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ORBITAL TRANSFER VEHICLE CONCEPT DEFINITION AND SYSTEM ANALYSIS STUDY

FINAL REPORT

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VOLUME IA
EXECUTIVE SUMMARY

PHASE 2

December 1986

GENERAL DYNAMICS
Space Systems Division

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December 1986

Prepared for
NASA MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

Prepared by
ADVANCED SPACE PROGRAMS
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VOLUME I A

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FOREWORD

This report summarizes the Phase 2 results of the Orbital Transfer Vehicle Concept Definition and System Analysis Study. This study was conducted by General Dynamics Space Systems Division (GDSS) under company funds from October 1984 through August 1986 for NASA Marshall Space Flight Center (Don Saxton - NASA MSFC OTV Study Manager). Final documentation is divided into ten volumes:

Volume I	Executive Summary - Phase 1
Volume IA	Executive Summary - Phase 2
Volume II	OTV Concept Definition & Evaluation
Volume III	System & Program Trades
Volume IV	Space Station Accommodations
Volume V	WBS & Dictionary
Volume VI	Cost Estimates
Volume VII	Integrated Technology Development Plan (and Centaur for OTV Technology Demo)
Volume VIII	Environmental Analysis
Volume IX	Phase 2 - Detail Summary

The GDSS Study Manager is Bill Ketchum. Many other GDSS personnel contributed to this study. The key individuals and their particular contributions are as follows:

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ACRONYMS AND ABBREVIATIONS

ACC	Aft Cargo Carrier
AFE	Aerobrake Flight Experiment
APS	Auxiliary Propulsion System
ASE	Airborne Support Equipment
CFMF	Cryogenic Fluid Management Facility
CG	Center-of-Gravity
CITE	Cargo Integration Test Equipment
CRYO	Cryogenic (H_2/O_2)
DoD	Department of Defense
DDT&E	Design, Development, Test and Engineering
ET	External Tank
EVA	Extravehicular Activity
FOC	Full Operational Capability
GB	Ground Based
GDSS	General Dynamics Space Systems Division
GEO	Geostationary Earth Orbit
GN&C	Guidance, Navigation and Control
GPS	Geostationary Positioning System
GR/E	Graphite Epoxy
HPA	Handling Positioning Aid
IOC	Initial Operational Capability
ISP	Specific Impulse
JSC	Johnson Space Center
LCC	Life-Cycle Cost
LEO	Low Earth Orbit
LGO	Lunar Geoscience Orbiter
LLO	Low Lunar Orbit
LTCSF	Long-Term Cryogen Storage Facility
MES	Main Engine Start
MMH	Mono-methyl Hydrazine
MRMS	Mobile Remote Manipulator System
MSFC	Marshall Space Flight Center

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ACRONYMS AND ABBREVIATIONS, Contd

MST	Module Servicing Tool
OCB	Orbital Cargo Bay
OMV	Orbital Maneuvering Vehicle
OPS	Operations
OTV	Orbital Transfer Vehicle
PGHM	Payload Ground Handling Mechanism
PIDA	Payload Installation and Deployment Aid
P/L	Payload
PRLA	Payload Retention/Latch Assembly
$\bar{R}$	Radial Vector
RCS	Reaction Control System
RMS	Remote Manipulator System
RSS	Rotating Service Structure
SB	Space Based
S-C	Shuttle/Centaur
SCB	Shuttle Cargo Bay
SDV	Shuttle-Derived Vehicle
SS, S/S	Space Station
STS	Space Transportation System
TDP	Technology Development Package
TDRS	Tracking Data Relay Satellite
TPS	Thermal Protection System
TSS	Tanking Safety System
VAB	Vandenberg Air Force Base
VPF	Vertical Processing Facility

SUMMARY

The Orbital Transfer Vehicle (OTV) Concept Definition and System Analysis Study was conducted by General Dynamics Space System Division (GDSS), a company-funded effort under the direction of NASA/Marshall Space Flight Center (MSFC).

This study was conducted in two parts. Phase I results were summarized in Volume I. This report, Vol IA, summarizes the Phase 2 results.

The objectives and accomplishments during Phase 1 of the "Orbital Transfer Vehicle Concept Definition and System Analysis Study" were to define preferred OTV concept(s) and programmatic approach(es) for the development of an OTV capable of providing reusable operations capabilities to geosynchronous orbit and beyond, and capable of growth to manned geosynchronous access. A major objective was to define the interaction between the OTV and the Space Station, and derive space-basing requirements on both.

The study provided technical and programmatic data for NASA pertinent to OTV requirements, configuration, accommodation needs, operational characteristics, and costs. Significant conclusions of the effort were:

a. An evolutionary program development leading ultimately to a reusable, space-based OTV is cost-effective and low-risk.

b. The performance benefits of cryogenic propellants justify their greater initial development costs and foster growth to manned and planetary mission applications.

c. OTV accommodations on the growth Space Station require a substantial facility with automated systems and teleoperated servicing equipment.

d. Aerobraking has the potential for significant performance gain and program cost benefits.

The objectives of the General Dynamics Phase 2 study were to improve our understanding of the OTV concept by focusing on the following three key issues:

a. Exploring how the mission requirements would be impacted when advanced civil and military missions (including those of STAS) are considered with their resultant effects on OTV system requirements.

b. Developing an increased definition of OTV basing concepts on the Space Station, Platforms, and/or remote locations, either manned or man-tended.

c. Examining the means to lower the costs of an OTV program to improve its economic benefits and support its acquisition.

Between Phases 1 and 2, several major changes occurred that had a significant impact on study results and recommendations. The mission model increased to include more total missions, including higher inclination missions. In addition to the STS, the availability of new launch vehicles (HLV) was introduced. Besides the Space Station, the possibility of separate OTV platforms was included. Finally, the aftermath of the Challenger accident puts renewed emphasis on flight safety in selection of an OTV for manned applications.

The space-based orbital transfer vehicle will allow safe launch operations, with higher performance and lower cost than any other chemical propulsion system, and will enable bold new mission opportunities.

The space-based OTV will be the result of many years of careful study using the best technology available to assure the U.S. continued access to space, safely, and economically.

SECTION 1

INTRODUCTION

NASA is proceeding toward a permanently manned Space Station to be initially operational in Low Earth Orbit in 1994. The Space Station concept provides for a six- to eight-person crew in a low-inclination orbit.

The Space Shuttle will launch and provide transportation to the Space Station and will permit crew rotation and resupply at three- to six-month intervals.

The Space Station will enable extensive commercial use of space by providing capabilities not currently available.

The Space Station is being designed to continuously evolve to enhance its capabilities into the next century. By 1997, the addition of a transportation support facility will provide a staging point for payloads requiring placement at higher orbit by an OTV, shown in Figure 1-1.

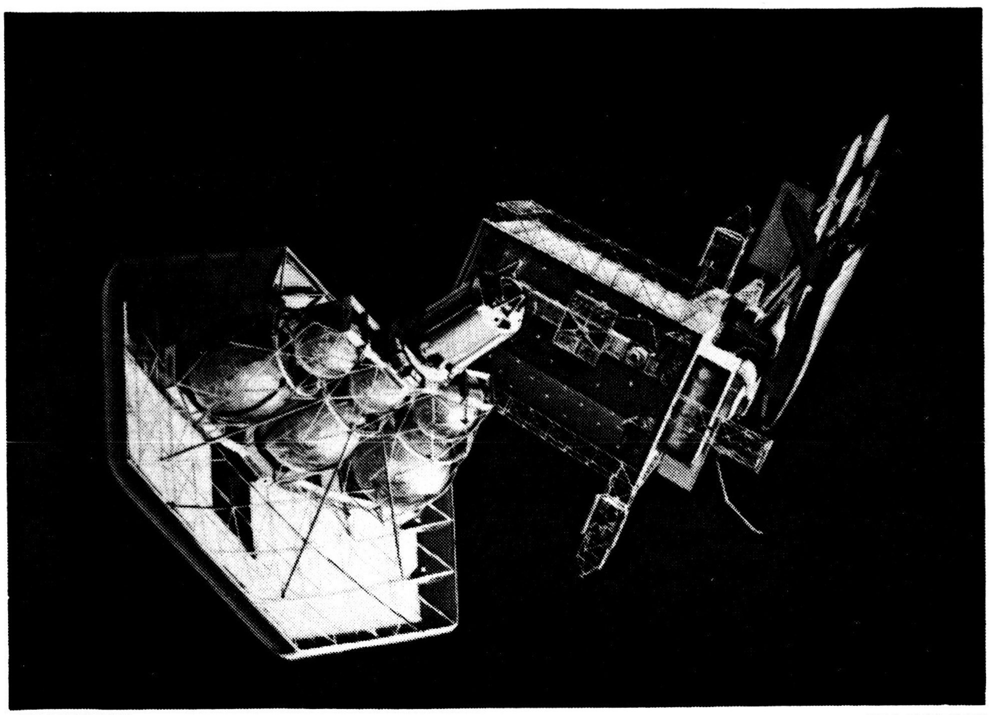

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Figure 1-1. Space-Based OTV/Servicing Facility

A space-based OTV will not be subjected to Earth-to-orbit launch loads and will not be constrainted in size or weight. Since it can be assembled in space from several components, it could carry large payloads. Its inherent reusability and ability to be refueled in space make the space-based OTV very economical to operate and most importantly, will enhance manned safety since it is delivered empty from Earth to orbit.

The operational scenario and mission profile of the OTV, shown in Figure 1-2, include the following:

a. Initial delivery of the OTV and the subsequent delivery of the OTV payloads and propellants from the Earth to the OTV/Servicing Facility by the STS/HLV and orbital maneuvering vehicle (OMV).

b. Integration of payloads on the OTV and refueling of the OTV from propellant storage tanks on the OTV/Servicing Facility.

c. Departure of the OTV and payloads to high orbits, translunar, or interplanetary trajectories.

d. Return of the OTV via aerobraking to the OTV/Servicing Facility.

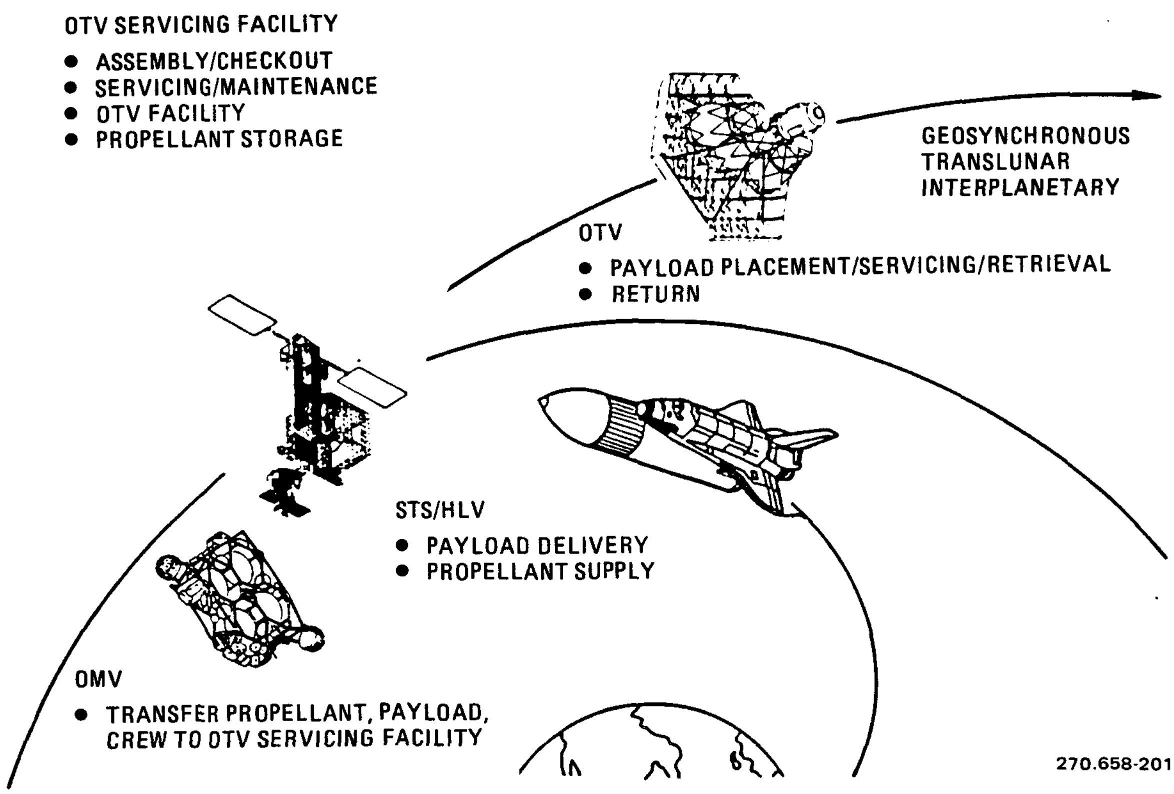

Figure 1-2. OTV Operational Scenario and Mission Profile

The schedule for development and operation of the Space Station, OTV, and Servicing Facility shown in Figure 1-3, anticipates space-based OTV operation by 1997. Continuing upgrades are expected into the next century as additional missions and requirements develop.

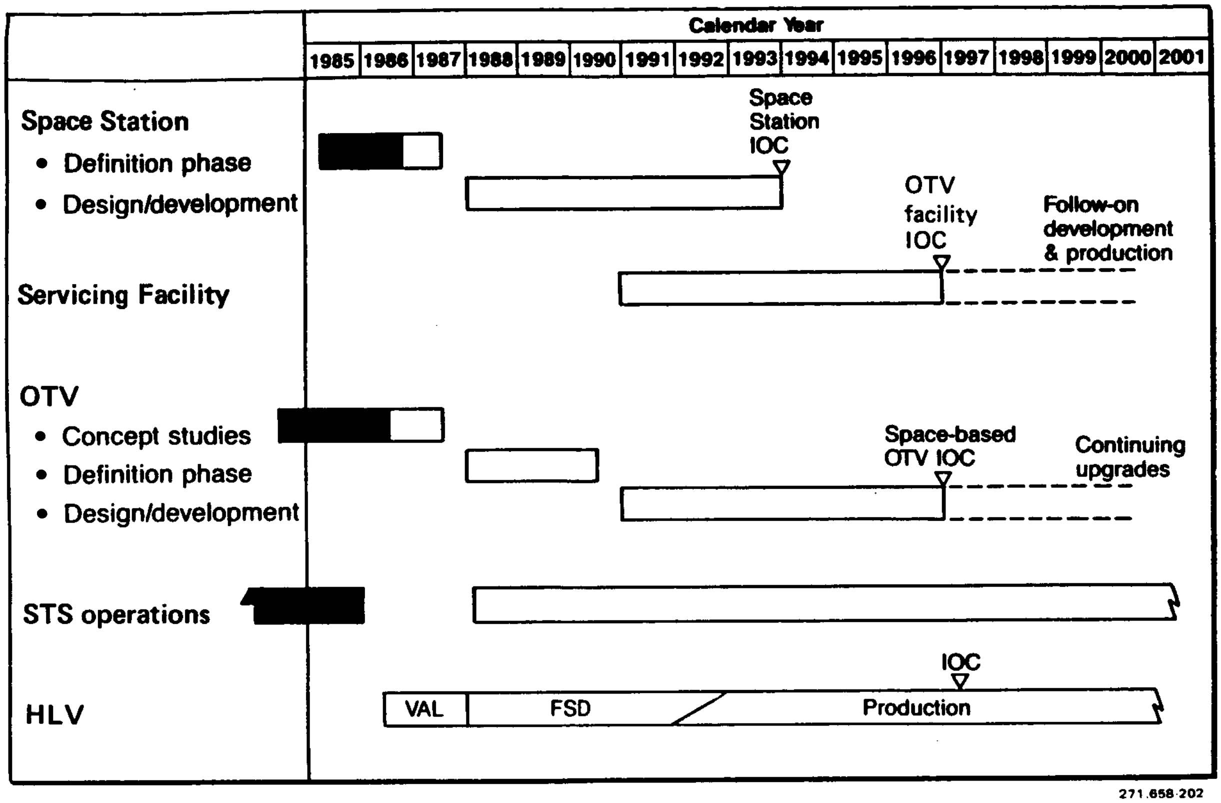

Figure 1-3. OTV Time-Phasing Relationships

SECTION 2

MISSION REQUIREMENTS

The NASA/MSFC OTV mission model includes a wide range of missions, shown in Figure 2-1. The driver missions are manned GEO Servicing, mid-inclination/ Polar DoD, and Lunar/Planetary.

The latest version of the NASA-MSFC OTV mission model (Rev. 9) includes STAS scenarios (1-5:292-872 missions). Scenario 2 (422 missions) is the baseline specified by NASA-MSFC for OTV Phase 2 study. These missions occur over a 15-year period (1995-2010).

Since Phase 1, the number of OTV baseline missions increased from 145 to 422 (Rev. 8 low, versus Rev. 9, Scenario 2) placing increased emphasis on OTV. The wide range of missions indicates the continuing need for modularity to give mission flexiblity without performance penalty.

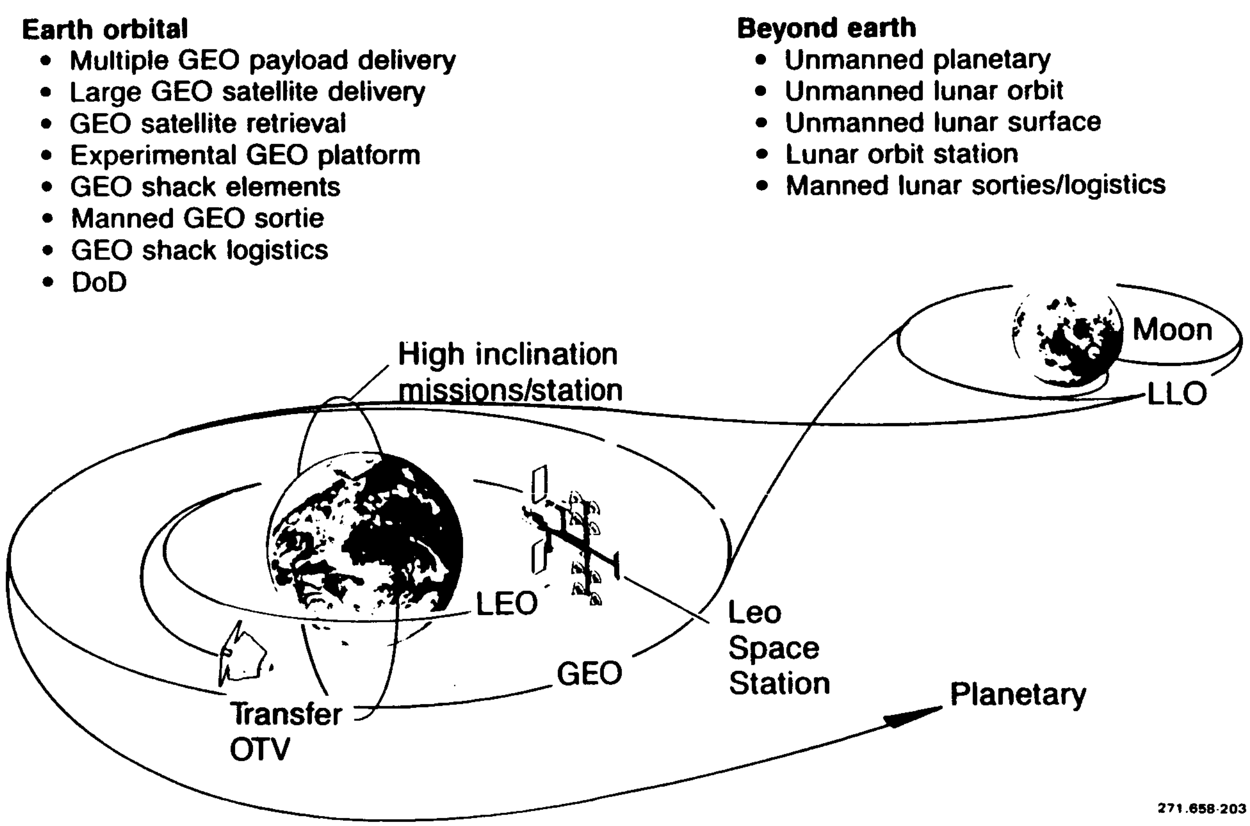

Figure 2-1. OTV Missions

The importance of high-performance OTVs (cryogenic propellants and aerobraking) is indicated by the increasingly demanding missions. (See Table 2-1.)

The number of missions per year for each Rev. 9 scenario and the nominal and low Rev. 8 model are shown. The baseline Rev. 9 model - Scenario 2 - is 5-10 missions per year in excess of the Rev. 8 Nominal. (See Figure 2-2.)

Table 2-2 shows the comparison of Rev. 8 and Rev. 9 for the candidate missions.

Using the Rev. 9 mission model, total annual OTV propellant requirements can reach 1.5 million pounds for the baseline scenario. (See Figure 2-3.)

Table 2-1. Driver Missions/OTV Requirements Summary (Rev. 9/Scenario 2/1995-2010)

Mission	Payload	Number of missions	IOC	OTV propellant/ number of tanks*
Multiple payload delivery	12,000 lb to GEO/2,000 lb return	84	1995	41,500 lb/1
DoD	10,000 lb to GEO, mid-inclination 5,000 lb to polar	240	1995	24,900 – 35,800 lb/1
GEO shack logistics	12,000 lb up/10,000 lb down	37	1999	66,900 lb/3
Manned GEO sortie	12,000 lb up/10,000 lb down	16	2002	66,900 lb/3
Reflights	20,000 lb to GEO	8	1997	64,600 lb/3
Manned GEO shack	25,080 lb to GEO	1	2004	72,000 lb/3
Lunar	72,680 lb to lunar orbit	4	2009	137,000 lb/3
Planetary	Various: up to $122C_3$; up to 32K lb, etc)	14	1995	Up to 123,000 lb/3 (6 with kick stages)

*Modular Space-based OTV, H_2-O_2, aerobraked
28½° & 60° platforms

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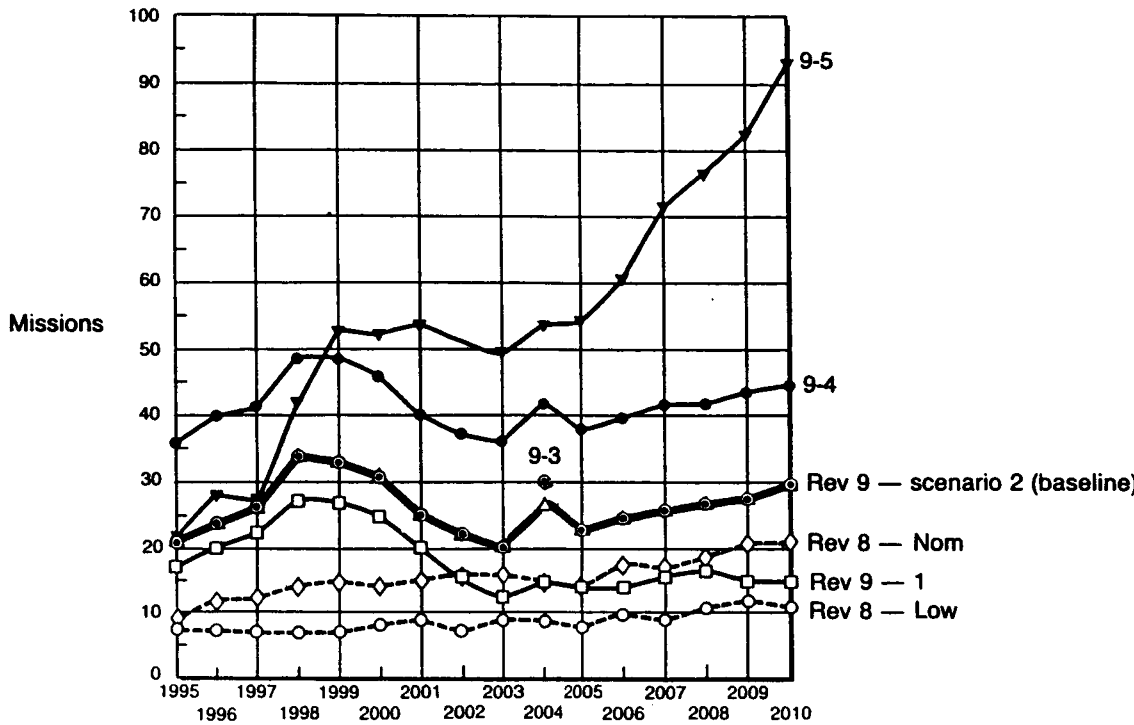

Figure 2-2. OTV Mission Model Comparison

Table 2-2. OTV Mission Model Comparison Rev. 9 vs Rev. 8

Mission group	Rev 8		Rev 9 Scenarios				
	Low	Nominal	1	2	3	4	5
Experimental GEO platform	1	1	1	1	1	1	1
Operational GEO platforms	5	6	0	0	0	0	0
GEO shack elements	2	2	0	2	2	2	2
Manned GEO sortie	3	17	0	16	16	16	22
GEO shack logistics	5	26	0	37	37	37	51
Unmanned planetary	6	14	14	14	17	14	25
Unmanned lunar orbit	2	2	0	3	3	3	4
Unmanned lunar surface	N/A	N/A	0	5	5	5	1
Lunar orbit station	0	1	0	0	0	0	1
Manned lunar sorties/logistics	0	11	0	0	0	0	8
Multiple GEO payload delivery	46	79	84	84	84	84	88
Large GEO satellite delivery	3	7	10	10	10	10	19
GEO satellite retrieval	0	0	2	2	2	2	2
Nuclear waste disposal	0	0	0	0	0	0	391
DoD (generic)	68	85	176	240	240	480	240
Subtotal	142	252	287	414	417	654	855
Reflights	3	5	5	8	8	13	17
Total	145	257	292	422	425	667	872

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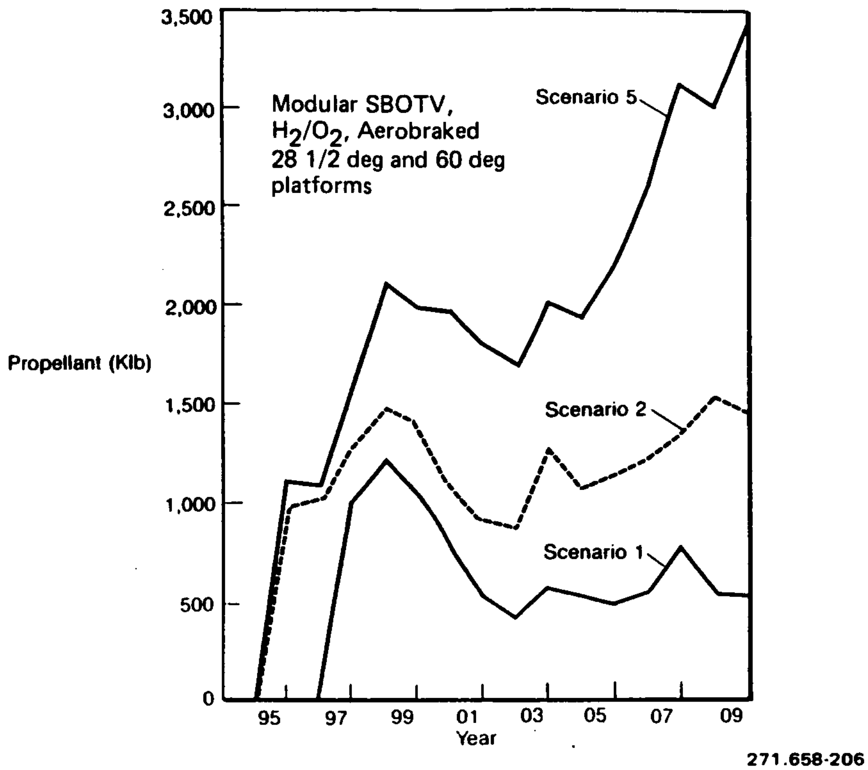


Figure 2-3. Total OTV Propellant Requirements

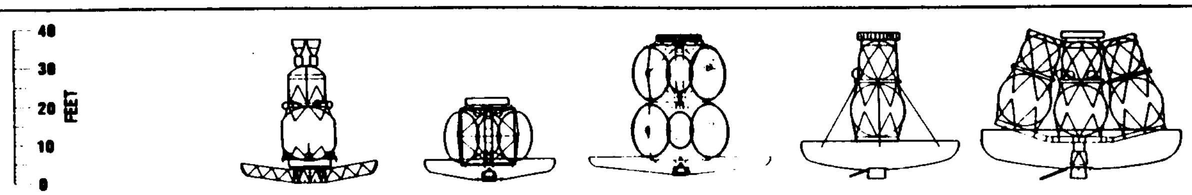
SECTION 3

OTV CONCEPTS/LAUNCH VEHICLES

To accomplish the missions, many OTV concepts were defined including ground-based launched either in the STS orbiter, the aft cargo carrier (ACC), or on the HLV, and a space-based OTV designed to be effective over a wide range of mission requirements without redesign or performance penalty. (See Figure 3-1.)

Study results indicate a significant advantage (economic and technical) for a cryogenic (H_2/O_2) space-based OTV.

Launch vehicles included the STS, a partially reusable cargo vehicle (HLV), and a fully reusable Shuttle II. (See Figure 3-2.) Study results indicate a significant advantage (economic and technical) for a partially reusable cargo vehicle (HLV).



Type description	Interim ground-based OTV	Advanced ground-based OTV	Adv. large tankset ground-based OTV	Adv. modular SBOTV core propellant	Adv. modular SBOTV 3 tanksets
Payload — geo circular	10,100 lb	10,280 lb	26,100 lb	13,500 lb	59,100 lb
— geo roundtrip	4,750 lb	4,930 lb	13,000 lb	6,450 lb	31,450 lb
Stage ignition weight	62,800 lb	50,870 lb	98,900 lb	48,340 lb	134,900 lb
Total thrust	30,000 lb	7,500 lb	15,000 lb	10,000 lb	10,000 lb
Main propulsion					
• Propellants - H_2/O_2	52,100 lb	41,500 lb	83,000 lb	40,800 lb	122,500 lb
• Engine description	RL 10-IIC	Adv. space engine	Adv. space engine	Adv. space engine	Adv. space engine
• Number of engines	2	1	2	2	2
• ISP — vacuum	444 sec	485 sec	485 sec	485 sec	485 sec
IOC	1992	1995	1996	1996	1996
Launch vehicle	STS-OCB (72K lb)	STS-ACC (72K lb)	HLV	STS/HLV	STS/HLV

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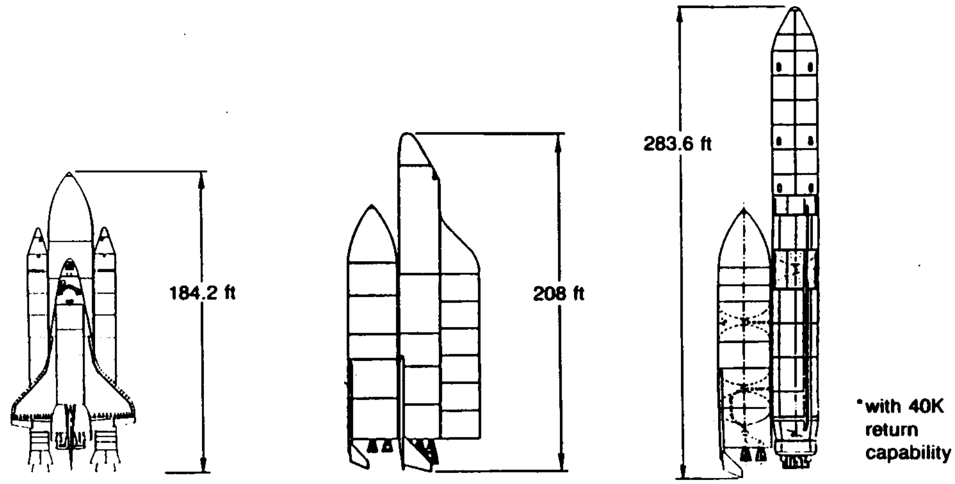
Figure 3-1. OTV Concepts



	STS	Fully reusable Shuttle II	Partially reusable cargo vehicle (HLV)
Payload Weight lb	- 63K	- 65K	- 150K
Size ft	- 15 × 60	- 15 × 60	- 25 × 90
Launch cost $	- 106M	- 20 M	- 70M (85M)*
IOC	- 1981	- 2002	- 1995

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Figure 3-2. Launch Vehicles

SECTION 4

TRADE STUDIES/SENSITIVITIES

System and program trade studies were conducted, using performance, cost, safety/risk, and operations/growth criteria, to identify preferred OTV concepts/approaches. Table 4-1 summarizes the results. The basis for these conclusions are discussed in the following sections.

The study shows that mission requirements and substantial economic benefits justify a reusable, cryogenic (H_2/O_2) space-based OTV to reduce operational cost, to return payloads, to permit growth, and to increase safety.

Table 4-1. Key Trade Studies

OPTION	RECOMMENDATION
• CRYOGENIC VS STORABLE PROPELLANTS	CRYOGENIC
• REUSABLE VS EXPENDABLE OTV'S	REUSABLE
• GROUND-BASING VS SPACE-BASING	SPACE-BASING
• STS VS HLV DELIVERY	HLV
• AEROBRAKE VS ALL-PROPULSIVE	AEROBRAKE
• ADVANCED ENGINE VS RL-10	ADVANCED
• LOW-PRESSURE TANKS VS CONVENTIONAL	LOW-PRESSURE
• ATTACHED VS FREE-FLYING OTV PLATFORMS	FREE-FLYING

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4.1 CRYOGENIC VERSUS STORABLE PROPELLANTS

Cryogenic (H_2/O_2) propellants resulted in 50% less propellant required, fewer vehicle stages/operations, lower life cycle cost (-$7B), and are available in quantity from the current STS infrastructure. (See Table 4-2 for propellant trades.)

Table 4-2. Propellant Selection Trade

Criteria	Storable (N_2O_4/MMH)	Cryogenic (H_2/O_2)
Performance	Lower I_{SP} (342) increases propellant requirement, number of stages	Higher I_{SP} (485) Less propellant Fewer stages
Cost	Higher operations cost Life cycle cost = $20B	Lower operations cost Life cycle cost = $13B
Safety	Toxic, hypergolic	Flammable in atmosphere
Operations/growth	Quantity production & operations not currently available	Large quantity production operations available (STS infrastructure) ET scavenging potential Space Station accommodations DDT&E not significantly different Possible lunar production (oxygen) for Space-based OTV

Phase I study eliminated storable propellants
Phase II study concentrated on cryogenic propellants

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In Phase 1, a $7B savings for use of H_2/O_2 propellant resulted. Applying Phase 2 factors (three times as many missions; 1/3 the propellant delivery cost using HLV instead of STS), approximately the same savings resulted (-$7B). (See Figure 4-1 for cryogenic versus storable propellants trades.) Throughout this report, all costs shown are in 1985 dollars and exclude contractor fee and program contingency.

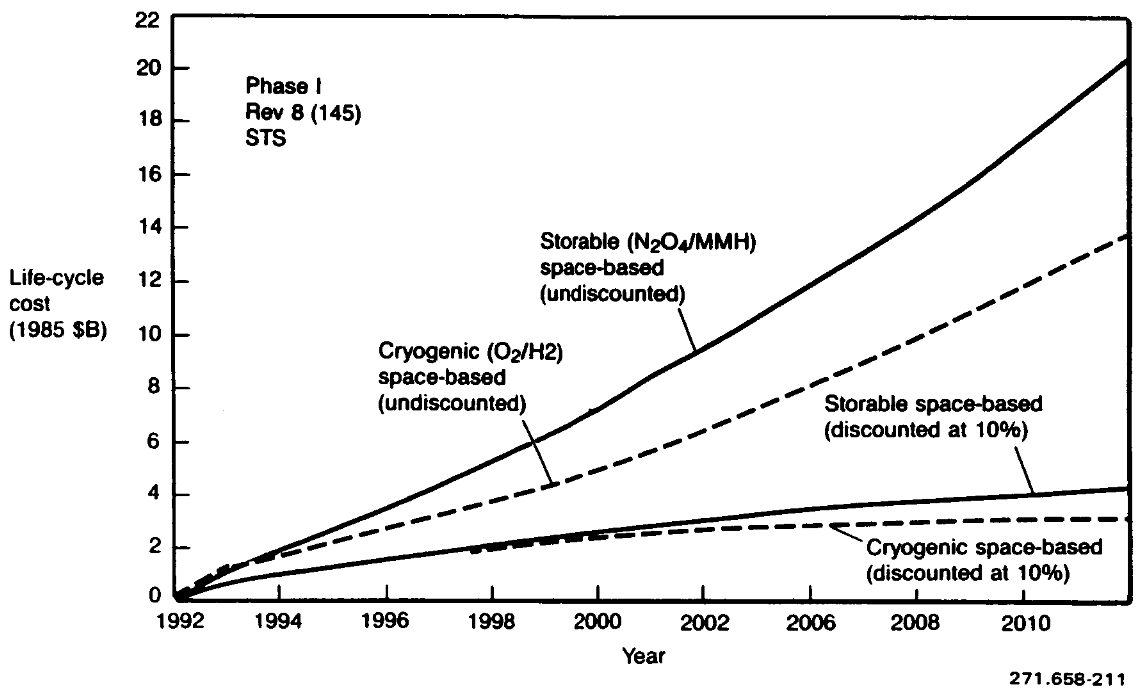

Figure 4-1. Cryogenic Versus Storable Propellants

4.2 REUSABLE VERSUS EXPENDABLE OTV'S

Reusable OTVs offer $9B lower life cycle cost and capture all missions (expendable OTVs fail to capture 55 missions out of 422 - manned GEO sortie, logistics, etc.). (See Figure 4-3.)

Table 4-3. Reusability Trade

Criteria	Expendable	Reusable
Performance	55 missions not captured	All missions captured (422: Rev 9 Scenario 2)
Cost	Lower DDT&E	Lower operations cost Lower LCC (–$9B)
Safety/risk	Limited crew involvement	Return to ground or to Space Station Crew involvement
Operations/growth	Limited	Can meet future mission needs

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The reusable OTV has a higher development cost. However, once the flight program starts, the expendable OTV production and operations cost dominate. (See Figure 4-2.)

Development of a new expendable OTV for better performance would not change the results, since a greater development cost would be incurred for a new expendable. Therefore, Centaur was used for the analysis. For the expendable to capture the other (manned) missions, development of an additional propulsion unit for de-orbit from GEO would be necessary, at additional cost.

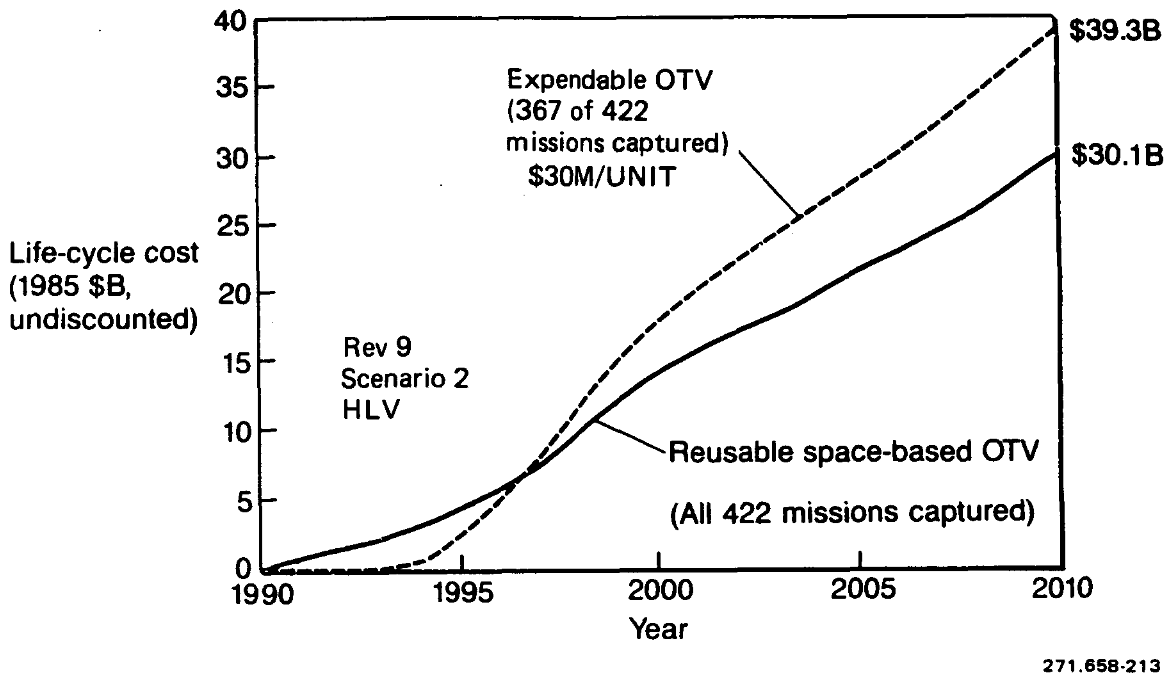

Figure 4-2. Cumulative Life Cycle Costs: Expendable Versus Reusable OTV

4.3 GROUND VERSUS SPACE BASING

A space based OTV is not constrained by launch vehicle dimensions/environment. It is delivered to orbit empty of propellants, and therefore is a lighter-weight structure design resulting in improved performance. Since it is not launched to orbit each time, its weight and dimensions do not detract from launch vehicle performance. The net result is lower operational cost for a life cycle savings of $9B over a ground-based OTV. Inherent safety advantages with manned launch vehicles (e.g., STS) results from lack of onboard propellants/interfaces for the OTV. Simple operations result since there is no need to return the OTV to the Earth after every mission. (See Table 4-4.)

The space-based OTV has more versatility and growth potential for future missions.

Table 4-4. OTV Basing Trade

Criteria	Ground-based	Space-based
Launch vehicle lift capability	OTV constrained by launch vehicle dimensions & loads	Lighter OTV with fewer dimension/load constraints, launched empty
Cost	Lower DDT&E Higher operations cost	Lower LCC (-$9B)
Payload volume	OTV payloads in cargo bay (or fairing) at same time - multiple launches required for some missions	Entire cargo bay (or fairing) available for payload
Mission difficulty	Complexity of mating multiple launch payloads and returning OTV to Earth after each mission Turnaround OTV on ground where manpower readily available	Turnaround OTV in space - mostly by teleoperations to conserve crew time Requires propellant delivery/transfer in space Modular design allows quick change-out
Propellant scavenging	Not applicable	Allows operations cost benefits
Safety	OTV launched full of propellants	OTV launched empty - fueled on orbit
Location of transportation nodes	Can launch payloads to desired inclinations	Cover all inclinations with platforms at 28.5° + 60°
Mission model evolution	Cannot easily grow to support advanced missions requiring multiple launches or large payloads	Can support large propellant mission requirements & especially advanced missions to the Moon and Mars
Availability of return transport	Requires Shuttle on orbit past mission required time of capture Complete new launch return/vehicle design	Return transport required only under special circumstances
Initial operational capability	Potentially earlier	Could operate Semi-space-based for early operational capability

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4.4 STS VERSUS HLV DELIVERY

The three launch vehicle options shown in Table 4-5 were evaluated for delivery of the OTV, propellants, and payloads.

Table 4-5. Delivery Mode Trade

Criteria	STS	HLV	Shuttle II
Performance Payload size	63K 15 × 60 ft	150K 25 × 90 ft	65K 15 × 60 ft
Cost per flight (DDT&E NC)	$106M $1680/lb	$70-85M $470-570/lb	20M $307/lb
Safety/risk	Crew involvement	No crew involvement	Crew involvement
Operations/growth	Would need more orbiters/operations	Fewer operations needed Applicable to other missions	Simple return operations
IOC	1981	1995	2002

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The HLV was selected as the baseline launch vhicle (over the STS) because of significant life cycle cost savings for the OTV program. Although the Shuttle II results in further cost savings, its late availability is a significant disadvantage. (See Figure 4-3.) Advancing the availability of the Shuttle II should therefore be considered.

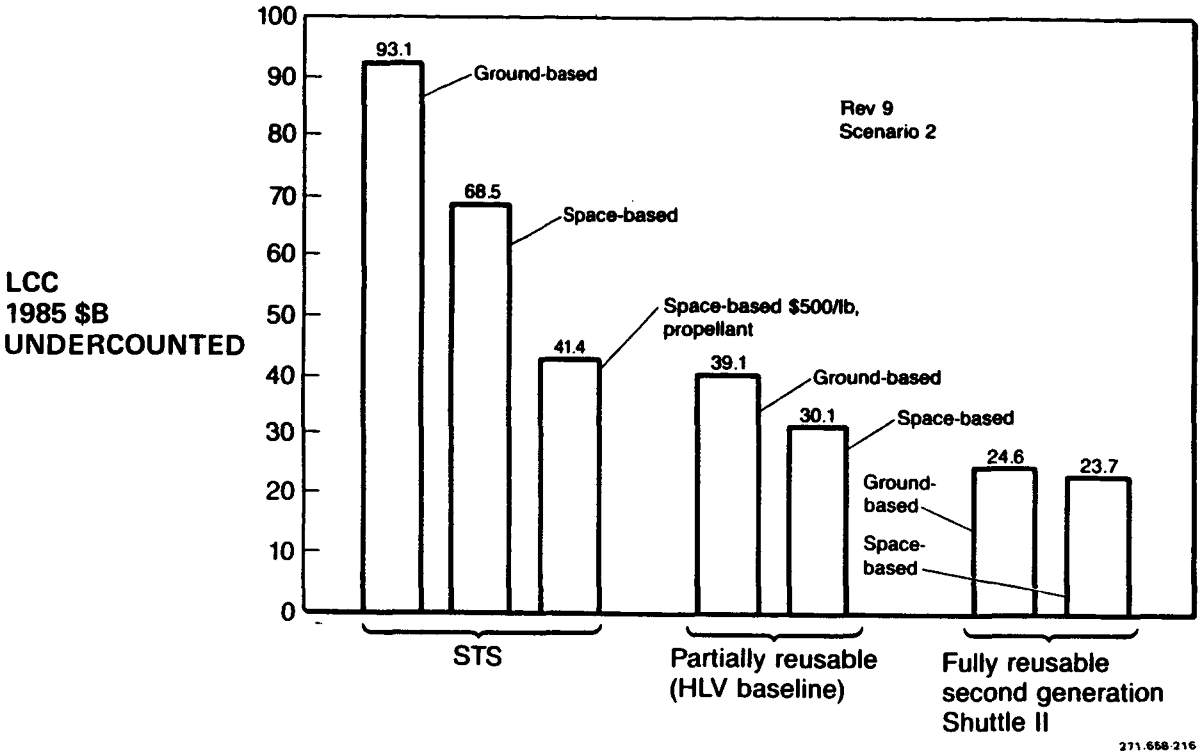

Figure 4-3. OTV Basing/Delivery Mode Life Cycle Cost Comparison

4.5 AEROBRAKE VERSUS ALL-PROPULSIVE

Aerobraking for OTV return to LEO reduces propulsive burn requirement and therefore propellant required (-7M lb), results in fewer vehicles/operations, and offers $3.5B lower life cycle cost. (See Table 4-6.)

Table 4-6. Aerobraking Trade

Criteria	Aerobraked	All-propulsive
Performance	Reduces return ΔV requirements, propellants required, stage size	More propellant/more stages
Cost	DDT&E ~$0.5B Lower operations cost Lower LCC (−$3.5B)	No special DDT&E investment Higher operations cost
Risk	Aerodynamic/aerothermo-dynamic environments Brake structures Thermal protection materials Adaptive guidance, navigation & control	No atmospheric pass
Operations/growth	Difficult to return if Ground-based Easily handled if Space-based	Easier to return Ground-based OTV to Earth Space-based OTV hangar can be smaller
	Aerobrake can be added onto all-propulsive stage	Need greater propellant capacity at depot

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The propellant saved by aerobraking over all-propulsive return to low Earth orbit results in a net savings of $300M per year. The investment in aerobrake technology, DDT&E and production (assumed to be $500M) is recovered within 2-3 years of OTV operations. Total net benefit of aerobraking is almost $3.5B. (See Figure 4-4.)

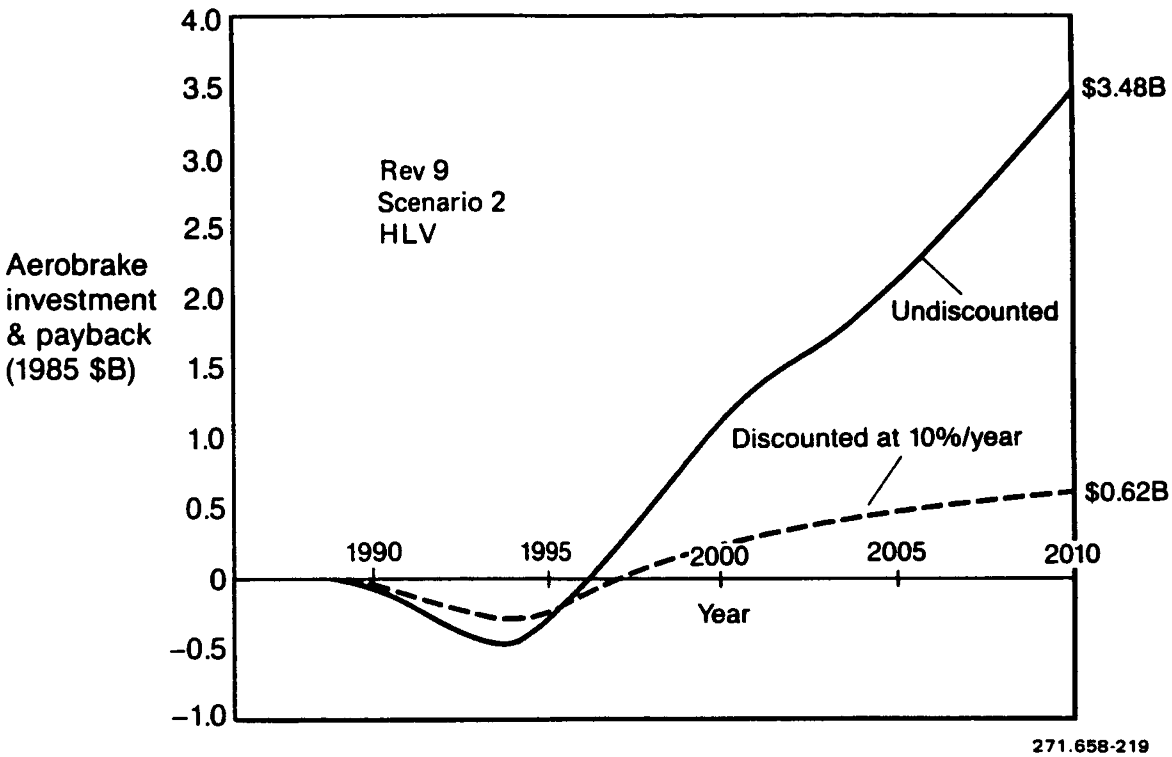

Figure 4-4. Aerobrake Cost Payback Function

4.6 ADVANCED ENGINE VERSUS RL-10

An advanced engine with higher Isp and longer life reduces the OTV propellant requirement (-5M lb), can be designed for the best thrust level, will be reusable, and offers $4.7B lower LCC. (See Table 4-7.)

Table 4-7. Engine Trade

Criteria	Advanced	RL-10 derivative
Performance	Higher Isp (485 sec) reduces propellant requirement Design for best thrust level	Less Isp (445 sec) 15K thrust imposes weight penalties
Cost	Requires: DDT&E investment ~ $0.3B Lower operations cost Lower LCC ($-4.7B)	Currently available Higher operations cost
Risk	Higher chamber pressure, turbomachinery speeds	Current technology
Operations/growth	Reusable Maintainable	Not designed for reuse Demonstrated high reliability

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Reduction in propellant delivery requirements for an OTV justify high-performance engines. The 485 sec Isp advanced engine provides $2.5B operating benefit over the existing RL-10 445 sec Isp engine. (See Figure 4-5.)

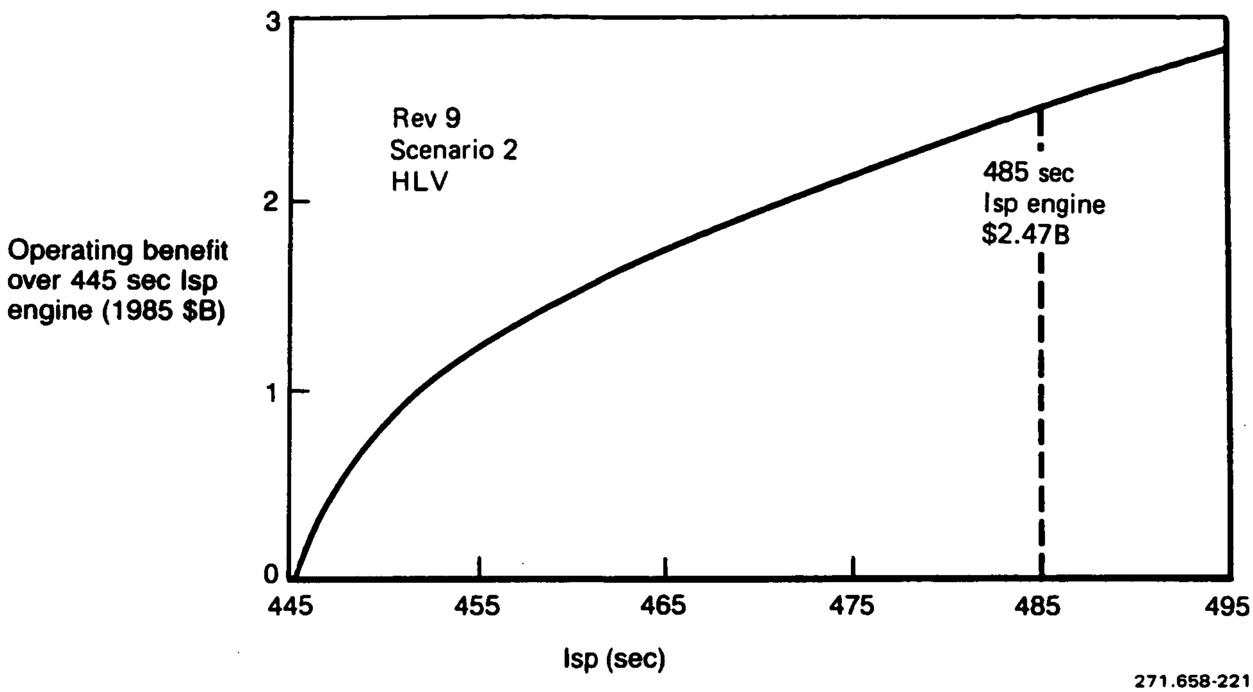

Figure 4-5. Economic Impact of OTV Engine Performance

Reusability (10-20 missions) offers substantial reduction in engine production and delivery costs. (See Figure 4-6.)

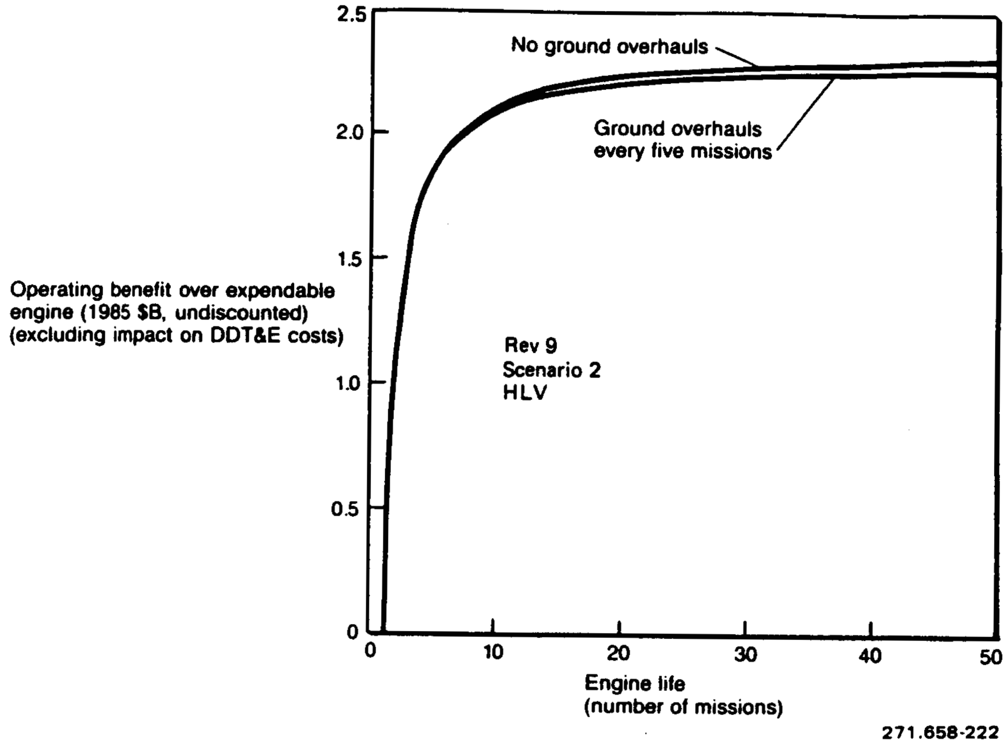

Figure 4-6. Economic Impact of OTV Engine Longevity

4.7 LOW PRESSURE TANKS VERSUS CONVENTIONAL

Low-pressure propellant tanks for a space-based OTV result in lower weight tanks (-700 lb per tankset), reduced propellant requirement (-1M lb), and $0.5B lower life cycle cost. (See Table 4-8.)

Operating with low tank pressures is possible for a space-based OTV since the tanks are only operated in a vacuum, and the propellants can be conditioned to low vapor pressures (<5 psia) as compared to ~20 psia for a ground-based OTV. The savings in tank weight results from reduced material skin thickness (0.008 aluminum lithium).

Table 4-8. Propellant Tanks Trade

Criteria	Low pressure	Conventional
Performance	Reduced weight, less propellant required	Heavier tanks
Cost	Lower operations cost Lower LCC (-$500M)	Lower DDT&E
Operations/growth	Handling more difficult Propellant conditioning system required (on the Earth)	More rugged

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The estimated $80M cost of developing low-pressure propellant tanks and required ground conditioning facilities for the space-based OTV is recovered within 3 to 5 years of OTV operations. These cost savings are made possible through reductions in propellant requirements and delivery costs. Use of low-pressure tanks saves approximately 700 lb in vehicle weight per OTV tankset used, resulting in a 1M lb reduction in OTV propellant usage over the course of the Rev. 9 mission model, for a net savings of over $0.5B. (See Figure 4-7.)

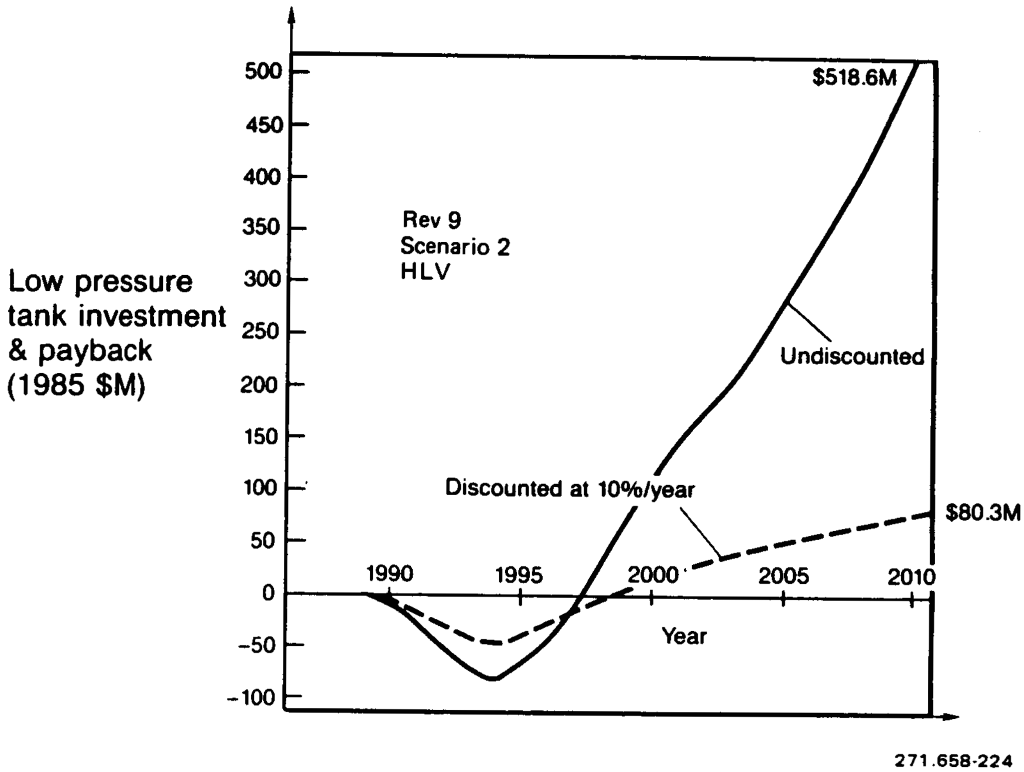

Figure 4-7. Low Pressure Tank Cost Payback Function

4.8 SENSITIVITY OF IOC DATE

Expendable or ground-based OTVs are more expensive to operate than a space-based OTV. Therefore any delay in IOC date for the space-based OTV results in a higher life cycle cost. (See Figure 4-8.)

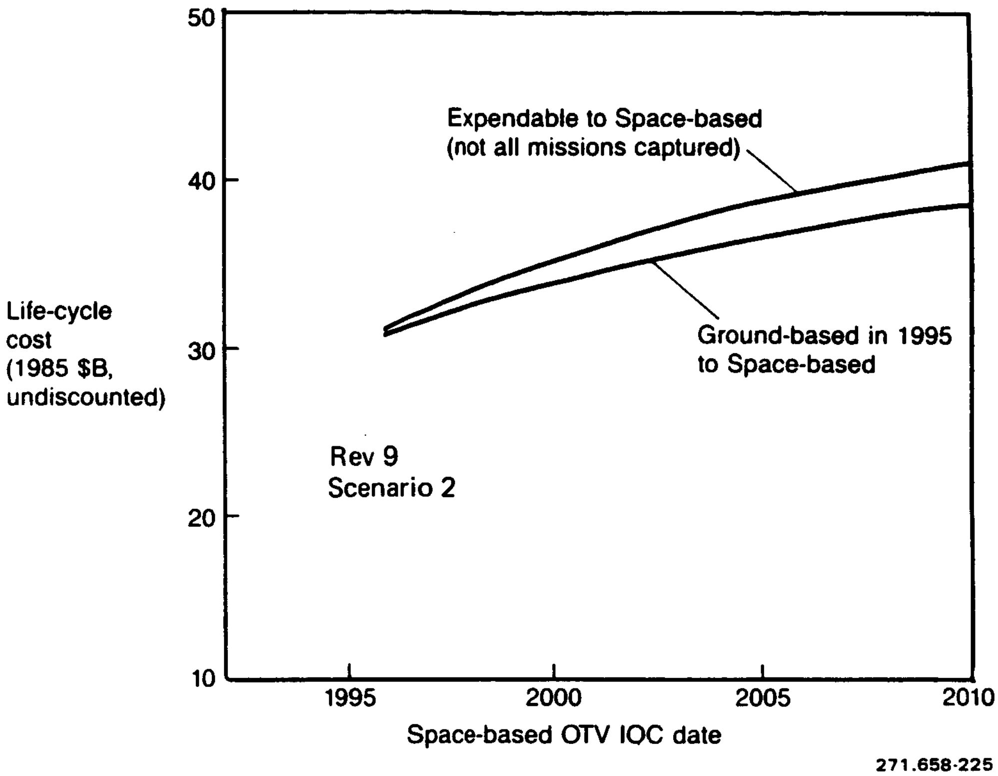

Figure 4-8. Impact of Space-Based IOC Date on OTV Life Cycle Cost

4.9 SENSITIVITY TO HLV CAPABILITY

OTV life cycle costs are most sensitive to HLV performance at the lower end of the HLV capability range (i.e., less than 100,000 lb to LEO). A higher performance HLV (than the 150,000 lb baseline) would not significantly affect the difference in life-cycle cost between the ground-based OTV and the space-based OTV, but a lower performance HLV could increase the economic advantage of space basing considerably. (See Figure 4-9.)

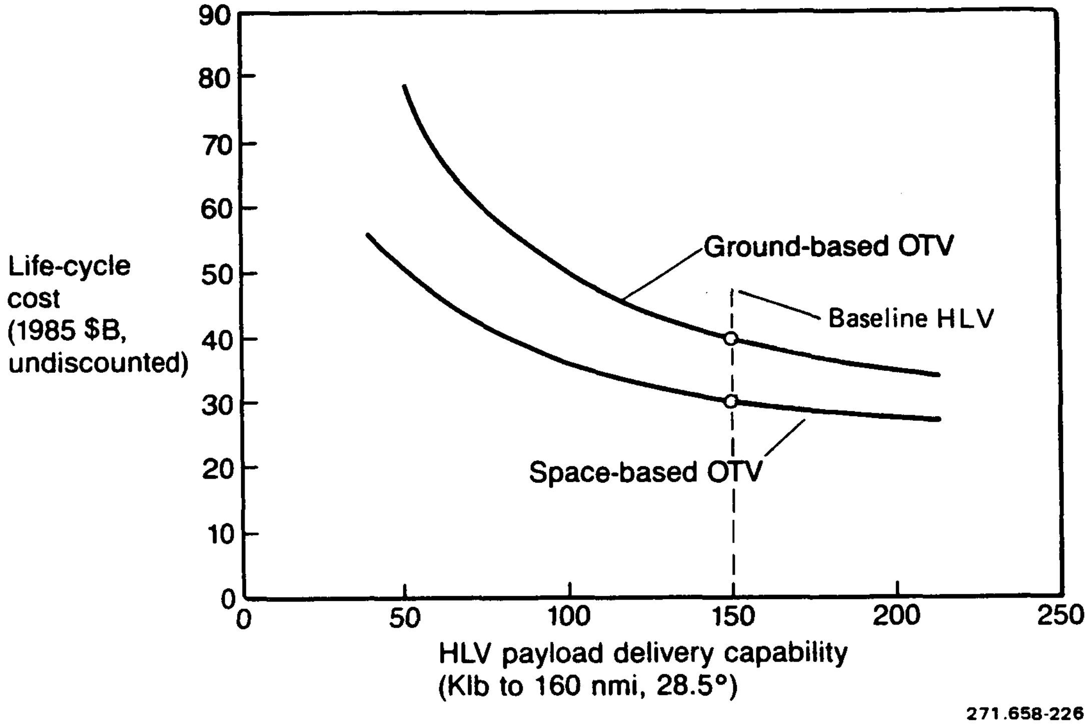

Figure 4-9. Impact of HLV Capability on OTV Life Cycle Cost

4.10 IMPACT OF HLV COST

Due to the greater payload delivery capability of the HLV, life-cycle costs for the ground-based OTV and the space-based OTV are not as sensitive to HLV costs as they are to STS costs. The ground-based OTV would become competitive with the space-based OTV if HLV cost could be reduced to $30 million or less. (See Figure 4-10.) Note that a ground based OTV requires a reusable carrier vehicle. An HLV with return capability costs more ($15M per flight).

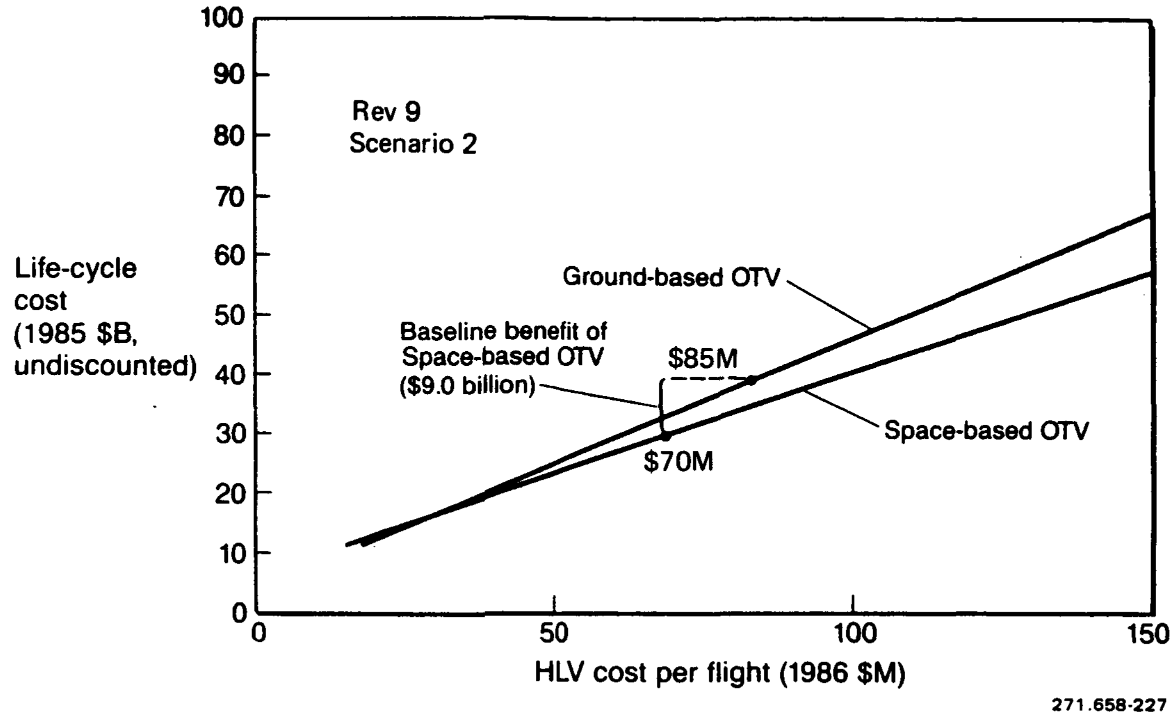

Figure 4-10. Impact of HLV Cost on OTV Life Cycle Cost

4.11 PRIORITY OF BENEFITS

The most beneficial features for an OTV are reusability, space-basing, and cryogenic propellants. Aerobraking and advanced engine technologies also offer significant benefits. Low-pressure propellant tanks for space-based OTV offer lesser but still positive benefit. (See Table 4-9.)

Table 4-9. Features of Most Cost Effective OTV

Recommended attribute	Life-cycle benefit (1985 $B)	Rejected alternative
Reusable	9.2*	Expendable
Space-based	9.0	Ground-based
Cryogenic	7	Storable
Aerobraked	3.5	All-propulsive
Advanced engine		
• High performance (485 sec. Isp)	2.5	Existing engines (445 sec Isp)
• Long life (≥20 missions)	2.2**	Expendable
Low pressure propellant tanks (5 psi)	0.5	Conventional tanks (20 psi)

* Theoretical benefit: expendable OTVs fail to capture 55 missions out of 422

** Does not include differences in engine DDT&E & production costs

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4.12 OTV ACCOMMODATIONS

Although more expensive ($0.4B), an unmanned co-orbiting OTV facility (separate from the manned space station) offers safety advantages, a more favorable space-station environment, and better growth potential. (See Table 4-10.)

This facility (see Figure 4-11) is a free-flying platform for storage, maintenance, fueling, etc of an OTV, OMV, and OTV payloads. It provides the same capabilities and services as a space station OTV facility, and uses similar structure and subsystems (power, attitude control, etc.). It is unmanned, but operated remotely (controlled from the manned space station a short distance away).

Table 4-10. OTV Accommodations Trade

Criteria	Space Station attached	Co-orbiting Platform
Cost	DDT&E & production: $1.0B	DDT&E & production: $1.4B
Risk	Low: Extension of Space Station capabilities	Low: Derived from Space Station subsystems
Inherent safety	Large quantities of propellants permanently stored on station Frequent rendezvous/docking operations at station	Platform normally unmanned
Versatility/growth	Limited	Facility readily expanded and/or replicated
Operational complexity	All in-space operations at one location	Occasional crew transport to platform Control functions performed at Space Station More complex logistics
Environmental considerations	Micro-g environment disruptions Added contamination sources	No adverse effects

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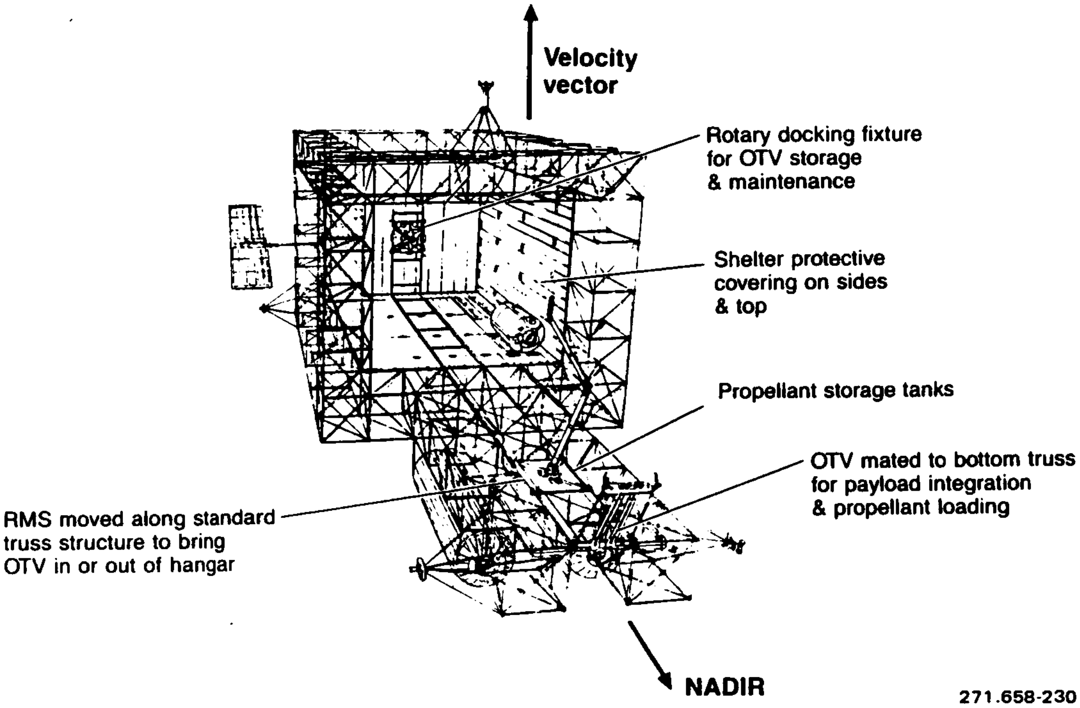

Figure 4-11. Co-Orbiting OTV Maintenance and Propellant Storage Platform

SECTION 5

RECOMMENDED OTY PROGRAM

The space-based OTV can provide the lowest cost transportation to GEO and beyond (one-third the cost of STS/TOS, and one-fourth the cost of Ariane IV).

With payloads delivered to the co-orbiting platform by STS, ELVs, or advanced unmanned cargo vehicles, the OTV will be indifferent to launch vehicles, and safe for manned sytems. It also will enable the U.S. to perform new, essential missions such as return of payloads from GEO, remote payload servicing, expeditions to the Moon and Mars, and implementation of critical military programs. (Refer to Figure 1-1.)

Economic comparison of space-baed OTV with existing upper stages shows that the space-based OTV offers the lowest operating cost. (See Figure 5-1.)

The total investment cost for a space-based OTV and servicing facility is less than $3B, with a peak annual funding requirement of less than $0.8B. (See Figure 5-2.) Refer to Figure 1-3 for the development schedule.

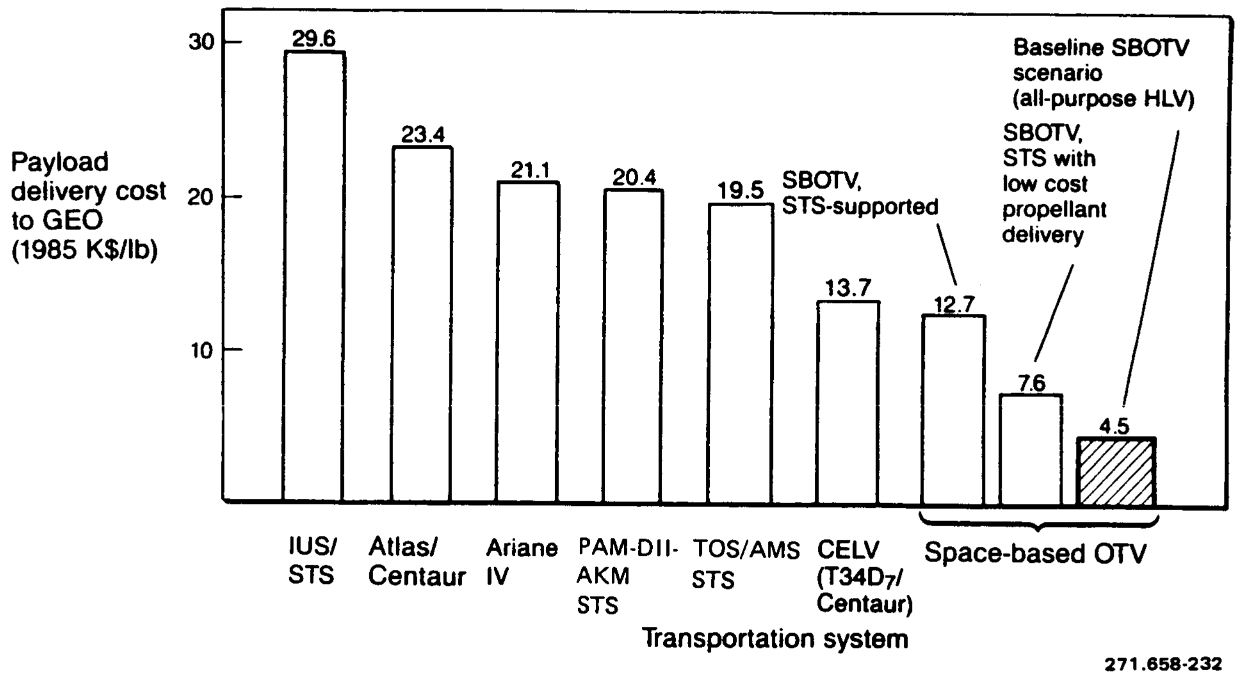

Figure 5-1. Cost/Pound to Geosynchronous Orbit for Various Space Transportation Systems

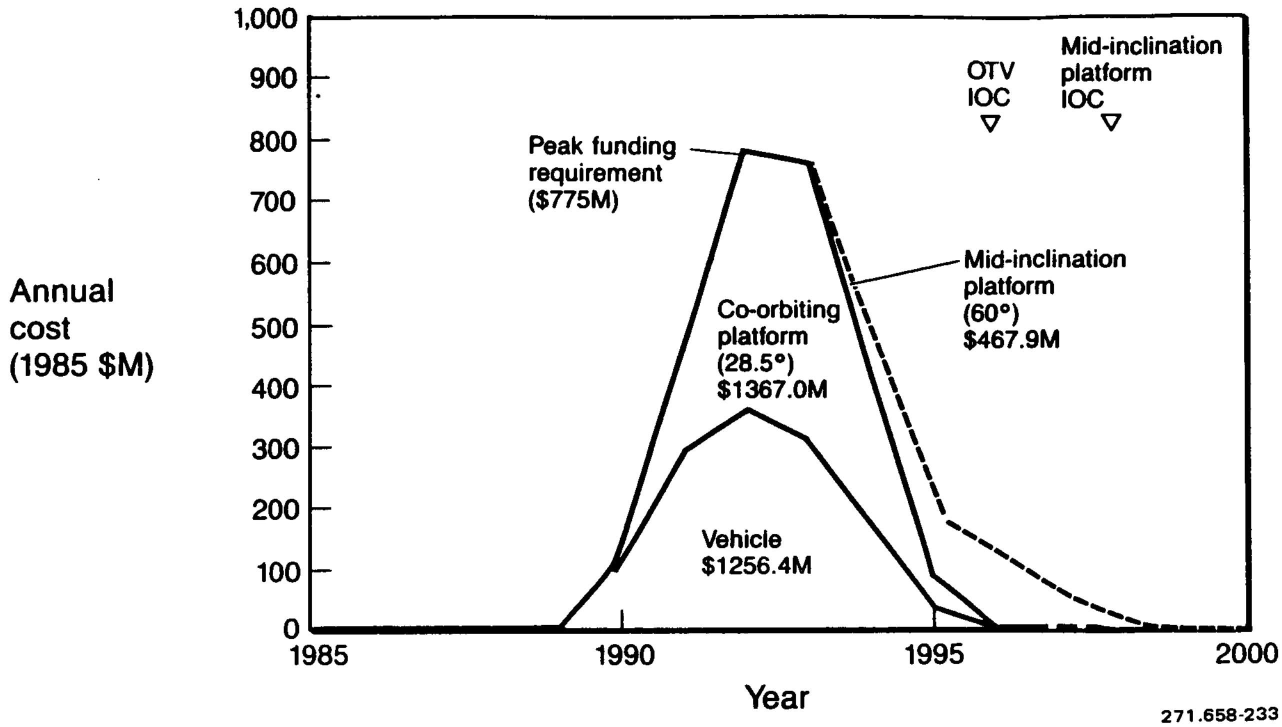

Figure 5-2. Annual Funding Requirements for Development of Space-Based OTV and Orbital Platforms

SECTION 6

CONCLUSIONS

A space-based OTV program should be a national objective.

This system can be operational as early as 1997, but to do so requires Phase B program authorization in FY 88.

Further concept definition is needed now.

Continuing study needs include:

a. OTV operations with HLVs:
   - Physical interfaces
   - Flight operations
   - Propellant delivery systems
   - Return of OTV to Earth

b. Logistics operations:
   - Turnaround operations
   - Ground support functions
   - Propellant resupply
   - Facility requirements

c. Accommodations facility definitions:
   - Platform studies
   - Space Station control module requirements
   - Crew transfer concepts
   - Updated trade studies

Critical technology development required for the space-based OTV includes:

a. Aerobrake
b. Engine
c. Cryogenic propellant management
d. Long life/low maintenance subsystems
e. In-space rendezvous/docking
f. Space logistics
g. Remote payload integration
h. Manned systems

SECTION 7

BIBLIOGRAPHY

1. D.R. Saxton, Revised Groundrules, Orbital Transfer Vehicle Concept Definition & System Analysis Studies, Follow-on Effort, NASA-MSFC, 1986.

2. D.R. Saxton, OTV Mission Model, Rev. 9, NASA-MSFC, 1986.

APPENDIX A

MODULAR SPACE-BASED OTV CONFIGURATION, WEIGHT, PERFORMANCE DATA

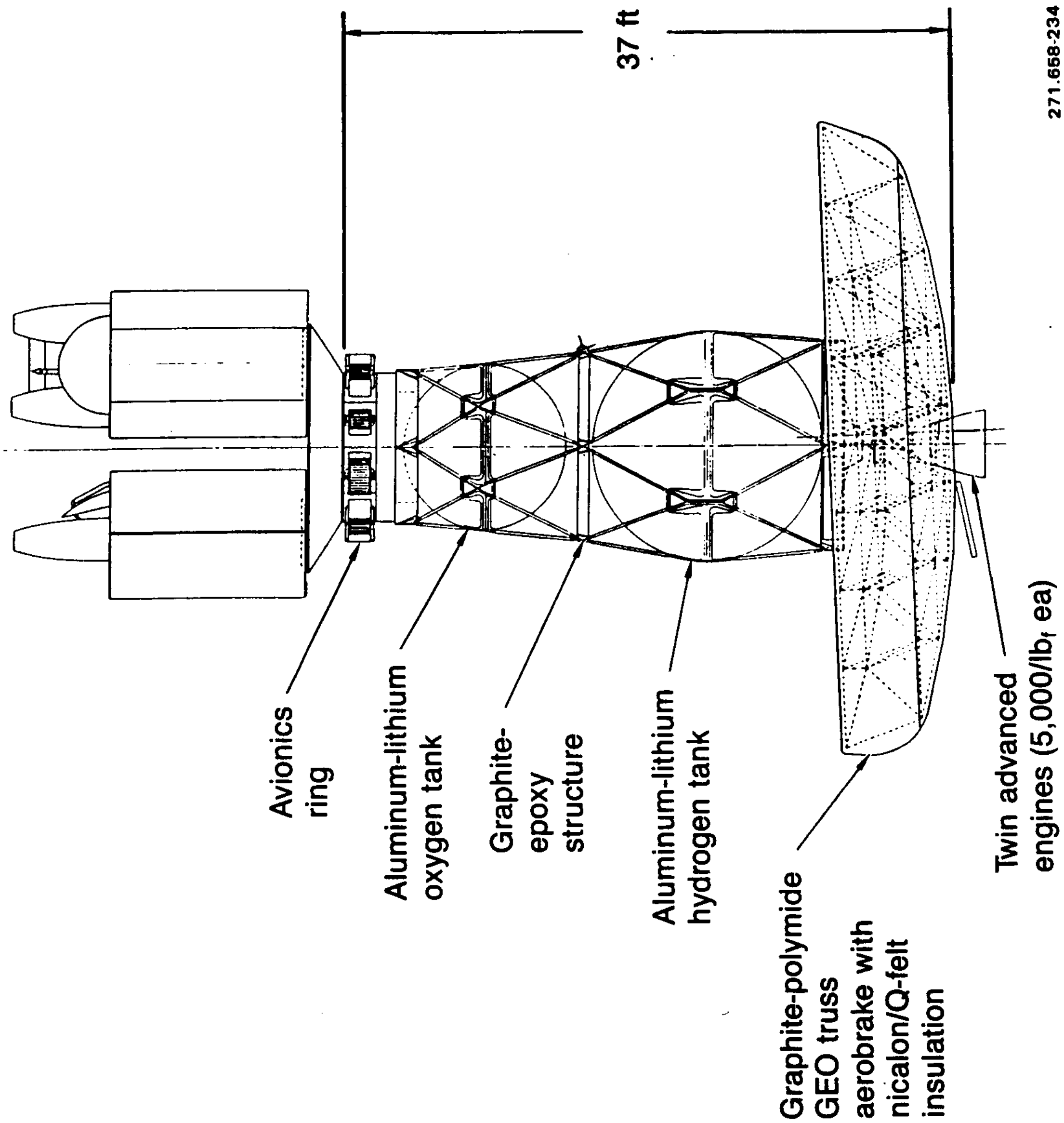

Figure A-1. Core Propellant Stage for Multiple Payload Delivery

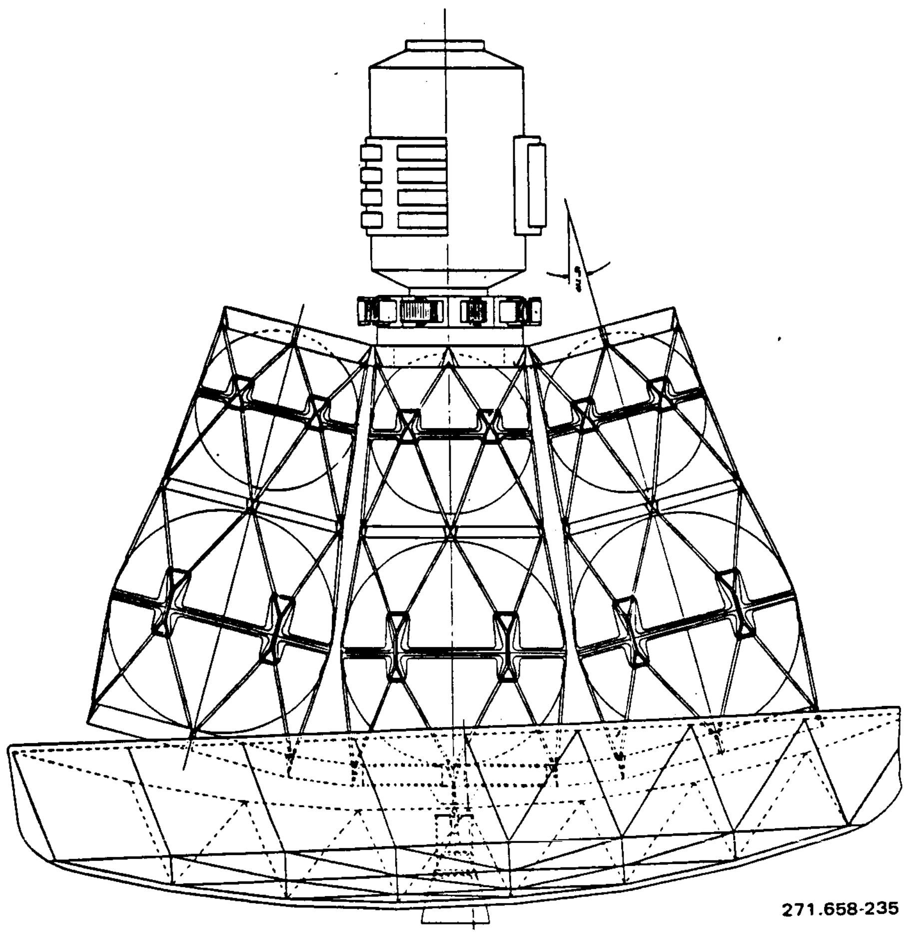

Figure A-2. Twin Outrigger Tankset Stage for Manned Missions

Tanksets	1	3	4	5	7
Structure	4,365	7,193	8,129	9,064	10,935
• Basic structure	(2,732.)	(3,514.)	(3,905.)	(4,296.)	(5,078.)
• Tanks	(292.)	(1,381.)	(1,926.)	(2,470.)	(3,559.)
• Aeroassist device	(1,341.)	(2,298.)	(2,298.)	(2,298.)	(2,298.)
Propulsion systems	1,178	1,828	2,153	2,478	3,128
• Main	(870.)	(1,520.)	(1,845.)	(2,170.)	(2,820.)
• RCS	(308.)	(308.)	(308.)	(308.)	(308.)
Thermal control systems	125	261	329	397	533
• Insulation	(125)	(261)	(329)	(397)	(533)
• Purge	(0)	(0)	(0)	(0)	(0)
Guidance, navigation & control	150	150	150	150	150
Electrical systems	555	555	555	555	555
Dry weight	6,374.	9,987.	11,316.	12,644.	15,301. lb
Residual propellant					
• Main	408	1,224	1,632	2,040	2,856
• RCS	121	302	363	423	545
Pressurant	9	27	36	45	63
Inert weight	6,912.	11,540.	13,347.	15,152.	18,765. lb
Usable propellant (incl FPR)					
• Main	40,843	122,529	163,372	204,215	285,901
• RCS	408	681	788	989	1,191
Other fluids (fuel cell, etc)	77	77	77	77	77
Transient losses	99	99	99	99	99
Stage Ignition Weight	48,339.	134,926.	177,683.	220,532.	306,033. lb
Propellant Mass Fraction	0.845	0.908	0.919	0.926	0.934

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Figure A-3. Space-Based OTV Stage Weight Summary

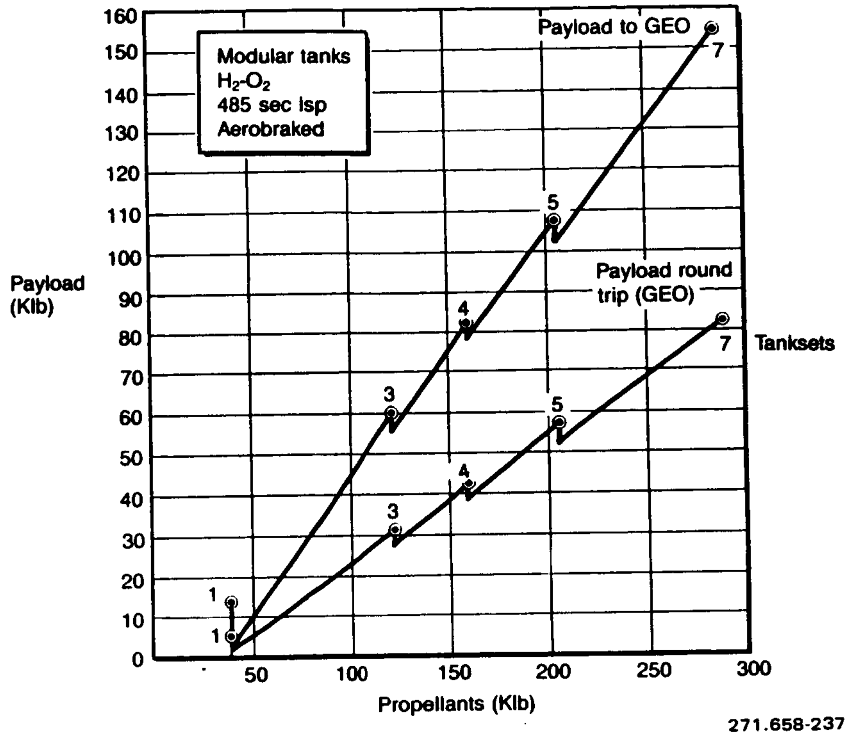


Figure A-4. Space-Based OTV Payload Capability

APPENDIX B

CO-ORBITING PLATFORM CONFIGURATION, ELEMENTS, AND WEIGHTS

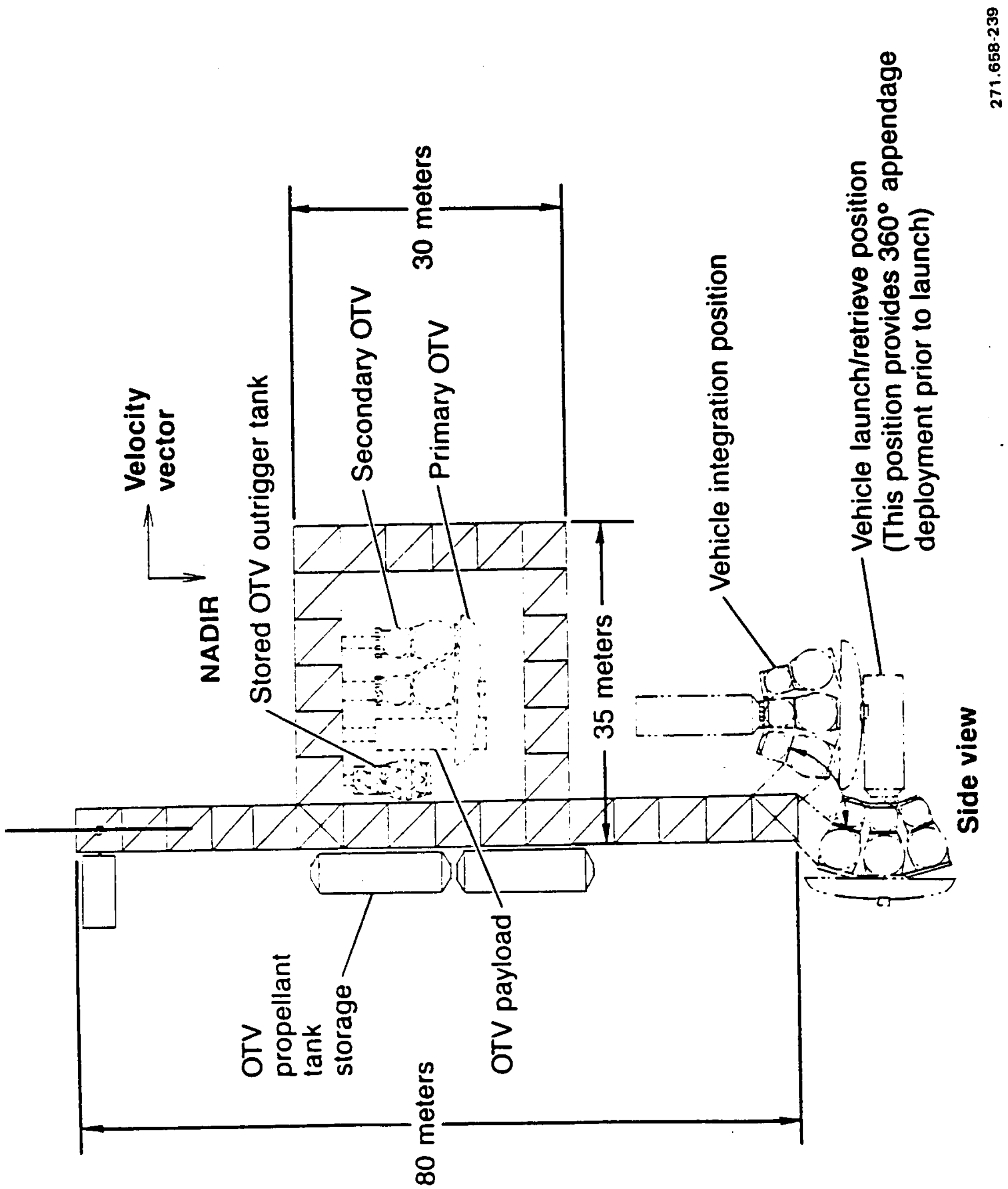


Figure B-1. Co-Orbiting OTV Platform

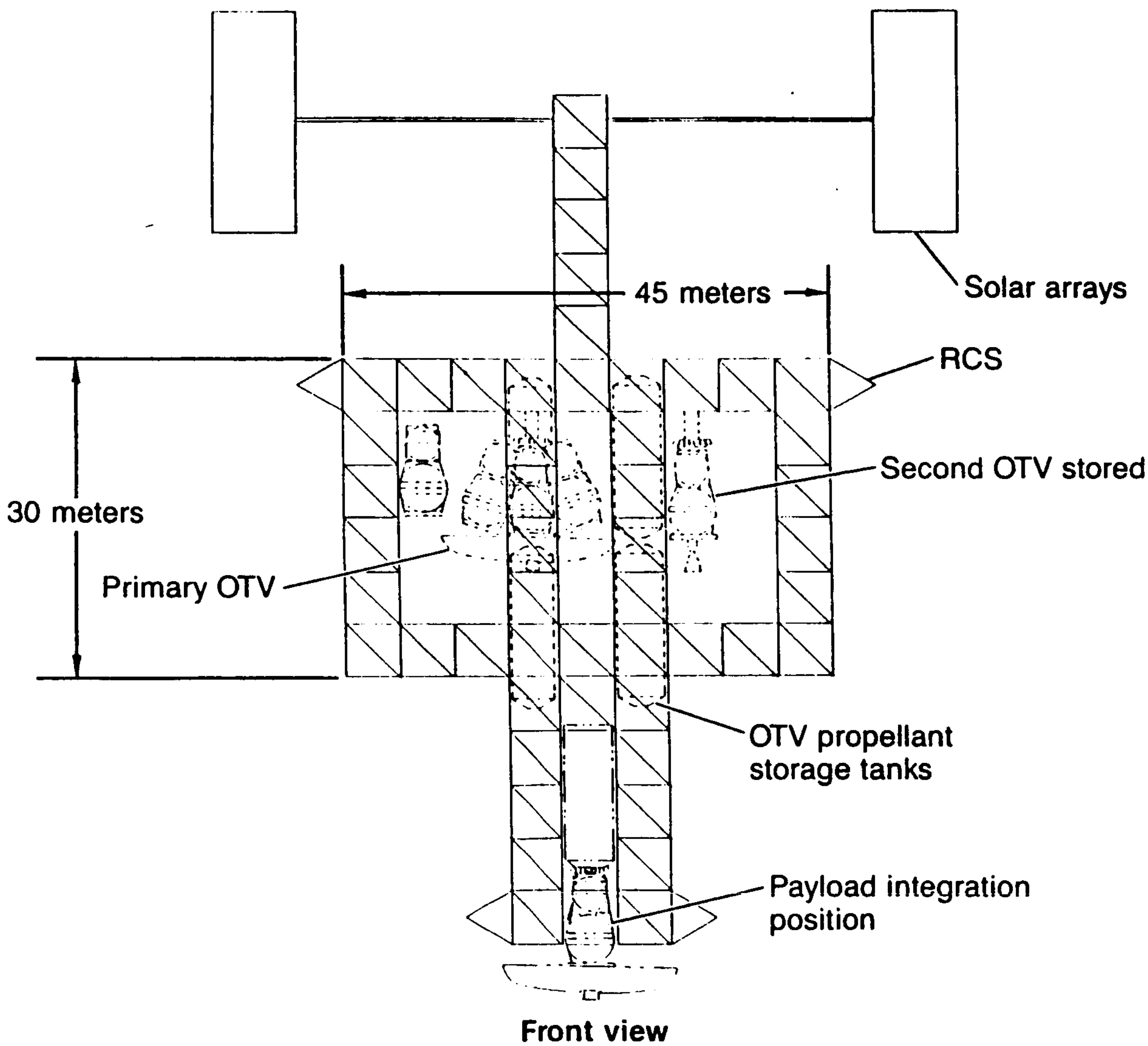
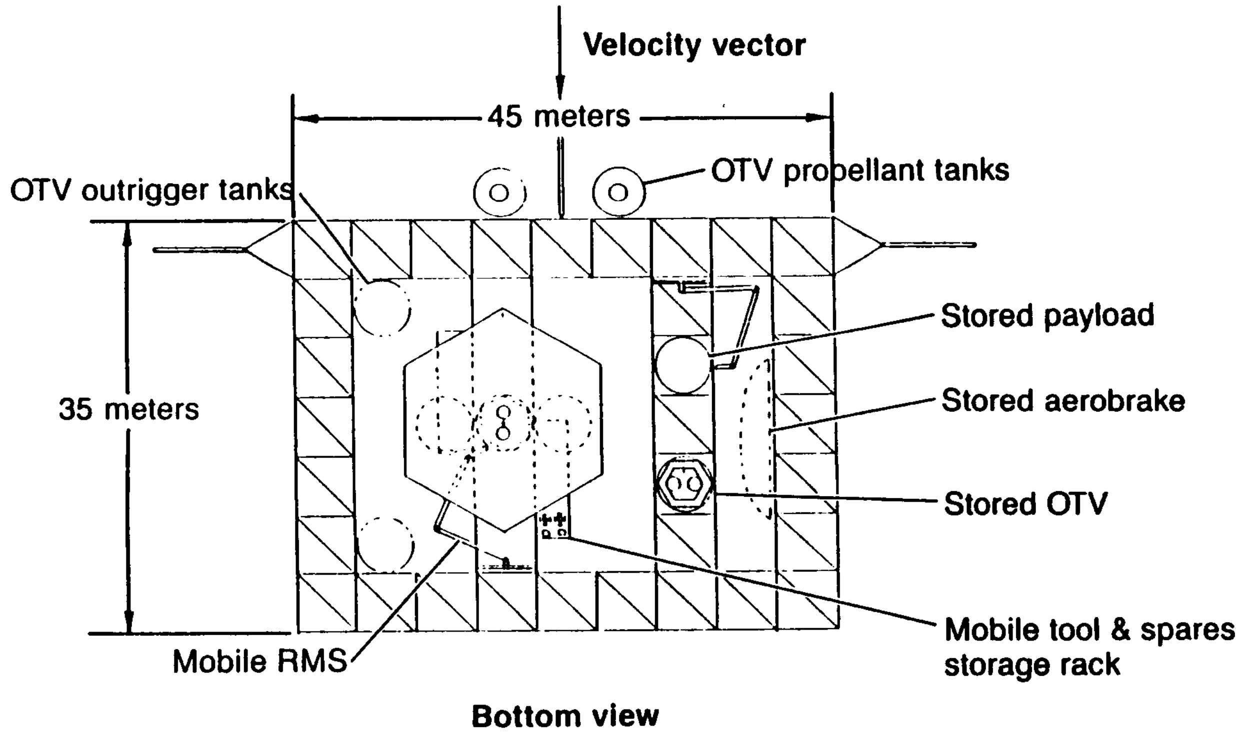


Figure B-2. Co-Orbiting OTV Platform



Weight statement (lb)					
OTV hangar	= 25,500	Maintenance equipment	= 2,000	OTV propellants	= 200,000
Berth/position mechanism	= 5,600	OTV spares	= 800	OTV dry	= 6,400
Propellant storage	= 62,456	Platform spares	= 600	Satellite	= 12,000
Control & checkout equipment	= 1,100	Platform subsystems	= 3,800		
				Total	**320,256**

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Figure B-3. Co-Orbiting OTV Platform