MODERATE LIFT-TO-DRAG AEROASSIST

Dwight E. Florence
General Electric Space Systems Division

Grahme Fischer
Grumman Aerospace Corporation

Numerous potential technology advances have been identified and evaluated that provide significant mission enabling and mission enhancing features to a wide variety of mid L/D AOTVs. In this paper, those advances associated with propulsion subsystems will be highlighted.

INTRODUCTION

Significant performance benefits can be realized via aerodynamic braking and/or aerodynamic maneuvering on return from higher altitude orbits to low Earth orbit, Reference 1-5. This approach substantially reduces the mission propellant requirements by using the aerodynamic drag, D, to brake the vehicle to near circular velocity and the aerodynamic lift, L, to null out accumulated errors as well as change the orbital inclination to that required for rendezous with the Space Shuttle Orbiter. A study has been completed where broad concept evaluations were performed and the technology requirements and sensitivities for aeroassisted OTV's over a range of vehicle hypersonic L/D from 0.75 to 1.5 were systematically identified and assessed. The aeroassisted OTV is capable of evolving from an initial delivery only system to one eventually capable of supporting manned roundtrip missions to geosynchronous orbit. Concept screening has been conducted on numerous configurations spanning the L/D = 0.75 to 1.5 range, and several with attractive features have been identified.

Initial payload capability has been evaluated for a baseline of delivery to GEO, six hour polar, and Molniya (12 hours x 63.4°) orbits with return and recovery of the AOTV at LEO. Evolutionary payload requirements that have been assessed include a GEO servicing mission (6K up and 2K return) and a manned GEO mission (14K roundtrip).

AOTV Performance

Previous studies, References 3 and 4, have considered only missions from LEO to Geosynchronous orbit and return. In this study, missions were defined to higher inclination orbits, where an aeromaneuvering vehicle was expected to become more attractive due to its ability to provide orbital plane change.

Performance studies have been conducted for return of mid L/D vehicles from GEO, 5 x GEO, and 6-hour Polar circular orbits. Steering laws have been employed that include constant deceleration cruise at the overshoot and undershoot bounds, and constant bank angle cruise. Orbital plane change obtained is summarized in

Figure 1, where it is shown that plane change capability increases with hypersonic L/D and entry velocity (maximum for the 5 x GEO return) for a specific steering law. The 90° bank angle provides the maximum plane change.

The insensitivity of an L/D = 1.5 AOTV to variations from the nominal in the atmosphere density or to errors in the apriori estimate of the drag coefficient have been evaluated by personnel from NASA JSC and are illustrated in Figure 2.

Configuration Development

Several classes of configurations exist that meet the hypersonic performance requirements. Thse include axisymmetric and elliptical cross section cones, biconics, cone cylinders and arbitrary bodies. Generally, the sphere cones are too long to meet the length constraint and package the required propellant tanks and payloads. Arbitrary bodies are generally geometrically more complex than necessary for this aeromaneuver vehicle and exhibit poor propellant tank packaging efficiency.

Biconic and cone cylinders were selected for this study because they were the best compromise on L/D and packaging efficiency; there is a large aerodynamic and design data base; the basic maneuvering concept has been flight proven for this class of vehicles. This concept was thoroughly evaluated for the planetary aerocapture mission and presents a feasible, well characterized, solution.

The aerodynamic configuration selected must: 1) meet the external dimensional constraints of the launch vehicle, and 2) provide packaging room for the propellant tanks and other subsystems so that the launch configuration with tanks full meets the launch vehicle center-of-mass requirement and the entry configuration with tanks empty meets the center-of-mass requirement to trim the vehicle at the desired angle of attack during the aeromaneuver. The desired angle of attack is obtained by placing the entry center-of-mass at the AOTV center-of-pressure location for that angle-of-attack. The selected angle of attack for the baseline vehicles will be that for which L/D is a maximum, thus insuring maximum plane change capability for the vehicle.

The aerodynamic configurations of mid L/D AOTV's evolved from review of an existing computational aerodynamic data base supplemented with additional calculations. The initial data base consisted of existing flow field calculations for aft frustum angles down to 4° and the AMOOS results for frustum angles of 0 and 1/2°. This data base was supplemented with new HABP, Reference 8, calculations for a frustum angle of 2°.

The effect of increased nose length or increased vehicle length on increasing the vehicle hypersonic L/D is illustrated in Figure 3. Note the large effect that increased nose length makes.

For packaging or aerodynamic reasons, a full nose bend, δ_n, may not be desirable. The effect of lesser nose bend on $(L/D)_{max}$ is also illustrated in Figure 3.

Several major configuration classes are possible by employing different staging techniques. Single stage vehicles were evaluated recently, References 1, 3 and 4, where the propellant tanks are enclosed within the AOTV and the entire vehicle makes the round trip. Stage and-a-half vehicles, AMOS, Reference 6, 9, MOTV, Reference 7, have been evaluated and were shown to offer payload delivery and cost advantages over the single stage vehicles. Two-stage vehicles have been evaluated and shown to offer payload delivery advantages. Specific configurations employing each of the above staging techniques have been evaluated.

For the single stage vehicles, propulsion stage packaging trends have been evaluated to determine vehicle center of mass possibilities for combinations of total vehicle length, Lv, and nose length, Ln. Two propulsion stages were used; one representing an extremely short stage, (utilizes torroidal oxygen tank) and one representing probably the longest stage possible (spherical tanks). Using these results, in combination with the parametric center of pressure locations, three configurations were defined, Figure 4, that span the range of L/D from 0.75 to 1.5 for further evaluation.

MAJOR FACTORS FOR IMPROVING MID L/D PAYLOAD DELIVERY PERFORMANCE

The performance capability of a mid L/D AOTV can now be enhanced considerably by combining many of the effects that incrementally improve performance of the AOTV into one vehicle. The improvements can be categorized into: 1) those that fall within current state-of-the-art, and 2) those that result from improvements in state-of-the-art, and are summarized in Figure 5.

Considering all of these effects, a representative ideal Geosynchronous delivery vehicle was defined for evaluation, Figure 6.

PROPULSION SUBSYSTEM TECHNOLOGY ADVANCES

As part of the Advanced OTV Propulsion System Program currently underway, improvements in specific impulse for LOX-H_2 fueled engines are projected to reach 480 to 490 seconds, References 10, 11 and 12. The potential improvement in AOTV payload delivery capability is illustrated for GEO and Polar delivery in Figure 7. Note that the payoff for increased specific impulse is about 60-65 pounds of payload for each second of specific impulse improvement.

The advantage of variable mixture ratio (MR) operation to maximize the specific impulse of a throttable engine was identified, Reference 10. In addition, increase of the mixture ratio reduces the size of the hydrogen tank by one foot for the 65K STS and 1.8 feet for the 100K STS at only a small loss of payload delivery capability.

The wide range of engine size and thrust level possibilities have been identified, Reference 10. The packaging advantages and the shorter (hence lighter) vehicles that result from use of multiple small engines have been evaluated. One to six engines, providing a total thrust of 15,000 lbs, and man-rating requirements have been considered. The results of this AOTV-engine weight trade are summarized in Figure 8 where it is seen that for a representative Mid L/D AOTV, six engines result in nearly a 5 foot shorter and 260 lbs lighter vehicle.

Some of the AOTV configuration-engine location interactions that were found are summarized in Figure 9.

SEVERAL ATTRACTIVE MID L/D AOTVs

Examples of several configuration classes were evaluated including both single and multiple stage vehicles, unmanned delivery and manned vehicles. Examples of these configurations employing some growth technology are illustrated in Figures 10 and 11 and their primary features enumerated.

Flight performance and payload delivery sensitivities across the mid L/D range for a single stage AOTV are summarized in Figure 12. The incremental increase in payload delivery capability, given a reduction in vehicle dry weight, or an increase in vehicle L/D is illustrated for vehicles at both ends of the mid L/D range. The incremental loss of payload delivery capability is illustrated for each degree of plane change generated propulsively in the initial mission orbit. Note the large differences in the effect of incremental L/D on payload delivery capability, Δ W P/L/ Δ L/D, between the GEO and 6 hr polar delivery missions.

ADVANCED TECHNOLOGY PAYOFFS

A detailed review of the current state-of-the-art in the various technology and subsystems areas was conducted to serve as a baseline point of departure for this study. Technology advancement possibilities identified in numerous recent studies of OTV, AOTV, SDV, and STS were reviewed. These results are compared with our in-house data base and parameters selected that represent improvements due to nominal expected growth resulting from normal funding of these technology areas. A number of these improvements resulting in from 10 to 70% reduction of subsystem weight are summarized in Figure 13. Other improvements include such items as increase of maximum operating temperature of the thermal protection system elements and increased confidence in the hypersonic aerodynamic characteristics.

Various techniques exist for ranking the technology benefits. The method selected for this study is as follows: given a subsystem weight reduction or other performance improvement possibility, the effect on increased payload weight was determined and this payload gain was converted to a customer cost benefit, given a nominal delivery cost to GEO of $8000 per lb. The mid L/D AOTV payload delivery sensitivities of Figure 12 have been combined with the delivery cost and the subsystem weight reduction possibilities to generate the results summarized in Figure 14 for the 38 ft and OH-3 delivery vehicles. Note that the 38 ft single stage vehicle has very different technology payoffs from the small OH-3 staged vehicle.

Additional technology advance benefits are summarized in Figure 15 for both vehicles. Aerodynamic uncertainties due to viscous and rarefaction effects will exist and could amount to as much as ± 0.1 of Δ L/D. This uncertainty requires a propellant contingency which in turn decreases the payload delivery capability. Flight vehicles have typically flown initially with a safety margin in the thermal protection system of as much as 25%. This translates into a very large payload loss (and hence cost benefit if it is decreased or eliminated) for the 38 ft delivery vehicle but a much smaller effect for the OH-3 vehicle due to its much smaller size. In the GN&C subsystem area, the ability to obtain aerodynamic plane change is translated into payload gain and hence customer cost benefit. The value of an "optimum" guidance system that has been selected because it is capable of obtaining the most aerodynamic plane change from a given vehicle configuration is illustrated for one degree of incremental plane change. The value of an "adaptive" guidance system that has the capability of updating during the early portion of entry is illustrated for each additional one degree of plane change that can be generated. The effect of encountering a 30% density shear (pocket) similar to that experienced by a recent STS flight has been demonstrated to have no effect on vehicle with L/D = 1.5 but to have a small effect on a vehicle with L/D = 0.6.

CONCLUDING REMARKS

The major conclusions of this study include the following:

- Use of mid L/D AOTV provides significant aerodynamic plane change capability and control authority over trajectory dispersions and off nominal atmospheres.

- All mid L/D AOTV enabling technology is ready today.
- Substantial performance improvements and hence cost benefit can be obtained by developing enhancing technologies.
- Six fixed, low thrust ($\approx$2000 to 3000 lb), advanced expander, LOX-hydrogen engines operating at a MR $>$6.0 offer attractive packaging possibilities.
- Manned mission to GEO with delivery of one ton payload is possible with the 65K STS, mid L/D AOTV, an advanced cryofueled engine and lightweight ASE (3000 lbs).
- Delivery of very long payloads (45 ft) is possible by use of very short AOTVs with drop tank.

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AOTV PLANE CHANGE CAPABILITY

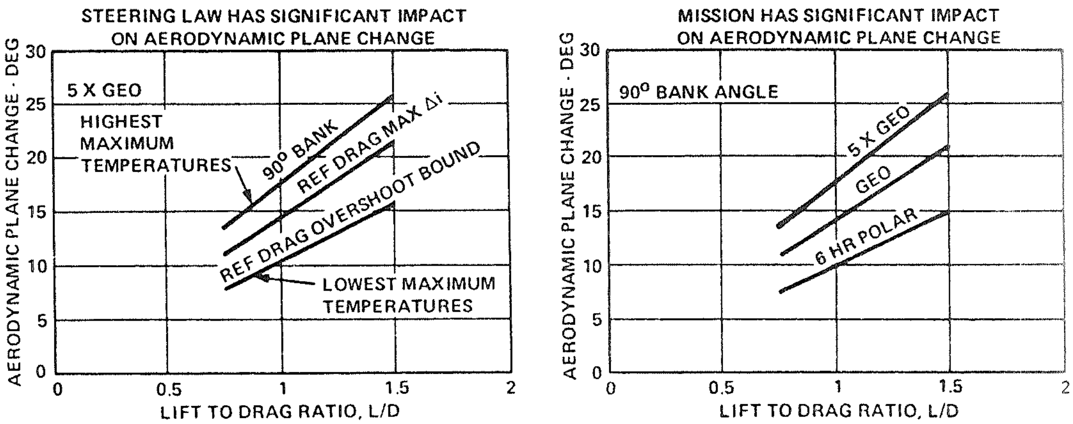


FIGURE 1

MID L/D AOTV IS RELATIVELY INSENSITIVE TO ATMOSPHERIC DENSITY AND DRAG COEFFICIENT UNCERTAINTIES

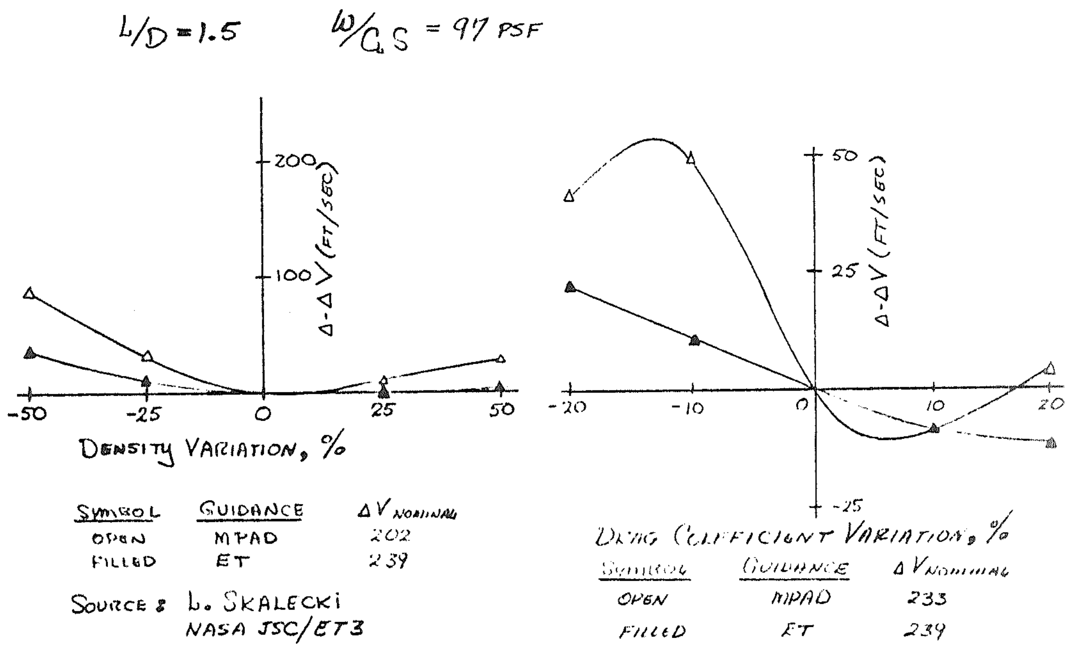
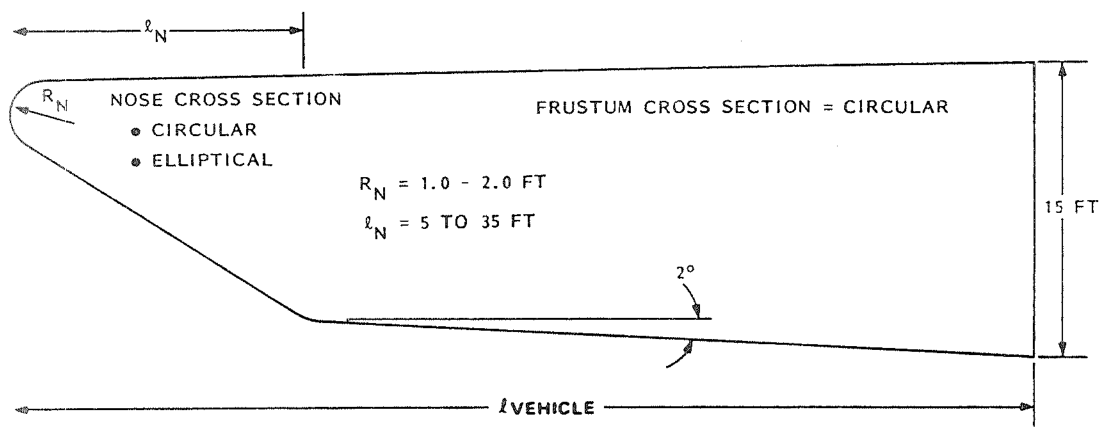


FIGURE 2

EFFECT OF NOSE BEND ON MAXIMUM L/D



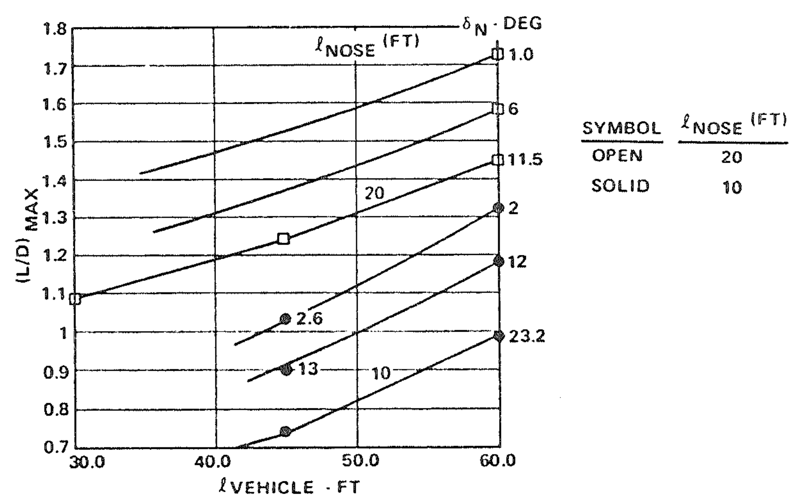


FIGURE 3

AOTV CONFIGURATIONS SELECTED FOR FURTHER SENSITIVITY STUDIES

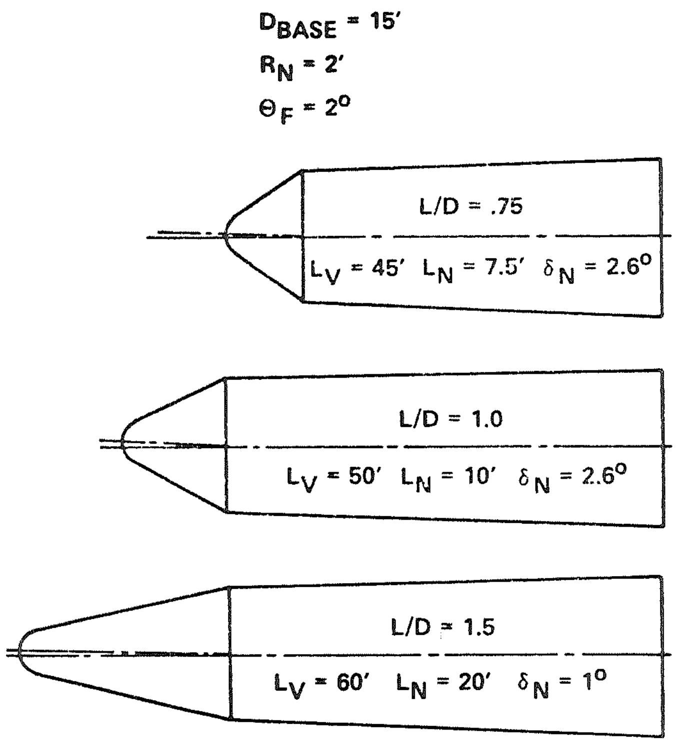


FIGURE 4

MAJOR FACTORS FOR IMPROVING MID L/D PAYLOAD DELIVERY PERFORMANCE

WITHIN STATE OF ART

REDUCE AOTV DRY WEIGHT
- SHORTEN VEHICLE
- COLD SOAK TPS PRIOR TO ENTRY

INCREASE L/D
- LENGTHEN NOSE
- STEEPEN FRUSTUM CONE ANGLE (BETTER X_{CP})
- DECREASE NOSE BEND ANGLE
- DECREASE NOSE RADIUS (HEATING LIMITATIONS?)

} LOSE PACKAGING VOLUME

IMPROVEMENTS IN STATE OF ART

REDUCE SIZE OF PROPULSION CORE
- INCREASE I_{SP}
- INCREASE MR - REDUCES LH_2 TANK SIZE
- INCORPORATE MULTIPLE SMALL ENGINES

REDUCE AOTV DRY WEIGHT
- STRUCTURAL SHELL, FRAMES AND SUPPORT
- FLAPS
- AVIONICS
- EPS
- PROPELLANT TANKS, TPS, ACS AND PROPULSION

FIGURE 5

A 38 FT GEO DELIVERY VEHICLE

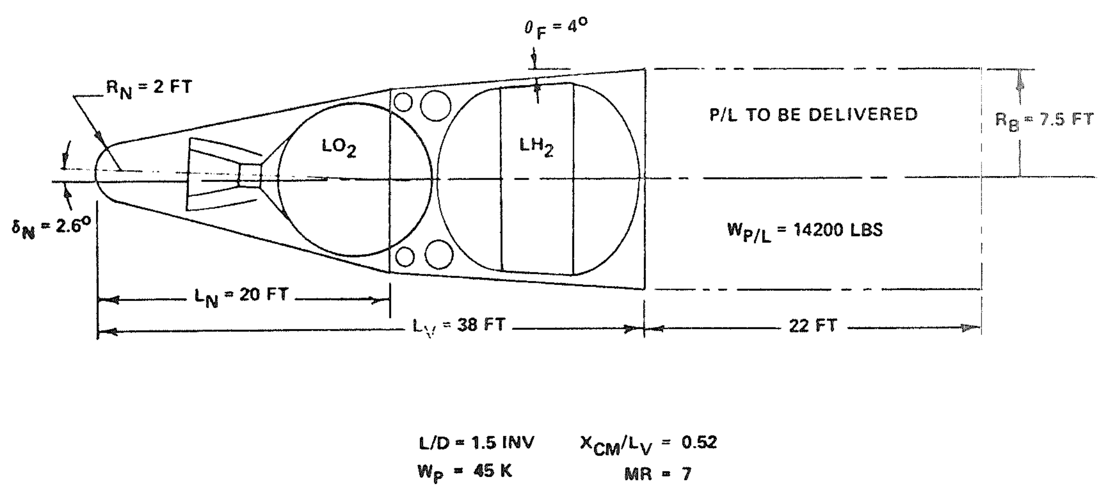


FIGURE 6

INCREASED SPECIFIC IMPULSE PROVIDES
MAJOR AOTV PERFORMANCE PAYOFFS FOR
BOTH GEO AND POLAR MISSIONS

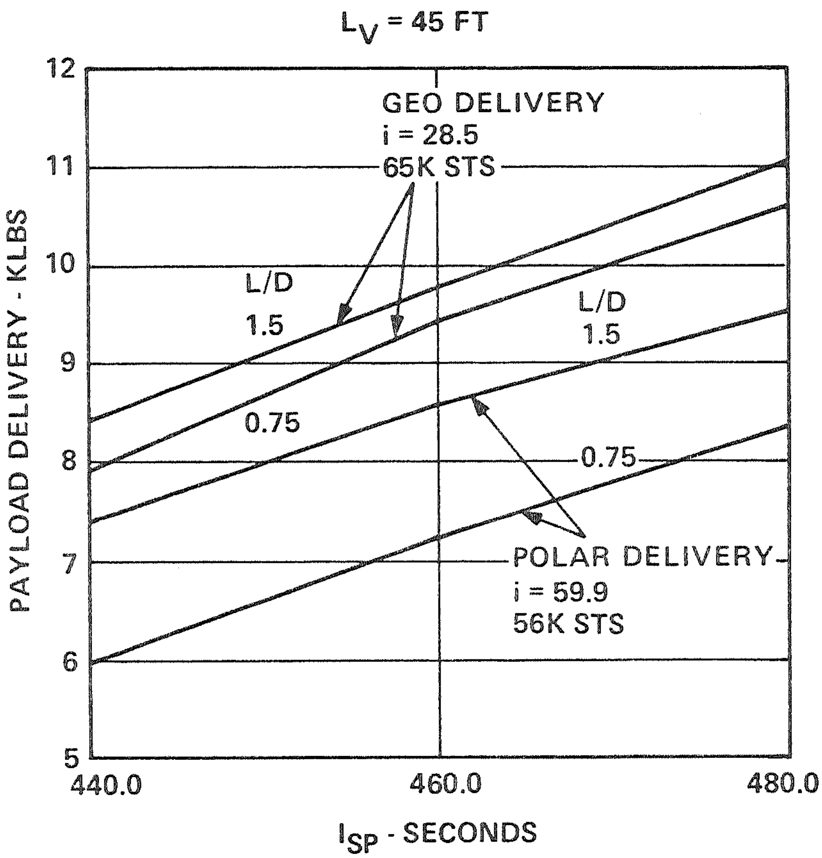


FIGURE 7

NUMBER OF ENGINES vs AOTV WEIGHT (MAN RATED)

- REPRESENTATIVE LARGE AOTV (e.g., H-1M)
  - 14.5' ϕ AT AFT END
  - AEROSHELL (TPS + STRUCTURE) WEIGHT ≈ 80 LB/FT OF LENGTH
- ADJUST PROPULSION SYSTEM TRADE FOR RETRACTABLE NOZZLES
  - ADD ≈ 10 LB/ENG FOR NOZZLE EXTENSION
- INCORPORATE RESULTS OF ENGINE/VEHICLE LENGTH TRADE
  - 15° GIMBAL ANGLE FOR 1 ⟶ 5 ENGS
  - MAXIMIZE ENG RADIAL LOCATION WITHIN AOTV
  - WITH ENG ℄ PARALLEL TO VEHICLE ℄, NOZZLE EXIT PLANE DEFINES END OF AEROSHELL

	GIMBALED					FIXED
NUMBER OF ENGINES	1	2	3	4	5	6
Δ VEHICLE LENGTH (FT)	0	- 0.25	- 2.25	- 3.17	- 4.83	- 4.92
Δ VEHICLE WEIGHT (LB)	0	-20	-180	-253	-387	-393
Δ PROPULSION SYS WT (LB)	0	+14	+ 1	+ 93	+185	+134
NOZZLE RETRACT ADJ (LB)	0	+24	+ 33	+ 40	+ 50	0
Σ = AOTV Δ WT (LB)	0	+18	-146	-120	-152	-259

MIN AOTV WEIGHT WITH SIX ENGINES

PREFERRED

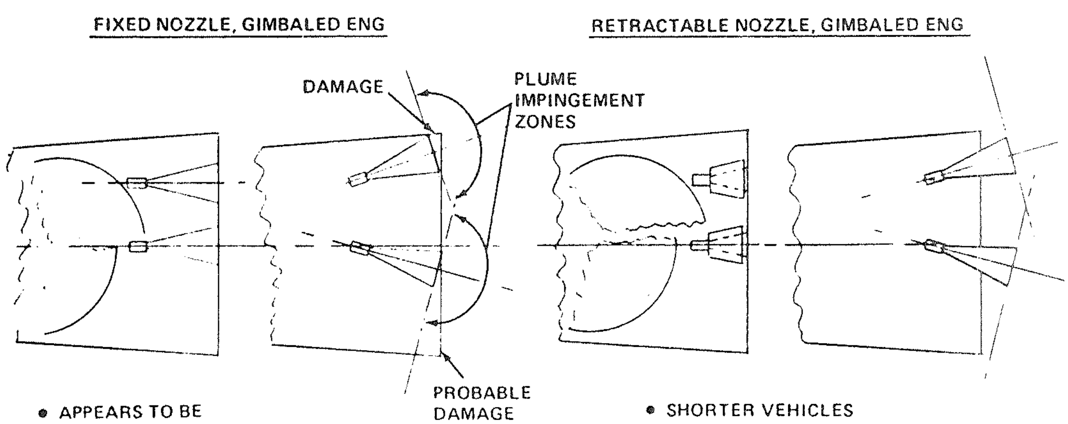
FIGURE 8

SOME BI-CONIC AFT END & ENGINE INTERACTIONS

- CURRENT AOTV GROUNDRULE: "ALL REUSEABLE AOTV COMPONENTS MUST BE PROTECTED BY AEROSHELL"

FIXED NOZZLE, FIXED ENGINE

- REQUIRES MULTIPLE ENGINES ⇒ "LOW THRUST" PER ENGINES ⇒ SHORT ENGINES
- SMALL ENGINES FIT INTO "CORNERS & HOLES"
  - SHORT AOTVs RESULT



- APPEARS TO BE UNACCEPTABLE

- SHORTER VEHICLES
- NO PLUME IMPINGEMENT DAMAGE

FIGURE 9

SMALL MANNED AOTV "H-1M'

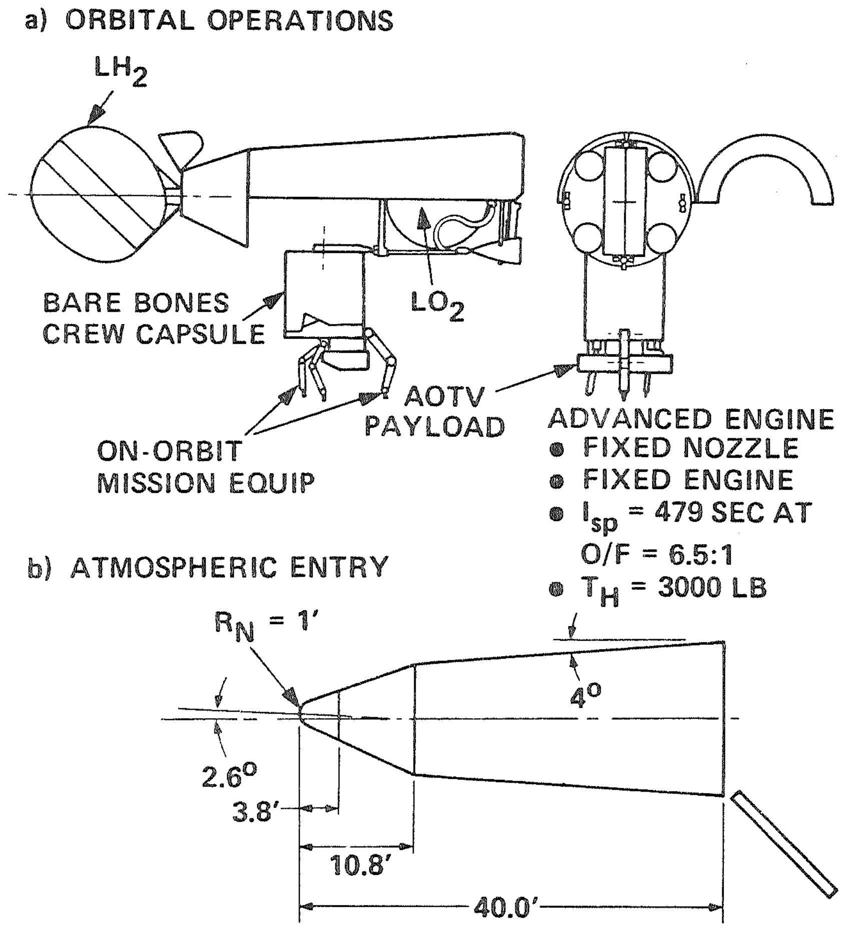
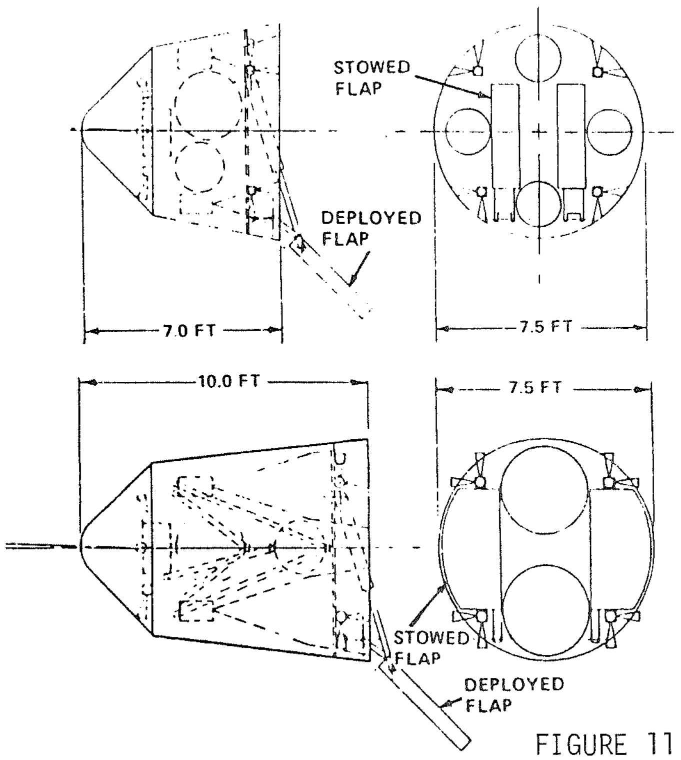


FIGURE 10

PERFORMANCE COMPARISON OF OH-3 & OH-1



OH-3

- FOUR ADVANCED EXPANDER ENGINES
  ϵ = 400: 1
  I_{SP} = 475 SEC
- TOTAL THRUST = 12,000
- EFFICIENT FOR OFFSET C.G.
- POSSIBLE ENGINE OUT CAPABILITY
- 4000 LB DRY WEIGHT
- PAYLOAD DELIVERY TO GEO TRANSFER ORBIT WITH 11,930 LB OF PROP: W_{PAY} ~ 11,400 LB

OH-1

- TWO ADVANCED EXPANDER ENGINES
  ϵ = 1000: 1
  I_{SP} = 480 SEC
- TOTAL THRUST = 6000 LB
- 4000 LB DRY WEIGHT
- PAYLOAD DELIVERY TO GEO TRANSFER ORBIT WITH 11,930 LB OF PROPELLANT: W_{PAY} = 11,400 LB

FIGURE 11

SUMMARY OF PAYLOAD DELIVERY SENSITIVITIES FOR A SINGLE STAGE AOTV-65K STS

PARAMETER		MISSION	P/L SENSITIVITIES L/D = 0.75	1.5
AOTV DRY WEIGHT	$\frac{\Delta W_{P/L}}{\Delta WT_{DRY}}$ (LB/LB)	GEO DELY	-1.65	-1.65
		6 HR POLAR	-1.7	-1.5
ENGINE I_{SP}	$\frac{\Delta W_{P/L}}{\Delta I_{SP}}$ (LB/SEC)	GEO DELY	64	64
LIFT-DRAG RATIO	$\frac{\Delta W_{P/L}}{\Delta L/D}$ (LB)	GEO DELY	430	430
		6 HR POLAR	2000	1700
		GEO MANNED RT	800	800
PROPULSIVE PLANE CHANGE AT MISSION ALTITUDE	$\frac{\Delta W_{P/L}}{\Delta i_{PROP}}$ (LB/o)	GEO DELY	-34	-34
		6 HR POLAR	-183	-183

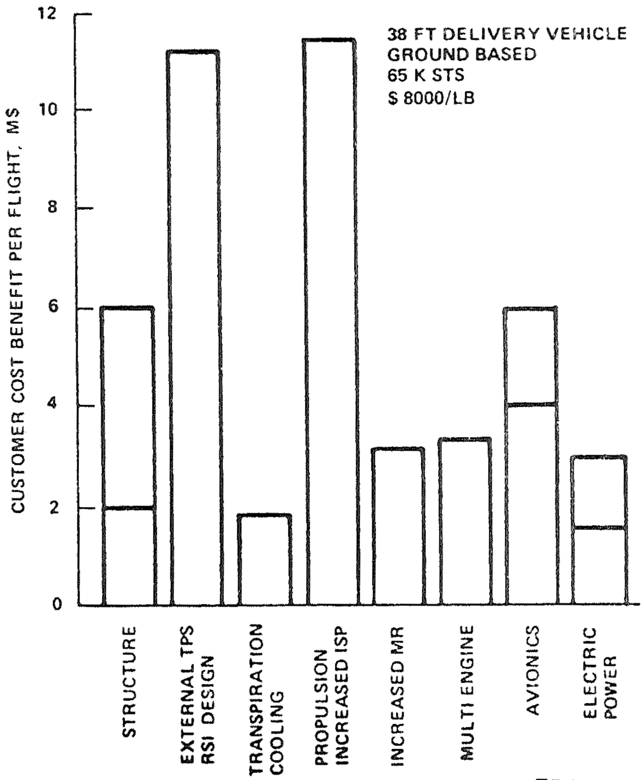
FIGURE 12

TECHNOLOGY ADVANCEMENT POTENTIAL

AOTV SUBSYSTEM ELEMENT	EXPECTED IMPROVEMENT
STRUCTURE (SHELL, FRAMES, SUPPORTS & FLAPS)	10 TO 30% WEIGHT REDUCTION
THERMAL PROTECTION SYSTEM	UP TO 69% WEIGHT REDUCTION
TRANSPIRATION COOLED NOSE	7° PLANE CHANGE INCREASE FOR 5 X GEO RETURN
AVIONICS	50 TO 70% WEIGHT REDUCTION
ELECTRICAL POWER SUPPLY	20 TO 38% WEIGHT REDUCTION
NEW CRYOFUELED ENGINE	Isp UP TO 480 SEC

FIGURE 13

EFFECT OF TECHNOLOGY ADVANCES ON CUSTOMER COST BENEFIT



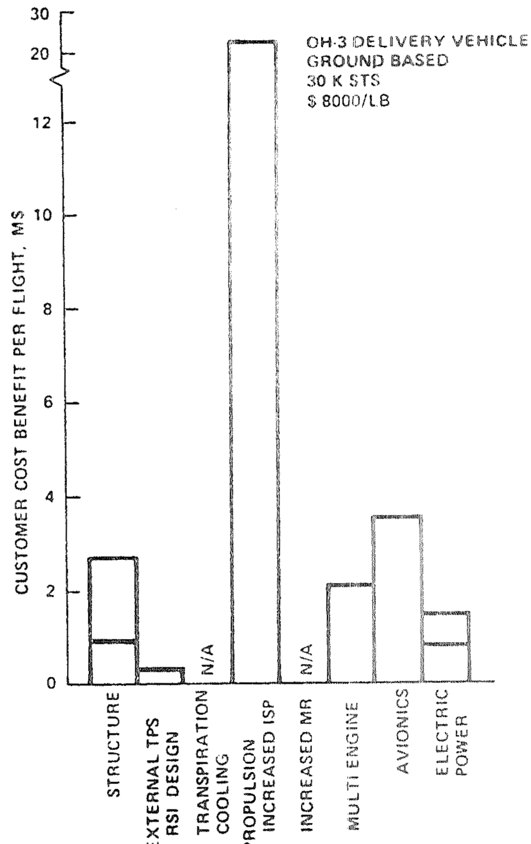


FIGURE 14

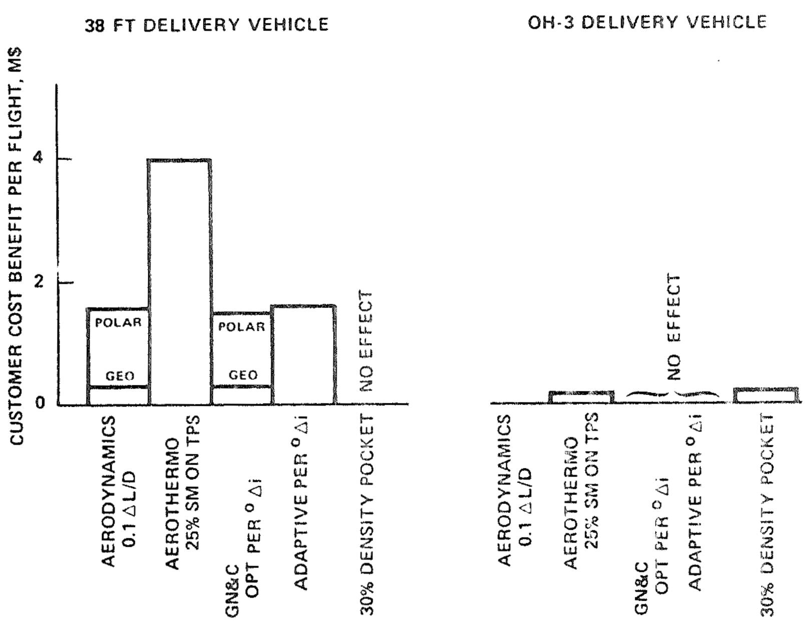
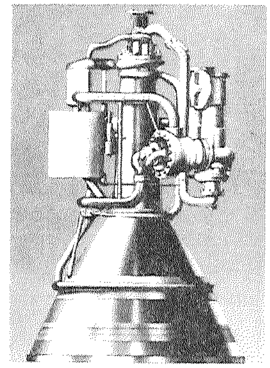


FIGURE 15

OTV PROPULSION SYSTEM CHALLENGES

GOALS

VACUUM SPECIFIC IMPULSE lbf-sec/lbm	520
VACUUM THROTTLE RATIO	30:1
NET POSITIVE SUCTION HEAD, lbf-ft/lbm	0
WEIGHT, lbm	360
LENGTH (STOWED), INCH	40
RELIABILITY	1.0
SERVICE LIFE	
BETWEEN OVERHAULS, CYCLES/hr	500/20
SERVICE FREE, CYCLES/hr	100/4



REQUIREMENTS

PROPELLANTS	HYDROGEN/OXYGEN
TOTAL VACUUM THRUST, lbf	10,000 - 25, 000
ENGINE MIXTURE RATIO	6 ± 1

CD-83-13814

FIGURE 16