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FUTURE REQUIREMENTS AND APPLICATIONS FOR ORBITAL TRANSFER VEHICLES

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ABSTRACT

The capability of the Space Shuttle will be enhanced by use of the high-energy Centaur to provide payload transfer to higher orbits (geosynchronous, etc.) and for planetary escape missions. Future orbital transfer vehicles (OTV) requirements for NASA, military, and commercial exploitation of space will require improvements and technological developments such as increased performance, increased reliability, and increased mission versatility. Eventual OTV space basing should offer further cost reductions through vehicle reuse, freedom from Shuttle constraints, and possible STS propellant recovery.

This paper summarizes Centaur characteristics, performance, and program status and presents future considerations for orbital transfer vehicles into the Space Station era, including their capabilities, operational requirements, and the technology developments required to make them a reality.

INTRODUCTION

The goal of space transportation is to provide increased launch opportunity at lower cost. This paper addresses orbital transfer vehicles (from low earth orbit to higher orbits) and how improvements to this segment of the space transportation system can contribute to this goal for a number of applications:

- Commercial programs
  - Satellite placement
  - Satellite servicing
- NASA programs
  - Planetary missions
  - Satellite placement
  - Manned orbital operations
- DoD programs
  - Satellite placement
  - Storage/reconstitution
  - Threat avoidance/defense

High OTV performance (through high I_{sp} and low vehicle weight) minimizes propellants and maximizes payload. Hydrogen-oxygen is currently the highest performing chemical combustion rocket propulsion system (50% higher I_{sp} than solids or storables). Centaur (Figure 1) is being incorporated into the Space Transportation System (STS) to take advantage of this in the near future at affordable cost, and methods to further improve performance and versatility are being considered. As part of the STS, Centaur mission assignments include Galileo, ISPM, and two for DoD (Figure 2). Under a joint NASA/Air Force program, NASA and the Air Force are sharing development costs of the Centaur G (short version). NASA is funding Centaur G′ (long version).

Hydrogen-oxygen OTV are expected to improve and endure for many years until noncombustion propulsion (chemical-electric) becomes available to effectively remove I_{sp} limits.

CENTAUR

Centaur is the world's first liquid-hydrogen-powered space vehicle. Today, it is the United States' premier upper stage for launching large geosynchronous communications satellites, solar exploration spacecraft, and observatories to study the farthest reaches of space.

The flight-proven Centaur system has been launched 67 times on Atlas and Titan boosters. It has performed flawlessly during the last decade of operation, due in part to the improved guidance, navigation, and electronics systems incorporated in the early 1970s. It is currently undergoing performance improvements for INTELSAT that will enhance its capabilities for the 1980s.

Integrating a modified Centaur high-energy stage with the Space Shuttle offers a significant increase in

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the high earth orbit and earth-escape performance capabilities of the STS. Centaur is the only affordable near-term solution for attaining this capability. Figure 3 shows Centaur performance for planetary and geosynchronous earth orbit missions, indicating its capability to perform the Galileo "direct" mission as well as placement of heavy payloads at GEO for DoD and other users.

Studies were begun in 1979 to integrate Centaur into the Space Shuttle using the current D-1 configuration with 30,000 pounds of propellant and cylindrical 10-foot-diameter tanks. Delay of the Galileo mission, however, increased energy requirements to the extent that additional propellant is required to perform the mission. A decision was made to increase the LH_2 tank diameter to the maximum allowed within the cargo bay (14.2 feet), and to lengthen the existing LO_2 tank by 2.5 feet (Figure 4). These modifications increase the usable propellant weight to 45,000 pounds and use the Shuttle cargo bay more efficiently. The resulting configuration — Centaur G′ — has a vehicle length of 29.1 feet, with 30 feet of the Orbiter cargo bay available to the spacecraft.

By maintaining the Centaur D-1 LO_2 tank diameter, the basic vehicle proplusion system remains unchanged, although the larger LH_2 tank does require an increased-diameter forward stub adapter and equipment module.

For longer spacecraft, a shorter Centaur version uses only 29,500 pounds of propellant at a slightly higher engine mixture ratio of 6:1 (the standard ratio is 5:1). This configuration, called Centaur G, is only 19.5 feet long and allows spacecraft up to 40 feet long in the Orbiter.

Shuttle/Centaur G will have the geosynchronous capability to deliver large communications satellites weighing 10,600 pounds with lengths up to 40 feet. This is more than double the IUS capability, with only five percent less spacecraft length. For heavier spacecraft, Centaur J, with propellant tanks resized to hold 35,000 pounds, will be capable of launching a 14,000-pound spacecraft up to 37.6 feet long into geostationary orbits.

These capabilities will dramatically enhance the United States' ability to launch large communication satellites. Without Shuttle/Centaur, the size of communication spacecraft would be limited until further performance improvements can be realized with Ariane or the IUS, or until the United States can afford to develop a new cryogenic OTV.

The limiting factor for Shuttle/Centaur geosynchronous payload capability is the maximum lift capability of the Orbiter: 65,000 pounds. One way to increase this capability is to use one Orbiter to launch Centaur and a second Orbiter to launch the spacecraft. With on-orbit rendezvous and assembly of the Centaur and spacecraft payload weights of more than 20,000 pounds can be placed in geosynchronous equatorial orbit.

This approach allows the spacecraft to use the full 60-foot length of the cargo bay; however, it uses only about one-third of the lift capability of the Orbiter carrying the spacecraft. Adding a propulsion stage to the spacecraft would use some of this excess capability, and Centaur could thus place even greater spacecraft weights into geosynchronous orbit.

FUTURE REQUIREMENTS

The basic drivers for increased capability orbit transfer vehicles (OTV) include performance, operations, and cost-effectiveness. Spacecraft growth from the current 5,000-pound range to 10,000 pounds and more is already beginning to happen. High velocities are needed for planetary and maneuvering spacecraft. In the 1990s, missions are contemplated with round-trip capability to service satellites at GEO and others for manned sortie. For this, OTV must fulfill the following requirements:

- Very high performance: 15,000 to 30,000-pound payloads, servicing and round trip.
- Low acceleration: maximize size of large space structures.
- Reusability: reduce operating costs and return payloads.
- Aerobraking: double round-trip payload (versus all propulsive).
- Manrating: Orbit transfer and sortie for crew modules.
- Spacebasing: free from Shuttle constraints.

Operations in space require quick reaction, restart for orbit relocation, or low acceleration to transfer very large, delicate spacecraft. Future space transportation systems (Figure 5), including growth versions of existing or new vehicles, should be more cost effective. Increased capability tends to lower the cost per pound of payload delivered to high orbit.

ENGINES

Design studies and tests by the major engine contractors indicated the feasibility of increasing hydrogen-oxygen I_{sp} to 480 seconds (compared with 450 seconds currently). Figure 6 indicates several candidate engines.

Relatively small increases are not without great consequence for such future missions as GEO round trips. For example, a 20-second I_{sp} increase could double the round trip payload of a shuttle-launched, all-propulsive, reusable (ground-based) OTV.

LOW THRUST

Spacecraft that are much larger and more complex are being proposed (large geostationary communications and/or surveillance systems). These large systems are stowed in the Orbiter cargo bay during launch and will require subsequent deployment and checkout (Figures 7, 8, 9).

Checkout before transfer to final destination orbit maximizes mission success by allowing malfunction corrections before the spacecraft leaves the Orbiter. Because these systems are designed for low loads when deployed, it is necessary to limit acceleration during transfer. This is accomplished with a low-thrust engine.

A new low-thrust engine offers high I_{sp}, low weight, and small size, but requires technology developments (small pumps, long burn times, multiple starts, etc.). The RL10 engine has demonstrated a low-thrust capability at a reduced I_{sp} when running at extreme off-design conditions. Solutions for feed system instabilities have been devised, such as oxidizer heat exchanger, cavitating venturi, etc.

Using multiple perigee burn trajectories for low-thrust LEO to GEO transfer, the ideal velocity requirements are about the same as for high-thrust (two-burn) trajectories.

Mission time for LEO to GEO is one to two days for low thrust, multiple (9 to 17) perigee burns versus one-quarter day for high thrust (two burn). With efficient thermal control systems, minimal boiloff occurs. A 1 kW fuel cell (sufficient for OTV needs) consumes less than 0.5 lb/hr. Attitude control is also on the order of 0.5 lb/hr. There are negligible losses associated with engine start/stop since tank head idle (burning) is used. Other losses such as leakage, etc., are negligible.

While multiple passes through the Van Allen belts incur increased radiation dose, avionics systems are increasingly being hardened to withstand extended time in space and to operate during peak solar activity periods, etc. Therefore little penalty for multiple passes through the Van Allen belts over one to two days is expected for vehicle or payload systems.

TORUS TANKS

As long as the shuttle is used as a launch vehicle, the payload bay length will limit the utility of single shuttle launches (payload and OTV together in cargo bay) unless the OTV can be made very short.

Studies performed for the Air Force and NASA have concluded that the use of a toroidal liquid oxygen tank with the main propulsion engine mounted in the central void space provides the minimum length OTV, assuming separated tanks. The use of this approach offers the potential for increasing the geosynchronous payload capability (for a stage and ASE of the same installed length as Centaur G) to 17,000 pounds (Figure 10).

Required toroidal tank technology development includes control of propellant slosh, reduction of residuals, propellant mixing for thermal control, load destribution/support, and manufacturing-assembly methods.

AEROBRAKING

For round-trip missions to GEO (manned, payload servicing or return, etc.), aerobraking (Figures 11 and 12) offers twice the payload than all propulsive by using atmospheric drag to dissipate kinetic energy and reduce return propulsive ΔV by 50 percent. Propellants for the last burn are eliminated and therefore do not have to be transported to GEO and back.

Required technology development includes lightweight, high temperature brake designs. Improved analytical techniques and further wind tunnel tests are needed to predict temperatures and loads in the transition and slip flow regimes.

SPACE-BASED OTV

The unique environmental features of space could permit a very high mass fraction space-based OTV with significant payload weight and cost advantages over heavier ground based systems:

Advantages

- Free from Shuttle constraints (size, loads)
- Reusable (lower cost)
- Modularity (mix and match capability)

Key Issues

- Long-term space exposure
- Orbital integration, servicing
- Efficiency (low weight, high Isp)
- Low-cost operations (propellant delivery to LEO)
- Deployment and retrieval
- Future payloads and mission characteristics

Technology needs

- Lightweight (thin-gage) tanks (explosive forming, advanced sub-minimum gage chemical milling)
- Lightweight (composite) structure

- Lightweight/high temperature aerobrake materials (fixed aerobrakes, adaptive contour control)
- Long life/space maintainable engine (modular components, quick release fittings, fixed high ϵ nozzle)
- Low vapor pressure (2-5 psia) cryogenic propellant management — thermal control (MLI insulation, mixing, venting), propellant acquisition, gaging
- Meteoroid and space debris protection (multilayer tanks, self-sealing tanks, space station hangar facility, onboard space debris location, classification & avoidance system)
- Redundant, fault-tolerant, hardened avionics
- Auto rendezvous/docking

Figure 13 compares performance of ground-based and space-based OTV, showing that the potential high mass fraction of a space-based OTV design could result in twice the payload of ground-based OTV (GEO payload placement, OTV-only return, all propulsive). An aerobrake is needed to maximize payload return/round trip missions, but the high mass fraction of a space-based OTV mitigates the advantage of aerobraking for OTV-only return missions.

Reduced weight is achieved with low tank pressures and low acceleration loads to permit very lightweight tanks and structure (Figure 14).

Usage of low vapor pressure propellants and an advanced space engine with low inlet pressure and NPSH requirements combine to reduce tankage skin gages. Use of a low-thrust engine reduces acceleration loading on the tanks and further improves their efficiency. Technology development required includes thin-wall tanks, low vapor pressure propellants, low thrust-space maintainable engine, etc.

Reduced cost is achieved with a reusable space-based OTV and low propellant refueling cost (Figures 15 and 16).

Two concepts have been proposed: The "Honeybee," and the dedicated ET tanker. The "Honeybee" concept calls for the OTV to leave the Space Station and dock to the aft end of an ascending ET shortly after MECO. The OTV would then load itself with residual propellants from the ET through a special docking port. The OTV would fire its engine during propellant loading to settle propellants and possibly deorbit the ET. After separation, the OTV either returns to the Space Station and off loads propellant to dewar storage tanks or is immediately integrated with a payload for ascent to a higher orbit.

Required technology development includes rapid rendezvous, propellant extraction, etc. The alternative concept, a dedicated ET tanker, is a simpler, but probably more costly approach. Larger quantities of propellants can be delivered for increased OTV traffic.

SUMMARY

Advances in OTV are needed to enhance our nation's ability to operate effectively in space, particularly to reduce the overall cost of space operations for transfer of increasing numbers and size of payloads to geostationary orbit.

Because the costs and performance of the vehicles necessary to perform space missions are directly related to the available technology, advanced development programs must be supported and sustained.

Liquid hydrogen-oxygen rocket propulsion systems, because of their high performance and versatility, are essential. Increases in specific impulse, reductions in total system mass, and increased degrees of reusability are also needed. While Centaur/Shuttle (IOC 1986) evolution can satisfy near-term (1986-1995) objectives, a space-based OTV is envisioned for the far-term requirements. Advanced technology & low cost operations are essential.

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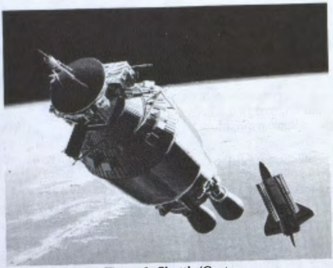


Figure 1. Shuttle/Centaur.

	Calendar year			
	1986	1987	1988	1989
Shuttle/Centaur				
Galileo	▼			
International Solar Polar	▼			
Venus Radar Mapper			▽	
DoD		▼ ▼	▽ ▽	▽ ▽
Geoplatform demonstration		▽		
Asteroid or comet				▽
Commercial communication		▽ ▽	▽ ▽	▽ ▽
Saturn Orbiter/probe			▽	
Total Centaur flights	2	5	6	5

▼ Firm
▽ Potential

Figure 2. Potential Shuttle/Centaur missions for NASA, DoD, and commercial applications.

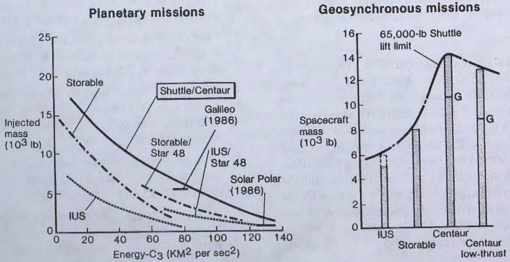


Figure 3. Centaur dramatically enhances Shuttle capability.

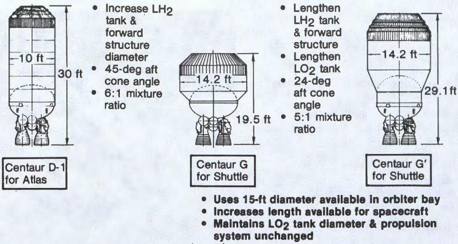
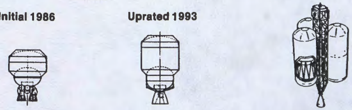
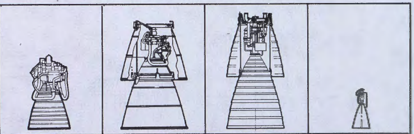


Figure 4. Shuttle/Centaur is minimum modification to current Centaur.



	Ground-Based Centaur: Initial 1986	Ground-Based Centaur: Uprated 1993	Space Based
Payload (lb)	**10-14K**	**10-25K**	**(12K round trip)**
Payload (ft)	**40-37**	**35-41**	**30**
Engines	Two RL10A3-3A, phased-in low thrust & deployable skirt	Single RL10 Cat IIB with idle mode	Advanced propulsion system man-rated
Avionics	Current single-string phase-in triple string	Triple-string fault-tolerant, hardened	Advanced round trip
Tanks	Wide body CRES 30-45K propellant capacity	Increased capacity (≤ 55K)	Separated tanks, ~100K propellant, orbital tanking
Structure	Titanium adapters — phase-in composite adapters	Reduced boiloff, aerobrake	May be dual stage, aerobrake
Operations	Expendable, SMM for spacecraft survivability	Reusable, may use kick stage Orbital assembly	May be space based, on-orbit assy, manned

Figure 5. Potential OTV evolution.



	RL-10A3-3A	RL-10 Cat IIB	Advanced Engine	Low Thrust
Manufacturer	Pratt & Whitney	Pratt & Whitney	P&W, R/D, ALRC	R/D
Status	160 successfully flown	Phase B studies	Conceptual studies component hardware	Technology studies
Isp (sec)	448.4	460	475 to 480	450
Thrust (1,000 lb)	15–16.5	15 (+10% idle)	10 to 20 (+10% idle)	0.5 (Long burn times)
Development: ($M) (years)	none required available	80 5	250 to 350 10	150 8

Figure 6. Candidate OTV engines.

- Platforms have significant economic advantage over individual satellites
  - — Sharing of subsystems & structure
  - — Built-in reliability & redundancy
- LEO deployment/checkout of payload prior to transfer to GEO increases reliability
  - — STS- or LEO-base for deployment/checkout
  - — High energy, low thrust orbit transfer vehicle
- Limited automated revisit is beneficial (servicing)
  - — Replenish consumables
  - — Exchange predictable wearout components
  - — Allow payload update & growth

Figure 7. Large space platforms (geostationary satellites).

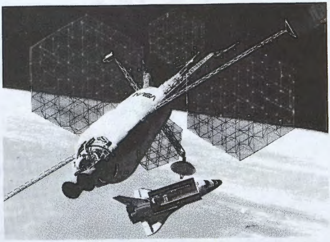


Figure 8. NASA LSS/Centaur.

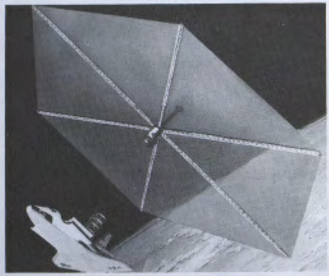


Figure 9. DoD LSS/OTV.

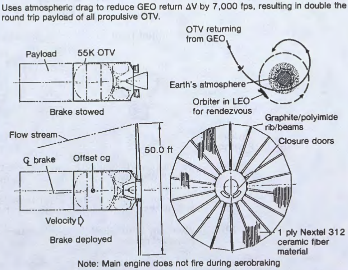
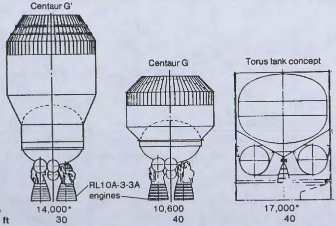


Figure 11. Lifting brake OTV for GEO return missions (servicing, manned).



	Centaur G'	Centaur G	Torus tank concept
Geo payload, lb	14,000*	10,600	17,000*
Payload length, ft	30	40	40
Thrust, lb	30,000	30,000	500
Isp, sec	446.4 (MR=5.0)	437.2 (MR=6.3)	476.7 (MR=6)
IOC	1986	1987	—

*65K STS

Figure 10. Compact tankage (TORUS) maximizes payload length and weight.

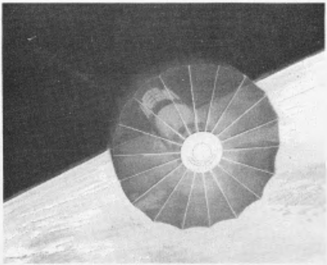


Figure 12. Lifting aerobrake OTV.

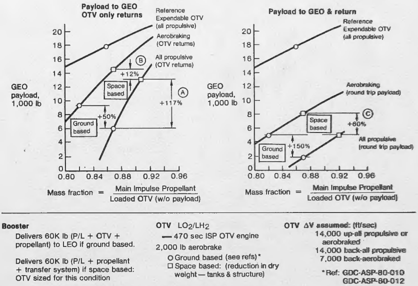


Figure 13. OTV performance.

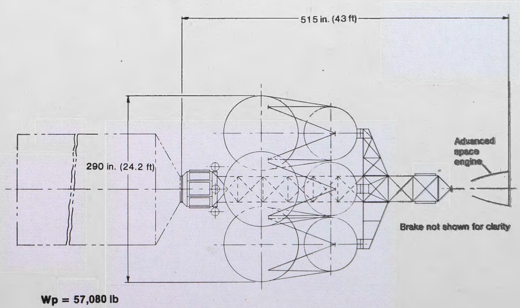
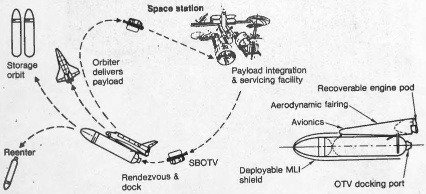


Figure 14. Representative space-based OTV concept.



Honeybee concept
- 9-36 klb residuals recovered per STS flight
- Propellant delivery cost — essentially free (no tanks in Orbiter)
- Supports 90-129 klb year to GEO

E.T. tanker concept
- 214-220 klb delivered per flight
- Propellant delivery cost — ≈ 235 $/lb
- Supplements Honeybee concept to support 360 + klb year to GEO

Figure 15. Low-cost propellant delivery concepts.

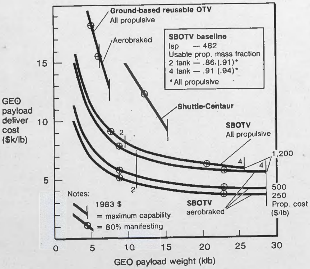


Figure 16. OTV performance comparison.