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Preliminary Design for a Space-Based Orbital Transfer Vehicle

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A space-based orbital transfer vehicle has been sized for a 5×10^4 payload delivery from low-Earth-orbit to a geosynchronous orbit. Space basing effected substantial reductions in cryogenic insulation, tank, and body structure. The tank and body structural masses are shown to be lower for space basing because of the larger difference in acceleration loads between the on-orbit case (0.2 *g*) and delivery (3.0 *g*), the latter applying to ground-based vehicles which are delivered to orbit fully loaded with propellants. Insulation masses are lower because of the absence of an atmosphere and the attendant heat transfer losses. Insulation systems masses are also reduced because of the elimination of the problem of liquefaction and freezing of moisture on the tanks.

Introduction

WHEN an orbital transfer vehicle (OTV) or space tug is guidelined for space basing, the major design loads are drastically reduced. This was the case in this design study. The loads on the major components—the propellant tanks—are considerably lower than tanks in Earth-to-orbit transports and much less than loads on comparable tanks in Earth-based tugs; tanks which are carried fully loaded through the entire ascent flight regime and a maximum acceleration of 3 *g*.

In addition to the operational mode of space basing, it was also decided in this study not to constrain the outside physical dimensions of the vehicle. The vehicle is required to have a design life of 50 missions before refurbishment.

Vehicle Design

The baseline OTV (Fig. 1) which evolved from the above design guidelines consists of two nearly spherical tanks, interelement structure consisting of graphite/epoxy tubes, and four 89 kN thrust LOX/LH_2 engines.[1,2] Estimated gross mass is 182.3 Mg for a payload delivered to geosynchronous orbit of 5×10^4kg (Tables 1 and 2). For purposes of comparison, 1 and 2×10^5 kg payload vehicles are also shown (Fig. 2).

Tanks

The tanks for the vehicle are fabricated from 2219-T86 aluminum. Both the LH_2 and the LOX tanks consist of two hemispheres separated by a small barrel section, an approach used (as opposed to a simple sphere) in order to provide a convenient surface for installation of reaction control engines (in the case of the LH_2 tank) and for attachment of structure on both tanks. For the hydrogen tank the aluminum gage for both hemispheres is 1.27 mm, while the ring gage is 2.54 mm; the latter increase is required to carry primary body loads, attachment fittings, and reaction control system engines. Overall, the mass fractions for space-based tanks are considerably higher (Figs. 3 and 4).

For the sake of simplicity in design and analysis, body loads are transmitted from engines around the main propellant tanks (except for equator rings) to the payload platform. Other configuration options are possible. One, in particular, is the transmission of engine thrust loads directly through the bottom hemisphere of the LOX tank, or through a completely enclosing structural shell at the maximum tank diameter.

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Table 1 OTV system mass properties

Subsystems	Mass, kg
Exterior insulation	272
P/L platform and flange	331
Struts—platform	62
LH_2 sphere	865
Struts—intersphere	192
Mounting provisions for helium tanks	121
Lox sphere	331
Lox insulation	99
Engine truss	87
Rocket engines (193 kg ea)	772
Pressurization and feed	348
Propulsion RCS (includes systems)	587
Electrical power	277
Avionics (communication subsystem)	159
Docking provision	25
Gimbal systems	47
Heat sheild	11
Margin	478
Dry mass	5064
P/L	50,000
LOX	104,481
LH_2	17,537
Nonrecoverable boiloff	1179
RCS ($MMH + N_2O_4$)	1158
Flight performance reserves	1587
Residuals (other losses)	1306
Gross mass	182,312

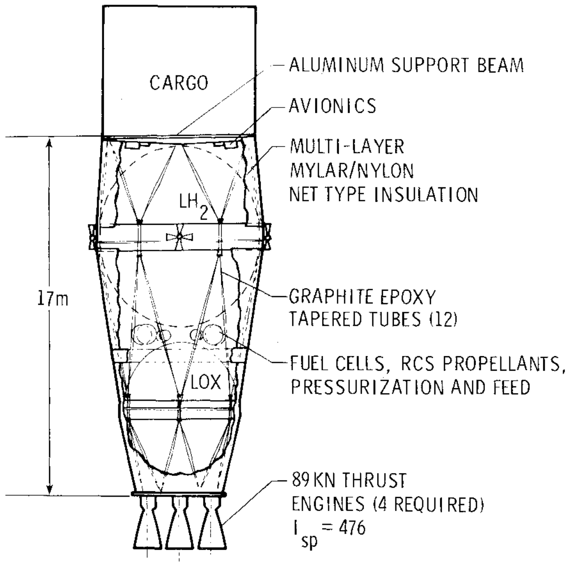

Fig. 1 50-metric-ton payload orbiter transfer vehicle.

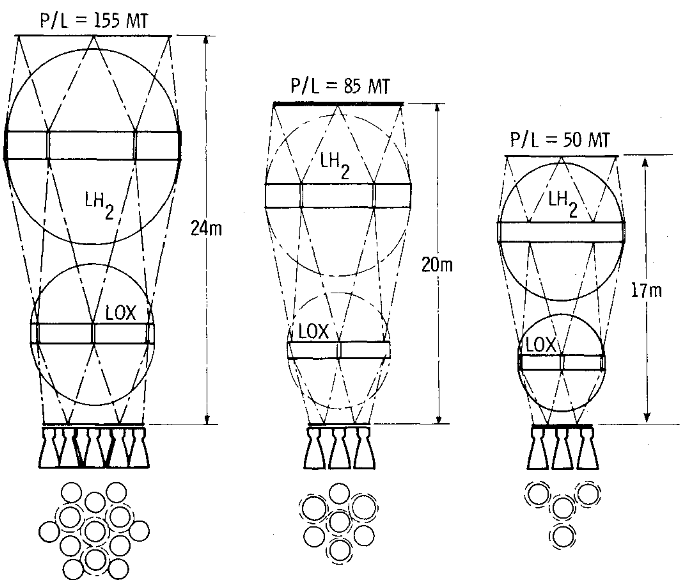

Fig. 2 Size comparisons for three orbital transfer vehicles.

Table 2 OTV sequential mass statement

Maneuvers	Sequential mass	Mass increments, kg	Velocity increments, m/s
Dry mass	5064		
Nonrecoverable boiloff	5064	1179	
Residuals other losses	6243	1306	
Flight performance reserves	7549	1588	
Rendezvous redock	9137	98	
LEO circulation	9235	6393	2458
Coast—4th burn alignment	15,628	45	
Deorbit burn	15,673	7210	1768
2nd burn alignment	22,883	12	
Drop P/L	22,895	50,000	
Rendezvous dock at GEO	72,895	788	
2nd burn (circulation)	73,683	33,885	1768
Coast—2nd burn alignment	107,568	115	
1st burn	107,683	74,532	2458
Undock alignment	182,215	98	
Gross mass	182,313		

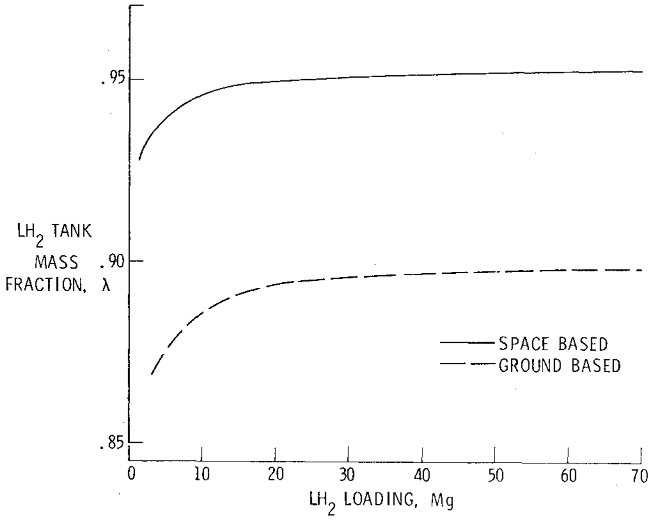

Fig. 3 LH_2 tank mass fractions, space basing vs ground basing.

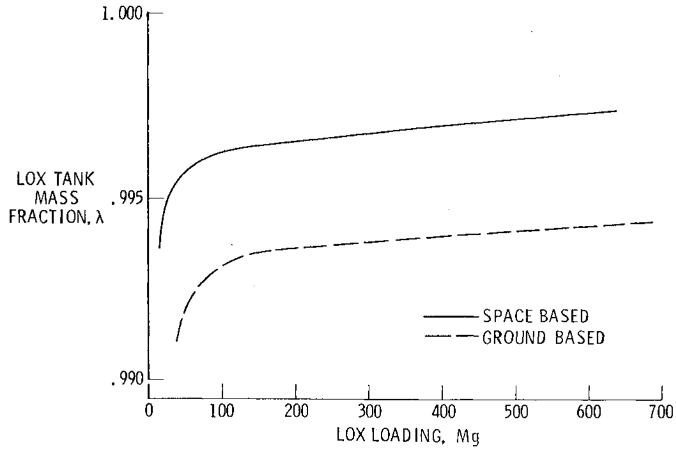

Fig. 4 LOX tank mass fractions, space basing vs ground basing.

On both tanks, however, it was necessary to stiffen the shells in order to avoid localized crippling due to compressive loads. These loads, which on occassion exceed loads from internal pressure, are induced by propellant slosh and unequal heating from the sun. Several schemes were considered for stiffening the shells, including isogrid, zee stiffeners, and honeycomb with only small differences in mass as a result. The zee stiffener concept was finally selected for purposes of determining tank masses. In this concept the stiffeners were placed every 10 deg and extend from a polar zee ring to an angle circumferential ring at the tank barrel section (Fig. 5). The depth of these stiffeners is gradually increased from poles to equator—the latter increase principally needed to react induced moments in the tank wall from intertank struts.

Intertank Structure

An approximate mass for the OTV intertank structure was obtained from information generated under one of the ongoing programs for the design of large space structures.[1] In this case, graphite epoxy tapered tubes are utilized. While the graphite/epoxy physical properties are known to degrade, particularly in high intense radiation belts, this material was selected nonetheless because of its exceptionally high specific strength, even after an estimated 25% degradation after 1 yr in orbit.

Propulsion

The main engine employed is a modified advanced space engine (ASE) described in Ref. 2. The engine mass properties

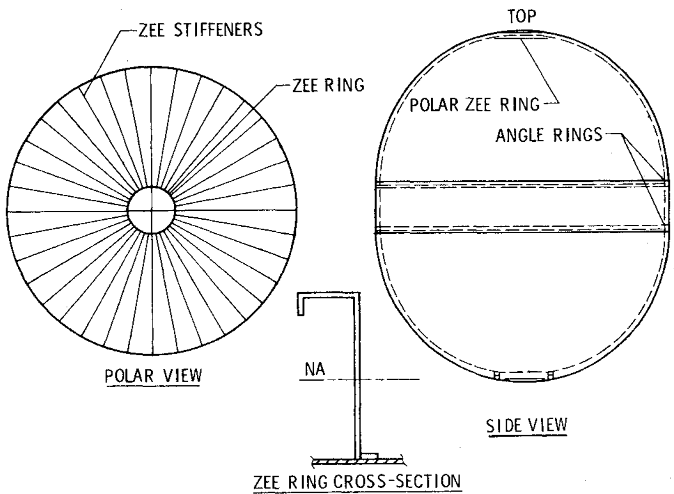

Fig. 5 Typical orbital transfer vehicle tank structure.

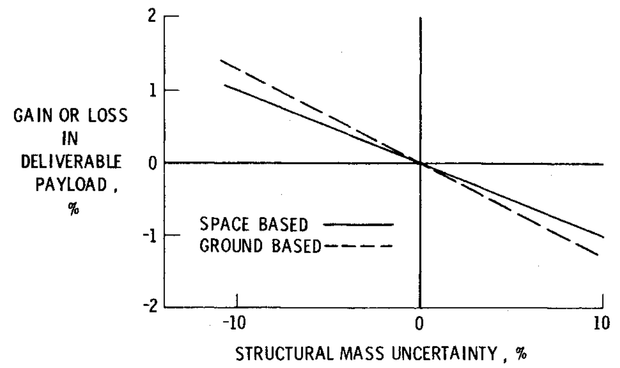

Fig. 6 Sensitivity of structural mass uncertainties to payload loss or gain.

have been changed to the extent that a retractable nozzle section is no longer required. This is another advantage of unrestricted geometry, since the retractable nozzle on an OTV is normally used just to reduce vehicle moldline dimensions. The resulting mass per engine, not including pressurization and feed, is 193 kg. Utilizing four engines, considerable flexibility in acceleration control during propellant depletion is possible. At ignition, for instance, vehicle acceleration is 2 m/s^2 and, as the transfer to geosynchronous orbit proceeds, propellant depletes and engines are sequentially shut down. On return to low-Earth orbit (LEO) and final circularization with one engine operating, the vehicle is subjected to accelerations of about 15 m/s.[2] The attendant loads would not be large since the vehicle is carrying no payload and the tanks are almost empty.

Insulation and Meteoroid Protection

Since the OTV is a space-based vehicle, this led to the selection of a multilayer insulation (MLI) system similar to that described in Ref. 3—a system which by itself would not be suitable for ground basing because of cryopumping and the possibility of damage in handling. In the hard vacuum of space, even in near-Earth orbit, this combination is very effective and consists of multilayers of aluminum-coated mylar (or Kapton) and a nylon "spacer" net. Probability of puncture by micrometeoroids is estimated to be low for a 1-yr service on-orbit for the thickness and size of tanks and MLI used.[4] The probability of tank puncture could be reduced substantially if the OTV were to be stationed within a depot when not in use. Additionally, for the stress levels assumed and the most probable size of the micrometeoroids involved, fracture mechanics predictions show that the punctured tank would leak but would not fail catastrophically.[5] Such an occurrence might require a mission abort or retrieval by another OTV, but would not involve destruction of the vehicle.

Overall, projections indicate that the 32 layers of MLI proposed will provide adequate meteoroid protection while minimizing boil-off. Although 1% of total inpulsive propellant was allowed for boil-off, this figure could conceivably be lower, based on tests of tanks in a simulated near-Earth and deep space environment.[6] Needless to say, an in-depth analysis was not made and boiloff will be sensitive to engine plume radiation heat inputs, exact mission timelines, and vehicle orientation during the mission relative to the sun and Earth.

Miscellaneous Subsystems

For attitude control, closure and docking, a monomethylhydrazine/nitrogen tetroxide system was chosen. Sixteen engines are required and are mounted at the hydrogen tank equator. Attitude control LOX/LH_2 engines could serve this purpose equally well.[7]

An allowance of 160 kg was made for avionics (communication subsystem)—a value of twice this mass is easily possible and the ultimate value is dependent upon the technology leverage applied. Considerable thought was given to this subsystem as to whether it would be fully automated, whether a ground link would be provided (in addition to direct communication with communication satellites), or whether an advanced or normal technology level would be used. The mass utilized for avionics assumes orbit-to-orbit communication and advanced technologies.

For the electrical source, fuel cells are utilized. Without a requirement for solar panels and directional antennas, much greater flexibility in vehicle orientation is provided. This operational mode yields the greatest mission flexibility and makes it possible to be selective with regard to vehicle/sun orientation for minimum propellant boiloff.

In general, the space-based OTV appears to be relatively insensitive to changes in subsystem masses. Unlike Earth-to-orbit transports, OTV mass properties analyses show payloads as approximately ten times the vehicle dry mass, while the former show payload fractions of one-sixth the dry mass. Therefore, alternate options involving different masses in subsystems or "weight" growth on an OTV make only minor inroads into the deliverable payloads (Fig. 6).

Research Needs

There are several areas in which it appears that further study and research would be advantageous if such a system were to be utilized in the future, namely: 1) orbital propellant storage and transfer systems; 2) an appraisal of the cost of a space depot for propellants and other supportive roles and a comparison made with an Earth-basing mode of operation; 3) material property changes with time for structural materials (particularly composites) for continuous operation in or near highly intensive radiation belts; 4) a more extensive analytical study of meteoroid hazards in terms of required life, reliability, tank wall thickness and tank size.

Conclusions

A preliminary design of a space-based orbital transfer vehicle has been made leading to the following conclusions:

1) If space basing becomes a practical operational mode, increased system efficiency will be possible through reduced OTV subsystem masses.

2) Because of the relatively low dry mass of these vehicles for the payloads delivered, sensitivities to subsystem alternatives (involving different masses) or "weight" growth are minimal.

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