

VEHICLE PERFORMANCE IMPACT ON SPACE SHUTTLE  
DESIGN AND CONCEPT EVALUATION

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INTRODUCTION

The continuing examination of widely varied space shuttle concepts makes an understanding of concept interaction with vehicle performance imperative. The estimation of vehicle performance is highly appurtenant to all aspects of shuttle design and hence performance has classically been a key indicator of overall concept desirability and potential. In this paper vehicle performance assumes the added role of defining interactions between specific design characteristics, the sum total of which define a specific concept. Special attention is given to external tank effects.

## ... SPACE SHUTTLE CONCEPT EVOLUTIONARY PROCESS

(Figure 1)

The evolution of a space shuttle vehicle is by nature an iterative process. Each element driving the concept synthesis is highly dependent upon each other element. For convenience we may classify the principal synthesis drivers in three categories: cost, deployment, and design and performance. Of these three, we at this meeting are concerning ourselves with design and performance. It is appropriate, therefore, to subdivide the broad category design and performance into working groups which encompass specific engineering disciplines. To this end consider the groupings, which shall be designated shaping and protection, propulsion, and mission considerations.

Shaping and protection considerations subsume those aspects of the vehicle which must be introduced to protect the payload and to allow the vehicle to perform its mission potential in an acceptable fashion. Shaping and protection would include the vehicle's body, aerodynamic surfaces, and thermal protection.

Propulsion considerations are introduced by the requirement that the payload be physically transferred from one state to another. Thus all vehicle components necessary to produce a thrust acceleration are termed propulsive.

Mission considerations are those components of the vehicle system responsible for the successful completion of the prescribed system goal. Included, therefore, are the avionics and control systems. Man, as pilot, is essential to completion of the total mission so he, too, must be included.

The iterative nature of the shuttle evolutionary process is most visibly manifest in the interaction between the design and performance groupings listed above. This paper will identify, explain, and subsequently investigate the primary channels of these interactions.

# SPACE SHUTTLE CONCEPT EVOLUTIONARY PROCESS

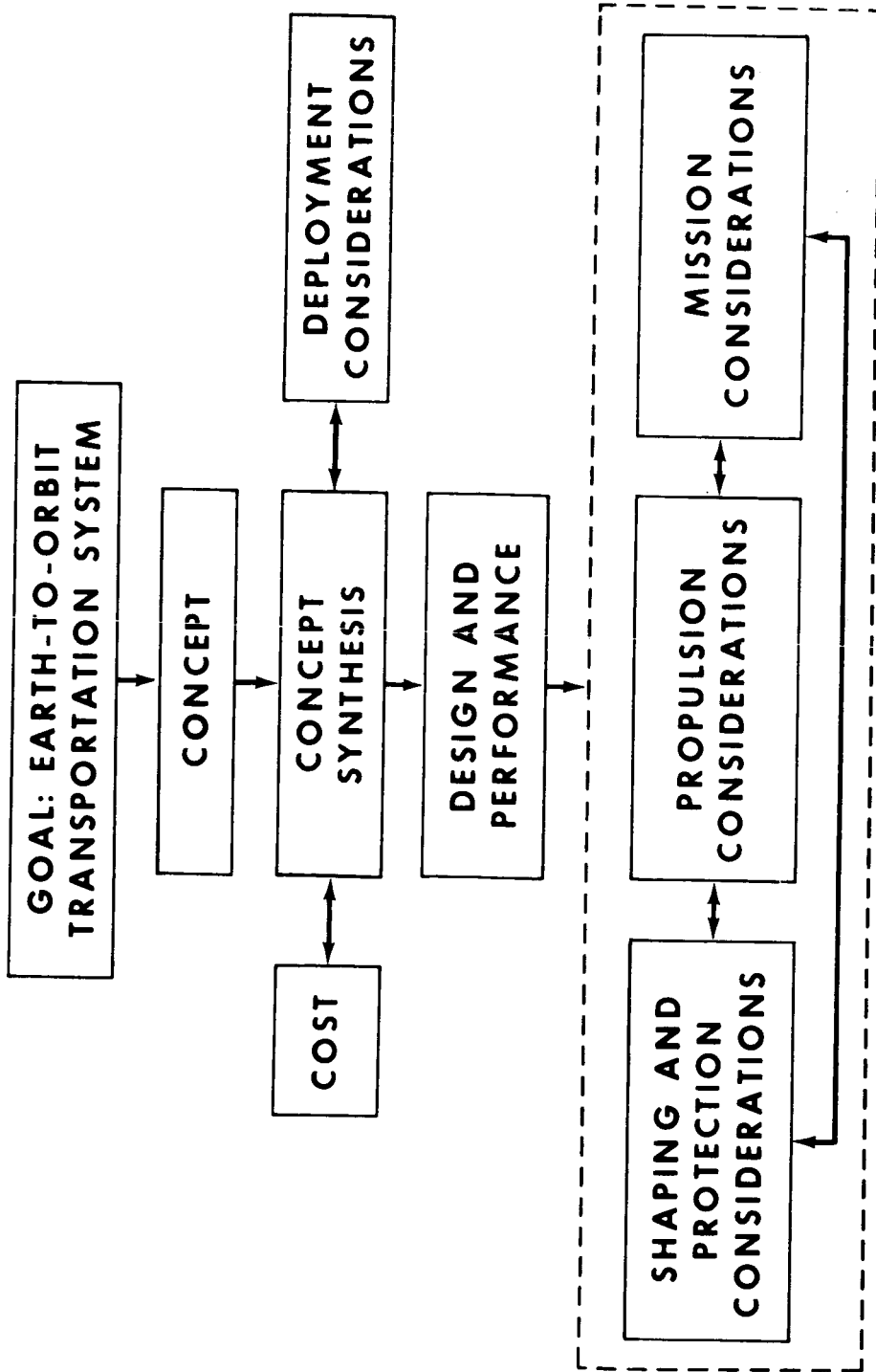


Figure 1

## DESIGN AND PERFORMANCE PENALTY COMPONENTS

(Figure 2)

The logical abstraction of figure 1 can be formulated in an analytic sense by expressing dependencies in terms of physical parameters, the most obvious of which is weight. The relative magnitudes of the shaping and protection, the propulsion, and the mission penalties, for a typical vehicle, are given in figure 2. As is to be anticipated, the propulsion penalty is far greater than either of the other two, its predominance attributable to the large quantity of propellants. The impact of vehicle performance on design, then, will be concerned primarily with the variation of propellant loading with mission requirements and the resultant efficiency with which the propellants are contained.

# DESIGN AND PERFORMANCE PENALTY COMPONENTS

PENALTY	SHAPING AND PROTECTION	PROPLUSION	MISSION
PENALTY COMPONENTS	BODY STRUCTURE WING TAIL TPS LANDING GEAR	MAIN ENGINES PROPELLANT SYSTEMS TANKS PROPELLANTS THRUST STRUCTURE ATTITUDE CONTROL SYSTEM ON-ORBIT PROPULSION	POWER SOURCE HYDRAULIC SYSTEM ENGINE GIMBAL AVIONICS ENVIRONMENTAL SYSTEM SURFACE CONTROLS PERSONNEL PROVISIONS ELECTRICAL SYSTEM PERSONNEL
PERCENT OF GROSS ORBITER WEIGHT (EXCLUDING PAYLOAD)	15	83	2

Figure 2

## SIZING DEPENDENCE ON STRUCTURE FACTOR

(Figure 3)

A parameter essential to an understanding of the impact of vehicle performance on sizing is the stage structure factor,  $\sigma$ . The structure factor is defined as the stage gross weight,  $W_o$ , minus the propellant weight,  $W_p$ , minus the payload,  $W_{PLD}$ , divided by the gross weight minus the payload. The structure factor, then, is that fraction of the stage weight which is not usable propellant, and as such, it represents a propellant packaging efficiency. A high structure factor indicates that a particular vehicle is an inefficient propellant container.

Figure 3 indicates the degree to which stage gross weight is dependent on structure factor and stage characteristic velocity. A propulsion specific impulse of 459 seconds was assumed. At low characteristic velocities the difference between vehicle gross weights with different structure factors is small. As characteristic velocity increases, however, vehicles with higher structure factors begin to experience exponential growth in gross weight. Vehicles with lower structure factors approach exponential gross weight growth as the characteristic velocity continues to increase. The net effect of structure factor, then, is to determine the vehicle performance region in which gains in performance are offset by unacceptable gains in vehicle gross weight.

# SIZING DEPENDENCE ON STRUCTURE FACTOR

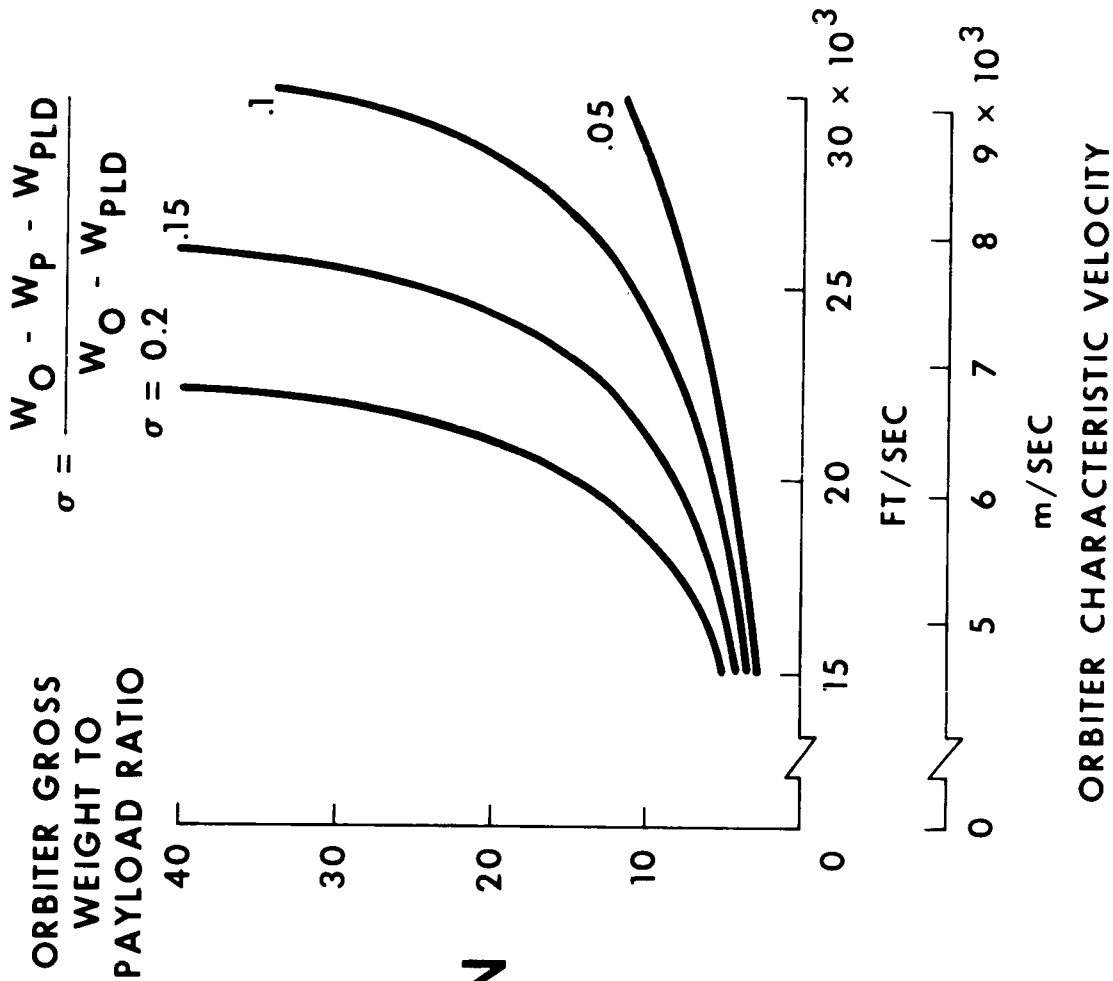


Figure 3

## CONCEPT IMPACT ON VEHICLE DESIGN AND PERFORMANCE

(Figure 4)

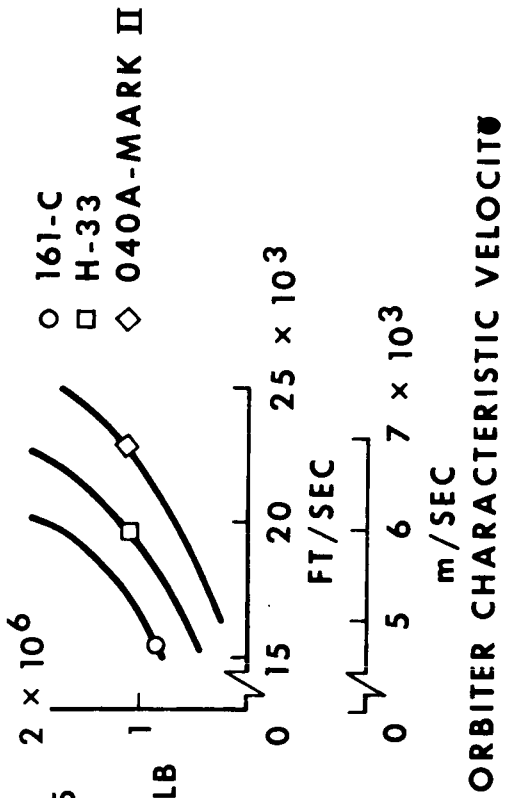
The implications of stage structural factor can be illustrated in no better way than by examining the impact of three current orbiter concepts on system performance. The three concepts to be considered are internal propellant tanks, internal oxygen tank and external hydrogen tank (EHT), and external oxygen-hydrogen tanks (EOHT). Examples of these vehicles are the NR 161-C, the GAEC H-33, and the NASA O4OA Mark II, respectively. All three vehicles are fueled by LOX-LH<sub>2</sub>, have high chamber pressure engines, and have a 40,000 pound (18,144 kg) payload capability to polar orbit. The size of the payload bay in each is 15 x 60 ft (4.9 x 19.7 m).

External tanks diminish the structural factor by isolating those penalties to the vehicle structure which accrue from propellant storage. As a consequence of this penalty partitioning, weight savings are generated on two primary levels. Initially, because at least a major portion of the propellant volume is external, the physical size, and thus weight, of the core vehicle can be greatly reduced, as is readily apparent from figure 4. This initial reduction in size, coupled with the fact that the external tanks are jettisoned at orbit injection, prompts yet another weight savings. Once the vehicle jettisons its external tanks, the weight at which it performs certain mission sequences is much less than the weight of its internal tank counterpart. Thus mission sequence dependent weights, such as landing systems and on-orbit propulsion systems, are reduced.

Reduction of aggregate vehicle weight prompts an improvement in performance. Examination of the gross weight-characteristic velocity capabilities of the internal tank and external tank orbiters reveals that a 50% increase in performance from the internal tank to the EOHT vehicle has been achieved with a 30% increase in gross weight.

The internal tank vehicle having been shown to possess a relatively poor structural factor, with little outlook for improvement, a detailed study of the performance-design characteristics of external tank vehicles follows.





**CONCEPT IMPACT  
ON VEHICLE DESIGN  
AND PERFORMANCE**

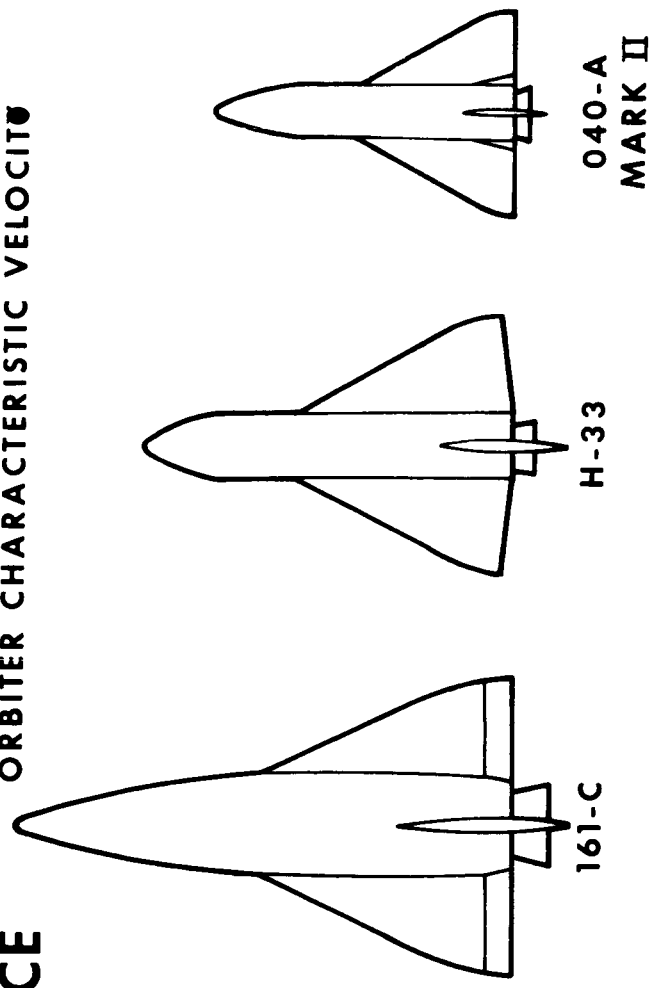


Figure 4

## STUDY VEHICLE CHARACTERISTICS

(Figure 5)

In a study of the interactions of vehicle performance with system concept and design, a commonality of certain concept characteristics is desirable to assure consistent interpretation of the results.

Allow this study to be premised, then, with the following primary assertions:

- (1) orbiter propellant is liquid oxygen (LOX) and liquid hydrogen (LH<sub>2</sub>);
- (2) the orbiter has three high chamber pressure engines of variable thrust level, the specific impulses of which are 459 seconds;
- (3) the vehicle is flown to a polar mission with insertion into a 50 x 100 n.m. (92.5 x 185 km) orbit;
- (4) the orbiter is sized to carry 40,000 lb (18, 144 kg) payload both into orbit and back from orbit.

In addition to these, several secondary assumptions have been made:

- (5) the orbiter has a cryogenic on-orbit propulsion system capable of a 650 ft/sec (198 m/sec) velocity increment;
- (6) 1% flight performance reserve (FPR) propellant has been allotted to the orbiter.

# STUDY VEHICLE CHARACTERISTICS

- LOX-LH<sub>2</sub> PROPELLANT
- 3 HIGH CHAMBER PRESSURE ENGINES
- POLAR MISSION
- 40,000 LB PAYLOAD UP/DOWN

## ORBITER GROSS WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

(Figure 6)

The orbiter lift-off weight (LOW) here experiences the trends which were described previously. The EHT vehicle demonstrates a much higher sensitivity to characteristic velocity than the EOHT vehicle, the sensitivity a consequence of a higher stage structural fraction. One additional effect has been included here, however, and that is the effect of the orbiter vacuum thrust-to-weight ratio,  $T/W$ . As the thrust-to-weight ratio increases the stage structural fraction is made yet greater by the increasing propulsion system weights. Hence, the higher thrust-to-weight ratios are more performance-sensitive than the lower thrust-to-weight ratios for both the EHT and EOHT orbiters.

# ORBITER GROSS WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

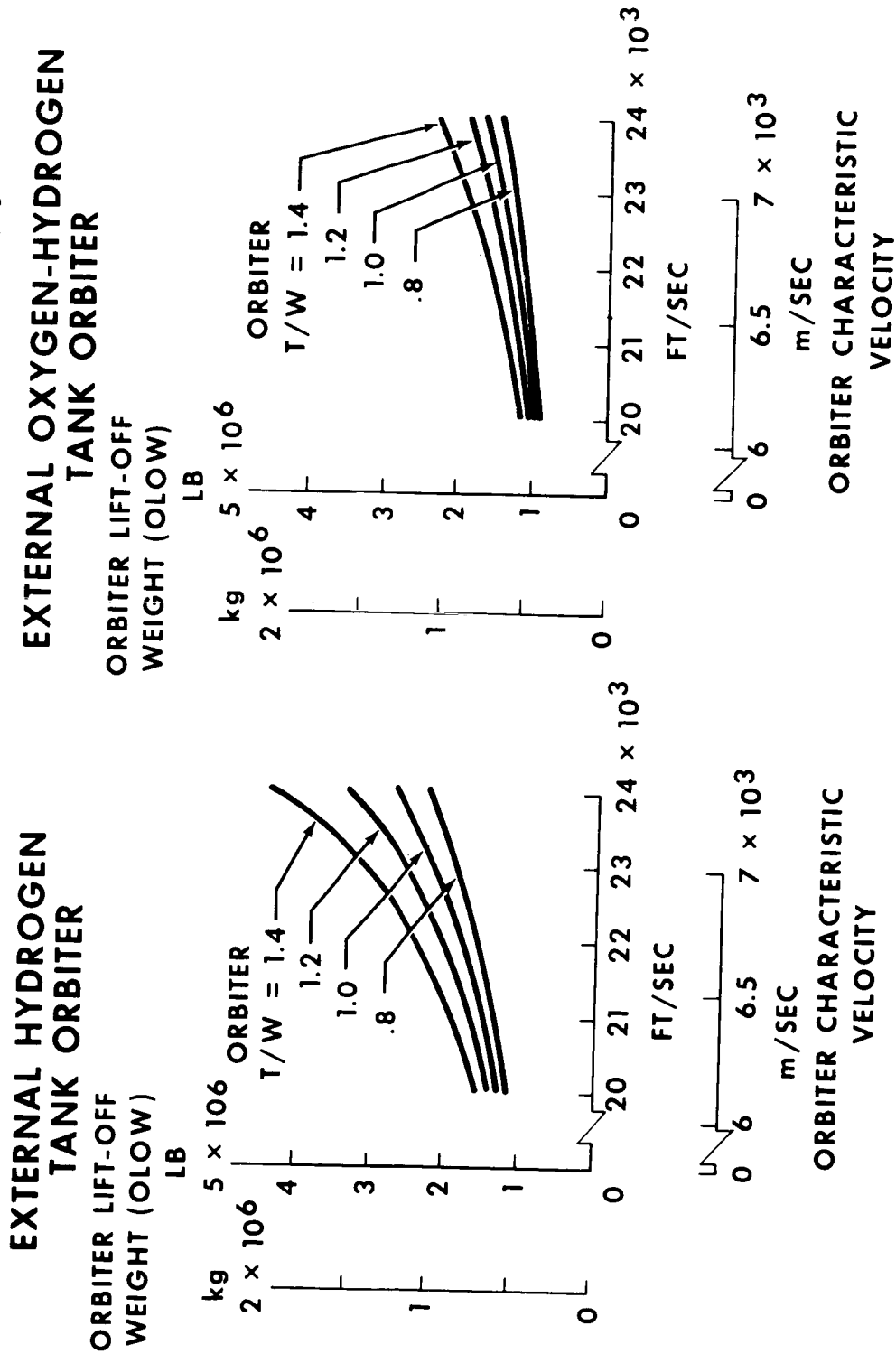


Figure 6

## ORBITTER INERT WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

(Figure 7)

The orbiter core inert weight is the weight of the orbiter exclusive of all expendable propellants and the external tanks. Core inert weight sensitivity to characteristic velocity, then, relates trends in vehicle growth without explicit reference to the external tank growth characteristics. The structural factor of the EOHT vehicle is influenced only by the changing engine thrust level and its corresponding perturbation of propulsion system weights. The structure factor of the EHT vehicle, however, while influenced by the propulsion penalty, must also take into account the penalty associated with the internal oxygen tank. The resultant structure factor for the EHT vehicle is somewhat greater than that of the EOHT vehicle.

# ORBITER INERT WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

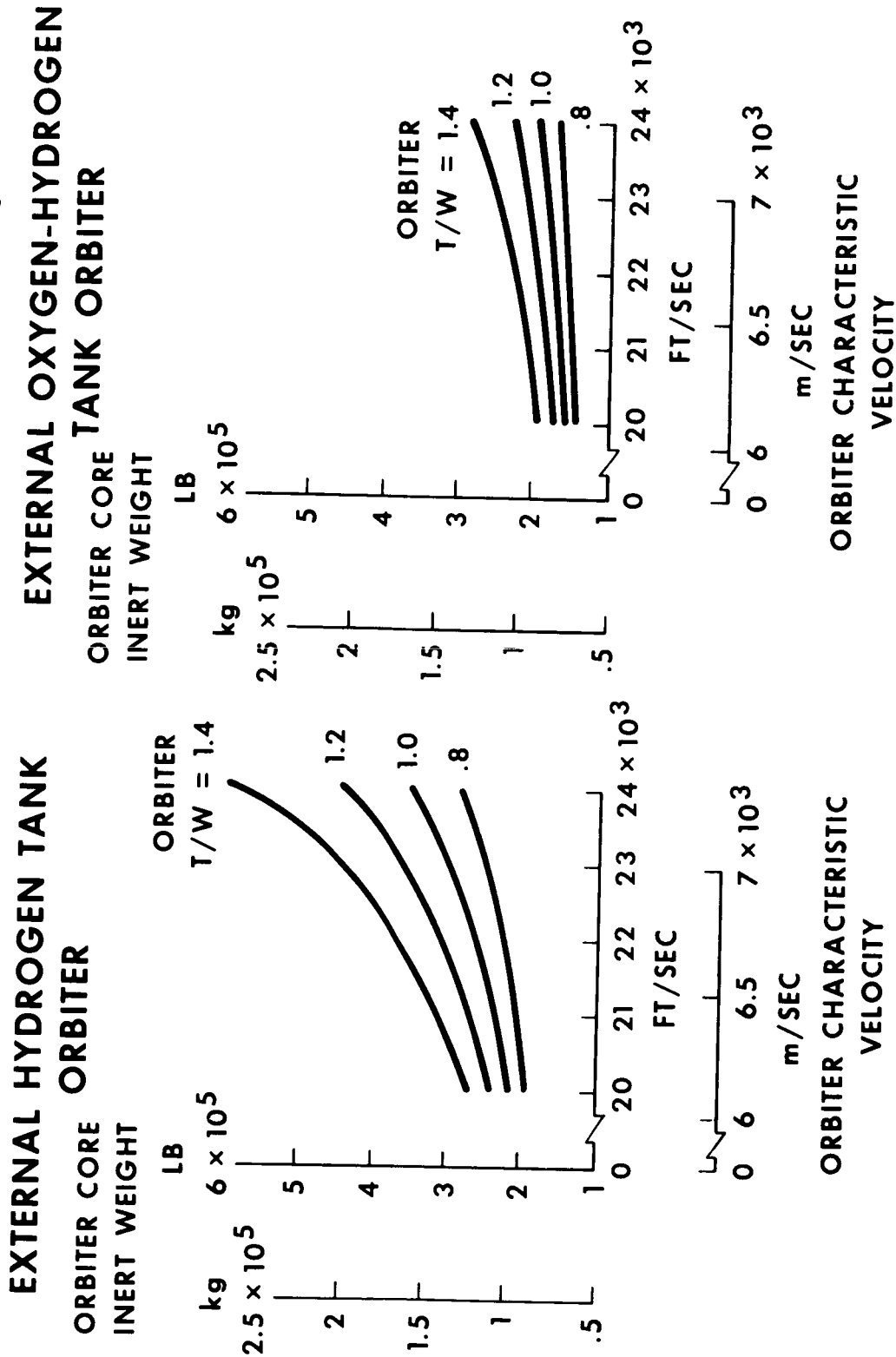


Figure 7

## EXTERNAL TANK DRY WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

(Figure 8)

The small weight differential between the external hydrogen tank and the external oxygen-hydrogen tank is deceiving. For a given characteristic velocity, the ratio of the propellant loading of the EHT vehicle to that of the EOHT vehicle is equal to the ratio of the gross weights (figure 6). For moderate thrust-to-weight ratios, the EHT vehicle has approximately 50% more propellant than the EOHT vehicle. Assuming an oxidizer-to-fuel ratio of 6:1, then, the EHT vehicle's external tank contains only 20% of the propellant, by weight, contained in the EOHT vehicle's external tank. The EHT vehicle's external tank, however, weighs 80% of the EOHT vehicle's tank.

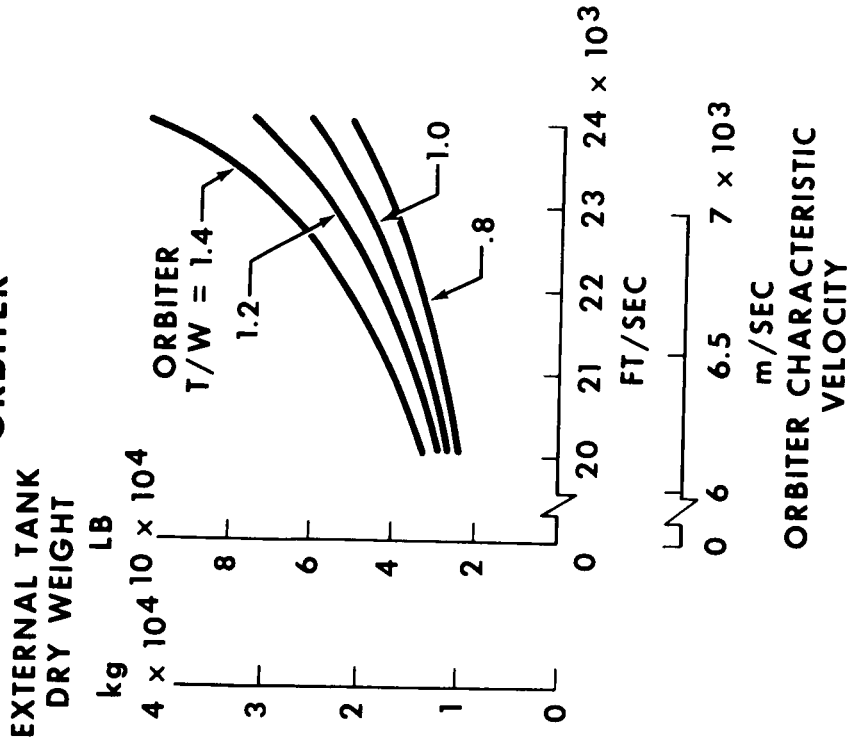
This apparent anomaly is made clear when one recognizes the key role which propellant density, and thus tank volume, play in determining tank weight. Liquid oxygen, with a density 16 times greater than that of liquid hydrogen, can be contained in 1/16 the volume. Thus, while the EHT vehicle's external tank contains only 20% of the EOHT vehicle's propellant by weight, it may contain as much as 90% of the EOHT vehicle's propellant by volume.

At the higher orbiter thrust-to-weight ratios, and hence higher stage structural factors, the EHT vehicle propellant loadings are so much greater than the EOHT vehicle propellant loadings that the volume penalty for the storage of  $LH_2$  becomes so prohibitive that the external oxygen-hydrogen tank is actually lighter than the corresponding external hydrogen tank.



# EXTERNAL TANK DRY WEIGHT DEPENDENCE ON VELOCITY CAPABILITY

EXTERNAL HYDROGEN TANK  
ORBITER



EXTERNAL OXYGEN-HYDROGEN  
TANK ORBITER

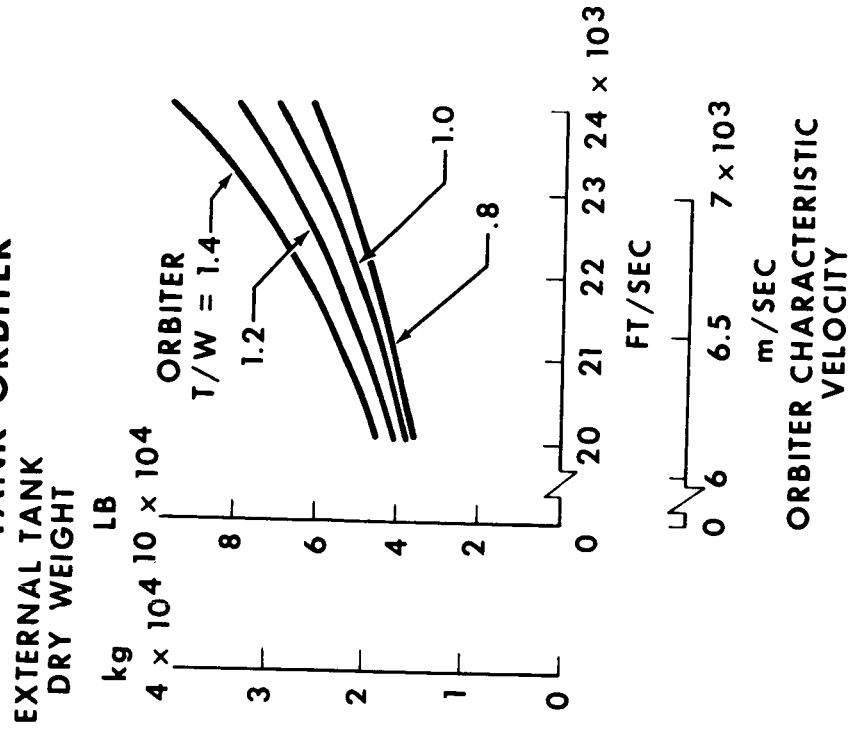


Figure 8

## ORBITER CHARACTERISTIC VELOCITY DEPENDENCE ON STAGING VELOCITY

(Figure 9)

While orbiter characteristic velocity is an excellent reference from which to examine certain basic vehicle design and performance relationships, its limited scope does not bring to light certain other effects which must be examined. The introduction of gravity and steering losses to the characteristic velocity forms the generalized staging velocity curves of figure 9.

The orbiter thrust-to-weight ratio is introduced as a necessary third parameter. At low thrust-to-weight ratios the effect on characteristic velocity becomes quite marked as the burn time to orbit insertion, and thus the propellant loading, increase exponentially.

A 1% flight performance reserve (FPR) allocation is accounted for in these curves.

# ORBITER CHARACTERISTIC VELOCITY DEPENDENCE ON STAGING VELOCITY

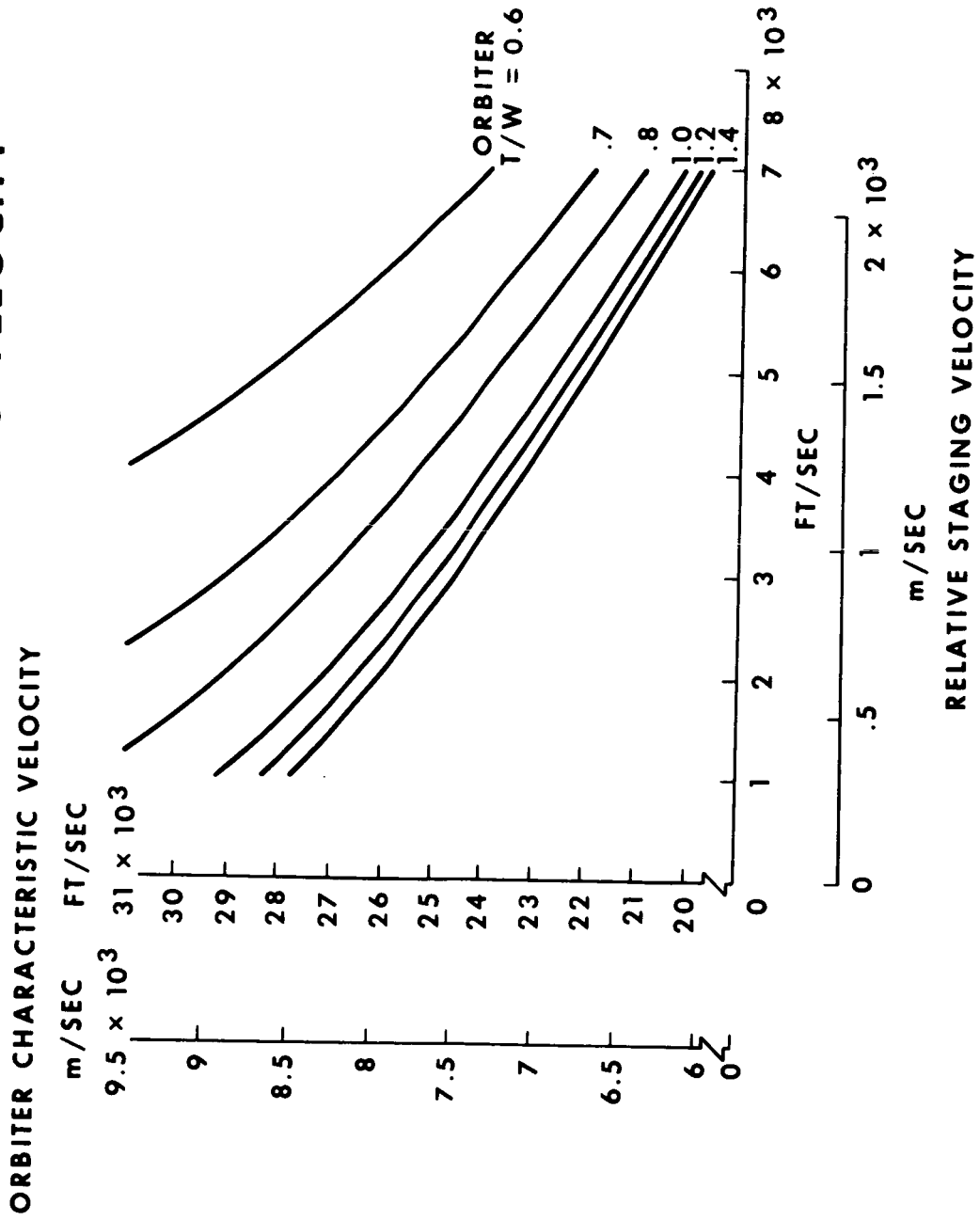


Figure 9

ORBITER CROSS WEIGHT DEPENDENCE ON STAGING VELOCITY

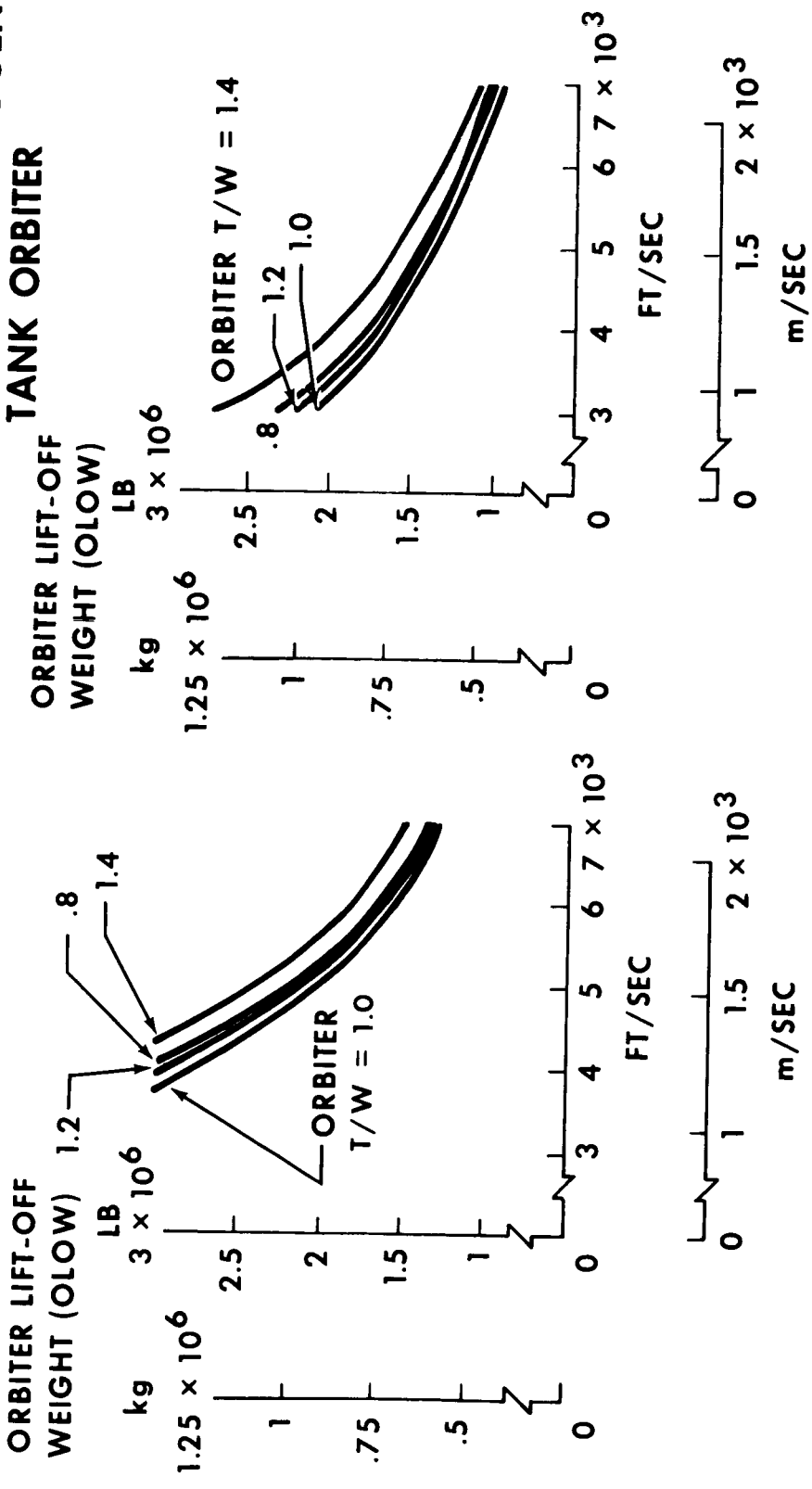
(Figure 10)

The low orbiter thrust-to-weight ratios which appeared attractive when considered only on the evidence of orbiter characteristic velocity, now appear rather undesirable. As was pointed out previously, low orbiter thrust-to-weight ratios increase the vehicle's burn time and thus the gravity losses which must be superimposed on the characteristic velocity requirement. There is a compromise, then, between sensitivities introduced by the increased propellant requirements of the low thrust-to-weight ratio vehicles and the increased propulsion system requirements of the high thrust-to-weight ratio vehicles.

The optimum thrust-to-weight ratio is very near 1.0.

# ORBITER GROSS WEIGHT DEPENDENCE ON STAGING VELOCITY

EXTERNAL HYDROGEN TANK ORBITER      EXTERNAL OXYGEN-HYDROGEN  
TANK ORBITER



RELATIVE STAGING VELOCITY

RELATIVE STAGING VELOCITY

Figure 10

ORBITTER INERT WEIGHT DEPENDENCE ON STAGING VELOCITY

(Figure 11)

Isolating the sensitivity of core inert weight to staging velocity clearly reveals the impact of the internal oxygen tank on the structure factor of the EHT vehicle. The diminished sensitivity of the inert weight of the EOHT vehicle is a result of that vehicle's lower structure factor, an advantage achieved by the divorce of propellants and tanks from the core vehicle.

# ORBITER INERT WEIGHT DEPENDENCE ON STAGING VELOCITY

EXTERNAL HYDROGEN TANK ORBITER      EXTERNAL OXYGEN-HYDROGEN TANK ORBITER

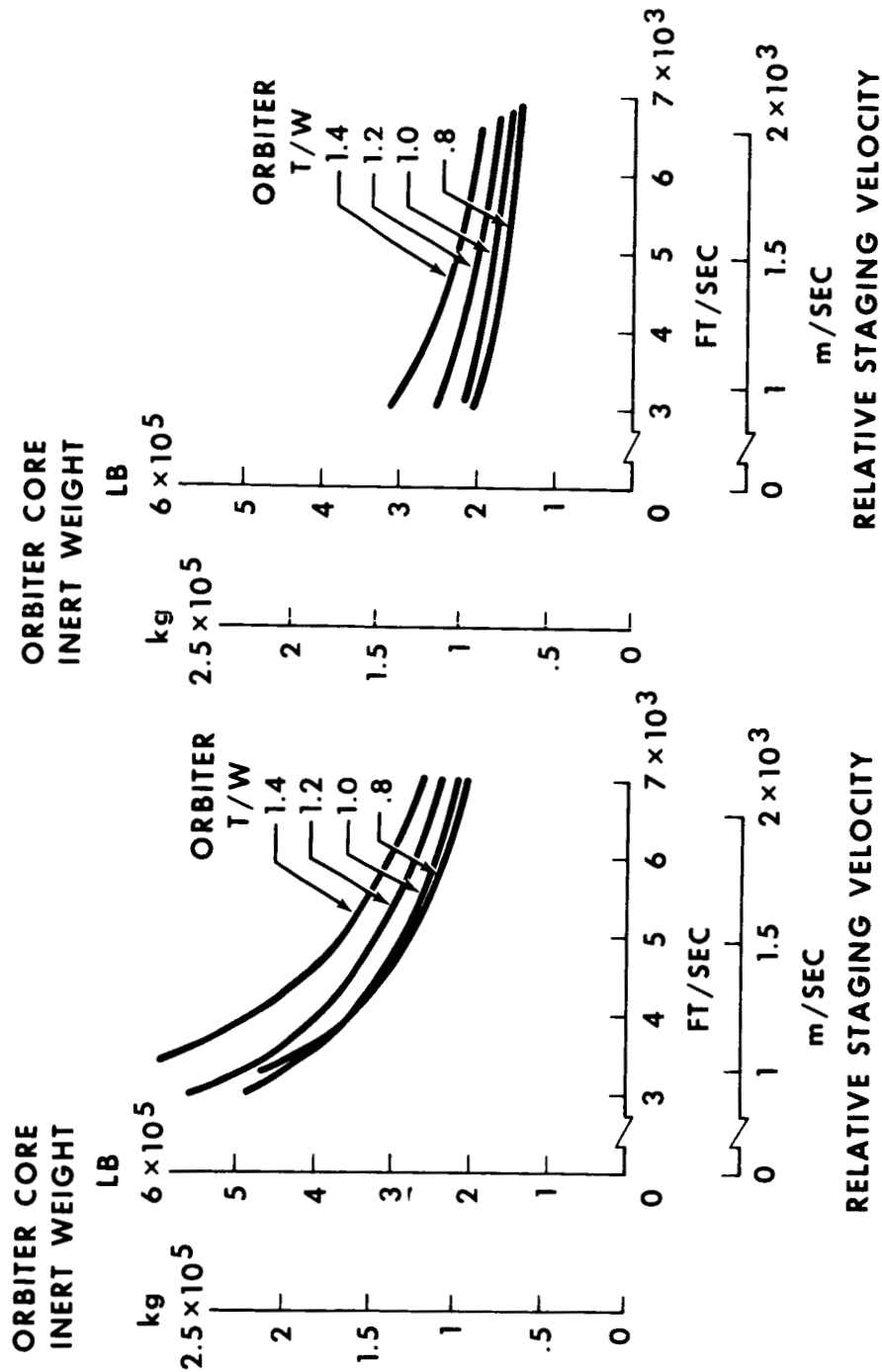


Figure 11

## EXTERNAL TANK DRY WEIGHT DEPENDENCE ON STAGING VELOCITY

(Figure 12)

The reduction in orbiter core weight of the EOHT vehicle over that of the EHT vehicle displayed in figure 11 must be compensated for by a weight differential between the external oxygen-hydrogen tank and the corresponding external hydrogen tank. The magnitude of this differential, as collated with the EOHT vehicle core weight savings, determines the ultimate advantage or disadvantage of the EOHT concept in relation to the EHT concept.

At a representative staging velocity of 6000 ft/sec (1970 m/sec), the EOHT vehicle has a core inert weight which is 78,000 lbs (35,400 kg) less than that of the EHT vehicle. The corresponding external oxygen-hydrogen tank dry weight is, however, 12,000 lbs (5450 kg) greater than that of the external hydrogen tank. An orbiter thrust-to-weight ratio of 1.0 has been assumed. The net vehicle inert weight reduction attributed to the EOHT vehicle concept, under these circumstances, is thus seen to be approximately 66,000 lbs (30,000 kg).



# EXTERNAL TANK DRY WEIGHT DEPENDENCE ON STAGING VELOCITY

EXTERNAL HYDROGEN  
TANK ORBITER

EXTERNAL OXYGEN-HYDROGEN  
TANK ORBITER

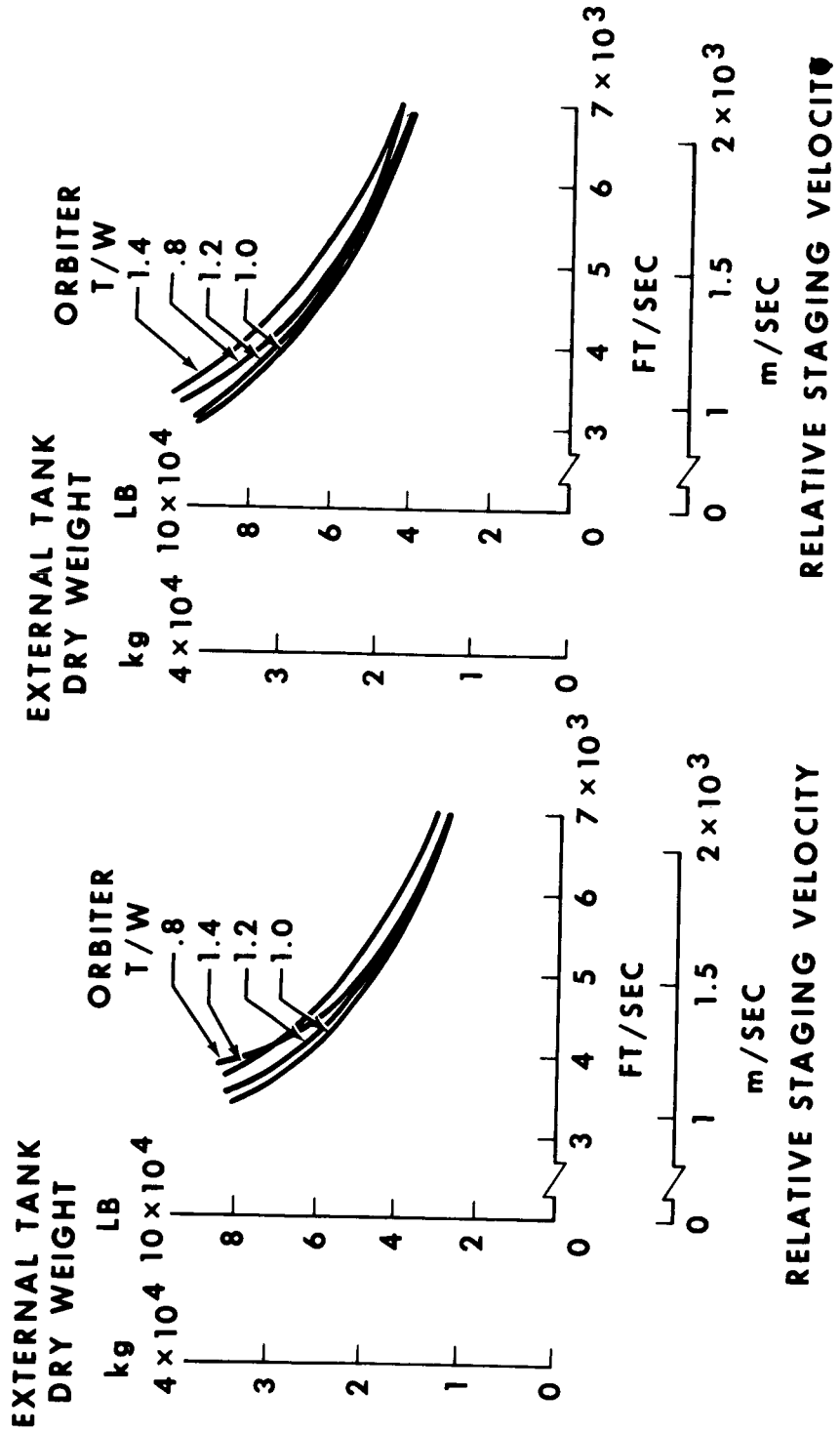


Figure 12

## PRESSURE-FED LOX/PROPANE BOOSTER

(Figure 13)

The analysis of orbiter design and performance as a function of staging velocity takes on added significance when a representative booster vehicle is also matched to staging velocity. To this end, consider a booster having pressure-fed engines fueled by liquid oxygen and propane. Velocity losses attributable to drag, thrust-atmosphere effects, and gravity are summed in figure 13 to form the booster characteristic velocity as a function of staging velocity. A lift-off thrust-to-weight ratio of 1.2 was assumed.

# PRESSURE-FED LOX/PROPANE BOOSTER

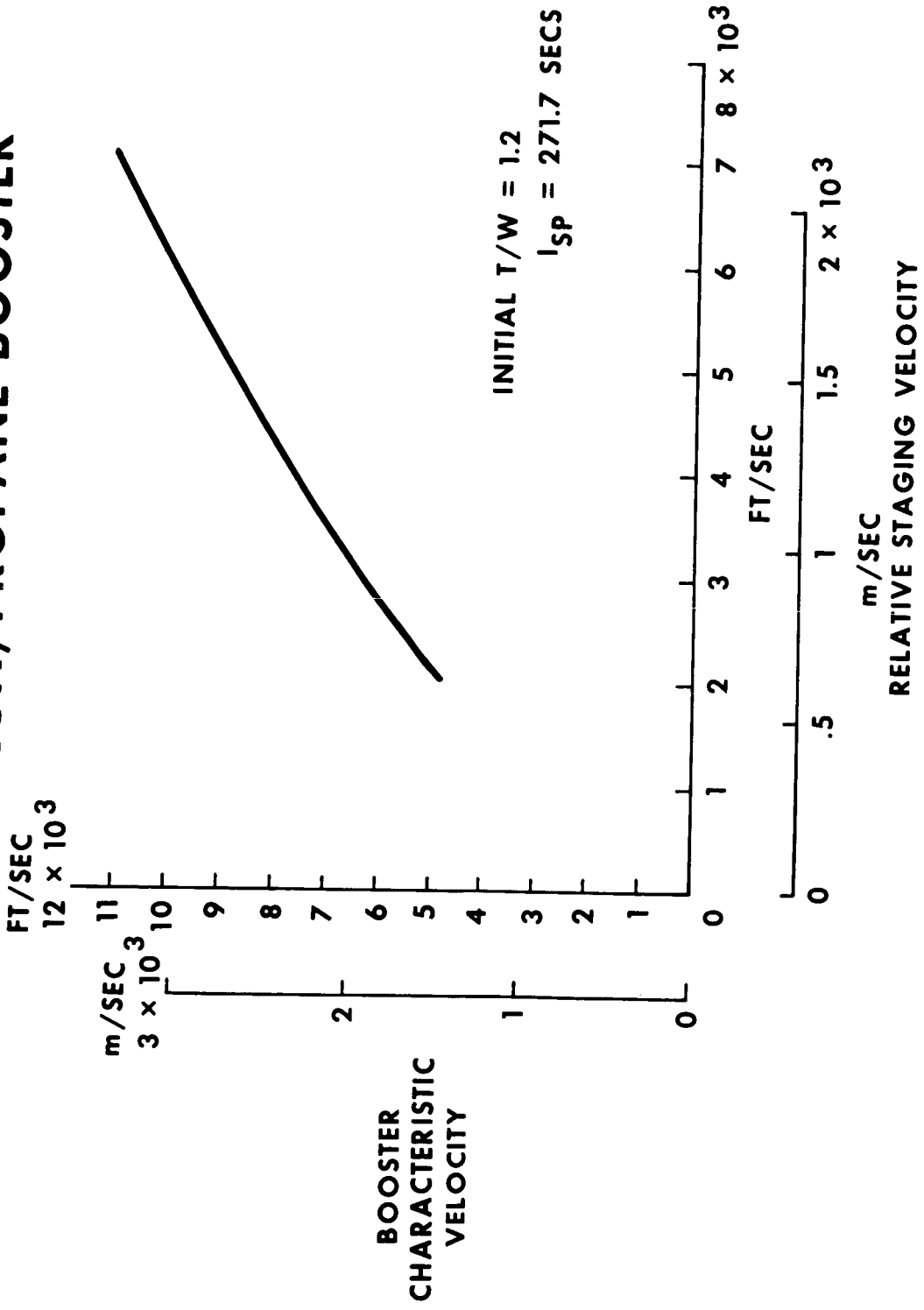


Figure 13

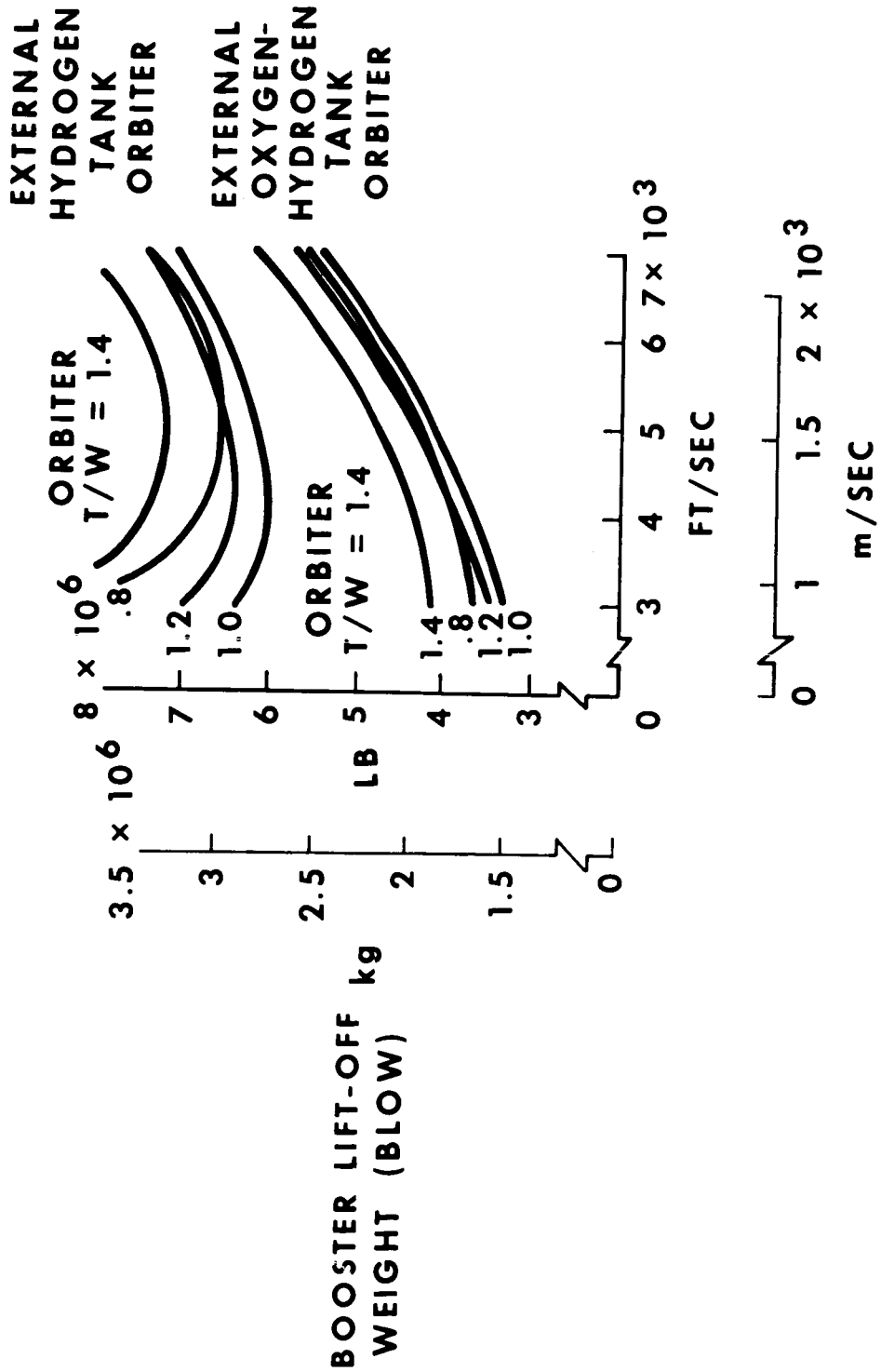
## PRESSURE-FED BOOSTER GROSS WEIGHT

(Figure 14)

Penalties introduced to the orbiter design as a result of high stage structure factors are amplified when a booster is sized to be mission-compatible with the orbiter. At a staging velocity of 6000 ft/sec (1970 m/sec) the higher structure factor of the EHT orbiter translates into a 1,810,000 lb (820,000 kg) increase in booster gross weight when compared to the booster gross weight corresponding to an EOHT vehicle.

The net effect of the low EOHT orbiter structure factor is to induce in the system a preference for boosters smaller than those which would be desirable for EHT orbiters.

# PRESSURE-FED BOOSTER GROSS WEIGHT



RELATIVE STAGING VELOCITY

Figure 14

PRESSURE-FED BOOSTER/EXTERNAL TANK ORBITER GROSS VEHICLE WEIGHT

(Figure 15)

The superimposition of the booster/orbiter primary sizing trends is to be seen in the overall vehicle gross lift-off weight dependence on staging velocity. To recapitulate, these include:

- (1) low orbiter thrust-to-weight ratios introduce excessive propellant penalties on orbiter performance;
- (2) high orbiter thrust-to-weight ratios introduce excessive engine weight penalties on orbiter design;
- (3) the best orbiter thrust-to-weight ratio for both EHT and EOHT orbiters is very near 1.0;
- (4) the improved EOHT orbiter structure factor reduces the vehicle gross lift-off weight from that of the corresponding EHT orbiter;
- (5) the improved EOHT orbiter structure factor and, hence, improved orbiter performance drive the system to smaller boosters and lower staging velocities.

# PRESSURE-FED BOOSTER/EXTERNAL TANK ORBITER GROSS VEHICLE WEIGHT

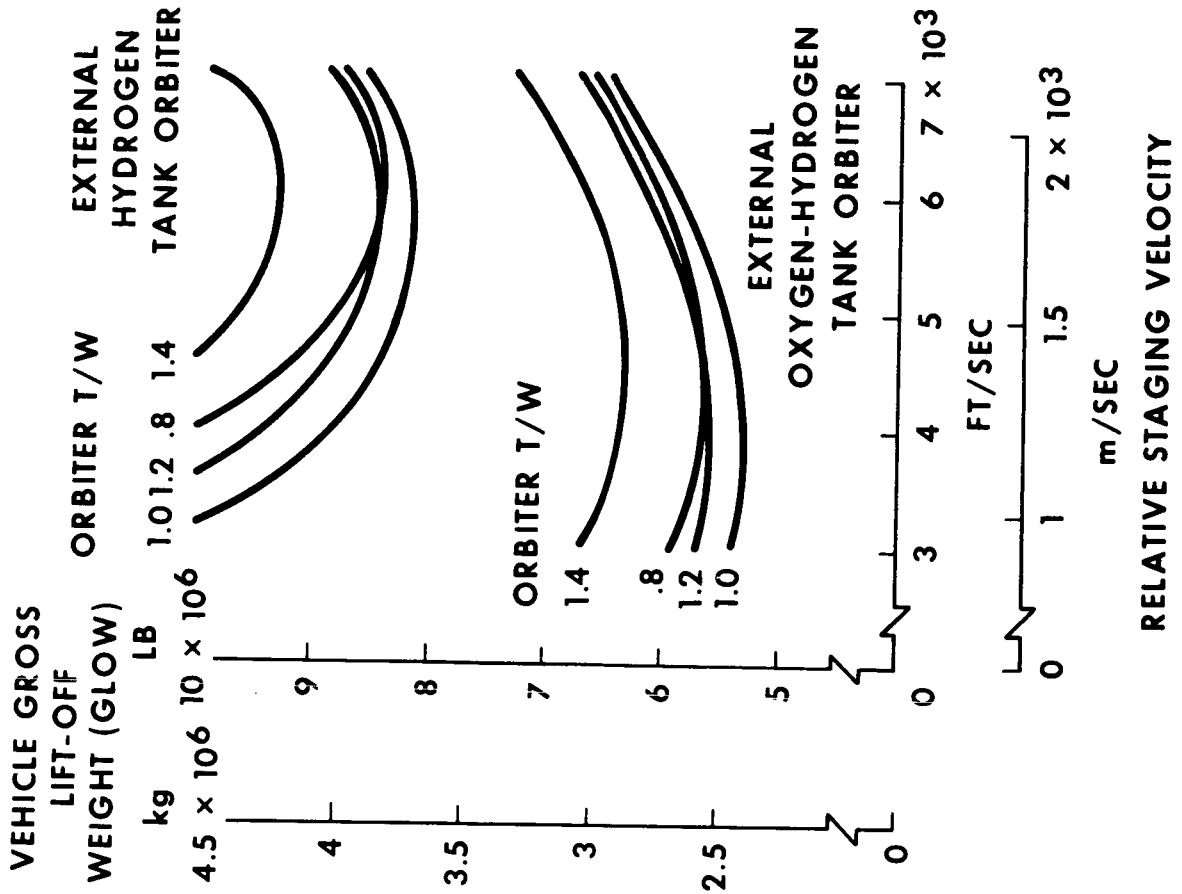


Figure 15

## BOOSTER COMPARISON

(Figure 16)

It is of some interest to compare the pressure-fed booster of the previous discussion with the reusable, pump-fed, F-1 engine booster. The F-1 engine booster is fixed in weight and propellant loading so that its maximum capability is specified. To achieve below maximum capability propellant must be off-loaded. In figure 16, for an EOH<sub>T</sub> orbiter with thrust-to-weight ratio equal to 1.0, the booster gross lift-off weights of the pressure-fed and the F-1 engine boosters have been plotted as a function of staging velocity. The F-1 engine booster has been off-loaded to achieve the minimum thrust-to-weight ratio at lift-off of 1.25.

Use of the F-1 booster becomes advantageous when staging velocities greater than 6500 ft/sec (1980 m/sec) are considered.



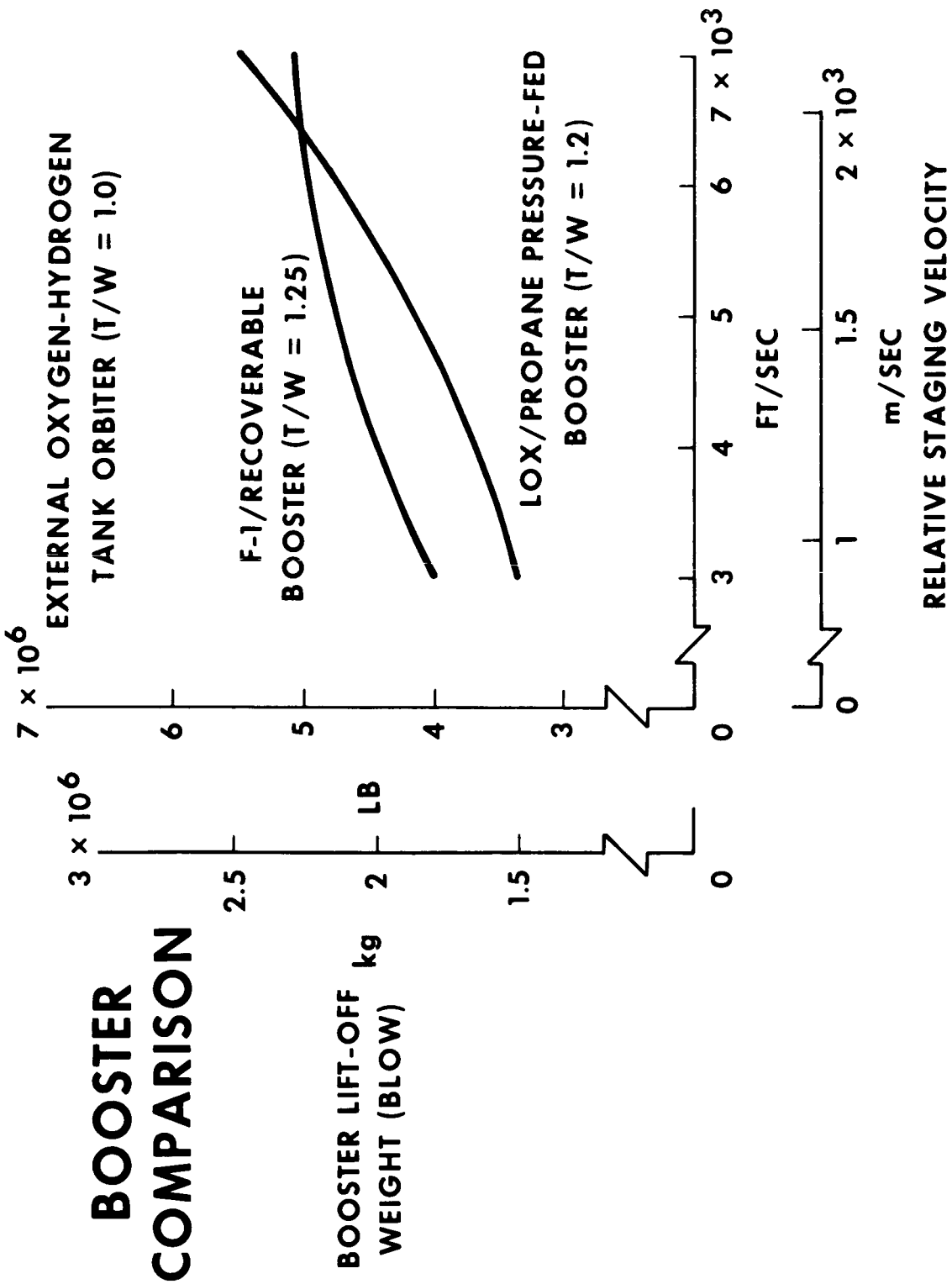


Figure 16

EHT/EOHT ORBITTER INERT WEIGHT COMPARISON

(Figure 17)

Increases in the orbiter core inert weight attributable to the EHT orbiter, when compared to the EOHT orbiter, increase as the staging velocity decreases. At high staging velocities the core weight increases appear to level off at about 30%. An orbiter thrust-to-weight ratio at 1.0 was assumed.

# EHT/EOHT ORBITER INERT WEIGHT COMPARISON

PERCENT INCREASE  
IN ORBITER CORE  
INERT WEIGHT

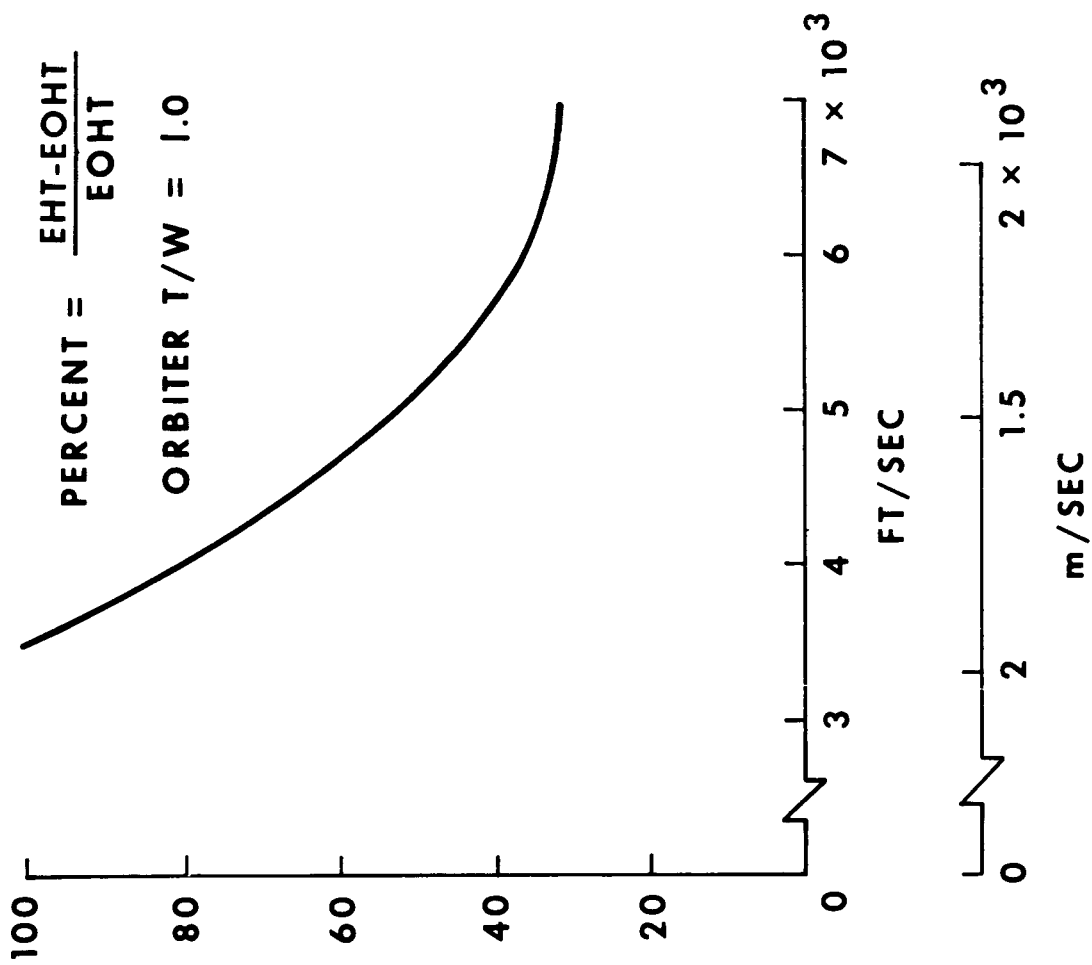


Figure 17

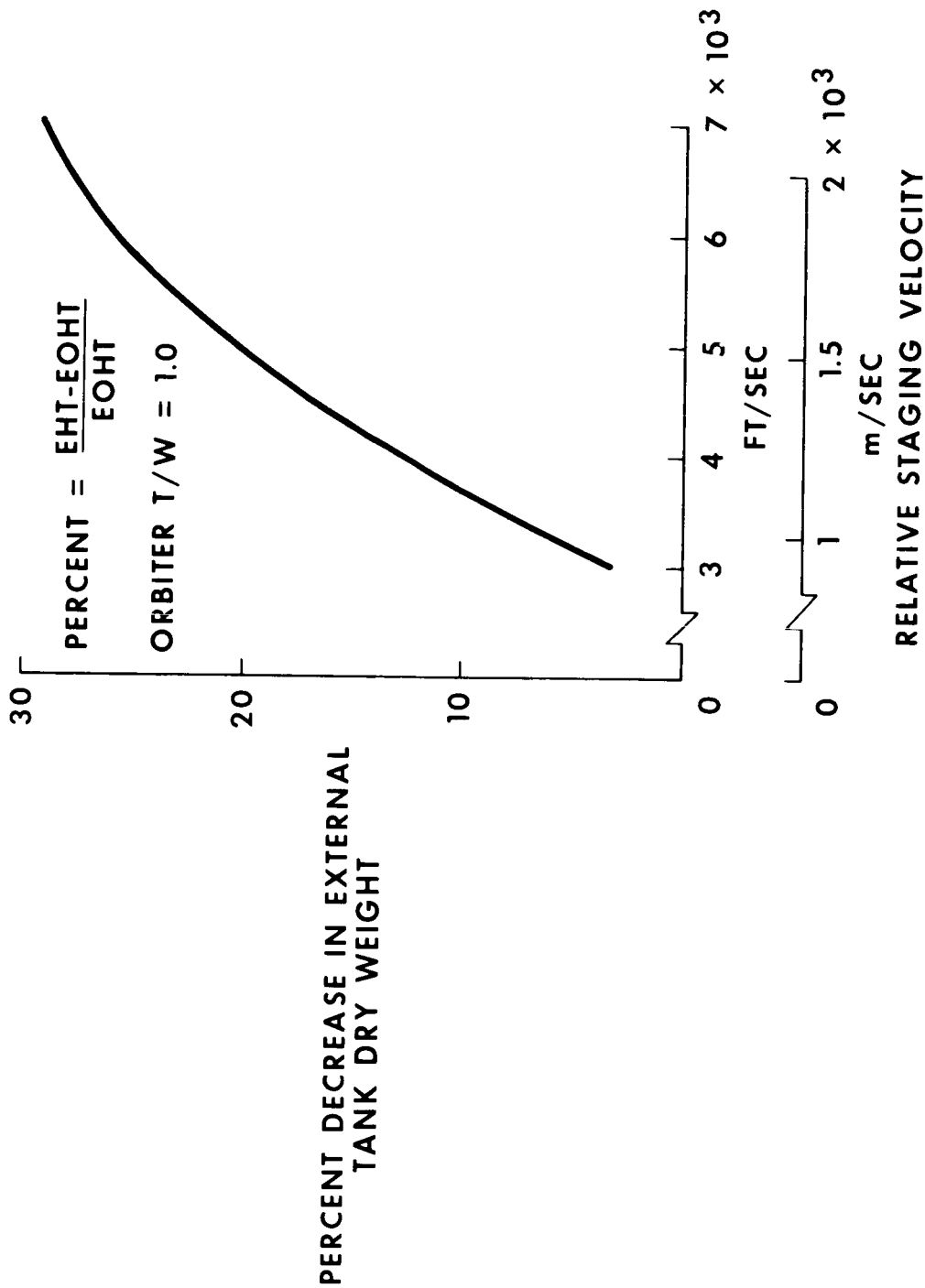
**EHT/EOHT EXTERNAL TANK DRY WEIGHT COMPARISON**

(Figure 18)

At low staging velocities the dry weight of the external tank is decreased by a few percent when only the hydrogen is placed in the external tank as opposed to placing both the oxygen and the hydrogen in the external tank. The large propellant penalties imposed by the EHT vehicle's higher structure factor are barely surpassed by the tank fraction penalty of including an oxygen tank in the external tank.

At high staging velocities the EHT vehicle's tank dry weight savings approach 30%.

# EHT/EOHT EXTERNAL TANK DRY WEIGHT COMPARISON



**EHT/EOHT VEHICLE BOOSTER GROSS WEIGHT COMPARISON**

(Figure 19)

Significant weight savings can be made in the pressure-fed booster gross weight by sizing it to an EOHT orbiter. At low staging velocities, where the EOHT orbiter is most compatible with this booster, a booster sized to an EHT orbiter would experience an increase in gross weight of approximately 90%. At higher staging velocities this increase approaches 30%.

# EHT/EOHT VEHICLE BOOSTER GROSS WEIGHT COMPARISON

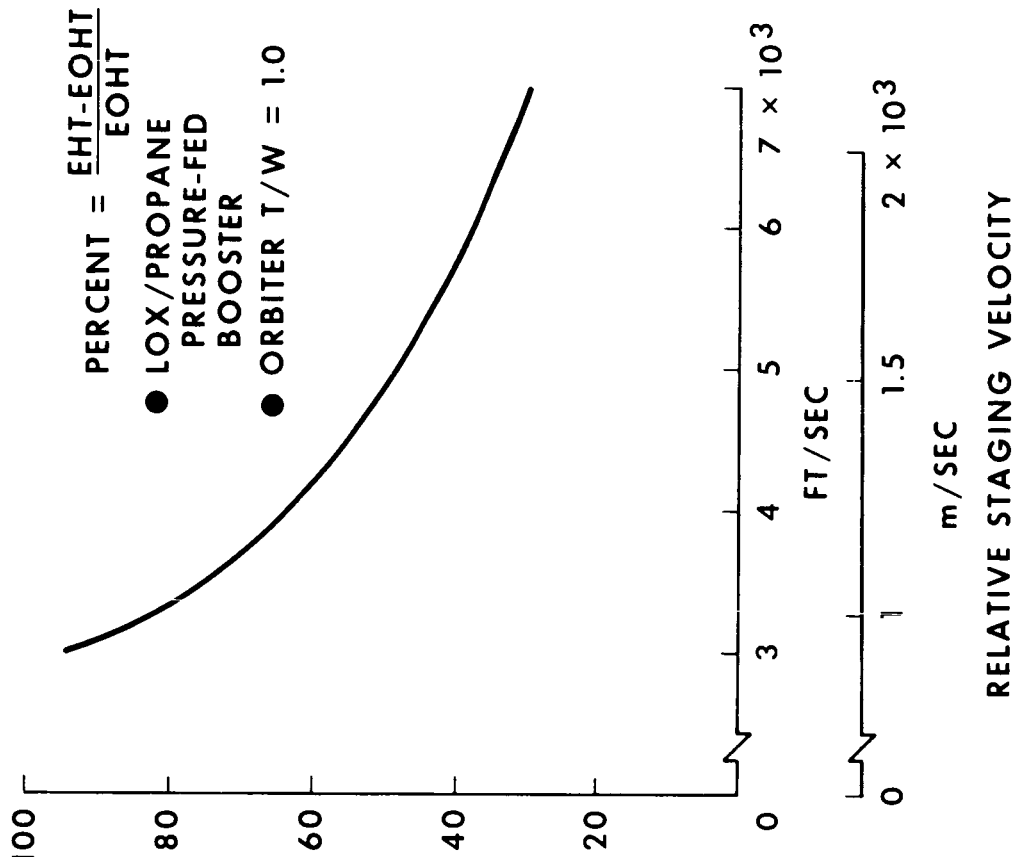


Figure 19

## CONCLUSIONS

(Figure 20)

Based upon the general trending analysis of this paper the following conclusions can be reached:

- (1) orbiter mass properties can be effectively decoupled from orbiter performance by using external oxygen-hydrogen tanks;
- (2) at staging velocities of current interest, an EOHHT orbiter has an inert weight which is approximately 40% lower than that of the corresponding EHT vehicle;
- (3) a pressure-fed LOX/propane booster will have a 40% lighter gross weight if designed to an EOHHT orbiter rather than an EHT orbiter.



# CONCLUSIONS

- ORBITER MASS PROPERTIES CAN BE EFFECTIVELY DECOUPLED FROM ORBITER PERFORMANCE BY USING EXTERNAL OXYGEN-HYDROGEN TANKS
- FOR STAGING VELOCITIES OF CURRENT INTEREST AN EOHT ORBITER HAS AN INERT WEIGHT WHICH IS APPROXIMATELY 40 PERCENT LOWER THAN THAT OF THE CORRESPONDING EHT VEHICLE
- A PRESSURE FED LOX/PROPANE BOOSTER WILL HAVE A 40 PERCENT LIGHTER GROSS WEIGHT IF DESIGNED TO AN EOHT ORBITER RATHER THAN AN EHT ORBITER

Figure 20