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Propulsion Issues for Advanced Orbit Transfer Vehicles

Larry P. Cooper
Lewis Research Center
Cleveland, Ohio

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PROPULSION ISSUES FOR ADVANCED

ORBIT TRANSFER VEHICLES

Larry P. Cooper

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

Studies of the United States Space Transporation System show that in the mid-to-late 1990s expanded capabilities for Orbital Transfer Vehicles (OTV) will be needed to meet increased payload requirements for transporting materials and possibly men to geosynchronous orbit.

This paper presents discussion and observations relative to the propulsion system issues of space basing, aeroassist compatibility, man ratability and enhanced payload delivery capability. These issues will require resolution prior to the development of a propulsion system for the advanced OTV. The NASA program in support of advanced propulsion for an OTV is briefly described along with conceptual engine design characteristics.

INTRODUCTION

This paper presents observations and discusses a number of issues related to the design of a propulsion system for an advanced Orbit Transfer Vehicle (OTV). It also includes a review of ongoing NASA sponsored efforts on advanced OTV propulsion systems.

For the 1990s and beyond it is envisioned that an integrated Space Transporation System consisting of the Space Shuttle, a Space Station, an Orbit Maneuvering Vehicle and an Orbit Transfer Vehicle will exist to deploy, service and retrieve payloads in high or geosynchronous orbit (GEO). The system would operate as shown in figure 1. In this scenario, the Space Shuttle would deliver and return payloads to the station located in low earth orbit. Potential payloads would include spacecraft to be placed in higher orbits, Orbit Transfer Vehicles and propellants to transport them, as well as supplies for the space station and free flying payloads for low earth orbit. It is envisioned that in addition to its scientific and industrial roles, the space station will become the operations and service center for Orbit Transfer Vehicles. Payloads from the Shuttle would be mated to the OTV, propellants loaded and prelaunch checkouts conducted. Upon return the OTV would rendezvous with the Space Station, payloads would be retrieved and maintenance performed to ready the OTV for the next mission. The Orbit Maneuvering Vehicle would serve as the utility spacecraft for low earth orbit. It transfers payloads and supplies between the Shuttle and Space Station as well as places, retrieves and services free flying satellites in low earth orbits. The Orbit Transfer Vehicle would operate primarily between low earth orbit and geosynchronous orbit as a reusable spacecraft and as an expendable vehicle for planetary missions.

The role of the Orbit Transfer Vehicle in placing, retrieving and servicing payloads in high earth orbits represents a significant departure from current design and operational philosophy for upper stages and is driven by the need to achieve significant reductions in payload placement costs. It is envisioned that the advanced OTV will be a reusable vehicle, based and maintained primarily at the space station. The vehicle will be man rated and sufficiently versatile to cost effectively perform planetary transfers and placement of large, acceleration-limited, space structures in geosynchronous orbit. The vehicle will incorporate some form of aeroassist on return to the low earth orbit as shown in figure 2. This maneuver uses the drag induced by the earth's atmosphere to reduce the OTV velocity and thereby reduces the propellants required for the retroburn. As shown in figure 3 payload delivery with aeroassist is nearly double that of an all propulsive return vehicle and only 25 percent below the expendable vehicle.

The cost effectiveness of an advanced Orbit Transfer Vehicle has been the subject of several government and industry studies; most recently in connection with studies (refs. 1 to 8) of space station needs. As shown in table 1 (ref. 2), the cost per payload pound to geosynchronous orbit for a reusable space-based, cryogenically-fueled OTV has been projected to be significantly less than its competitors. Life cycle cost advantage of course is dependent upon the assumed mission model, but as shown in table 2 (ref. 2), over one billion dollars per year could be saved based on 75 percent market share of potential 23 OTV missions per year.

PROPULSION ISSUES

The characteristics envisioned for an advanced Orbit Transfer Vehicle offer a number of opportunities and challenges to the designers of propulsion systems. In particular, the impacts of space basing, compatibility with aeroassist maneuvering and man ratability must be included for the first time in addition to enhanced payload delivery capability. Propulsion studies (refs. 9 to 11) and discussions among government and industry have defined numerous options and approaches which could be utilized.

Space Basing

Early studies (refs. 12 to 14) of reusable Orbit Transfer Vehicles assumed the OTV would be flown into LEO with its payload and returned for maintenance on earth. More recently studies have focused on the benefits of basing and maintaining the OTV in space. These studies (refs. 1 to 8 and 15) have shown generally positive results for space basing ranging from approximately 10 percent to 100 percent cost savings over a ground based OTV depending on the mission model, vehicle characteristics and propellant costs. The space based Orbit Transfer Vehicle has the additional advantages of increased payload length capability. The full shuttle bay can be utilized for the payload since the payload and OTV are being mated in orbit.

The space based OTV propulsion issues reside primarily in the design philosophy to be adopted for health monitoring and maintenance of a resuable propulsion system. The OTV and Space Station studies have identified a number of options for OTV servicing including pressurized shirt sleeve enclosures, remote mechanized servicing and space suited astronauts. It is anticipated that the propulsion system could be made space serviceable at the subcomponent, component or total engine levels if cost effective. Accessibility of the engine and its subelements will need to be addressed since current practice is to minimize packaging volume and to use welded and flanged joints with numerous bolts. As shown in figure 4 (ref. 11) a number of possibilities exist with more open, accessible designs or plug-in components on a pallet.

A servicing philosophy of preventive maintenance coupled with graceful component degradation and removal-for-cause will need to be developed. In particular a determination of engine subelements which can be replaced without compromising flight certification will be required, as well as, a spares stocking policy.

A critical element of an advanced space based OTV engine will be its health monitoring system. This system will be a key contributor to maintenance decisions, provide the automated checkout for pre and post flight inspection and guide flight decisions by warning of anomalous conditions. The design architecture of this system will be significantly influenced by the selected maintenance philosophy and the service environment. Sensor capabilities may need to be significantly upgraded over the technology of the reusable Space Shuttle main engine to support this architecture.

Aeroassist Compatibility

Aeroassist has emerged as an attractive technology for enhancing the capabilities of reusable Orbit Transfer Vehicles. As shown in figure 5, the required total OTV mass for a typical manned mission can be nearly halved by utilizing aeroassist technology. Approximately eighty million dollars would be saved by eliminating the Shuttle flight to deliver the additional propellants. If missions are constrained to single shuttle launch capability, aeroassist would be mission enabling for manned servicing of satellites in GEO.

A number of aeroassist concepts have been conceived and studied by government and industry (refs. 16 to 18). As shown in figure 6 these have ranged from low lift to drag concepts (< 0.75) such as the inflatable ballute and aerodynamic brake through moderate (0.75 to 1.5) lift to drag biconic shapes, to high (> 1.5) lift to drag vehicles. The operational considerations and limitations of these concepts differ significantly, creating a challenging environment for the propulsion designer.

A key operational concern is introduced by the variability of the earth's atmosphere which displays a degree of nonuniformity in density. While progress has been made in prediction of the general atmospheric variations, more localized, seeming random pockets of density nonuniformity have been found which cannot be predicted. Since aeroassist OTVs rely on the atmosphere to reduce the velocity for LEO insertion, atmospheric variability, and worse, unpredictability considerably complicate guidance, navigation and control algorithms. Use of the propulsion system in either rapid stepwise or continuously throttlable thrust modes for drag modulation may be necessary to achieve the required orbital accuracy.

Another operational concern may surface from unreliability associated with aeroassist concepts. Should a failure of the aeroassist elements occur preceding or during the atmospheric pass, the propulsion system may be required to perform at emergency levels to save the vehicle and payload.

An important issue for propulsion compatibility with aeroassist concepts is the engine length. In general, aeroassist concepts to date prefer short engine length with high engine performance. Reasons for short length include management of the center of gravity in the Shuttle payload bay, reduced weight of vehicle, improved packaging and improved control characteristics. Approaches to short engine length while maintaining high engine performance have included multiple small engines with fixed high area ratio nozzles and larger engines with high area ratio nozzles which can be extended and retracted. Since both approaches appear acceptable, the selection will hinge on other considerations, such as complexity, reliability and cost.

Man Ratability

NASA and Contractor Mission Models project manned missions to geosynchronous orbit beginning in the late 1990s. These missions are primarily to service or repair satellites although retrieval of payloads from GEO is also envisioned.

The definition of man ratability is a primary issue in terms of establishing propulsion design requirements. Surveys of historical precedents reveal that no universal definition has existed. The degree of allowable risk for astronauts that industry and government consider acceptable has varied considerably. Approaches to reducing the perceived risks have included failure analysis to identify and replace single point failure sites with redundancy and design approaches which incorporate large safety factors. In both cases considerable system weight and complexity have been introduced, often without quantifiable benefit.

A quantifiable approach which has been suggested for determining required man rated reliability is based on historical career mortality risks (ref. 13). As shown in figure 7 the 1969 historical mortality risks for jet fighter pilots and astronauts were considerably higher than airline pilots and policemen. If, in the future, we wish to make the OTV astronaut's risk similar to that of a commercial pilot, an OTV mission reliability of at least 0.9986 would be required for an astronaut with 10 career flights. Lower OTV reliability is acceptable at greater astronaut risk.

Use of mortality data to define OTV reliability may only establish minimum reliability levels. The mortality approach would only be based upon crew safety considerations and in most scenarios the payload and mission objectives would be sacrificed. High spacecraft costs including acquisition, launch and insurance, as well as urgent military payloads may require that mission success reliability exceed man rated reliability.

After establishing required OTV system reliability, assignment of acceptable levels of reliability to the various subsystems is the next step as shown in figure 8. This would be based on projections of historical data or actual test data when available. In the case illustrated, the main propulsion system contributes 25 percent of the total unreliability and must be 0.9996 reliable to meet the man rating criteria. It should be noted that this approach can be extended to include reliability associated with OTV mainte- nance, storage, orbital debris and even the utilization of a rescue vehicle, crew shelters or direct earth return capability.

Assignment of propulsion subsystem reliability is of course a function of the subsystem design maturity. For the propulsion system of an advanced OTV a number of design approaches incorporating quantifiable component reliability, and graceful degradation coupled with redundancy and design margins have been suggested. While multiple engine configurations are generally accepted as necessary, considerable uncertainty remains over the number of engines and if multiple components should be included. These issues will ultimately be resolvable through life cycle cost analysis comparing the degree of redundancy and component reliability.

Enhanced Payload Delivery Capability

Mission models for Orbit Transfer Vehicles contain a wide range of mission types in terms of payload mass, volume, length and operational concerns. These require enhanced payload delivery capability. The primary requirements for the propulsion system are for increased thrust range for mission versatility and higher performance with reduced maintainence for lower payload delivery costs. In addition, most mission models have a fair degree of uncertainty and often do not extend much into the next century. Based upon the experience with the Centaur upper stage and the RL10 engines it would be reasonable to expect that the OTV and propulsion system will need capability for growth well beyond their original configuration.

A wide variety of OTV configurations and operational approaches have been proposed to provide the required mission versatility. These include the various aeroassist concepts, multistage vehicles, propellant combinations and basing modes as well as multiple burn strategies. The primary propulsion issue resides in satisfying the wide thrust range requirement imposed by the various missions in a cost effective manner.

Total thrust levels for the OTV missions range from the low levels imposed by transport of large acceleration limited space structures and the use of the low thrust exhaust plume for thermal protection of some aeroassist concepts up to the high thrust levels needed by priority military payloads, manned missions and planetary injection. Several solutions have been proposed to satisfy these requirements including multimode engine operation to give several discrete thrust levels, fully throttlable operation and multiple engine operation. The optimum approach will need to be interactively resolved with the vehicle and operational scenario.

With regard to cost effectiveness of payload delivery by an advanced OTV, it is anticipated that the predominant GEO delivery costs will continue to be associated with initial placement in low earth orbit prior to transfer to GEO. As projected in figure 8 (ref. 2) for a space based cryogenic OTV, only 5 percent of the total costs are related to the OTV operations while 95 percent is associated with payload and propellant delivery to LEO. Other studies with storable propellants show similar results. Consequently reduction of propellant requirements by increasing engine performance can have a significant effect on payload placement costs with generally 1 sec of I_{sp} being worth $1 million per OTV flight because of reduced Shuttle launch requirements. For this reason, it is generally accepted that the high performance of cryogenic hydrogen-oxygen propellants are the most cost effective propellants for a reusable OTV. As shown in figure 10 when the reduced propellant costs from increased performance are accumulated over a typical mission model (ref. 19) from 1994 to 2000 considerable cost savings are possible.

Another issue relative to propulsion system cost is maintenance and engine life. It has been projected that space based maintenance operations will cost on the order of $50 000 per hour and that removal and replacement of an engine will consume 18 to 25 hours (ref. 20). This suggests that propulsion designs will need to have long life between removal, that maintenance be minimized and that designing for maintainability should be pursued.

ADVANCED OTV PROPULSION TECHNOLOGY

To meet the propulsion requirements for advanced OTV, NASA has established the Advanced OTV Propulsion Technology Program. The program's objective is to establish by the early 1990s the technology base for high performance, multiple restarts, variable thrust orbital transfer propulsion systems which could be man rated, space basable and compatible with aeroassist maneuver vehicles.

As a precursor to the development of an advanced OTV propulsion system, this program will allow the latest technology to be incorporated into the advanced engine while providing a low risk, minimum cost development program.

APPROACH

The advanced OTV propulsion technology program has been structured around a projected need date for an advanced engine of 1995 with a development program beginning in 1991. The technology program is composed of three elements:

Conceptual designs and technology definition. - consisting of study efforts to conceptually define advanced OTV propulsion systems and to identify, screen and propose advanced technology concepts at the subcomponent, component and propulsion system levels which would benefit the future OTV propulsion system.

Exploratory research. - Consisting of analytical and experimental efforts to evaluate advanced technology concepts critical to the success of future OTV propulsion systems.

Critical component technology. - To experimentally verify the technology readiness of critical components.

A programmatic schedule is shown in table III. Conceptual Design and Technology Definition was initiated in 1981 with three rocket engine manufacturers and will continue throughout the program, generating technology concepts for advanced propulsion systems. Exploratory Research has been initiated in 1983 while the Critical Component Technology would begin in 1986.

Propulsion System Characteristics

The propulsion system characteristics for this program have been discussed in detail in reference 21 and are presented in table IV and table V. Based upon these characteristics Conceptual Designs and Technology Definition Studies were initiated in 1981 with Aerojet TechSystems Company, United Technologies Corporation-Pratt & Whitney Aircraft Group and Rockwell International-Rocketdyne Division, to define propulsion concepts for an advanced Orbit Transfer Vehicle and to identify the technologies which would be required to demonstrate readiness for a Design, Development Test and Engineering (DDT E) program in the early 1990s. The concepts and technologies defined by each Contractor have been discussed in reference 21 and are summarized in figure 11.

All utilize the expander power cycle rather than the staged combustion cycle. Pratt & Whitney and Rocketdyne use the hydrogen expander cycle while Aerojet uses a hydrogen and oxygen expander cycle. By applying advanced technology, the chamber pressure of the simpler expander cycle can be increased so that performance is comparable with a staged combustion cycle engine of similar size while retaining superior life features of the expander cycle. All the engine concepts utilize high chamber pressure and large area ratio nozzles to obtain high performance.

The Aerojet single engine thrust level of 3000 pounds was selected to facilitate multiple engine installation, reflecting Aerojet's approach to reliability for a man rated OTV. Similarly the selection by the other Contractors of 15 000 pounds thrust concepts reflects their current assessment of manned missions and man rating of OTVs. A single engine OTV is optimally sized at nominally 15 000 pounds thrust for manned GEO missions and with suitable backup systems may represent a viable approach to man rating the vehicle.

Hydrogen turbopump speeds are well beyond the state-of-the-art for all concepts. Each engine concept utilizes a different approach. Aerojet's turbopump has the highest operating speed. The design utilizes hydrostatic bearings for long life and stiff shaft approach to avoid operation above the first critical speed. Pratt & Whitney's turbopump utilizes roller bearings and an extremely stiff shaft design to avoid the 1st critical speed. Rocketdyne's turbopump design operates between the 3rd and 4th critical speed and could encounter subsynchronous whirl.

The oxygen turbopump of the Aerojet concept is oxygen driven while Pratt & Whitney and Rocketdyne favor conventional hydrogen drive. Oxygen drive presents some interesting options in engine packaging and eliminates interpropellant seals. However, the metal ignition hazard must be carefully addressed. Only Pratt & Whitney has gear driven turbomachinery. This approach simplifies control, but represents a considerable technology challenge to obtain long engine life and low maintenance.

For propulsion system control, Aerojet and Rocketdyne have selected closed loop control to maintain flexibility for optimum mission performance and in Aerojet's case to enable multiple engine thrust vector control. Pratt & Whitney has selected the open loop control method. All engine concepts would provide sufficient monitoring sensors to establish maintenance needs.

CONCLUDING REMARKS

Analyses of mission models for Orbit Transfer Vehicles generally support the need for developing a new vehicle with enhanced capabilities. The economic arguments suggest that this vehicle be reusable, space basable and utilize aeroassist technology. With missions ranging from manned servicing of satellites to low acceleration transfer of large structures, the vehicle must be highly versatile, reliable and cost effective.

It is anticipated that the new vehicle will embody significant departures from current design and operational philosophy for upper stages. The NASA program for Advanced OTV Propulsion is addressing the issues of reuse, space basing, aeroassist, man ratability and low cost payload delivery capability with regard to the propulsion system. This will provide the technology base for development, in the 1990s, of an advanced engine engineered for the needs of the next century.

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TABLE I. - OTV ECONOMIC COMPARISONS

Cost-per-pound to geosynchronous orbit

\$17 000/lb	PAM-D
\$21 000/lb	PAM-D11
\$21 000/lb	PAM-A
\$30 000/lb	IUS
\$9000/lb	Shuttle/Centaur
\$13 000/lb	Shuttle-based OTV
\$6000/lb	Space-based OTV

TABLE II. - OTV ECONOMIC BENEFITS ANALYSIS (1984$)

[Economic benefit per OTV mission = $125.5M - $62.9M = $62.6M; average number of OTV missions per year (1994-2000) = 17.3; OTV economic benefit per year = $62.6M x 17.3 = $1.08 billion.]

Cost factor (per 10 000 lb of payload)	Mission cost, millions of dollars	
	OTV	Competitor average[a]
Upper stage cost	0.5	17.0
Upper stage delivery to LEO	0.5	108.5 (includes payload)
Payload delivery to LEO	45.4	0
Operations/spares costs	3.0	0
Propellant delivery to LEO	13.5	0
Total	62.9	125.5

[a]PAM-D, PAM-D11, Leasat, PAM-A, Atlas/Centaur, Shuttle/Centaur, TOS, Shuttle-based OTV.

TABLE III - ADVANCED OTV PROPULSION TECHNOLOGY PROGRAM SCHEDULE

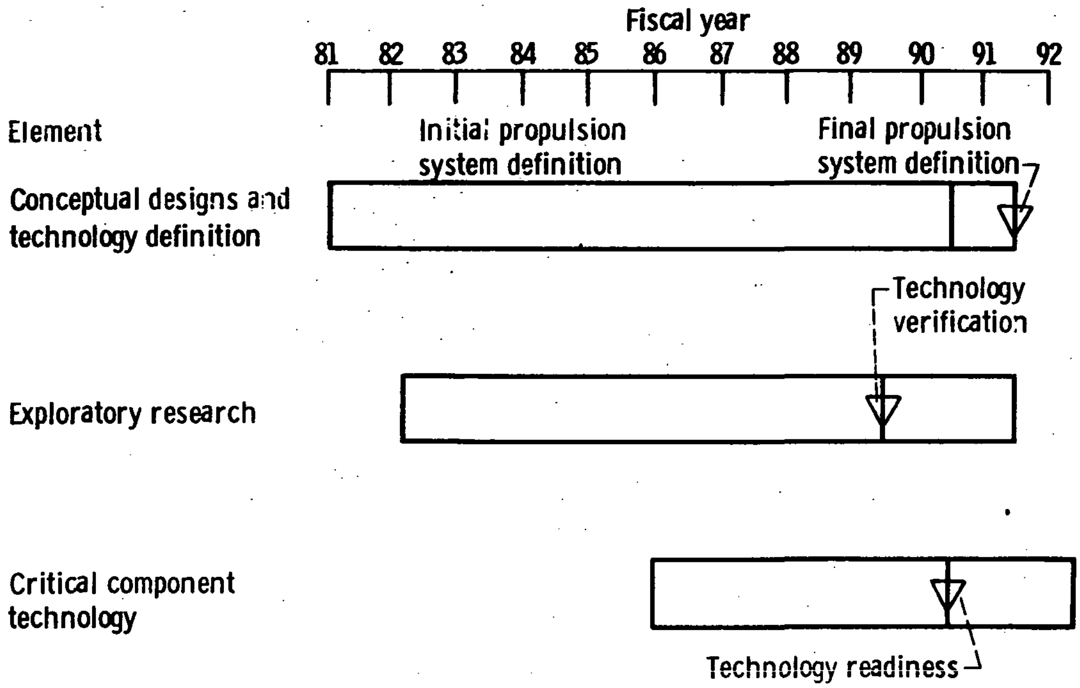


TABLE IV. - REQUIRED ADVANCED OTV PROPULSION SYSTEM CHARACTERISTICS

Characteristic	Requirement
Propellants - fuel	Hydrogen
oxidizer	Oxygen
Vacuum thrust (design point range)[a]	10 000 to 25 000 LBF
Engine mixture ratio, O/F (design point)	6.0
Engine mixture ratio range, O/F	5.0 to 7.0
Propellant inlet temperature - Hydrogen	37.8° R
oxygen	162.7°
Thrust vector control	±6.0 (square pattern)
Start cycle	Chilldown with propulsive dumping of propellants, engine start with pump inlets at propellent tank vapor pressure.

[a]Vacuum thrust range may be obtained from either a single engine or multiple engine configurations having total thrust within the specified range.

TABLE V. - ADVANCED OTV PROPULSION SYSTEM GOALS

Characteristic	Goal
Vacuum specific impluse, lb-sec/lbm	520
Vacuum thrust throttle ratio	30:1
Net positive suction head, ft-lbf/lbm	
Hydrogen	0
Oxygen	0
Weight, lbm	360
Length (stowed), in.	40
Reliability	1.0
Service life	
Between overhauls, cycles/hr	500/20
Service free, cycles/hr	100/4

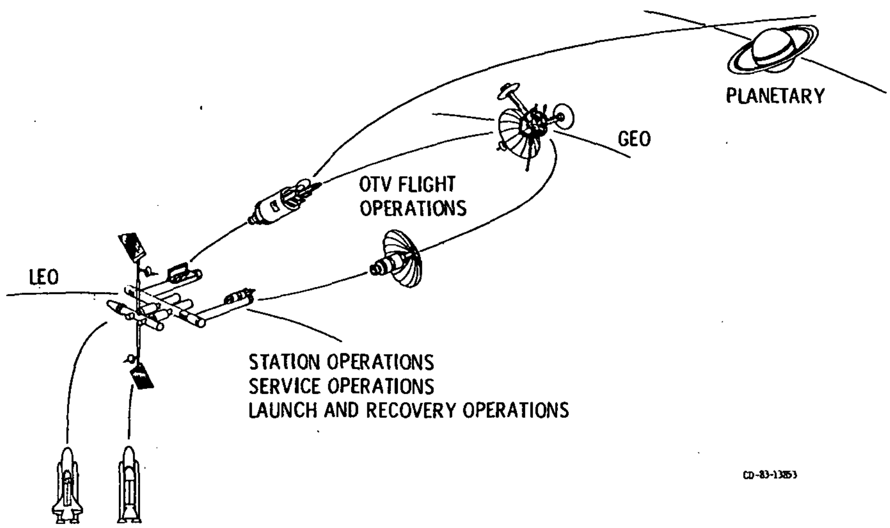


Figure 1. - Integrated space transportation systems, 1990's scenario.

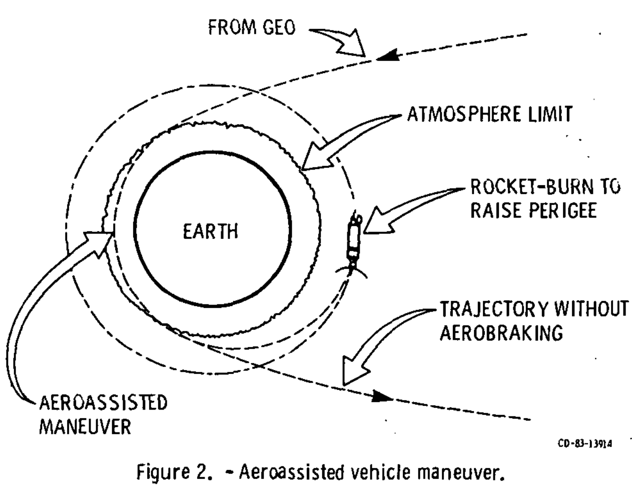


Figure 2. - Aeroassisted vehicle maneuver.

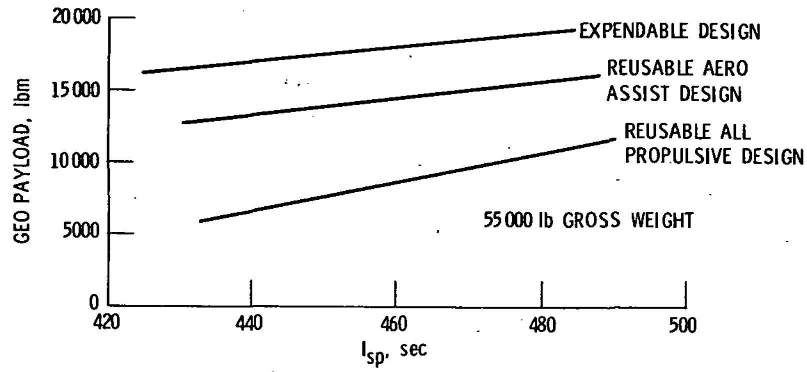


Figure 3. - OTV payload capability for GEO delivery.

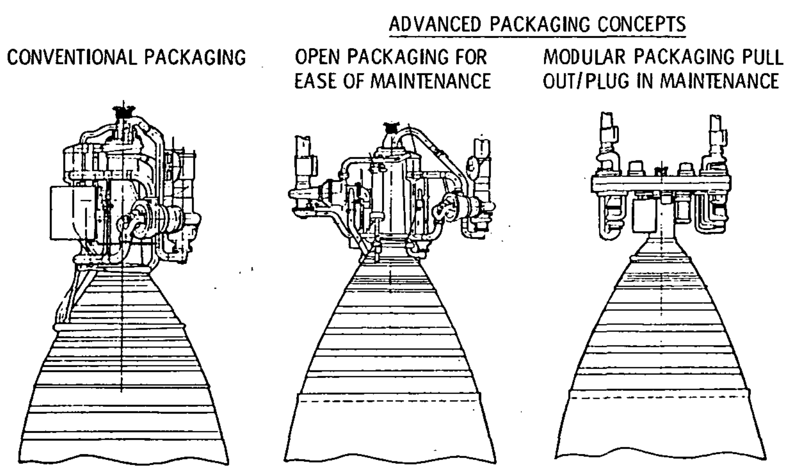


Figure 4. - STS/Space basable packaging concepts.

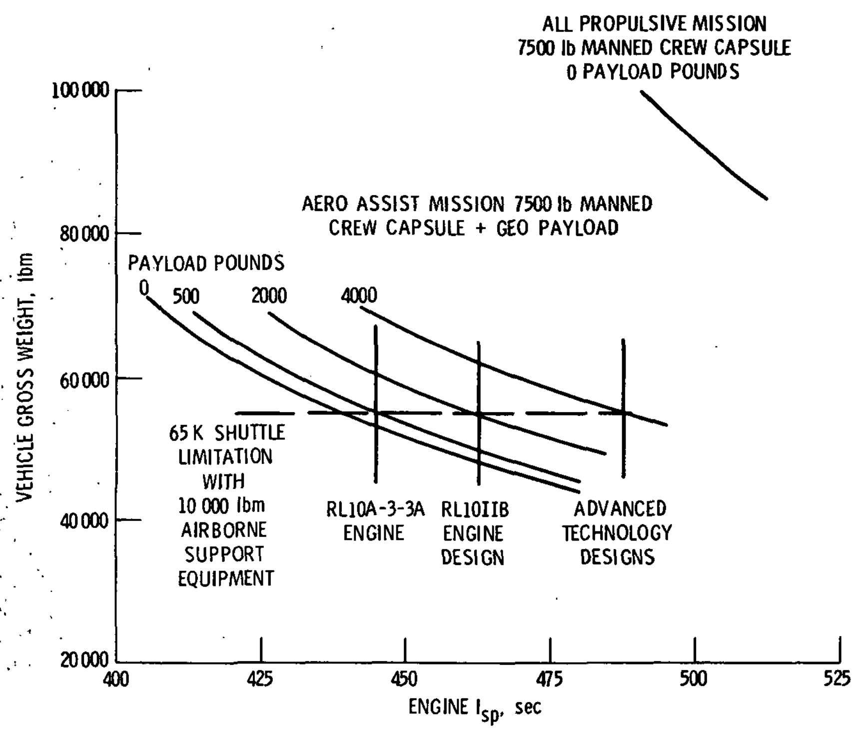
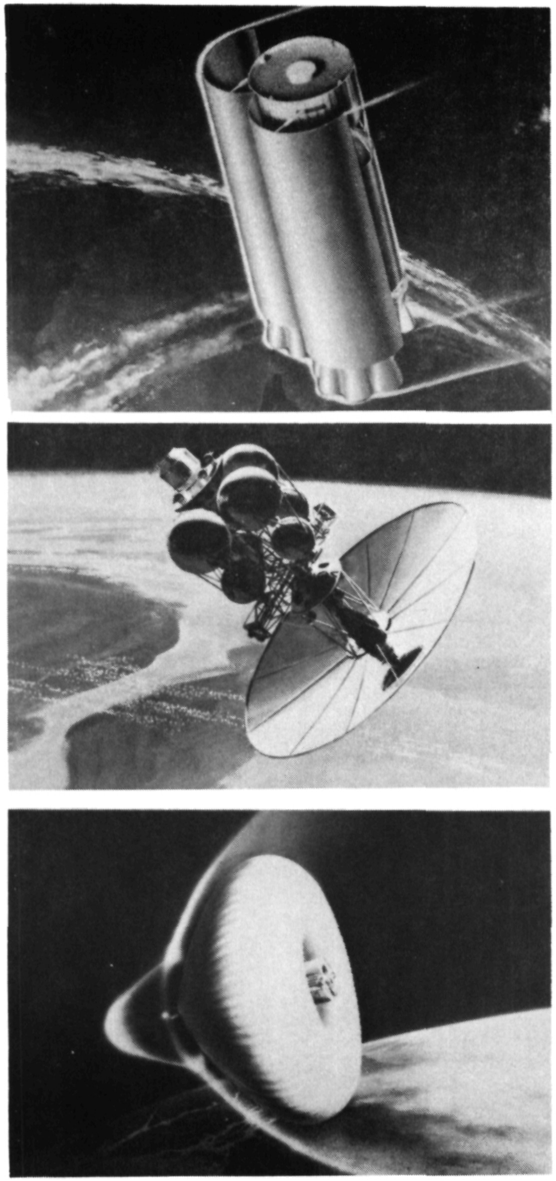
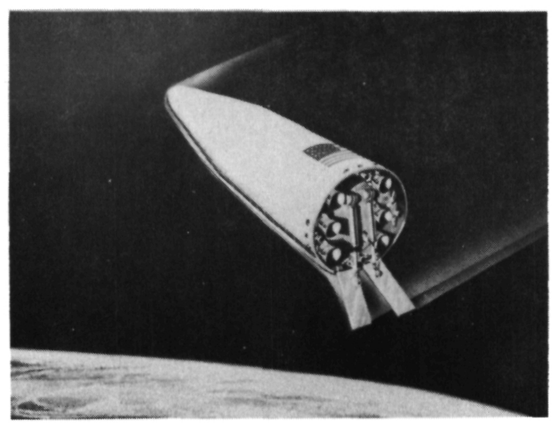


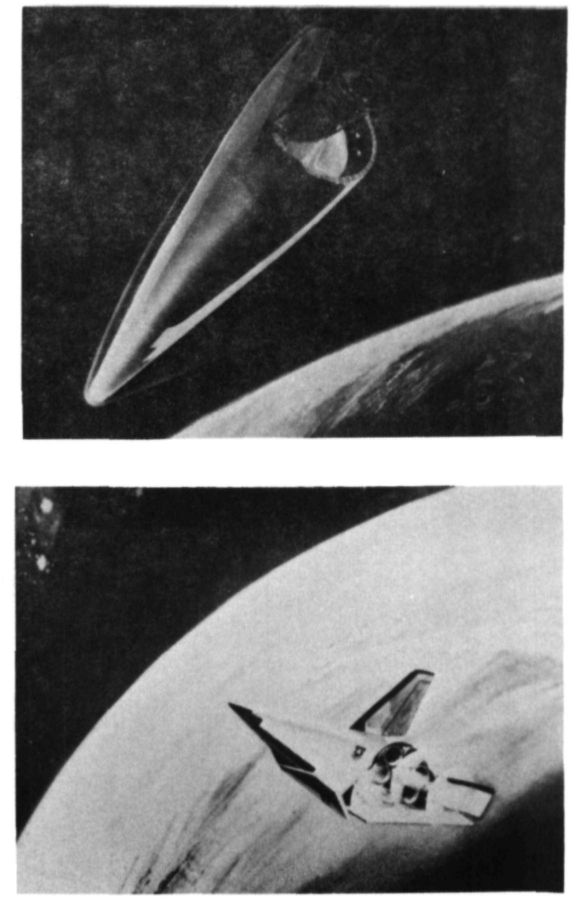
Figure 5. - OTV gross weight sensitivity and payload capability for manned missions as a function of engine performance.



(a) Low lift/drag.



(b) Medium lift/drag.



(c) High lift/drag.

Figure 6. - Aeroassist vehicle concepts.

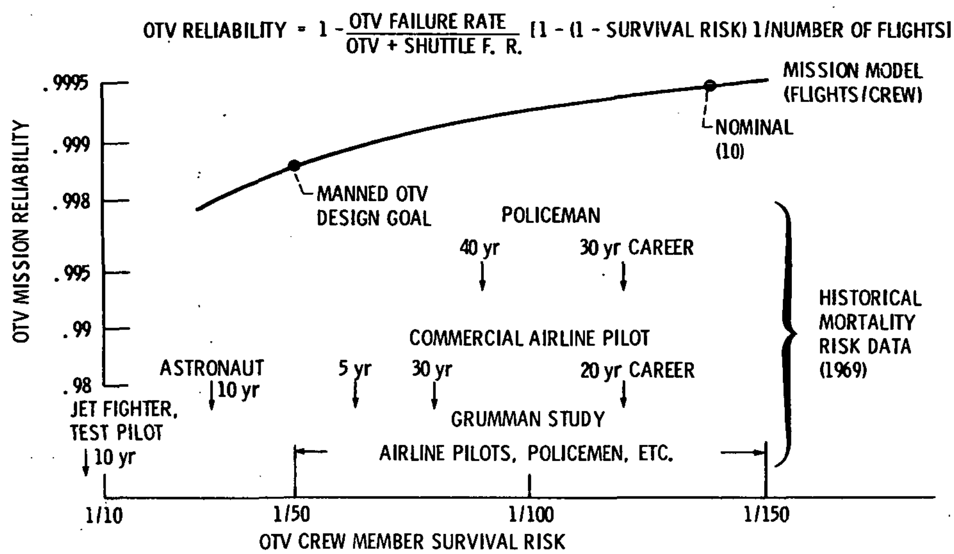


Figure 7. - Manned OTV mission reliability requirements.

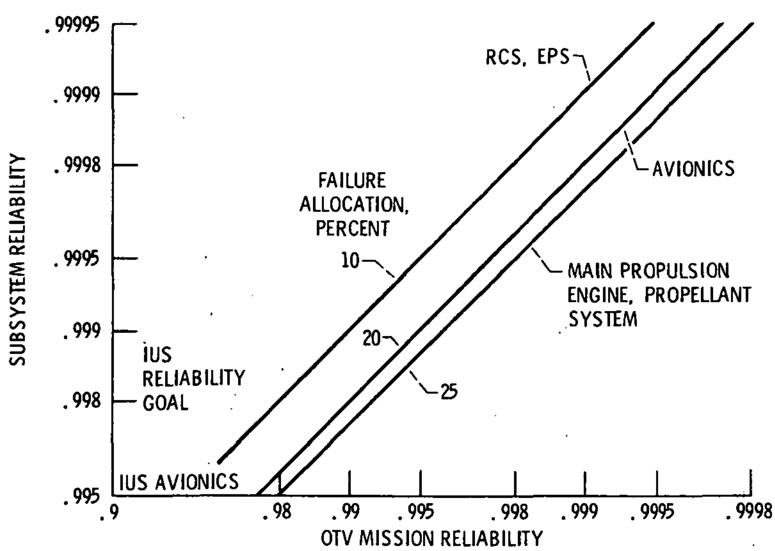


Figure 8. - Manned OTV subsystem reliability requirements.

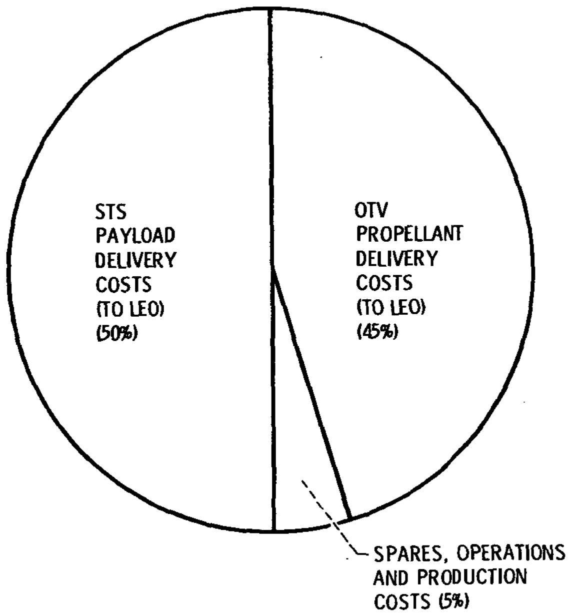


Figure 9. - Space based OTV major economic drivers.

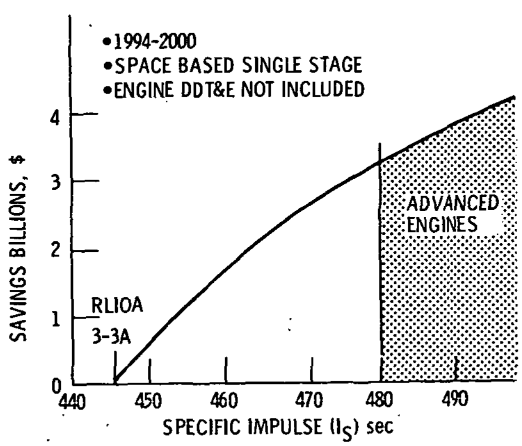
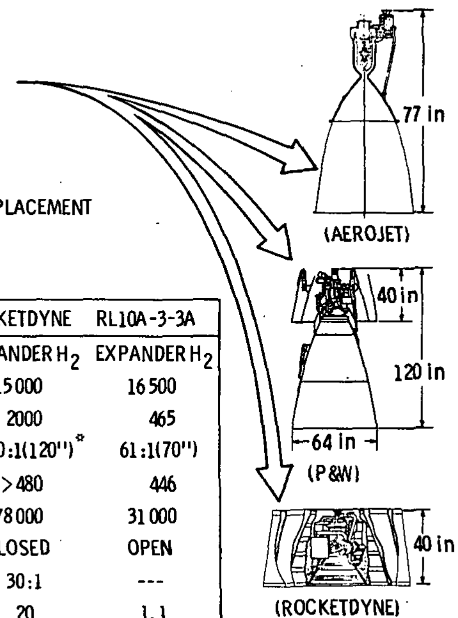


Figure 10. - Cost savings from increased engine performance.

PROPULSION DRIVERS

- SPACE BASING
- AERO ASSIST
- MANNED MISSIONS
- LOW G TRANSFERS
- LOW COST PAYLOAD PLACEMENT



KEY TECHNOLOGIES

GASEOUS OXYGEN TURBINE
ANNULAR COMBUSTION CHAMBER
MULTIPLE ENGINE CONTROL

HIGH SPEED GEARS LIFE
ADVANCED CHAMBER MATERIAL
HIGH AREA RATIO NOZZLE MATERIAL

HYDROGEN PUMP CRITICAL SPEED
MULTI VARIABLE CLOSED LOOP CONTROL
HIGH AREA RATIO NOZZLE MATERIAL

	AEROJET	P & W	ROCKETDYNE	RL10A-3-3A
CYCLE	EXPANDER H_2-O_2	EXPANDER H_2	EXPANDER H_2	EXPANDER H_2
THRUST, lbf	3000	15 000	15 000	16 500
PRESSURE, psi	2000	1500	2000	465
AREA RATIO	1200:1(77")	640:1(120")*	1300:1(120")*	61:1(70")
I_{sp} sec	> 480	> 480	> 480	446
H_2 rpm	200 000	150 000	178 000	31 000
CONTROL	CLOSED	OPEN	CLOSED	OPEN
THROTTLE RANGE	30:1	30:1	30:1	---
LIFE, hr	20	20	20	1.1

* RETRACTS TO 40 in.

Figure 11. - Advanced OTV propulsion concepts.

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Larry P. Cooper

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16. Abstract

Studies of the United States Space Transporation System show that in the mid-to-late 1990s expanded capabilities for Orbital Transfer Vehicles (OTV) will be needed to meet increased payload requirements for transporting materials and possibly men to geosynchronous orbit. This paper presents discussion and observations relative to the propulsion system issues of space basing, aeroassist compatibility, man ratability and enhanced payload delivery capability. These issues will require resolution prior to the development of a propulsion system for the advanced OTV. The NASA program in support of advanced propulsion for an OTV is briefly described along with conceptual engine design characteristics.

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