination of a large percentage of Booster thermal protection systems; less sensitivity to design variations with greater mission flexibility; elimination of internal Orbiter purge systems for LH_2 tanks; and provision for additional LOX, providing for vehicle growth at minimum weight penalty. An additional point that should be noted is that in an abort situation, LH_2 dump would be simplified.

TABLE 4. VEHICLE COMPARISON DATA WITH DROP TANKS ON THE ORBITER

	Percent LH_2 in Drop Tanks (Orbiter Only)				
	0	25	50	75	100
GLOW, kg (lb)	1 635 654 (3 606 000)	1 498 669 (3 304 000)	1 414 301 (3 118 000)	1 338 551 (2 951 000)	1 270 059 (2 800 000)
Booster Length, m (ft)	61.6 (202)	59.7 (196)	58.5 (192)	57.6 (189)	56.4 (185)
Booster Propellant Weight, kg (lb)	1 030 108 (2 271 000)	942 111 (2 077 000)	884 959 (1 951 000)	838 239 (1 848 000)	789 251 (1 740 000)
Booster Dry Weight, kg (lb)	213 642 (471 000)	205 931 (454 000)	194 137 (428 000)	183 251 (404 000)	178 261 (393 000)
Orbiter Length, m (ft)	50 (164)	45.7 (150)	42.4 (139)	38.7 (127)	34.4 (113)
Orbiter Propellant Weight,[a] kg (lb)	237 682 (524 000)	200 034 (441 000)	185 519 (409 000)	172 365 (380 000)	156 036 (344 000)
Orbiter Dry Weight,[a] kg (lb)	91 626 (202 000)	82 100 (181 000)	75 750 (167 000)	69 400 (153 000)	62 596 (138 000)
Drop Tank Size, m (ft)	0	2.43 by 14.3 (8 by 47)	3 by 18 (10 by 59)	4.27 by 17.7 (12 by 58)	4.27 by 17.7 (14 by 58)
Drop Tank Propellant Weight, kg (lb)	0	7415 (16 348)	14 258 (31 434)	20 706 (45 648)	26 036 (57 400)
Drop Tank Dry Weight, kg (lb)	0	2191 (4831)	3743 (8251)	5319 (11 727)	6572 (14 489)

a. Does not include drop tank weights.

TABLE 5. COMPARISON OF BASE LINE WITH CONFIGURATION WITH DROP TANKS ON ORBITER (HIGH CROSS-RANGE)

	Base-Line Booster and Orbiter	Base-Line Booster/ Drop Tank Orbiter
GLOW, kg (lb)	2 102 401 (4 635 000)	1 428 816 (3 150 000)
Orbiter		
Length, m (ft)	58.5 (192)	40.8 (134)
Gross Weight, kg (lb)	405 965 (895 000)	382 832 (844 000)
Propellant Weight, kg (lb)	268 980 (593 000)	272 609 (601 000)
Inert Orbiter Weight, kg (lb)	114 759 (253 000)	83 461 (184 000)
Inert Drop Tank Weight, kg (lb)		9525 (21 000)
Payload Weight, kg (lb)	11 346 (25 015)	11 382 (25 092)
Booster		
Length, m (ft)	68.6 (225)	58.2 (191)
Gross Weight, kg (lb)	1 696 435 (3 740 000)	1 045 984 (2 306 000)
Propellant Weight, kg (lb)	1 341 726 (2 958 000)	823 270 (1 815 000)
Inert Weight, kg (lb)	259 454 (572 000)	175 540 (837 000)
Number of Engines	15	10
Flyback Range, km (mi.)	503 (375)	428 (266)
Flyback Propellant Weight, kg (lb)	77 564 (171 000)	36 287 (80 000)
Staging Velocity, m/sec (ft/sec)	2967 (9733)	2308 (7571)

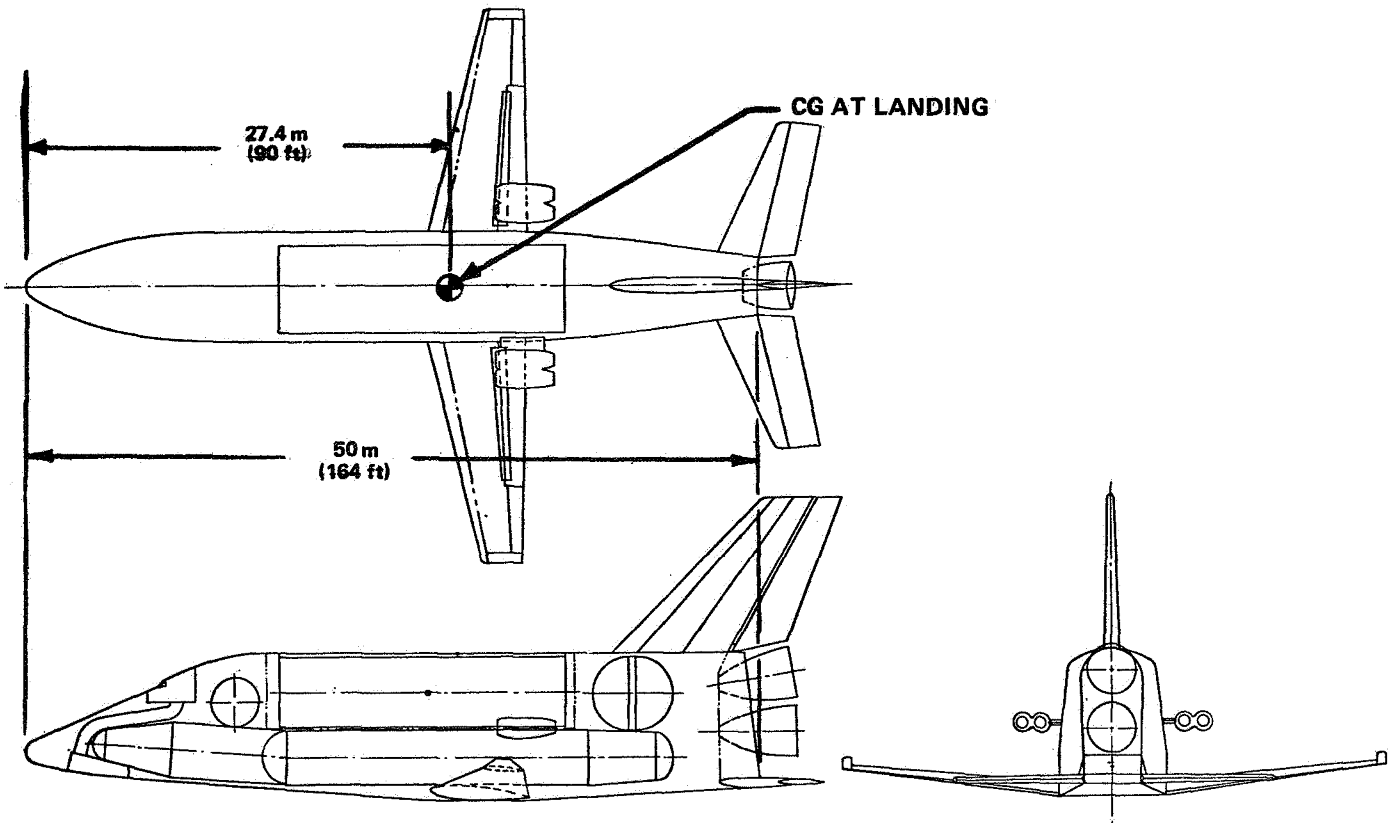


Figure 1. Low cross-range Orbiter configuration (base line).

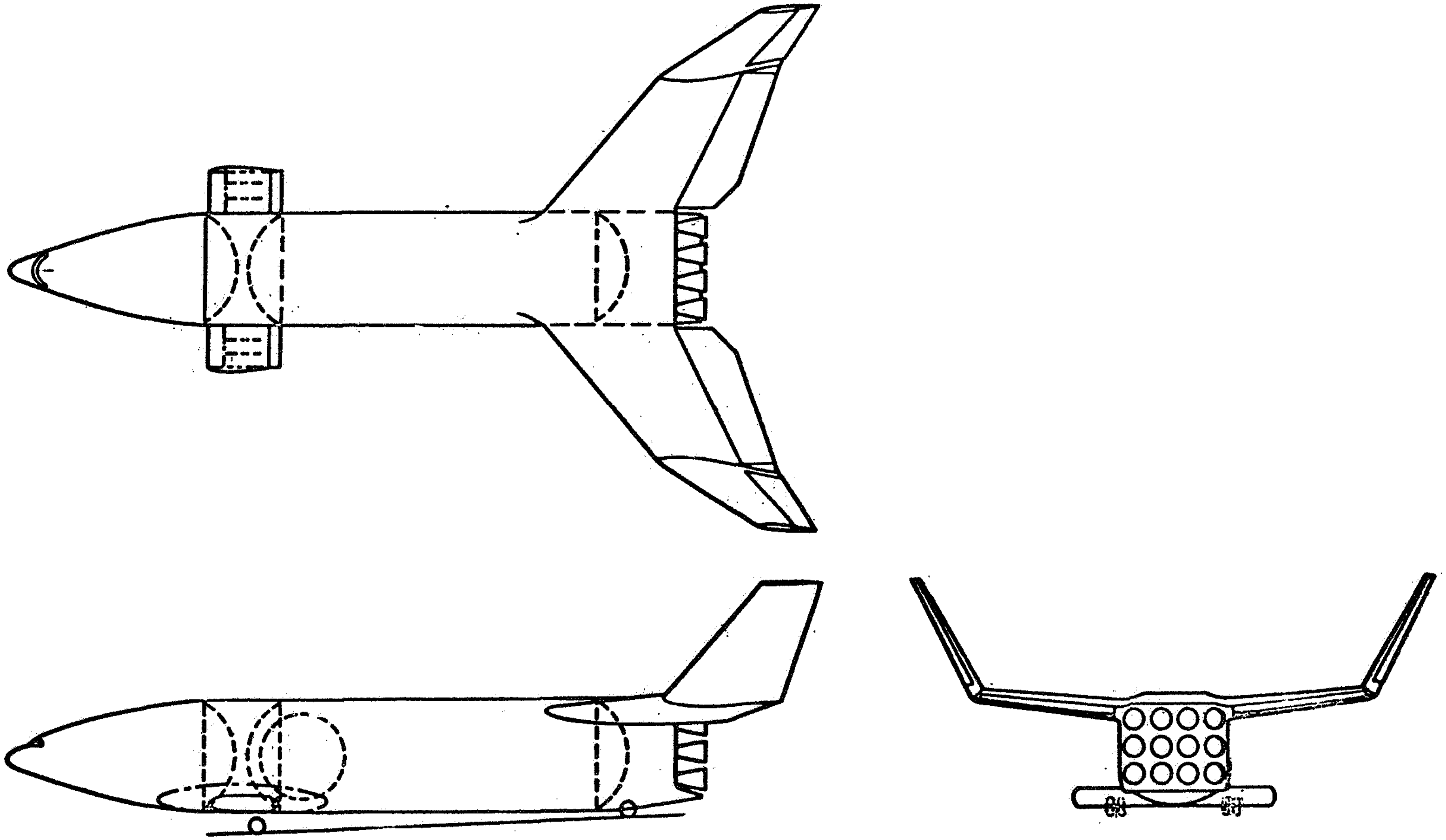
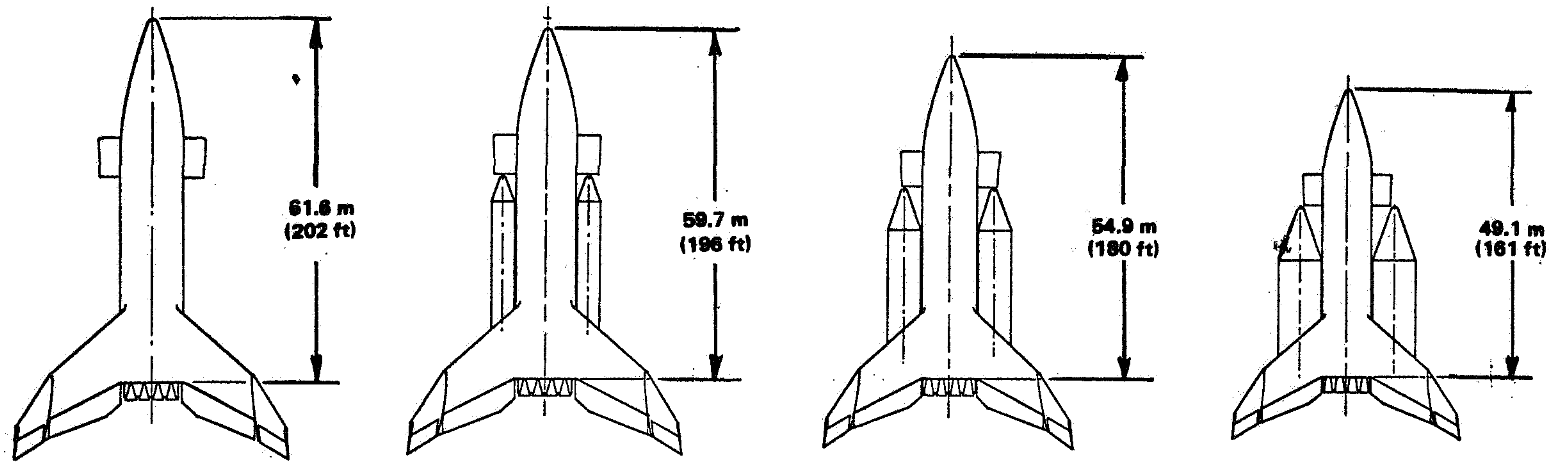


Figure 2. Single-body canard Booster (base line).



	BASE-LINE	25% LH_2 IN DROP TANKS	50% LH_2 IN DROP TANKS	75% LH_2 IN DROP TANKS
W_p =	1 133 074 kg ((2 498 000 lb)	1 133 074 kg (2 498 000 lb)	1 133 074 kg (2 498 000 lb)	1 133 074 kg (2 498 000 lb)
W_{dry} =	229 888 kg (506 817 lb)	220 025 kg (485 071 lb)	207 144 kg (456 674 lb)	193 074 kg (425 656 lb)
W_{dt} =	0	10 501 kg (23 150 lb)	18 711 kg (41 250 lb)	27 669 kg (61 000 lb)
DROP TANK — DIA x LENGTH	0 x 0	3.96 x 26.5 m (13 x 87 ft)	5.79 x 27.1 m (19 x 89 ft)	7.31 x 27.4 m (24 x 90 ft)

Figure 3. Single-body canard Booster with drop tank configurations.

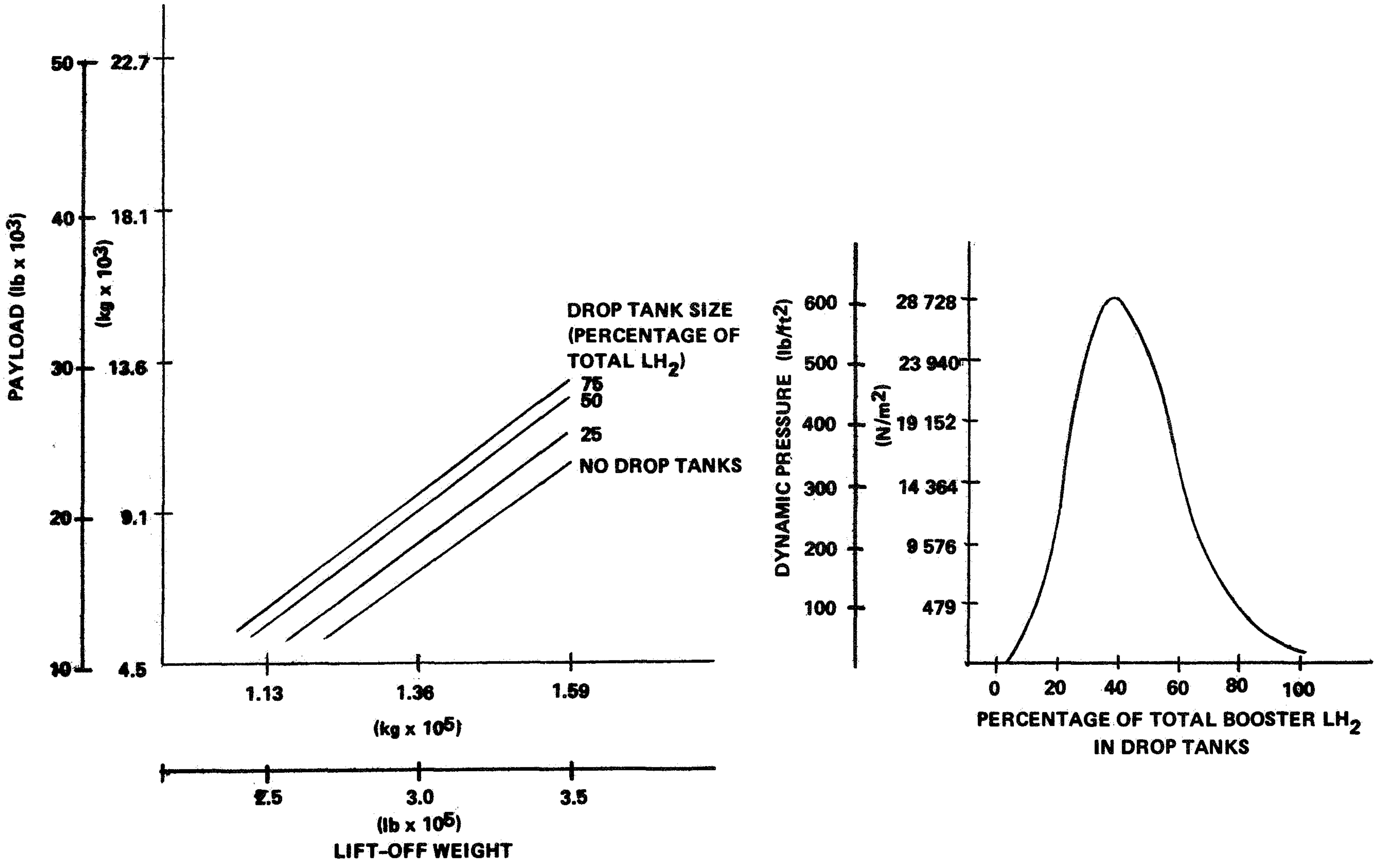


Figure 4. Booster drop tank analysis.

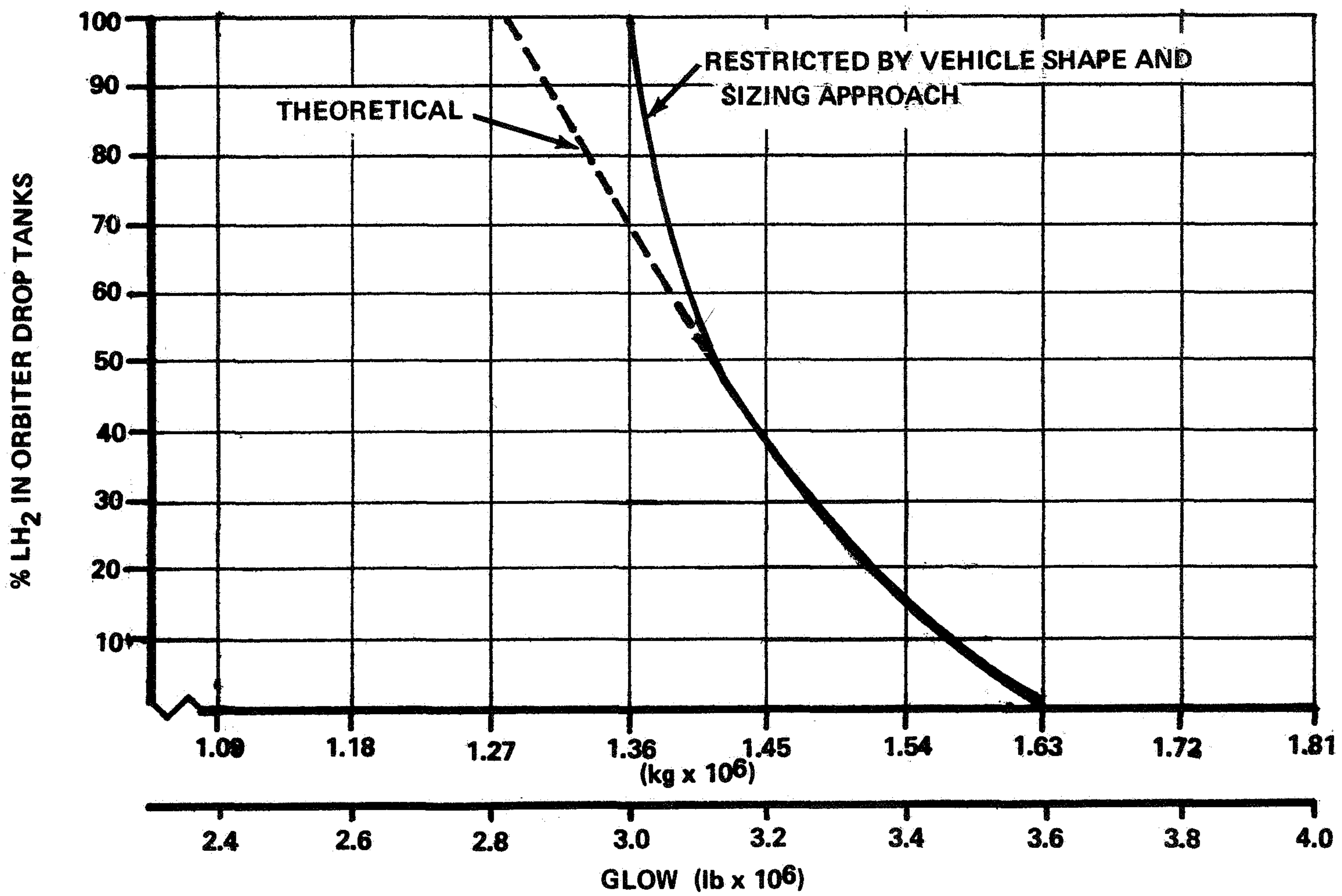


Figure 5. GLOW versus percent LH_2 in drop tanks for a fixed-wing 11 340-kg payload Orbiter.

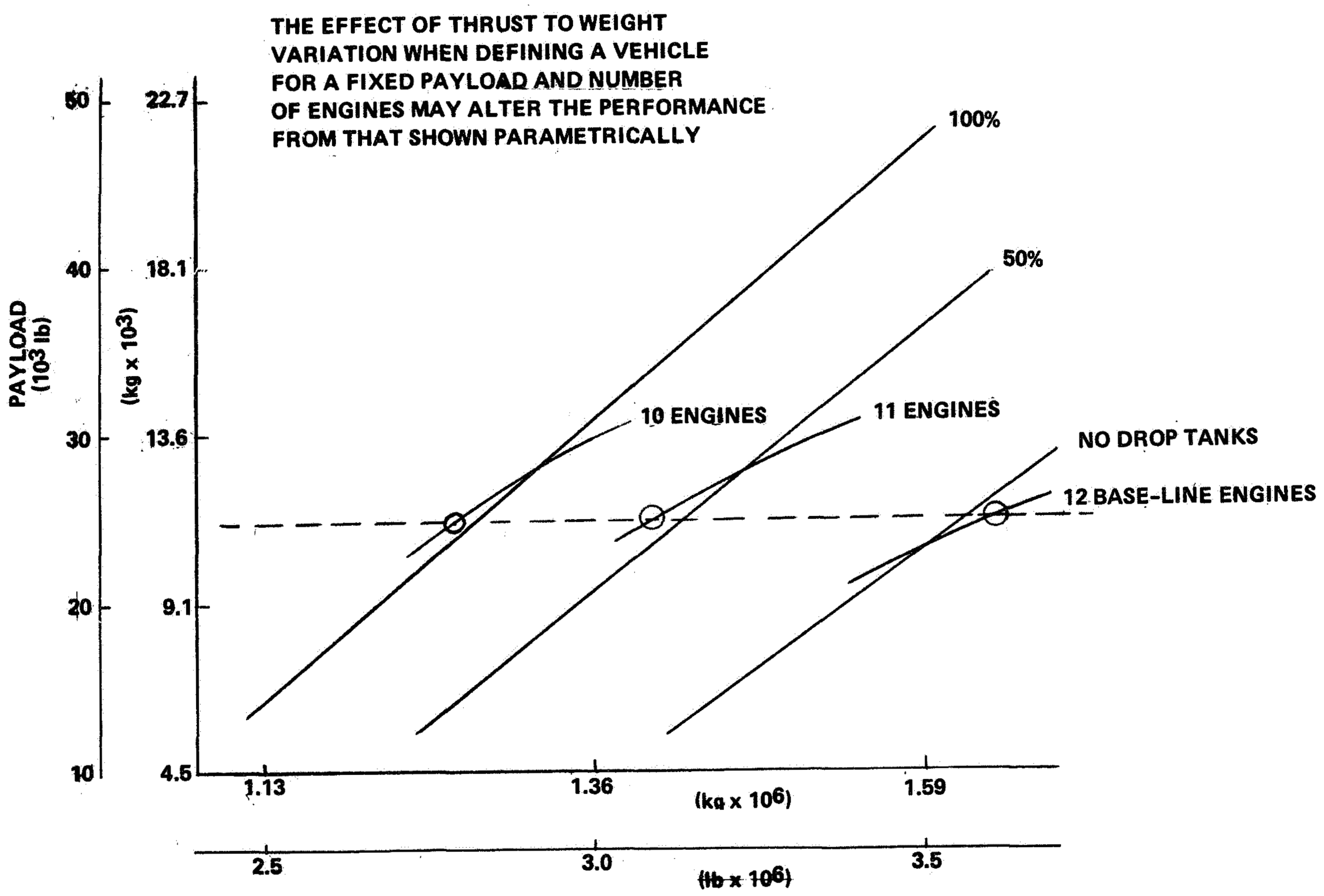
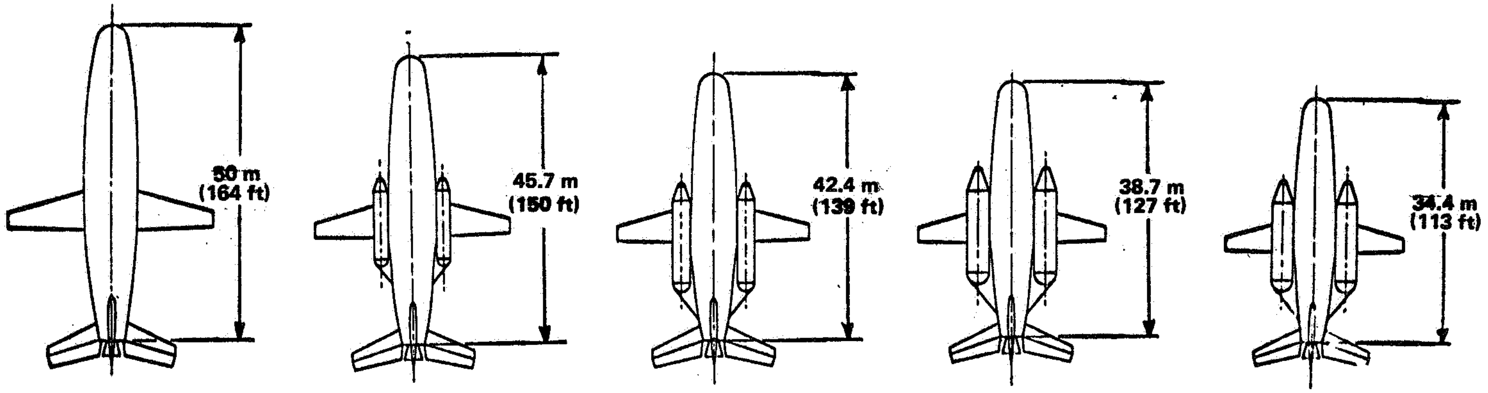


Figure 6. Vehicle performance with drop tanks on Orbiter.



	BASE-LINE	25% LH_2 IN DROP TANKS	50% LH_2 IN DROP TANKS	75% LH_2 IN DROP TANKS	100% LH_2 IN DROP TANKS
W_p	– 237 682 kg (524 000 lb)	207 745 kg (458 000 lb)	199 581 kg (440 000 lb)	193 230 kg (426 000 lb)	181 890 kg (401 000 lb)
W_{dry}	– 91 626 kg (202 000 lb)	82 100 kg (181 000 lb)	75 750 kg (167 000 lb)	69 400 kg (153 000 lb)	62 596 kg (138 000 lb)
W_{dt}	– 0	2191 kg (4831 lb)	3743 kg (8251 lb)	5 356 kg (11 807 lb)	6 572 kg (14 489 lb)
Tank Size		2.43 x 14.3 m (8 x 47 ft)	3m x 18m (10 x 59 ft)	3.66m x 19.2m (12 x 63 ft)	4.27m x 17.7m (14 x 58 ft) 4.27 x 20.7 m (14 x 68 ft)

Figure 7. Orbiter size comparisons (theoretical) at 11 340-kg payload.

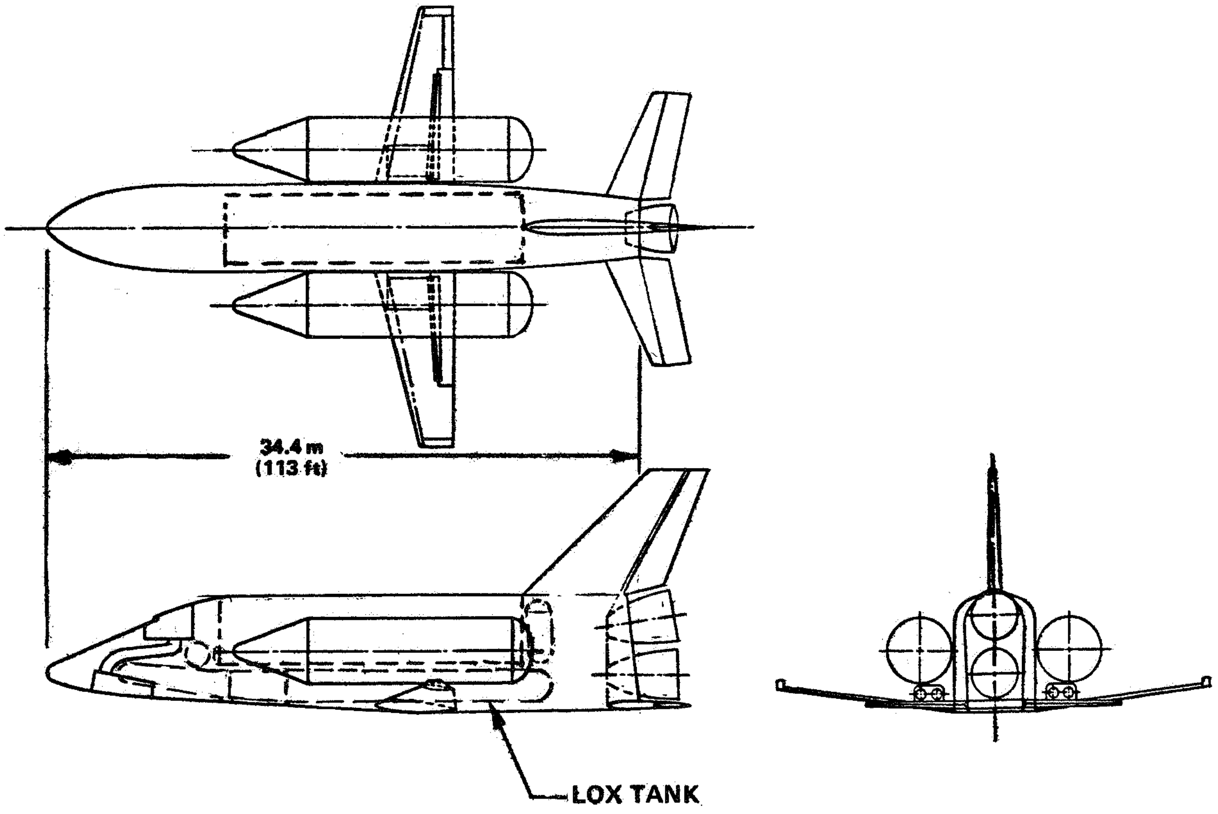


Figure 8. Low cross-range Orbiter configuration with 100 percent LH_2 in drop tanks.

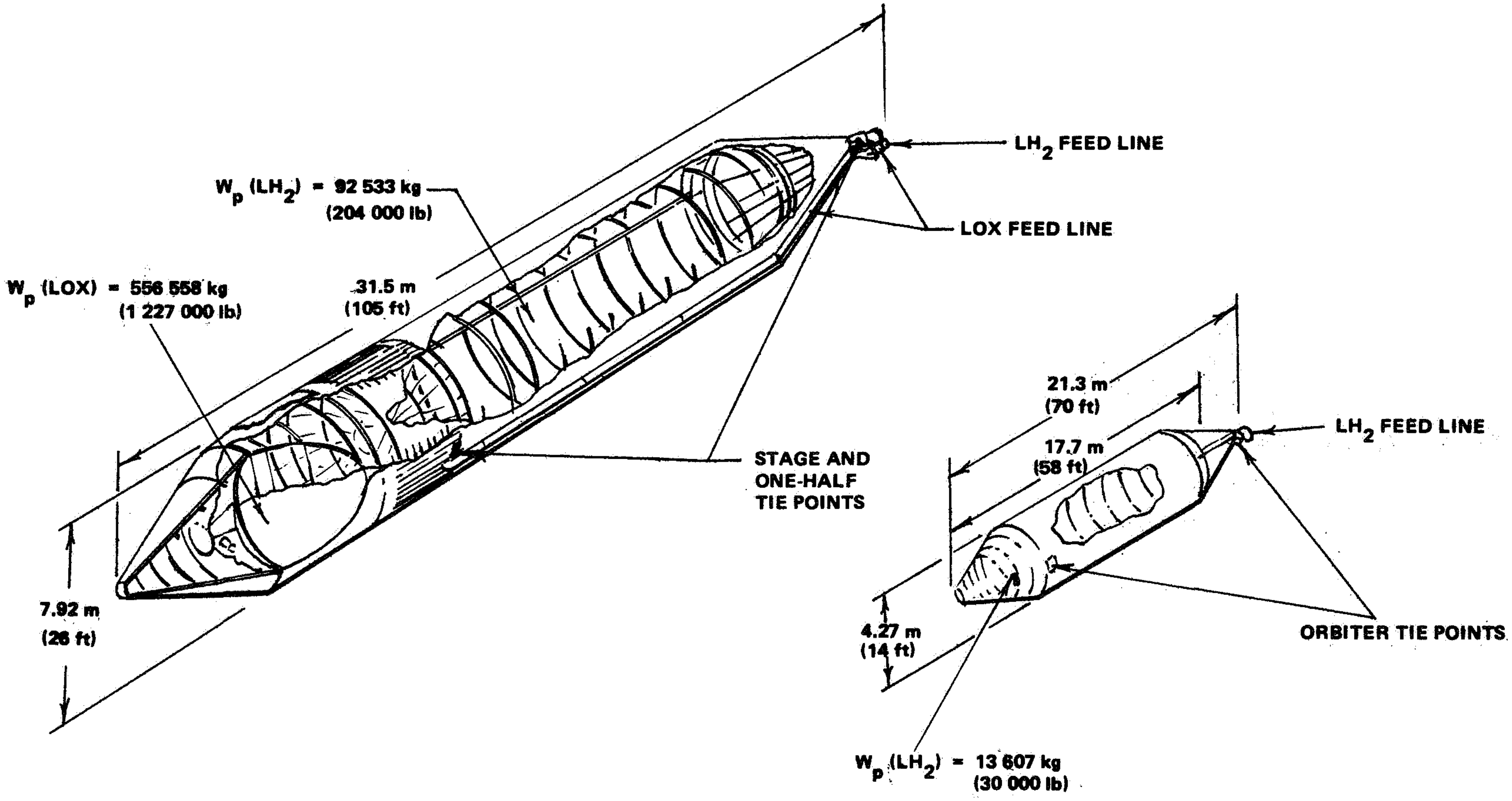


Figure 9. Comparison of the LH$_2$ drop tanks with stage and one-half drop tanks.

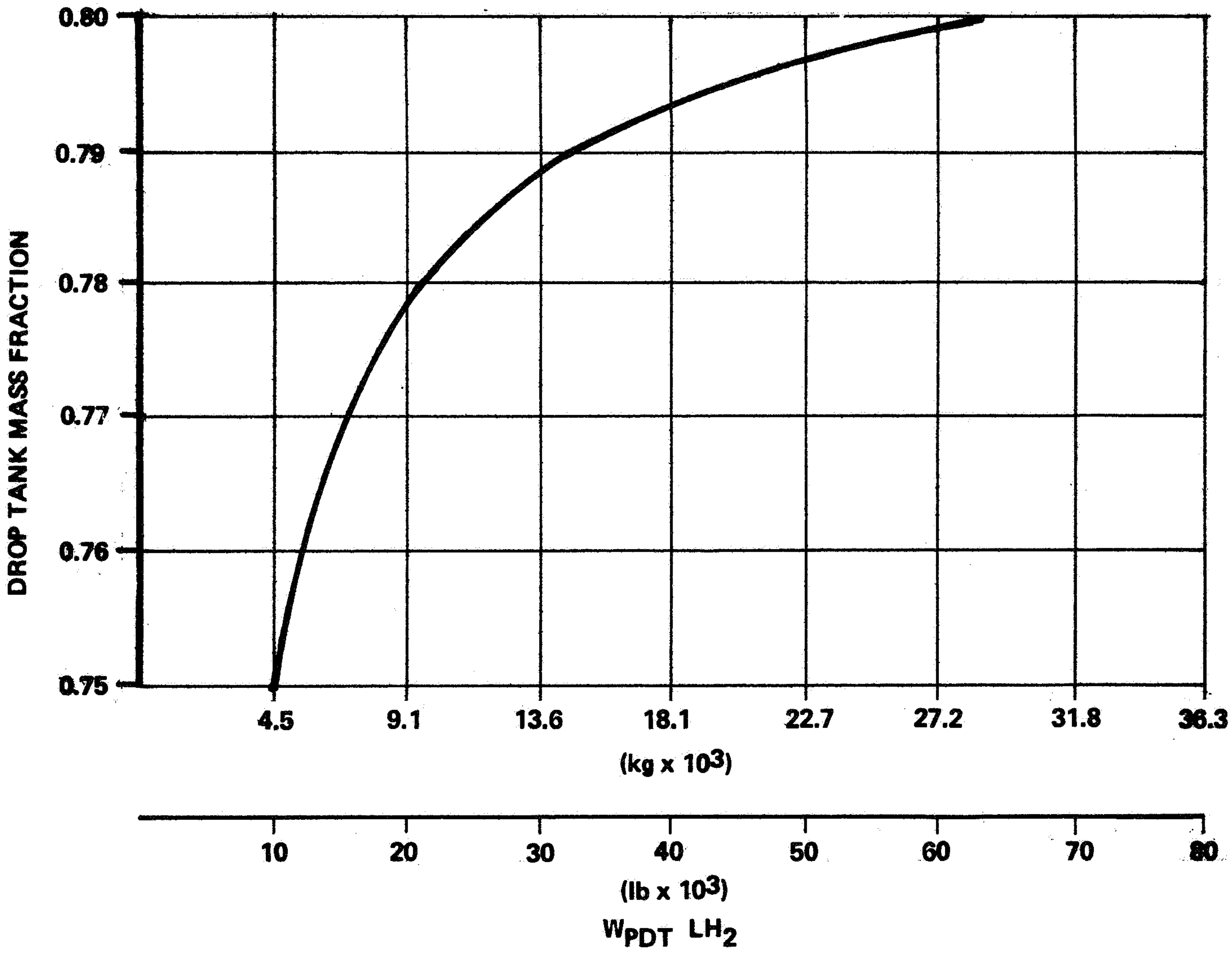


Figure 10. Orbiter drop tank mass fraction versus propellant weight.

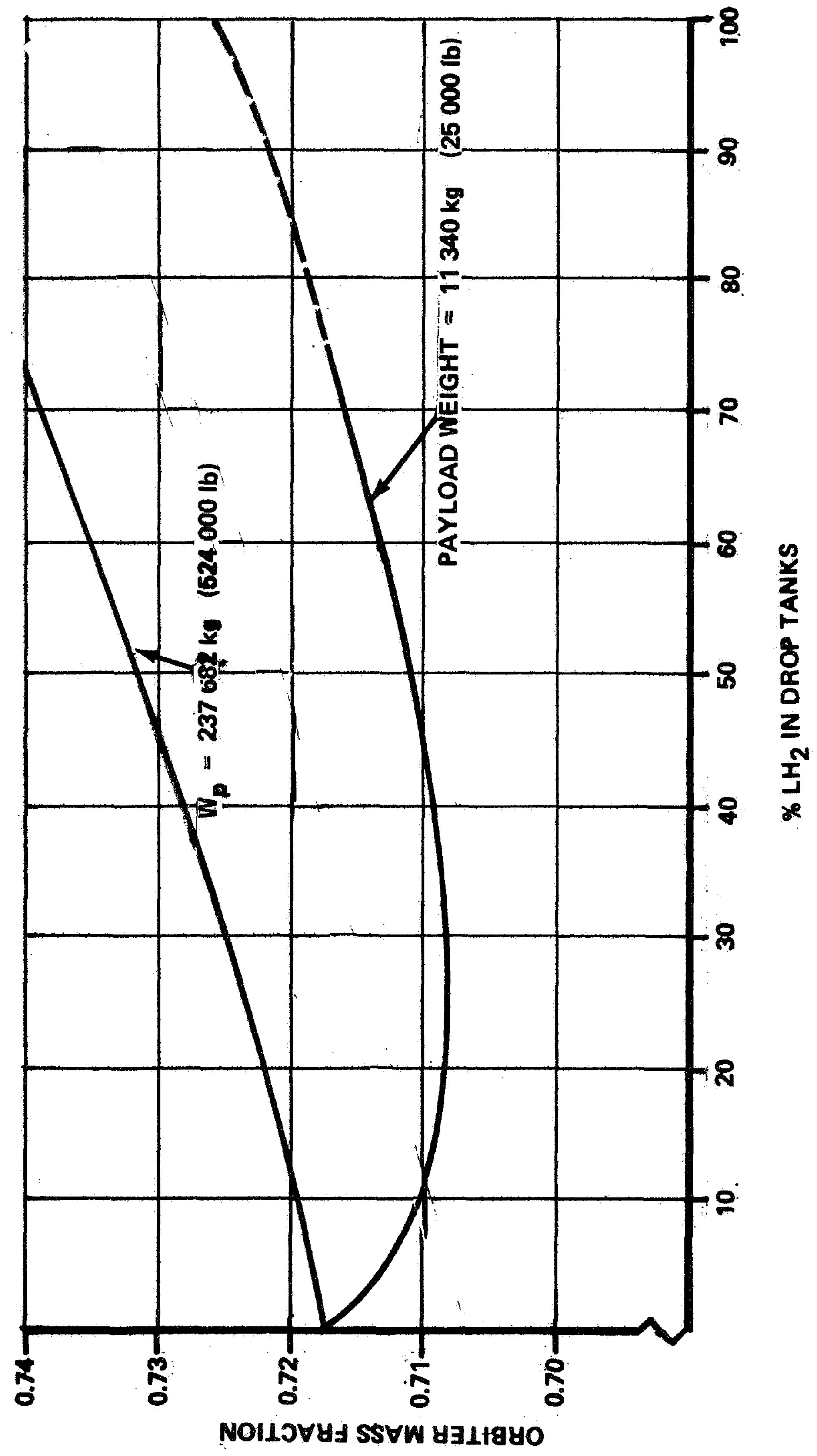


Figure 11. Orbiter mass fraction versus percent LH_2 in drop tanks.

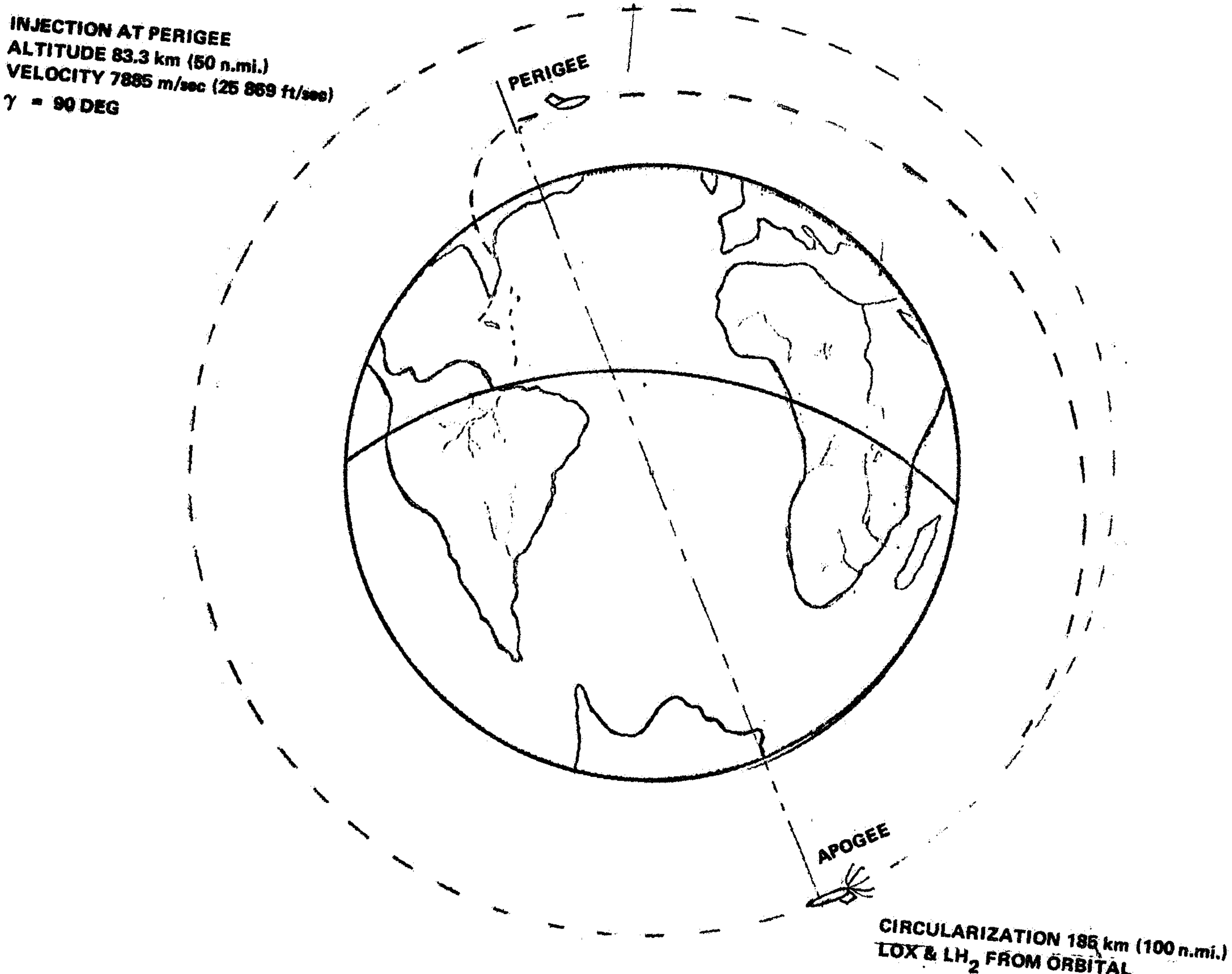


Figure 12. Nominal flight profile.

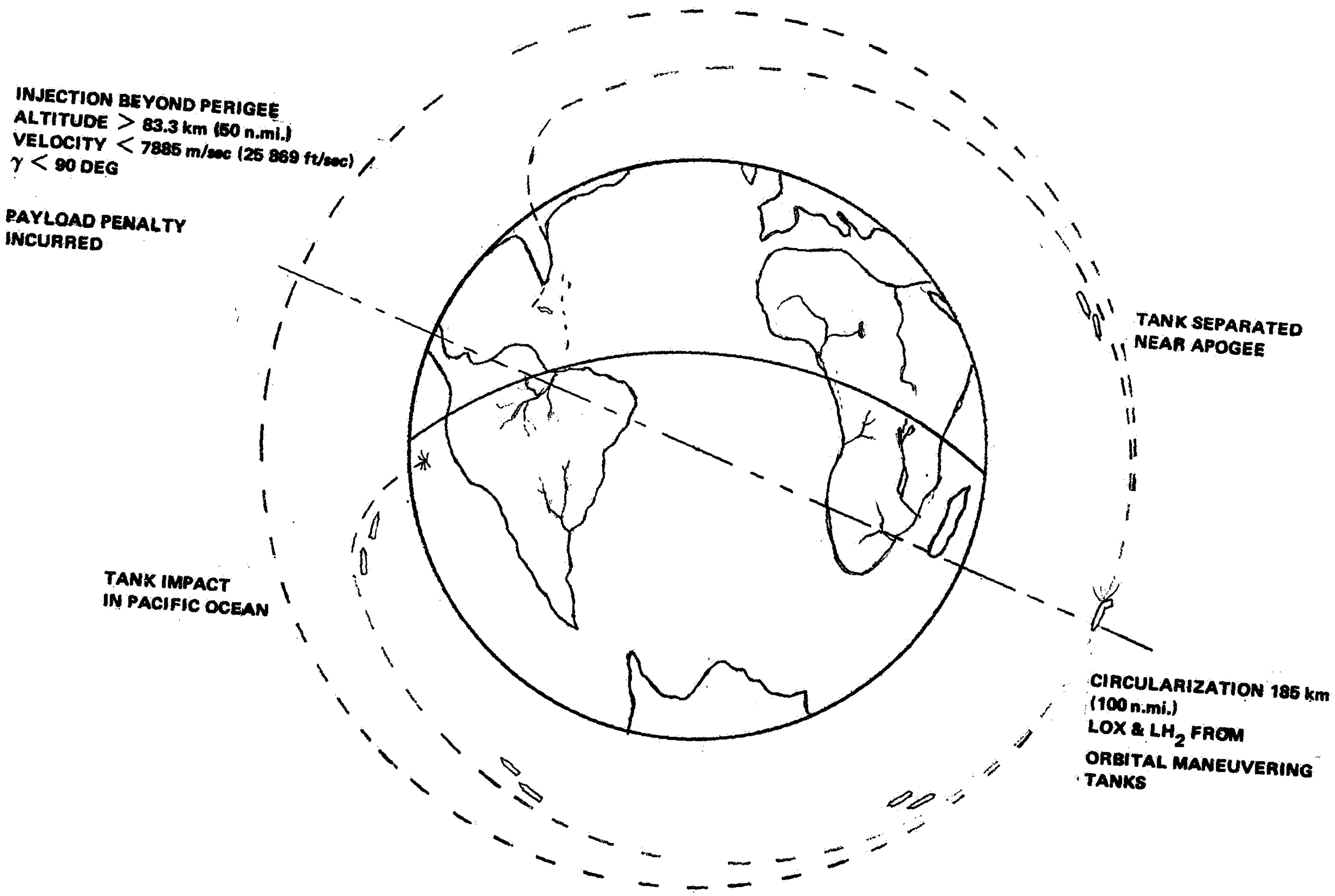


Figure 13. Alternate flight profile and tank impact.

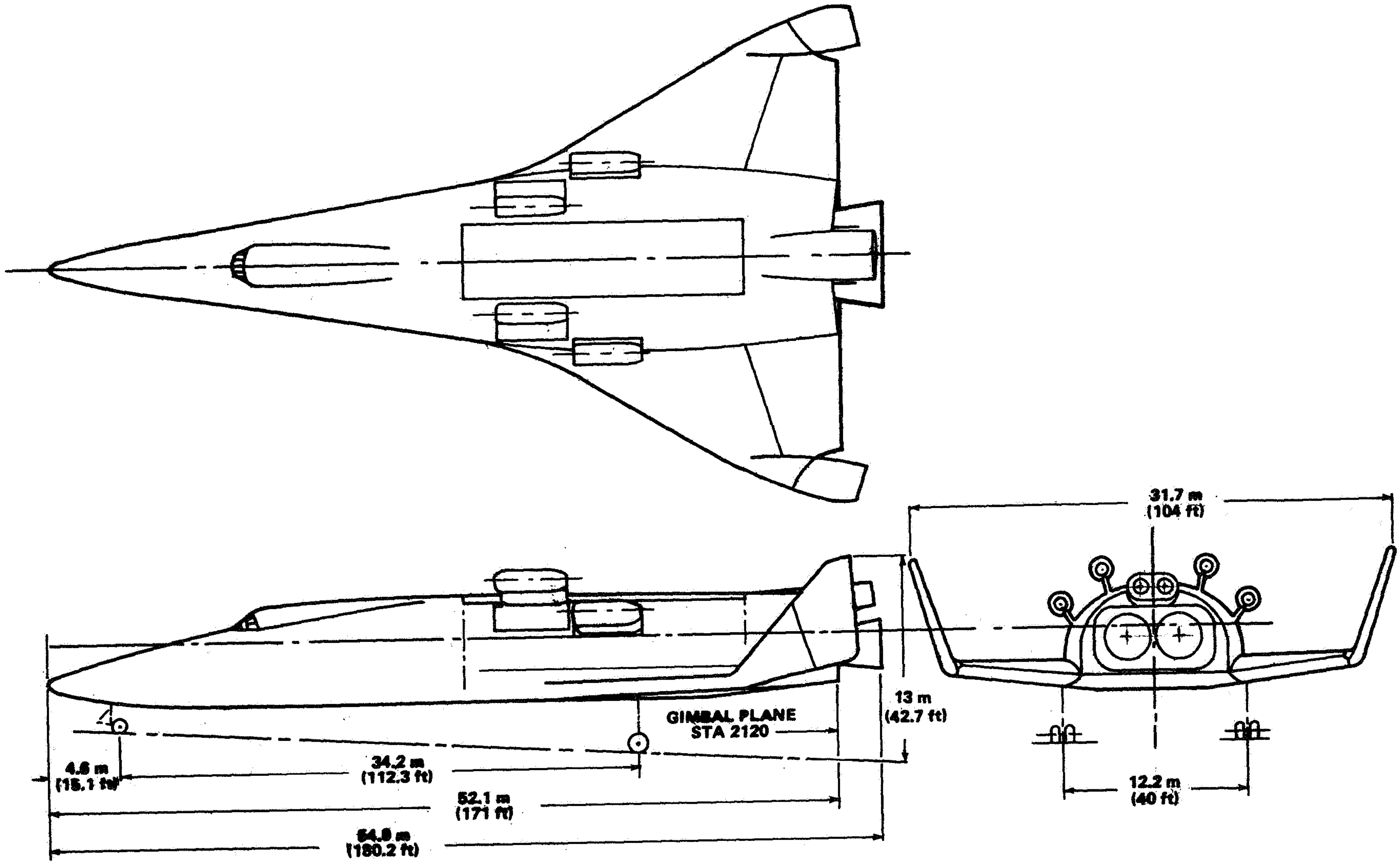


Figure 14. High cross-range Orbiter configuration (base line).

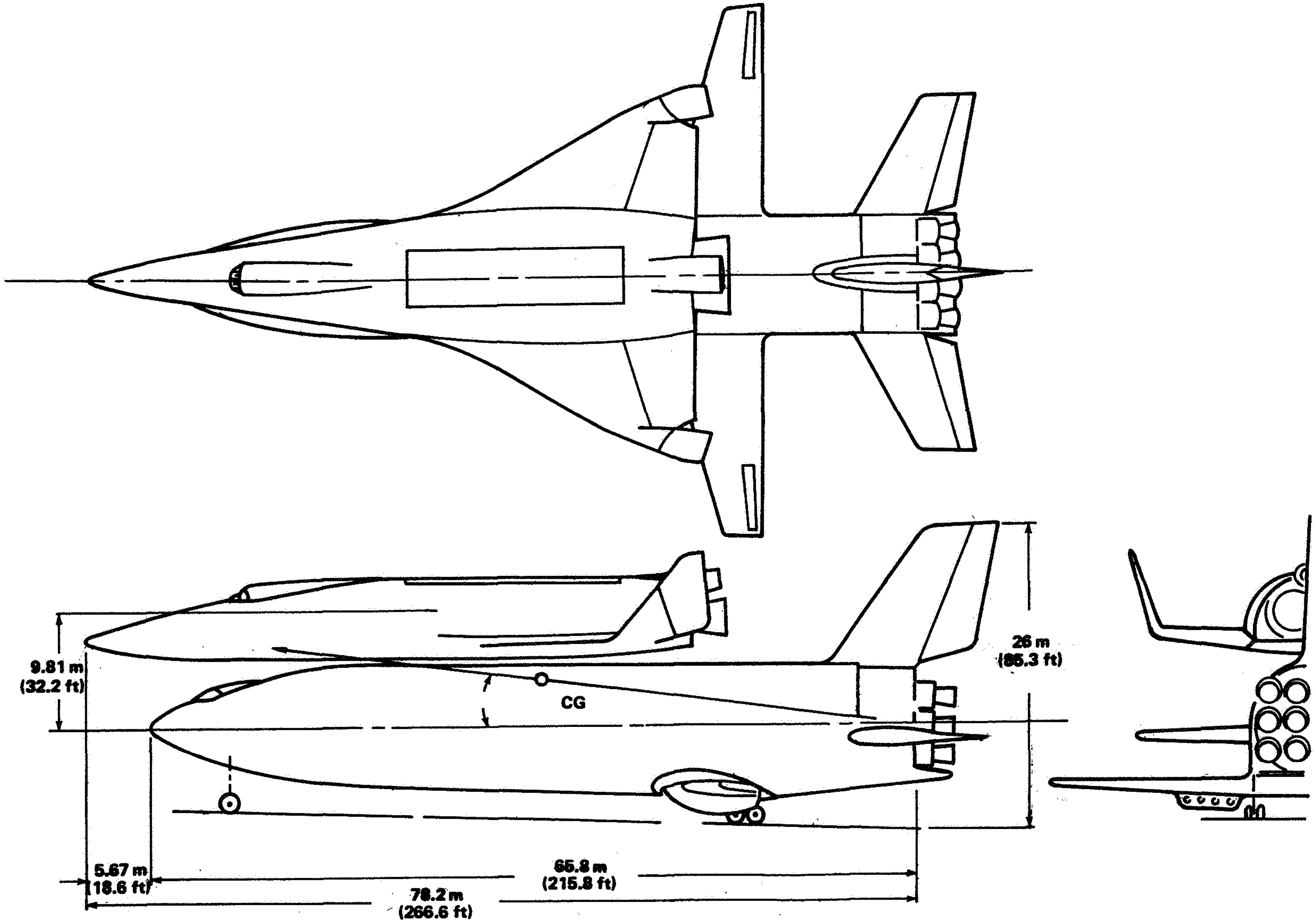


Figure 15. High cross-range Orbiter with Booster.

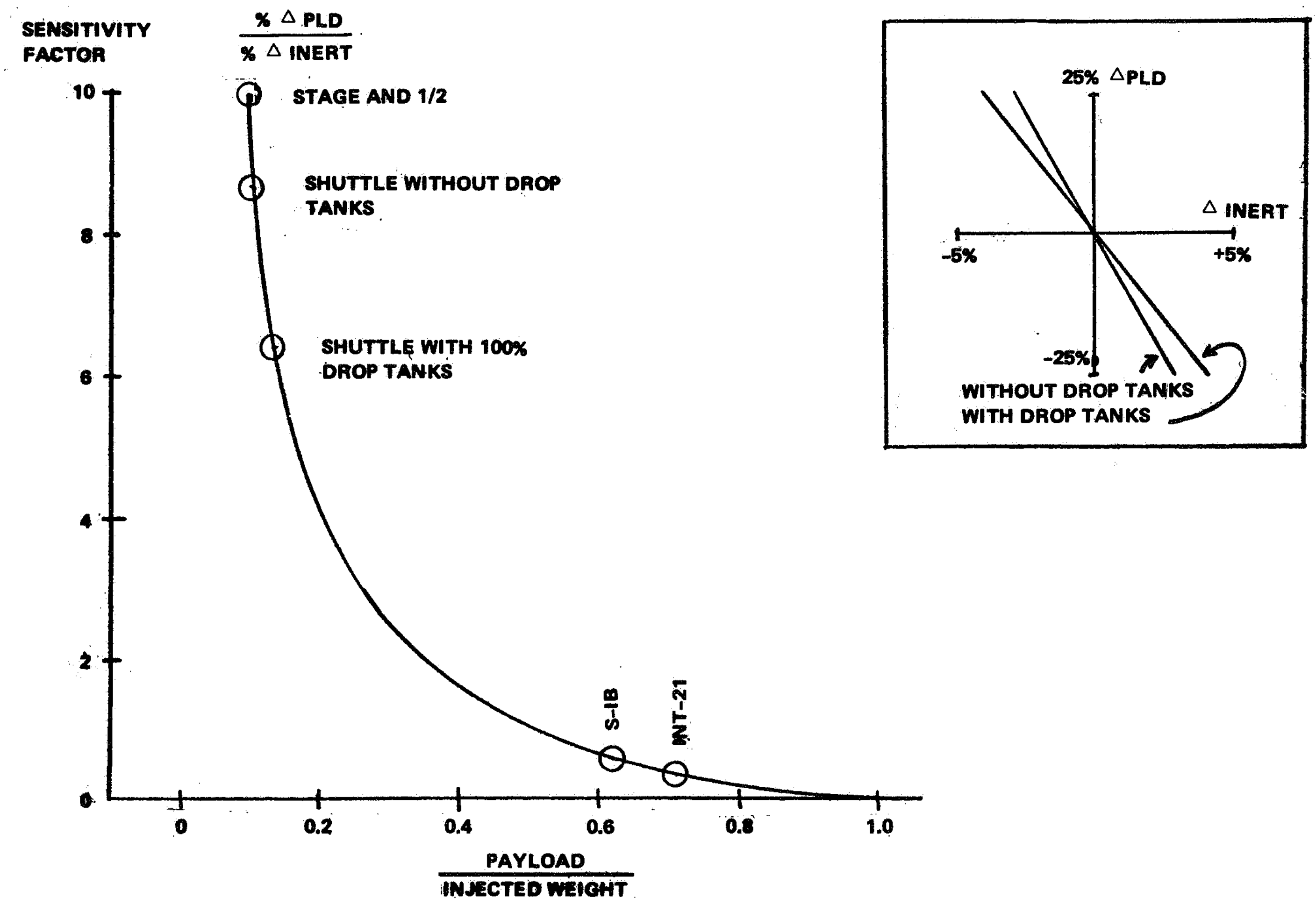


Figure 16. Fully-reusable Shuttle vehicle sensitivity.

APPROVAL

NASA TM X-64579

SPACE SHUTTLE WITH EXTERNAL HYDROGEN DROP TANKS

By Herman E. Thomason

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This document has also been reviewed and approved for technical accuracy.

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