

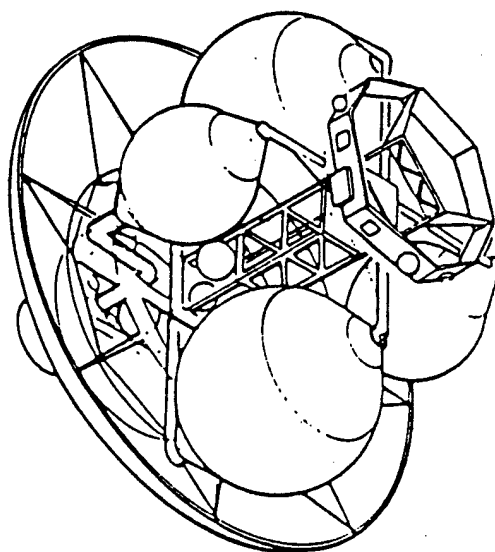
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Volume I

**Executive
Summary**

February 1986

**Orbital Transfer Vehicle
Concept Definition And
System Analysis Study**



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**ORBITAL TRANSFER VEHICLE
CONCEPT DEFINITION AND SYSTEM ANALYSIS STUDY**

VOLUME I - EXECUTIVE SUMMARY

February 1986

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FOREWORD

This final report, Volume I-Executive Summary, was prepared by Martin Marietta Denver Aerospace for NASA/MSFC in accordance with contract NAS8-36108. The study was conducted under the direction of NASA OTV Study Manager, Mr. Donald R. Saxton, during the period from July 1984 to October 1985. This final report is arranged into ten documents:

Volume I	Executive Summary
Volume II	OTV Concept Definition and Evaluation
	Book 1 Mission and System Requirements
	Book 2 OTV Concept Definition
	Book 3 Subsystem Trade Studies
	Book 4 Operations
Volume III	System and Program Trades
Volume IV	Space Station Accommodations
Volume V	Work Breakdown Structure and Dictionary
Volume VI	Cost Estimates
Volume VII	Integrated Technology Development Plan
Volume VIII	Environmental Analyses

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The other volumes of this final report will be published at the end of the current study extension.

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1.0 INTRODUCTION - OTV OVERVIEW

The NASA sponsored, advanced upper stage studies conducted during the past decade will provide major solutions to help determine the future program for advanced technology orbital transfer vehicles operating both from the ground and from a space base. The space based systems will provide a new era of payload delivery capabilities for a wide variety of users, with space basing advantages and new economics for the users. This study describes our recommended cryogenic OTV operating from the ground to meet mid 1990s user needs. The ground based OTV evolves to a space based system operating from the NASA Space station now being defined. The proposed OTV plan incorporates the best features of a new OTV, the IOC and growth Space Station, the Orbital Maneuvering Vehicle (OMV) for support operations, and the STS expanded with the multipurpose external tank Aft Cargo Carrier (ACC) as a logistics system. The ACC provides launch cargo space to augment the Shuttle bay volume and supports an STS propellant scavenging system.

2.0 SUMMARY OF THE PHASE A STUDY

2.1 STUDY OBJECTIVES

This OTV Phase A study defined a new OTV with an operational capability for the US to meet realistic user requirements and world competition. Future user payload requirements impose driver conditions on the technical system, the potential affordable cost, and the political application and environment. Our advanced technology focus--selected leading edge techniques and materials, productivity through manufacturing and production advancement, and time phased evolution of OTV and Space Station accommodations for orderly fiscal development--is integrated into our recommendations for development of an OTV. An initial reusable operations capability to GEO is provided. Manned delivery and return capability to the moon is provided. After assessing space based requirements, assets, and advantages, economics, alternative technical, programmatic, and logistics concepts, the study provides recommended approaches to the following challenges:

- Define the OTV System;
- Define the evolutionary approach;
- Define Space basing requirements;
- Define OTV/Space Station interactions;
- Identify User Benefits.

2.2 CONCLUSIONS --RESULTS

Our Phase A Study conclusions indicate that a new technology OTV has a cost advantage over today's upper stages. NASA should continue the development of a cryogenic liquid oxygen-liquid hydrogen, reusable, aeroassisted, orbital transfer vehicle. This new OTV would provide a much needed, cost effective, high orbit delivery and manned access capability. It warrants starting a Phase B development program within 2 years. A GEO delivery cost of \$3820/pound (FY '85 \$) is possible with such a vehicle.

Two primary technical features are: an initial operational capability version of an advanced main liquid cryogenic rocket engine (475 second I_{sp} , 7500 pound thrust, used alone or as a pair depending on the application); and an integrated rigid/flexible aerobrake using thermal protection of advanced ceramic materials and the blunted 70 degree conical shape proven by the two successful

Viking Mars Landers. User flexibility, versatility with high performance over a broad span of missions, and an effective plan of growth will assure a long lifetime based on realistic mission models.

An initially ground based system is envisioned. It would be operational in 1994, and would be launched as a complete stage, fully loaded with propellants and carried below the Shuttle external tank in the aft cargo compartment. The vehicle evolves into a space based system by 1997 correlated in time with the growth Space Station, the OMV, and the increased 72,000 pound payload capability Orbiter. An ACC based propellant resupply approach provides logistic support for the space based system. Updated KSC ground support facilities, mission operations centers and communications networks support OTV operations. Rapidly expanding robotics and artificial intelligence technology is expected to enable the automated space based operations envisioned.

2.3 RECOMMENDATIONS

We recommend that the NASA continue the funded OTV phase A studies to provide continuity with the ongoing MSFC Phase B space station efforts that are in process. Use of the space station as a transportation node is one of its most cost beneficial missions. The Space Station accommodations for OTV represent 40% of the total OTV/Space Station delivery system costs and include the largest volume and mass impacts yet to be identified for the growth Space Station. In addition, NASA should implement a joint Space Station, OMV, OTV, Spacecraft and users group to provide a regular forum to assess and firm the potential requirements, interfaces, and incompatibilities for the Space Station, much as the working groups were implemented for both Skylab and Shuttle experimental operations.

3.0 MISSION and SYSTEMS REQUIREMENTS

3.1 MISSION MODEL

The Revision 8 OTV mission model and the predecessor, Revision 7, incorporate requirements for the OTV growth capabilities over time. The low Revision 8 model summarized in Figure 1 includes 145 flights while the nominal model, 257 missions, advances the events (in parentheses) as indicated. The initial ground based OTV system will be STS launched and carry unmanned multiple payload delivery flights in 1994 (1994). Initial space based operation commences in 1999 (1997) from the Growth Space Station which can support the full 20,000 pound payload capability OTV with a complete array of assembly, checkout, loading and maintenance accommodations. Unmanned GEO servicing missions, delivering and retrieving a robotic spacecraft servicer, begin in 2008 (2004). OTV manned delivery capability, carrying a 7500 pound manned capsule to GEO and return to the Space station, begins in 2008 (2002). Manned Sorties to the Moon in 2015 (2006) are anticipated.

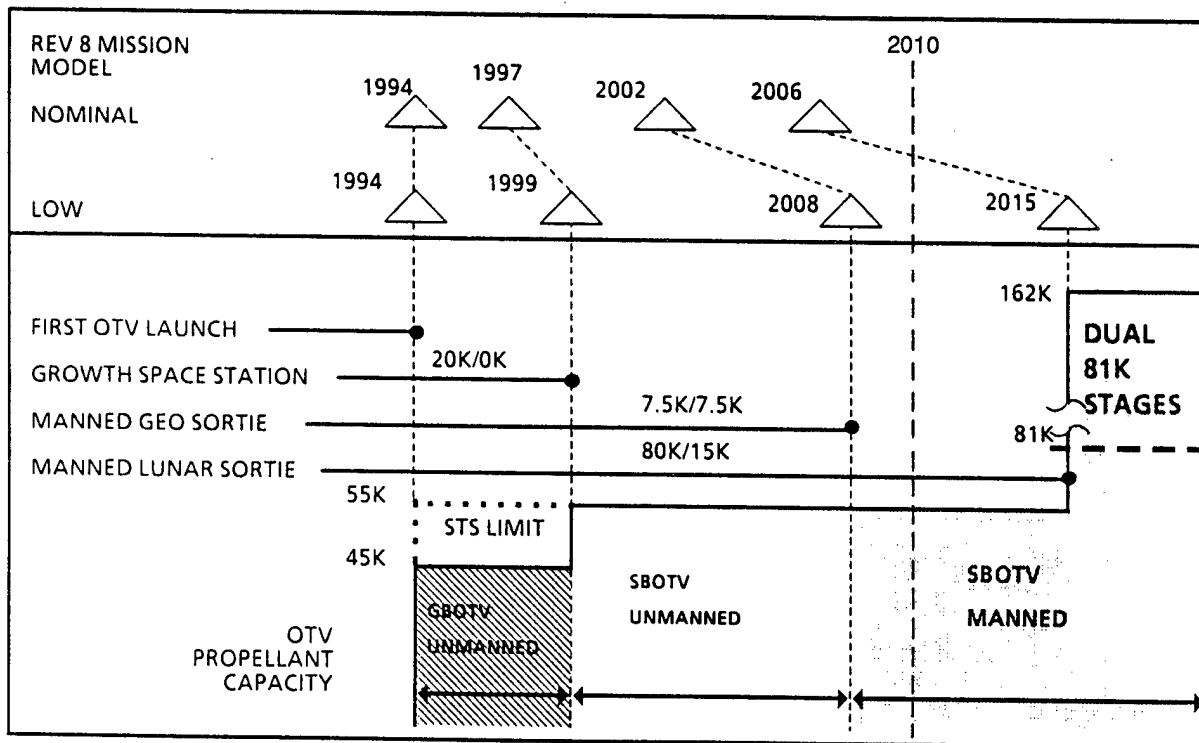


Figure 1 Revision 8 OTV Mission Model

3.2 DRIVER REQUIREMENTS

The NASA Revision 8 OTV mission model focused OTV requirements on high performance missions, in excess of any current upper stage capabilities and beyond the demonstrated STS delivery envelope from KSC. Investments in technology recommended in this study have been justified on the basis of the low version of the Revision 8 OTV mission model. This is a conservative approach from the point of view of minimizing early year expenditures. Consideration of any more ambitious model will justify at least this level of technology development, and could suggest a more aggressive approach. Evaluation of the low mission model, which involves 110 space based OTV flights through the year 2010, results in the following sensitivity of a key program cost element, propellant delivery to the Space Station, to improvements in OTV characteristics.

**PROPELLANT DELIVERY
COST SENSITIVITY**

OTV PARAMETER	COST SENSITIVITY
DRY WEIGHT REDUCTION	\$280K / Lb
ENGINE ISP INCREASE	\$19.5M / SEC

Any near term investment in technology capable of improving OTV characteristics that requires a significantly smaller near term investment is justifiable. Our studies have concluded that high performance flight systems (mechanical, avionics and propulsion subsystems yielding low stage mass fractions and high I_{sp}) are justified and have been incorporated in our designs.

A similar logic led us to keep the functional capability of OTV consistent with the operational role of a high performance, efficient, orbital transfer truck--rather than adding functions more properly part of the spacecraft being delivered. This leads to simple payload integration for a wide variety of potential users. Cost reduction through reusability saves cost for stage production with an acceptable balance in the cost and complexity of the ground and flight supporting systems and the software complement incorporated in all facets of the system. Selective use of leading edge technology will assure a long useful lifetime with time phased mission based evolution from multi payload delivery to GEO servicing and return capability. Unmanned followed by manned servicing flights require flexibility and safety. Reusability is a key feature providing total system, technical, and payload integration with favorable cost and schedule features for all users.

4.0 KEY TRADE STUDY SUMMARY

The key trade studies for an STS delivered OTV are functions of the four evolutionary paths available:

- First - Continuation of an existing all expendable upper stage fleet, with or without future space station involvement;
- Second - A cryogenic OTV, either ground or space based;
- Third - An OTV system using storable propellants;
- Fourth - An OTV system using an alternative advanced propellant .

Our studies reduced the viable paths to three:

- A new cryogenic OTV;
- A new storable, pump fed, OTV;
- A growth version of existing expendables.

The decision network in Figure 2 shows that new OTV concepts for both propellant options were developed through the point where space basing impacts were understood before a selection between them was made. Within each propellant option, the definition sequence first traded reuse options against expendability. The cryo path included an aeroassist versus all propulsive trade. Engine selection was of major importance for both propellant options. OTV delivery to orbit using the ACC versus the cargo bay was considered, then time phasing of man-rated capability. Vehicle designs suitable for space basing were defined. Engine selection and the mode of stage delivery to the space base were considered. Trades were conducted to establish space station accommodations, including the propellant tank farm location and the level of onboard capability and automation required for servicing and launch operations. The time phasing most appropriate for achieving man-rating was reevaluated. In addition to the decisions depicted in Figure 2, the preferred method of transporting propellants to orbit for the space based options (using the STS, tanker scavenged propellants or a new heavy lift or Shuttle derived propellant tanker) was assessed and selected. At this point, it was possible to select between cryogenic and storable propellants, since all pertinent data was available. The major program scenarios, discussed in paragraph 5, are also displayed in Figure 2 . They include evolution of OTV from ground to space based operation, use of only a space based OTV, and comparison with growth of existing expendables to

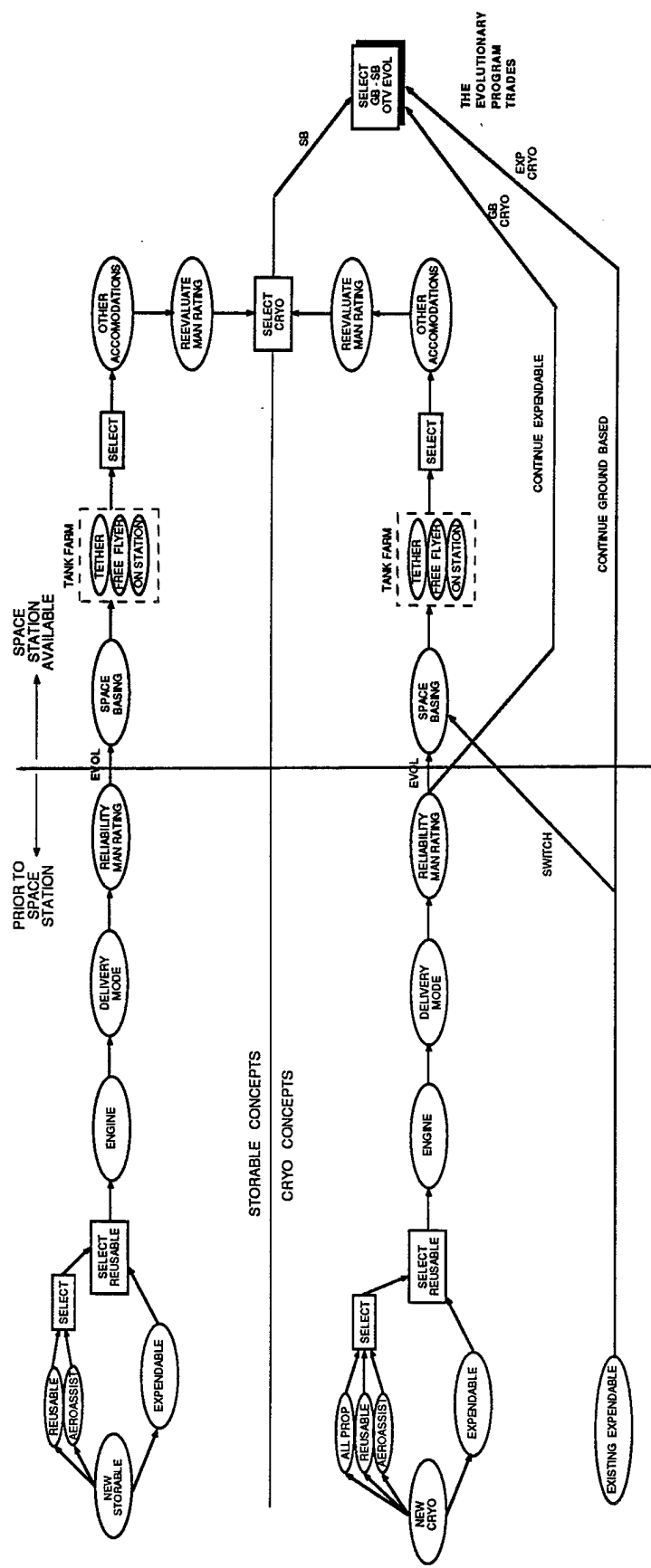


Figure 2 Decision Network

accommodate mission requirements. It should be noted that the trade study cost comparisons were done on a common basis, but not on the same basis as the final program costs presented in paragraph 9.

The first vehicle trade addressed the issue of whether a new OTV should be expendable or reusable. It considered the lower recurring build cost of the expendable versus the much smaller number built for the reusable vehicle. The comparison also included delivery from the factory, test, checkout, and preflight preparations for each new expendable flight vehicle versus inspection and refurbishment operations for a reusable vehicle. The STS orbiter has already provided significant demonstration of the benefits of reusability when other economic and technical factors enable it. A reusable ground based stage must be returned in the orbiter bay after each mission for ground recycling (servicing & maintenance) and reenter the orbiter ground flow for the next OTV mission. The complexity of retrieval operations favors the cargo bay configuration over the ACC configuration, but both approaches have been shown to be feasible. Coordination of the reusable vehicle timeline with the shuttle ground operations timeline poses no significant discriminators in the reusable/expendable trade, since all inspection and refurbishment operations are conducted offline. The principal remaining discriminator in establishing whether or not a new OTV should be reusable or expendable is the performance issue. A reusable vehicle will be heavier and require more propellant to perform a specific mission than an expendable vehicle. For a space based vehicle, this means a higher cost of propellant logistics must be overbalanced by a reduction in the cost of expendable hardware for the reusable concept to win. In the case of cryogenic vehicles, our studies showed a clear advantage for the reusable single stage concept. The storable case is more complex. On delivery missions, a two stage storable concept (where a lower perigee stage is reused and an upper apogee stage is expended, see Figure 3) is preferred over any all expendable concept. The final discriminator in the case of the ground based concepts is the ability to perform, in a single STS launch, missions that occur before space basing can be introduced. We found these reusable concepts can perform the required model missions while retaining their cost advantage.

Our conclusion is that OTV 's should be reusable from the inception of the new OTV program.

The next trade, aeroassist versus all propulsive, was addressed for the cryo case, where the highest likelihood of an all-propulsive win exists. This trade is decided by the recurring propellant delivery to orbit economics and the duration and frequency of the mission model. This establishes whether sufficient traffic exists to pay back development cost quickly enough to be economically viable. In all the models and delivery scenarios evaluated, aeroassist wins by at least 15% and will

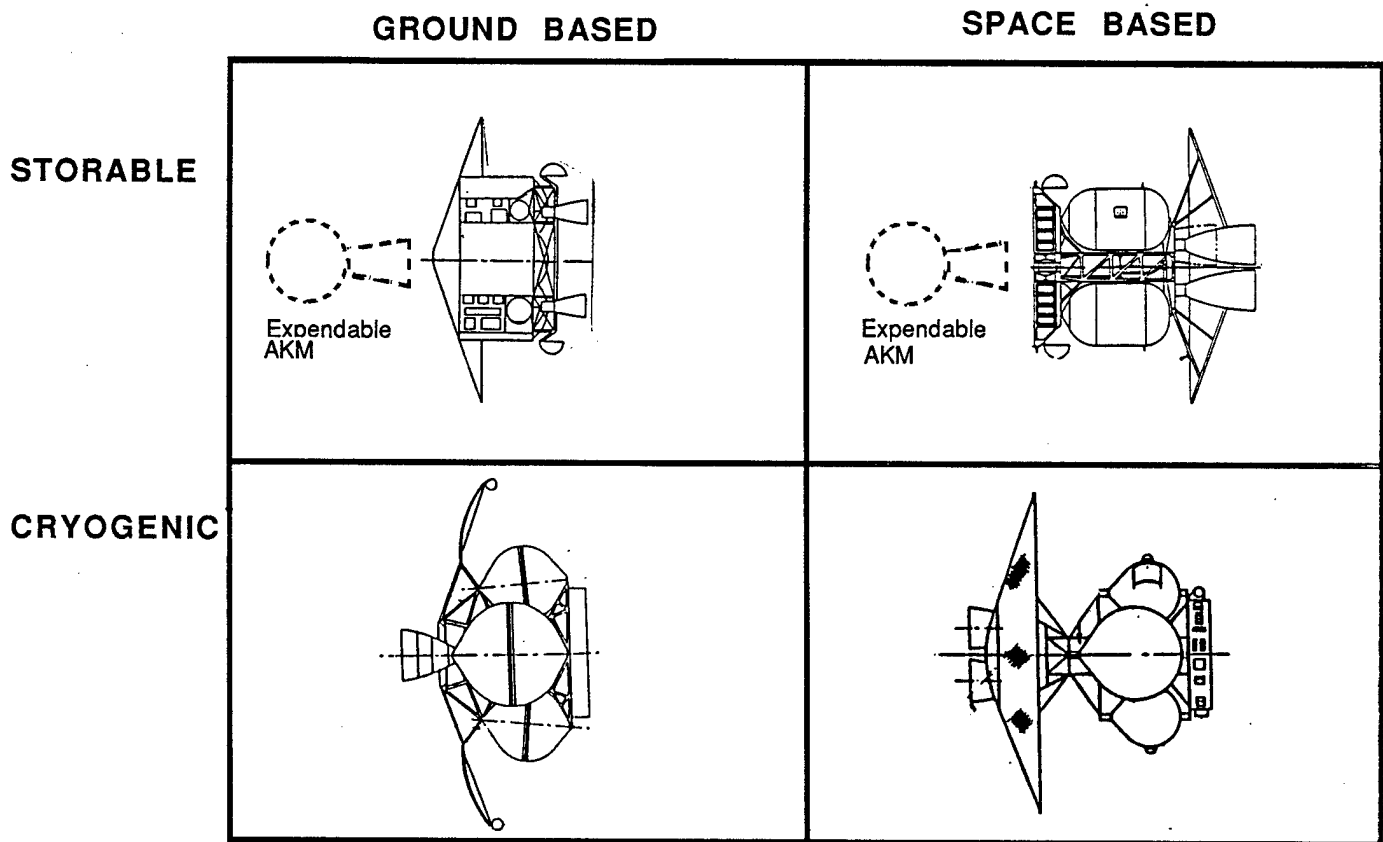


Figure 3 OTV Stage Concepts

justify an R&D investment of 1.7 times its projected \$244M development cost (which includes a flight development proof test of the winning aerobrake and guidance configuration).

Our conclusion is to incorporate aeroassist from the beginning of the new OTV program.

Next, consider the broad issue of the preferred propellant for OTV use. At the outset of the study, the primary advantage of cryogenic propellants was recognized to be their higher specific impulse which would lead to less propellant required to perform model missions. It was anticipated this advantage could be offset by the higher density of storable propellants which supports more compact stage design, and their 'storable' aspects which leads to elimination of boiloff during extended missions, simpler propulsion management systems, simpler storage at the space base and lower development cost. At the study midterm, it was directed that all decisions should be justifiable on the basis of the low Revision 8 mission model. This model comprised only 145 missions through the year 2010, included missions as long as 21 days, and reduced the weight of performance driving missions. This model with its limited flight rate set up a situation that displayed storables at their maximum advantage.

We evolved candidate storable and cryogenic programs that met model requirements with highly efficient, cost effective systems. The cryogenic program optimized with single stage concepts, the storable program with two stage concepts. Storables used expendable upper stages for delivery missions, reusable upper stages for retrieval missions. The engine specific impulse available in the vehicle development time frame, and its adaptability to both unmanned and man carrying missions is critical. Cryogenic propulsion systems evolving from the currently operational 440 second I_{sp} to between 470 and 483 seconds offered the highest gain in performance for the minimum dollar development investment, and were incorporated in the candidate cryogenic stage designs. Storable engines are evolving from the current 315 second I_{sp} pressurized main engine systems to 345 second pump fed engines. This development draws on the NASA STS OMS and RCS successes and is supported by ongoing multicontractor developments for the USAF RPL. This new pump fed storable engine technology was incorporated in the storable stage designs. The storable engine development was found to be cheaper by 20% than the cryo engine development. Contrary to the anticipated result, we found the cost of a space station cryogenic propellant farm is slightly less than a storable propellant farm. The Space station propellant farm cost of \$190M-storable vs \$171M-cryogenic is driven mainly by a helium gas scrubber for the returned storable propellant. A passive cryogenic storage system that vents only hydrogen gas, which is in turn used to supply space station orbit maintenance propellant requirements, provided a further cryogenic system advantage. Considering all these aspects, we projected a comparably based DDT&E of \$1365M for the cryogenic program and \$1238M for the storable program. Storables were a DDT&E winner as anticipated, but not by a sizable margin.

The storable fleet size was found to be twice as large at 4 stages as the cryogenic fleet at 2 stages. In fact, a single 55k propellant capacity cryogenic system encompasses the entire mission model (Rev 8 low model) through the lunar missions beginning in the 2010 period -- the initial 15 years into the OTV life cycle. As a consequence, the comparable base production cost for the cryogenic systems was a winner at \$239M compared with the storable at \$314M.

The recurring cost of propellant delivered to orbit, a direct function of the unfavorable specific impulse ratio 470/345 (1.36), yields the cryogenic system a large recurring cost advantage. This is further enhanced by the greater yield of the cryogenic scavenging system. Considering these factors, we estimated the comparable cost per flight of all recurring operations at \$61M for the storable, vs. \$45M for the cryogenic stage. Either one significantly bests the \$123M for the average comparable mission using today's expendable stages.

The total cost of a 145 mission program shows a cryogenic system advantage of \$10.4 B to \$8.2B in FY'85\$, of \$2.6B to \$2.3 B in discounted \$. Without other driver requirements for extended duration, loiter, evasive maneuvering, or other maneuvers more adaptable to a compact

storable stage, an all cryogenic vehicle is the selected option.

Our conclusion is that cryogenic propellants are the proper selection for the low mission model, and that greater use would make the selection even more advantageous.

The cryogenic main engine selection includes complex trade issues. The RL-10 engine and its derivatives (440 second to nearly 470 estimated I_{sp}) with an ongoing funded performance improvement program supporting the STS and CELV programs provide strong candidates. It provides a highly reliable 1960's based engine with the lowest possible development cost and risk. At 500 psia maximum chamber pressure it has limited capability for marked reduction in size and weight.

Advanced engines are now in technology development under NASA Lewis funding by three contractors. They offer the maximum in efficiency (to 98% of theoretical I_{sp}) small size, more efficient thermodynamic and combustion cycles, utilization of the lessons learned from the STS main engine development and flight programs, improved materials, reusability, software, instrumentation and man rating experience. Development of a new engine is a lengthy process, and this technology development program is key to achieving success. The manufacturing and production techniques necessary to achieve 98% of theoretical performance are complex and time consuming. Downsized engines do not permit scaling of running clearances in high pressure turbomachinery, so increased precision, stiffness, interference running seals, and individual contoured cavities which efficiently direct the fluids and gases are necessary to achieve the very high performance levels necessary in the injector, chamber, feed plumbing, pump and turbine systems. These advanced engines resulting from this development program are strong candidates for OTV application.

We have included an initial, limited capability, advanced engine candidate. Its development program provides an advanced engine capability in time to support initial OTV missions, and provides an economical evolutionary path to advanced performance capability. It will be proven by a ground test program of over 700 hot firings during engine DDT & E and through flight thereafter. The motivation here is to employ a tried and proven military operational evolution technique where operational experience is used to meet hardware qualification requirements. The OTV unmanned flight program would be used to save at least 25% of the man rating development cost through the in flight reliability testing available during the 8 - 14 years (mission model dependent) of unmanned delivery missions planned prior to the first manned round trip mission.

An alternative is the acceleration of the Lewis cryogenic technology program to provide a prototype engine which cuts 1 to 3 years from the current 7 to 10 year development cycle. There are mixes or combination developments starting with the RL-10 and also proceeding to an advanced engine 5 to 10 years into the OTV program, or starting with the initial capability engine and considering it the initial design in an advanced engine evolutionary cycle. We assessed the known foreign competition for cryogenic stages and do not detect an off the shelf competitor.

Our trades indicate the low Revision 8 model can best be served by a middle of the road 1990 state of the art initial capability engine of 7500 pound thrust, with a 6:1 mixture ratio, weighing 280-300 pounds, and delivering 475 second I_{sp} . A nozzle with a 60 inch stowed length, up to 120" long with nozzle extended, a bell diameter under 50 inches, capable of being gimbaled to 20 degrees, step throttled to 50%, and capable of usage either singly or as dual engines is needed. A target development schedule of 60 months, and a cost to unmanned flight of \$175 M is specified. Demonstration and proof testing for manned flight will evolve during the normal unmanned delivery and spacecraft return missions forseen for this new system.

We recommend an Initial Capability Advanced Engine design evolving from a competition held just prior to the OTV phase C-D Program Initiation.

Propellant delivery to the space station represents 82% of overall OTV program cost, the major recurring expenditure for the long term 145 (low model) to 257 (nominal model) flight programs. We must maximize the Space Station/OTV use of propellant scavenging and use of potentially unused STS capability resulting from less than 100% efficient STS cargo manifesting. This available propellant is controlled by NASA manifesting philosophy, which currently favors OMS N_2O_4 /MMH overload or extra crew provisioning. This resource is particularly significant since up to 2.3 STS flights to space station can potentially be scavenged to support each OTV flight. The location of the scavenge tanks is significant with the ACC system providing a 2:1 advantage over the cargo bay system. The ACC system provides 4.59M pounds of scavenged propellants [328 flights at an average 14,000 pounds. per flight], while only 2.5M pounds [181 flights] are available from a cargo bay based system. Development cost of the ACC system is nearly double the development cost of the cargo bay based system, but it can be shared with the development of an ACC based OTV system. The new heavy lift tanker, shows a break even at 290 flights and \$75M cost per flight if its \$2.2 B estimated DDT&E is assumed fully chargeable to the

OTV project. This makes it an impossible solution for any of the Rev 8 mission models. Our trade analyses show a \$417/pound average delivered propellant cost for the STS tanker, compared with: \$1014/pound for delivery with dedicated STS flights; and \$322/pound for ACC scavenging with propellant delivery requirements supplemented by STS flights dedicated to propellant delivery using an STS based propellant tanker.

Our conclusion is propellant should be delivered to space station with an STS propellant scavenge system located in the ACC, supplemented by an STS based propellant tanker .

Based on the trades presented in the preceding paragraphs, it is apparent that the ACC has application as the ascent location for a ground based OTV, and as a location for the STS propellant scavenging system. The cost for its development can be effectively shared by both of these initiatives. Further, we have found that ACC scavenging operations are best implemented in low orbit, with propellant transferred to the space station by the OMV. This situation leads to this final conclusion:

The ground based OTV, loaded with propellants, should be launched in the ACC. An ACC based scavenging system using the OMV for propellant transport from the orbiter at 140 miles to the space station at 270 nm. is recommended.

5.0 EVOLUTIONARY SCENARIOS and APPROACHES

We evaluated seven evolutionary paths to capture the Rev 8 mission model at the four discrete capability levels indicated in Figure 1. The time phased OTV capability required supports initial delivery missions in 1994 using a single STS launch. Larger delivery and unmanned servicing missions in 1999 (1997 in the nominal model) coincide with the potential availability of a space station capable of supporting a space based OTV. The next capability step is for the manned GEO sortie mission in 2008 (2002 nominal model). A final step exists only in the nominal model, and is to support the manned lunar delivery and return mission by the year 2006.

Figure 4 summarizes six evolutionary options considered. In options I,II and VII, the initial operational capability is provided by a non-man-rated ground based, ACC delivered OTV. Options IV and V provide this capability with an existing non-man-rated expendable stage launched in the cargo bay, while option VI provides it with a new, non-man-rated, cargo bay OTV.

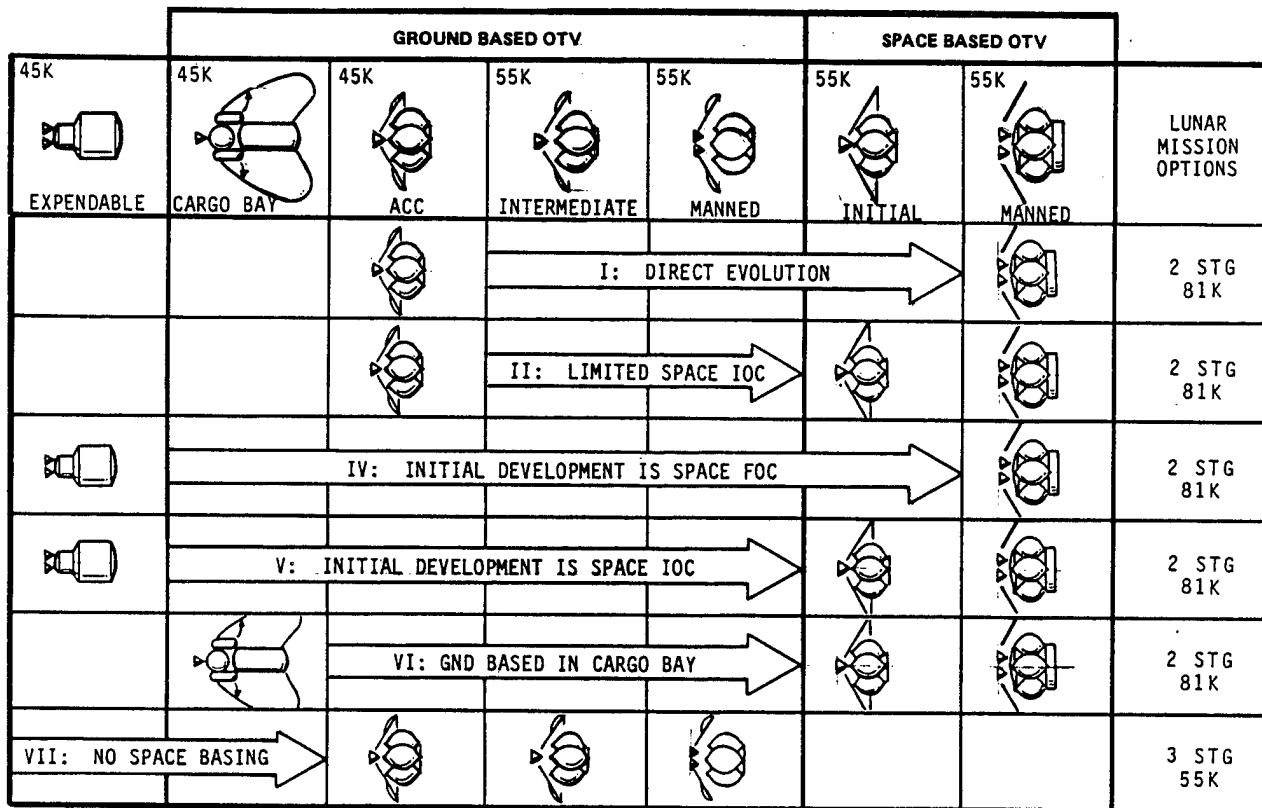


Figure 4 Alternative OTV Growth Paths

The second time period, coinciding with the Growth Space Station, provides a capability to deliver a 20000 pound payload to GEO with no payload return and to transfer an unmanned GEO servicing mission of 7,500 pound to GEO with 7,500 pound return beginning in 1999 (1997 in the nominal model). Three options were evaluated:

An unmanned space based OTV (Options II, V & VI);

A manned OTV incorporating all the provisions for the higher reliability manned missions (Options I & IV);

An unmanned ground based vehicle with no space basing requirements (Option VII).

The third period begins with man carrying OTV missions to GEO with a 7,500 pound up and 7,500 pound return payload weight requirement. Beyond these missions, Lunar and all future candidates should be man-rated and capable of operational manned delivery and return missions of 2 to 20 days duration. Options I through VI are space based, option VII investigates retaining a ground based approach to achieve this capability.

The fourth period, applicable only to the nominal Rev 8 model, includes a manned 80000 pounds delivery to and 15000 pounds return from low lunar orbit. This mission requires a massive increase in capability that is best accommodated by multi-stage arrangements. Recommendations are to be based on the low mission model which does not include this requirement prior to 2010. It should be noted that the impact of reaching this lunar capability on OTV stage design and cost as well as the added Space Station accommodations size, cost, and complexity will be significant but do not form a decision criteria at this time.

We eliminated the cargo bay based configurations based on a head to head comparison of Option II with Option VI. This comparison included the options of using the cargo bay versus the ACC for propellant scavenging, and an evaluation in benefit accrued from excess payload weight and volume on the 35 (low mission model) ground based flights. While the development cost of the ACC for both ground based OTV delivery and propellant scavenging was highest, it led to higher return on investment and greater cost benefits relative to the all expendable approach.

The cost comparison of the remaining candidate options relative to the all expendable approach is shown in Figure 5. It is apparent that the OTV development should be initiated as soon as possible because all options show a considerable benefit over the expendable approach. It is also clear that there is a significant benefit to using the space based operational mode over the ground based mode. The principal reason for this benefit is that scavenged propellants accumulated

at the space station provide a marked improvement in the cost of propellant logistics. Finally, the decision between man-rating the first space based vehicles and delaying man-rating until required by the mission model is close. We recommend man-rating earlier because the cost impact is small, while the benefit of gaining operational experience with the system well before committing it to manned use seems significant. Safety will be operationally proven for exactly the same system the man will fly on, without the block change in engine and avionics configuration that would be involved with man-rating immediately prior to manned flight.

We conclude that option I is the preferred evolutionary program. It starts with a reusable, ACC configured OTV in the ground based era, and transitions to a manned space based capability as soon as it can be accommodated by the Space Station. Propellant logistics are supported by an ACC based scavenging system. Growth to the manned lunar sortie capability is readily accommodated, but is not acquired prior to the horizon of this study.

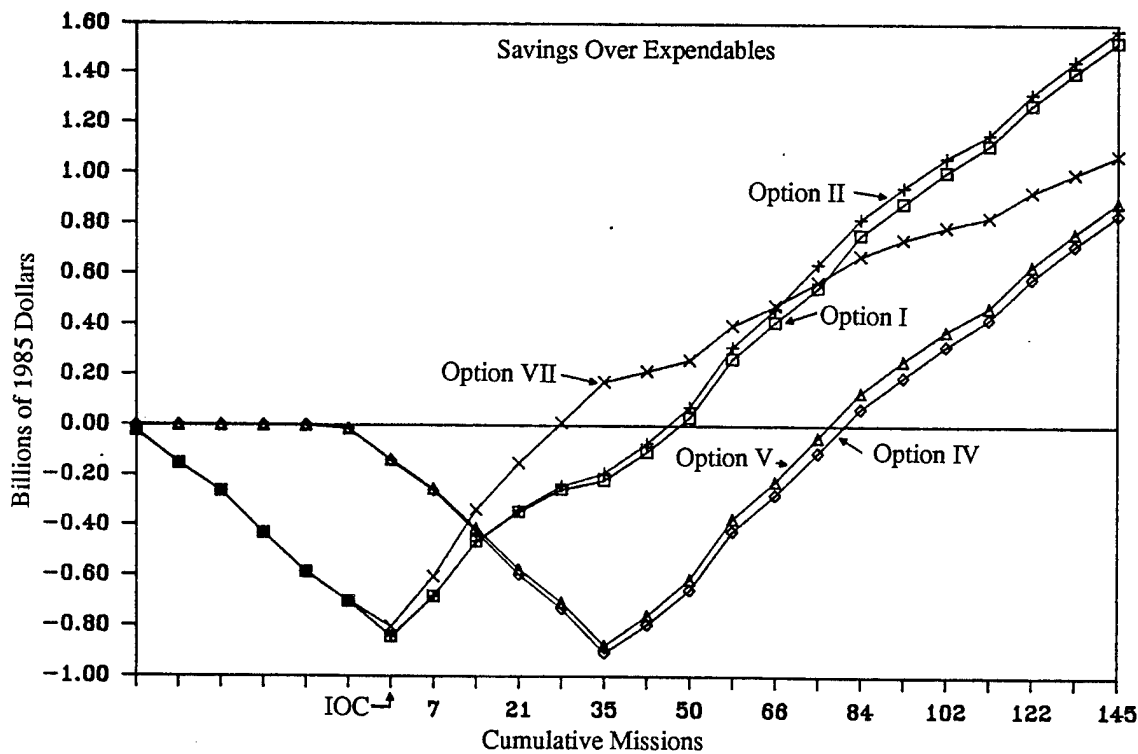


Figure 5 OTV Evolutionary Strategy Comparison

5.1 GROUND BASED

A ground based OTV could evolve to perform the entire mission model through the year 2010. In its most rudimentary form, such a program could evolve as a modified existing expendable stage kitted with a new engine, interchangeable in its mounting provisions, and fitted with an aerobrake kit. The aerobrake kit could be configured to attach around the existing engine mountings and the cargo bay ASE (i. e. CISS). Evolutionary avionics and structures could provide a cosmetic update to the still basically expendable vehicle, which would be optimized for space maintenance, delivery to orbit, etc.. This approach could be grown, step by step, to accommodate the entire mission model. Many of the more advanced missions in the Rev 8 model will require the OTV to be returned to the ground on a different flight than the one that carried it up because of the long mission duration involved. This adds the parameter of frequent down manifesting of OTVs on Orbiters that carried other missions aloft to operations requirements. This is considered to be a significant drawback to the completely ground based approach, as witnessed by the Long Duration Exposure Facility which has been awaiting a return ride for over a year. Our evaluations indicate that a clean slate ground based OTV, configured to operate out of the ACC, transitioning to a space based mode is economically more desirable.

5.2 SPACE BASED

The space based OTV evolution starts in 1999 (or 1997, nominal model). Our initial space based OTV incorporates subsystems and design approaches proven in the ground based program. The general arrangement remains a four tank, aeroassisted vehicle with main propulsion firing through doors in the heat shield. While we considered an initial space based capability using a non-man-rated vehicle, we recommend going to a two engined, man-rated concept at the time of transition to the space based operational mode. Space basing requires development of accommodations at the space station to support assembly, checkout, loading, launch, retrieval, inspection and maintenance of OTV systems. In our trade studies the cost of these accommodatings have been considered a part of the total cost of acquiring a space based OTV capability. These trades showed that space basing was the preferred approach.

5.3 SPACE TENDED

We considered the intermediate approach of space tending. Space tended OTV concepts for an operational program, while offering the potential of reduced accommodations at the space station, appear generally undesirable. A ground based OTV operating in conjunction with the space station could carry a partial load of propellant to orbit, up to the limits of the current orbiter capability. For those missions requiring more propellant, drop tanks or a half-stage of auxiliary tanks could be preloaded on the ground and delivered to a rendezvous with OTV and a previously delivered payload. Mating, checkout, mission launch, and retrieval could then be accomplished in the vicinity and under supervision of the space station. Most such concepts require closely scheduled follow-up orbiter supply missions of from 1 to 7 day duration. For example, if the delivered propellant goes directly into the OTV tanks, or if loaded half-stage or drop tanks containing flight propellant are delivered and used without the participation of intermediate on-station storage tanks, we anticipate a significant program risk. We have assessed incremental additions of Space Station accommodations capabilities using a gradual build up. We found that partial OTV and spacecraft support facilities which do not include adequate capability for systems checkout, diagnostics or launch abort impose risk and cost for each element's recycle to earth in the event of an anomaly. Limited in-situ space maintenance and servicing capability could not always diagnose or correct potential failures. The added risk to the users appears substantial both for the OTV and the payload, and without value added for the station involvement.

6.0 OTV CONCEPTUAL DESIGN

The STS launched OTV emerging from these trades has unique configuration requirements and constraints. Our designs are based on key criteria and design philosophies representing the results of user driven flight delivery system requirements, and based upon our Titan, Transtage, Gemini, Skylab, and STS payload integration experience for the NASA, DOD, Commercial and international customers.

6.1 DESIGN APPROACH

Two basic cryogenic vehicle designs were developed in detail during this study. The first provided an unmanned, ground based, delivery capability in 1994. This vehicle was configured to be carried to orbit in the Aft Cargo Carrier. The second cryogenic vehicle design provided a manned space based capability whose IOC coincided with that of the full capability Space Station (assumed to be 1999 in the low Rev 8 mission model, 1997 in the nominal model). This vehicle was designed to be assembled and maintained at the space station, and to be transported there in segments in the Orbiter cargo bay. The design growth path from one of these vehicles to the other was as common as possible considering the differences in IOC and operational requirements. The basic design approach to the various subsystem elements is described in this section, the specific resulting designs in the subsequent paragraphs.

STRUCTURE AND TANKAGE

All of our cryogenic configurations are short, using four side by side tanks with engine(s) mounted aft and firing through a door in an aerobrake (see Figure 3). The payload is mounted forward, providing a configuration that is generally axially symmetric. Our modular growth systems begin with a highly efficient, structure using high strength, high modulus, low weight, primary structure. Graphite epoxy is used for the central box structure and outriggers which carry the four large cryogenic propellant tanks. The ground based configuration is compact to enable packaging the assembled, loaded vehicle within the confines of the ACC. The general arrangement of the space based vehicle is more open to accommodate easy assembly and maintenance at the space station. The more compact ACC structure is lighter, even though the loading conditions are more severe since the ACC structure that is permanently attached to the ET carries a major portion of the launch loads. The main cryogenic propellant tanks are thin wall, sphere /cone configured, fabricated from 2090 aluminum/ lithium alloy. 2090 alloy is expected to combine the excellent cryogenic characteristics and weldability of the proven 2219 we currently use in constructing the ET, but with higher strength to produce 20% lighter tankage. Plumbing, insulation and particle

impact shielding requirements are different for the ground based and space based vehicles, and are discussed in the appropriate following paragraphs. The Space based vehicle can accommodate 50% larger tanks without changing primary structure, enabling ready upgrading and growth. This design feature maintains the same number of plumbing and electrical connections and valves so vehicle integrity is not reduced with a multiplicity of added components and functions.

AEROBRAKE

Both configurations accommodate atmospheric reentry during an aeroassist maneuver with a 70 degree blunted conical aerobrake whose shape was derived from our Viking Mars Lander technology. They comprise a rigid 13.5 foot diameter center section incorporating two foldaway main engine doors and a flexible outer section providing the required overall aerobrake diameter. The rigid center section is faced with STS FRCI 20-12 tiles. The flexible outer portion of the aerobrake is supported by a folding graphite polyimide backup structure chosen for its high temperature tolerance and stiffness. The outer section frontal temperatures encountered during the six minute aeropass, which approach 2500 degrees fahrenheit, are resisted by a TABI thermal blanket. TABI is a thick, three dimensional, woven sandwich of Nicalon (silicon carbide) fibers, interwoven with Q felt inserts, over a Nextel (aluminum borosilicate) cloth impregnated with RTV sealant that eliminates gas flow through the shield face. The blanket thickness required is different for the ground based and space based vehicles, due to changes in retrieved weight. Our integral shield design firmly attaches the TABI sandwich to the backup structure to utilize its inherent stiffness, rigidity, and damping characteristics to provide a very light weight, extremely rigid aeroshield assembly that is stiffer than most aircraft wing assemblies.

PROPULSION

All of the cryogenic configurations use a compact LO_2/LH_2 engine design that reflects an initial operational capability of the next generation, small, advanced technology, cryogenic space engine. The basic engine is pump fed and operates at a chamber pressure of 1500 psi. It delivers 7500 pounds of thrust at 475 seconds specific impulse through a two position nozzle with a retracted length of 60 inches and an extended length of 120 inches. This engine is step throttleable to 50% thrust to accommodate transfer of 'g' sensitive payloads. A single engine is used on non-man-rated ground based vehicles, two on man-rated space based vehicles. Autogenous generation of GO_2 and GH_2 provide main propellant tank pressurization, and a thermodynamic vent system efficiently manages boiloff losses. A propellant utilization system minimizes outage in the multi-tank configuration. Propellant grade fuel cells are fed from the main tankage, as is bipropellant reaction control propulsion for the space based vehicles (monopropellant hydrazine was selected for ground based attitude control). With this approach, most mission expendables are fed from the main cryogen tankage, and no compromises in tank size are required to perform the

wide variety of different missions in the model.

AVIONICS

The avionics design draws heavily upon leading edge advancements in control, data management, communications and electric power supply technology. Ring laser gyro and star scanner systems, updated with position and velocity data from GPS, will provide the accuracy required for the longer OTV missions that exceed current upper stage duration by two orders of magnitude. The data management subsystem is configured in a distributed architecture that includes two executive computers. A broad band data bus network incorporating Ada software provides both the airborne and ground checkout systems with compatible information and facilitates the usage and sharing of general purpose equipment and software for a variety of users. Guidance, navigation, and control software is expected to include 250,000 lines of code to minimize the individual mission peculiar initialization loading now required for each STS expendable upper stage mission. OTV basic communications utilize S-band to TDRS and L-band for GPS navigation updates, and will use airborne equipment under development for other space projects. We have selected advanced fuel cells that use propellant grade fuel collected from the main propellant tanks. Fuel cell and radiator configuration is tailored for the ground or space based application.

PAYLOAD INTERFACE

Payload interface provisions are simple but flexible, with single connectors for power, data, and communications to accommodate the essential safety functions required for the OMV/OTV/Payload stack during launch and retrieval proximity operations near the Space Station. A universal payload docking ring is provided on the aft face of the OTV with differential pickup points to accommodate various interface payload diameters for boost or retrieval, and to provide the proper lateral mounting locations to maintain overall stack c.g. during all flight regimes.

Multiple payload carriers are provided to assure the low cost delivery of multiple manifested payloads of the PAM, IUS, Transtage, TOS-AMS and Centaur class which make up 65% of the Rev 8, Low mission model. This same multiple capability will be available for return to LEO of full or partial payloads within the performance envelope of the OTV. Ground integration of the payloads on the carrier will provide faster reaction for space launches but the flexible design accommodates spacecraft 'mix and match' at the station. Ground based OTVs will be mated to the payload at the orbiter using the PIDA and the RMS in combination. Space based configurations are mated using the automated robotics in the OTV assembly hangar and payload specialist control and monitoring available at the Space Station.

6.2 GROUND BASED OTV

The selected ground based cryogenic OTV, Figure 6, uses the four tank configuration with a single initial advanced capability engine. The ACC based OTV will utilize the ACC support structure as an integral load bearing member for the basic design loads during boost to LEO. The structural configuration mounts the tanks closely together to fit within the ACC envelope. The thin gauge aluminum /lithium tankage (.018 for the LH₂ and .014 for the LO₂ tank) is sized to carry 45,000 pounds of propellant, adequate to meet any of the mission model requirements. The main tank periphery is covered with 25 layers of double aluminized kapton. A substrate of 0.5 inch of SOFI is added to the hydrogen tanks to eliminate liquefaction of air in the MLI during launch processing. Composite structures are selectively shielded with lightweight tape and insulation. The 40 foot diameter flexible aerobrake, using hard ceramic foam tile center, folds forward during launch in the ACC. The fully loaded stage weighs 50350 pound including a dry weight of 4916 pounds and 45434 pounds of propellant and other fluids - sufficient to carry a 16, 500 pound payload to GEO from a 72,000 pound payload capacity orbiter.

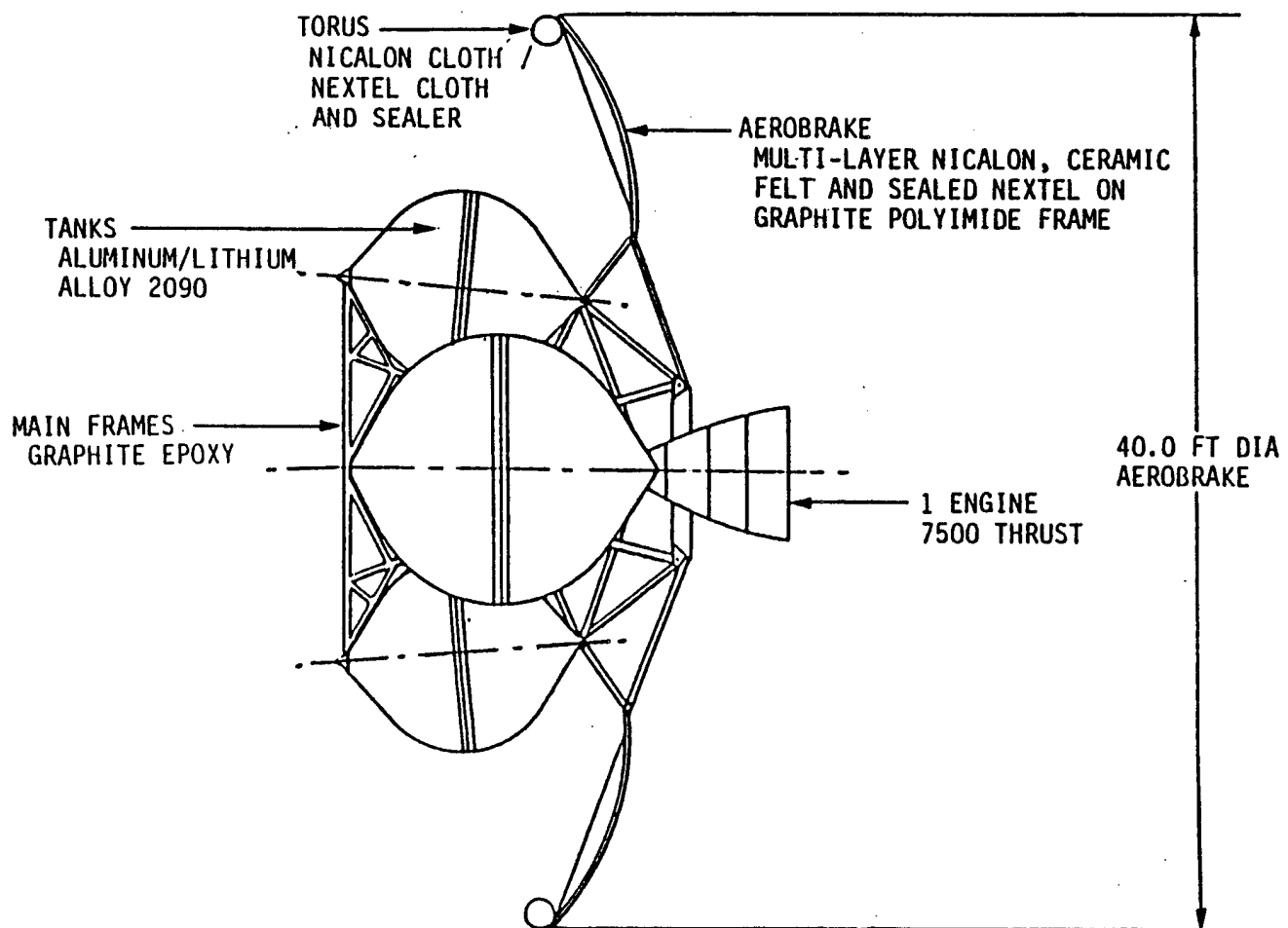


Figure 6 Ground-based Cryogenic OTV Concept

Payload attachment is through the four hardpoints at the forward end of the propellant tanks that also serve as the attachment to the ACC during ascent. Avionics are located on the primary structure and are accessible for servicing while in the ACC on the pad. Selected subsystem redundancy assures that unmanned flight reliability goals and dual fault tolerance when in the vicinity of the Orbiter are achieved. The hydrogen tanks and aeroshield on the ground based configuration are designed for removal in space after mission completion. The aeroshield is discarded, while the hydrogen tanks are stowed in the Orbiter bay separated from the main stage for return to earth.

6.3 SPACE BASED OTV

The selected Space Based OTV shown in Figure 7 is an evolutionary growth of the ground based vehicle. Several differences in design approach are the result of its design for space basing, mode of transport to orbit (unfueled, in segments, in the cargo bay), and man-rating. Its general arrangement is open to facilitate automated on-orbit servicing with backup EVA capability. The all-composite structure incorporates servicing cradle interface trusses and OMV interface points. All the space based vehicle tanks are designed for automated installation and replacement in space.

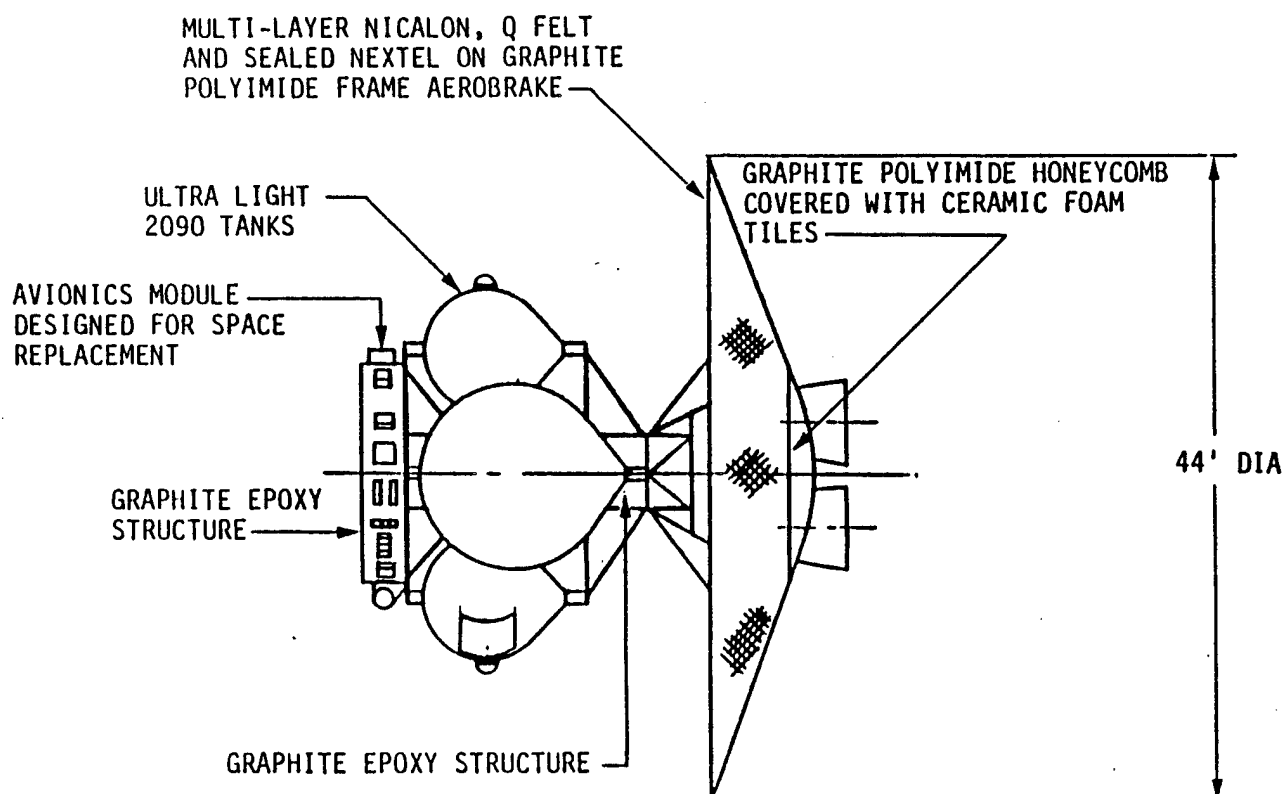


Figure 7 Initial Space-based Cryogenic OTV

The main tanks mount at the top and bottom in sockets. A single multi-element no-leak-or-drip quick disconnect accommodates the fill, drain, vent, pressurant, and sensor connections in a single pneumatically actuated, functional element for automated robotic removal and replacement. The minimum main tank gauges are reduced to .012 in the LH₂ tank and .010 in the LO₂ tank, reflecting the launch-empty operation. The main tank periphery is covered with 50 layers of double aluminized kapton, and covered with a 6 mil stand off aluminum bumper for meteoroid protection during the missions. The Space Station hangar provides the LEO meteoroid and space debris shielding for the storage periods between missions to minimize OTV scar weight not required for mission operation. Avionics units are strategically arranged on an octagonal ring structure at the aft end just below the payload interface. Redundant capability to support the manned mission reliability requirements is incorporated. Two 7500 pound thrust IOC advanced engines with retractable nozzles are utilized. Quick disconnect features enable replacement of the entire engine for space maintenance. The 44 foot diameter integrated rigid/ flexible TPS aerobrake is designed for a 34 psf peak pressure for return of the manned GEO capsule. The vehicle weighs 62379 pound fully loaded with a 7364 pound dry weight and 55015 pounds of propellant and other fluids. It will support the 20,000 pound payload delivery to GEO or the 7,500 pound round trip manned GEO sortie mission.

Modular growth is provided by direct replacement of the 55000 pound capacity tank assemblies with larger 81000 pound capacity tanks. They provide the growth capability necessary to accommodate the manned lunar sortie mission (80,000 pound delivery and 15,000 pound return) in a 2 stage configuration. The 44 foot aerobrake TABI will either be designed to withstand increased pressure and heating during the lunar return or a multipass mission design will be employed. RCS propellants and fuel cell consumables are fed from the main tanks. Subsystem capabilities are adequate to support the 24 day mission duration requirement.

7.0 OPERATIONS

Launch and flight operations analyses were conducted to determine operational impacts, constraints, support requirements and interfaces for both the ground and space based OTV concepts in the planned STS and Space Station design and operations environment. Candidate launch operations concepts were developed for ground and space based OTVs using either cryogenic or storable propellant configurations, launched to LEO either in the cargo bay or in the ACC. Launch operations scenarios were developed and evaluated based on extensive KSC and VAFB experience to provide baselines for space station accommodations and orbital launch processing.

Flight operations analyses defined mission scenarios to derive vehicle design considerations, flight operations support requirements, and the fleet size required to support the mission model. Propulsive maneuvers, powered and coast trajectories, and supporting operations sequences were timed for driver model missions. These timelines, coupled with ground turnaround timelines and mission traffic established fleet size requirements. Definition of mission control approaches and evaluation of STS and Space Station proximity operations provided the data required to generate the operations descriptions required to complete the operational cost comparisons of candidate OTV concepts.

7.1 GROUND OPERATIONS

For our selected ground based configuration launched in the ACC, prelaunch processing requires a dedicated facility at KSC equipped to perform man tended automated robotic assembly, servicing, and checkout of the OTV, as well as post flight turnaround after return from orbit. The OTV is integrated with the ACC in the VAB and enters the STS launch flow as shown in Figure 8. Should access on the pad be needed, doors in the ACC provide entry for limited component removal and replacement. Major OTV component removal on the launch pad would require a field splice modification in the current ACC design. Alternatively, a destack of the ET and major OTV element replacement in the VAB would be required, an approach that is not recommended. Launch site processing for delivery of space based OTVs is minimal under the "ship and shoot concept" where final acceptance and cryogenic testing is accomplished at the contractor facility prior to delivery to the launch site. In this mode, the STS flight to LEO is performed with the OTV treated as a dormant payload.

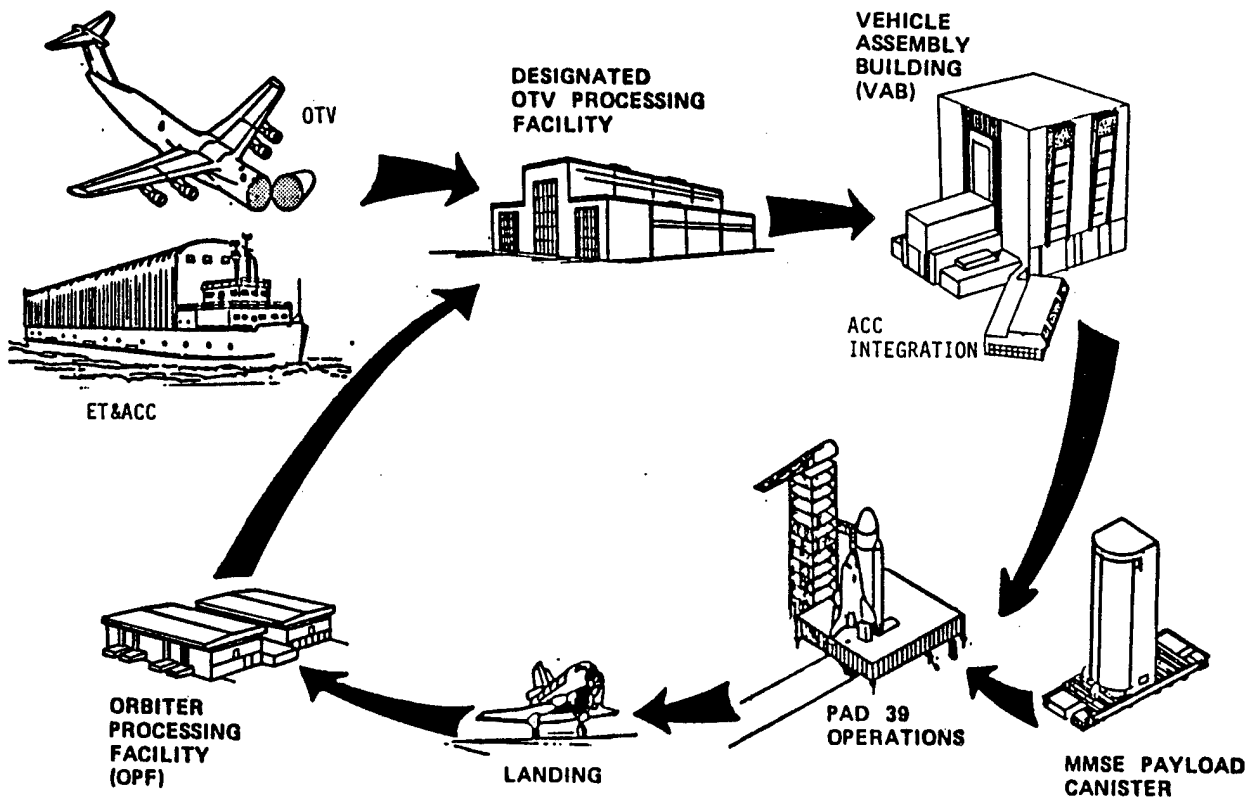


Figure 8 Ground-based OTV Ground Processing

Figure 9 shows the "vertical processing" ground operations flow at KSC for a space based OTV. This operational mode is preferred because it intersects the STS flow later in the count than horizontal processing. For the space based OTV, a dedicated OTV facility at KSC is not required, although if evolved from a ground based OTV it likely would share the same ground based facility. The space based OTV requires a minimum of ground processing since the major buildup, test and servicing will be performed at the space station.

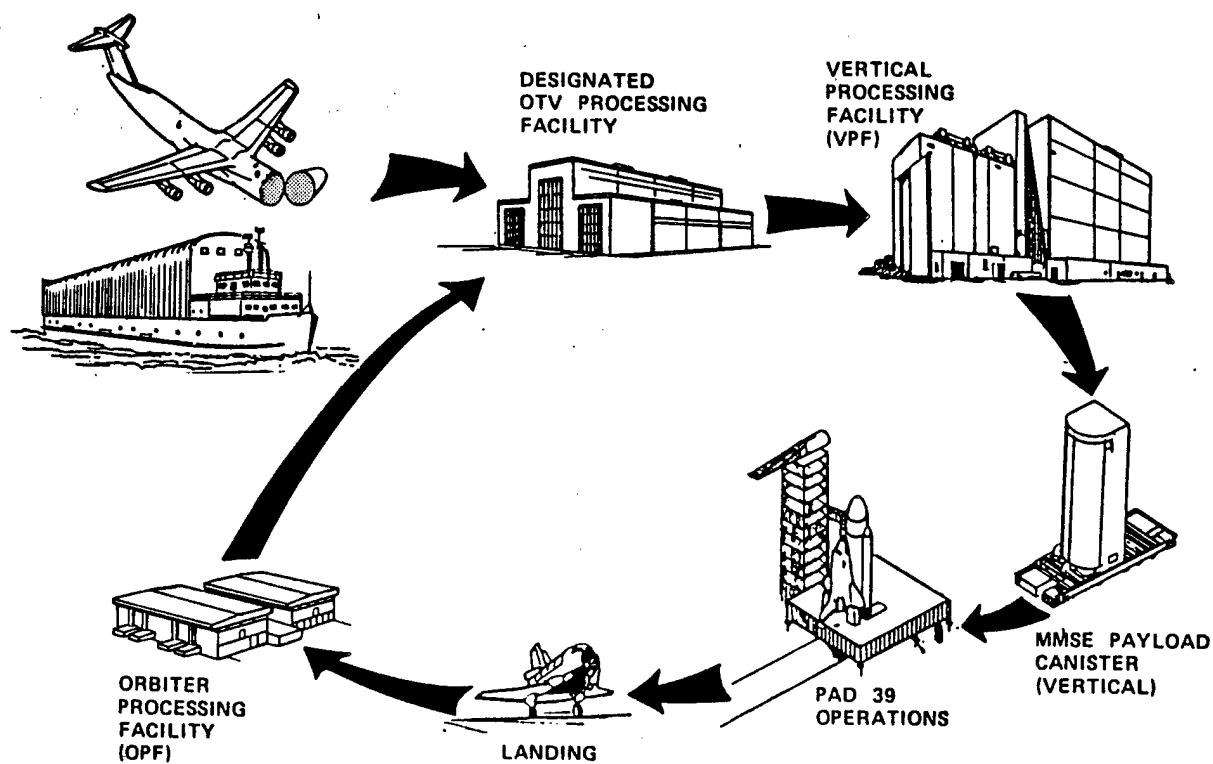


Figure 9 Space-based OTV Ground Processing - Vertical

7.2 FLIGHT OPERATIONS

The flight operations scenario used for the ACC configured OTV is depicted in Figure 10. Payload and OTV are launched on the same flight with the OTV in the ACC and the payload in the cargo bay. The fully fueled GBOTV is separated from the suborbital ET shortly after MECO and it flies itself to LEO. The orbiter carrying the spacecraft performs a rendezvous with the passivated OTV. Subsequent payload mating uses the orbiter RMS under flight crew control. The payload delivery mission is performed by OTV, and it returns to the vicinity of the orbiter using an aeroassist maneuver that requires navigation updates from the GPS system. OTV propellant tanks are purged prior to orbiter approach for retrieval. The OTV hydrogen tanks are removed and stowed in the orbiter bay together with the core OTV. The aeroshield is discarded. The vehicle is then returned to the ground for inspection, refurbishment and reflight. This scenario is more complex than that required for a cargo bay OTV, but it has inherent advantages in improved OTV mass fraction, increased payload bay volume availability, and elimination of the hazard of cryogenic fuels in the orbiter bay during launch.

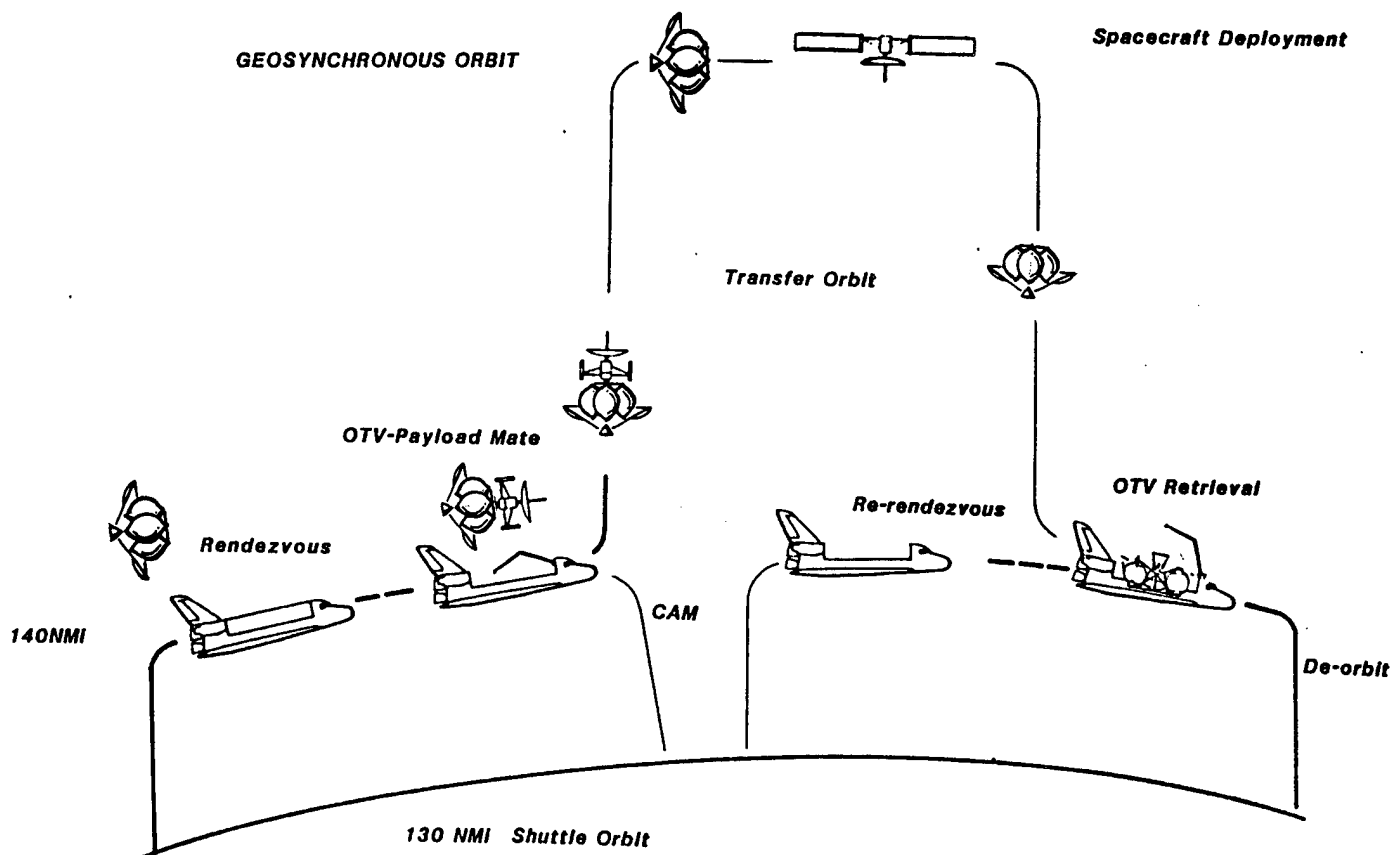


Figure 10 Ground-based Mission Overview

Figure 11 shows an overview of the space based OTV mission. Spacecraft and propellant delivery logistics are effectively decoupled from OTV flight operations. They are performed at the convenience of the Shuttle and interfacing systems, and their performance efficiency is enhanced by use of the OMV and the ACC based propellant scavenging system. The space based OTV/Payload stack is launched using a motorized cradle to impart separation velocity from the station while attached to the Space station hangar structure. The OTV free flight mission is performed in much the same way as the ground based free flight mission, using a GPS updated aeroassist maneuver for retrieval. The OMV is used for precision proximity operations during retrieval. Use of OMV, which is designed for proximity operations, eliminates the need for complex, duplicative propulsion and avionics systems in the OTV design.

The required OTV interfaces are few and simple. The NASA/DOD communications network interfaces the OTV via S - band to TDRS and L-band to GPS. Additional communications interfaces to Space Station, STS, OMV, MMU or the ground RTS are readily available for individual payload users.

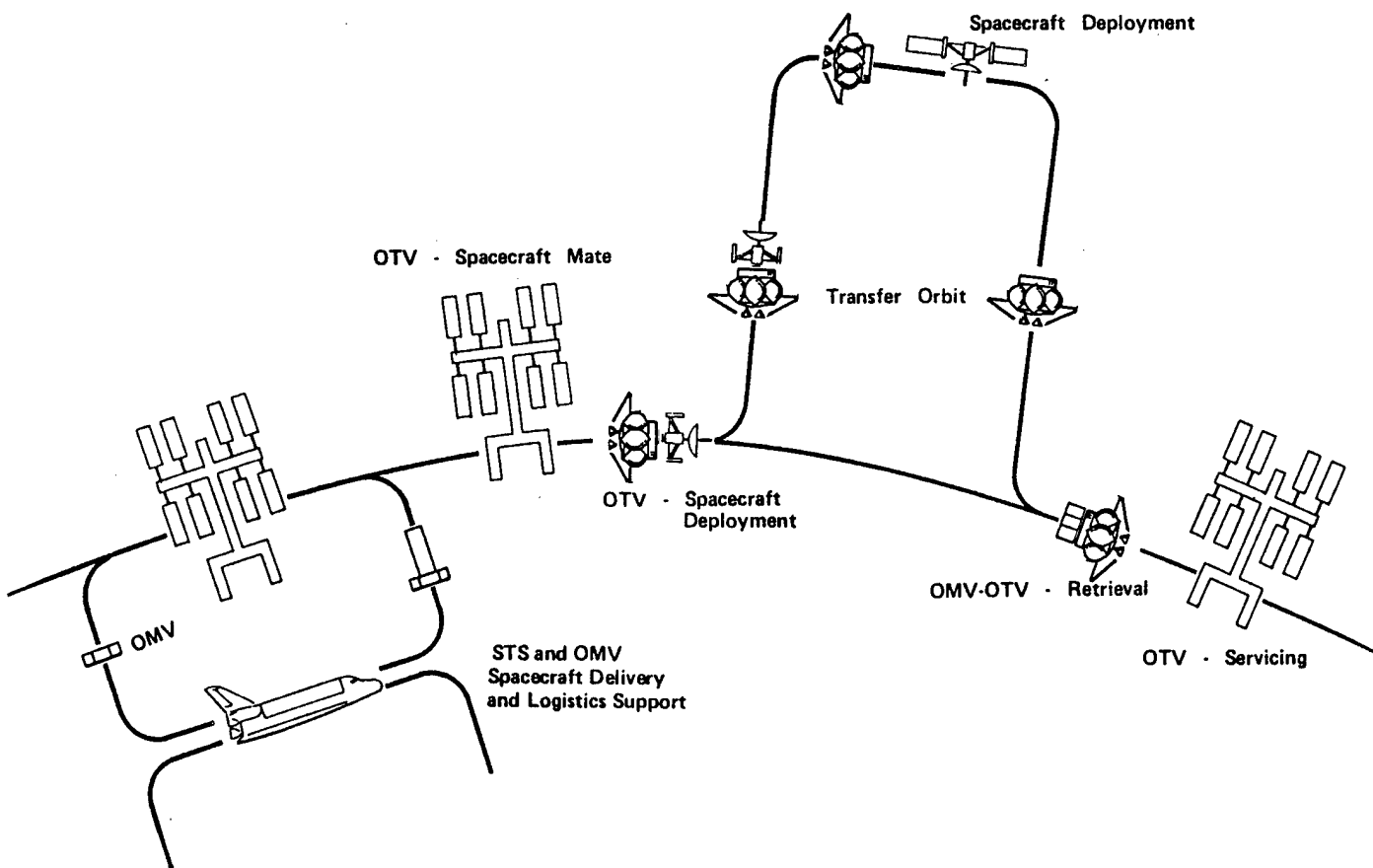


Figure 11 Space-based Mission Overview

7.3 FLEET SIZING

The active fleet size is a function of the mission model frequency, annual launch rate, allowable turnaround time, number of parallel flights required and the manifesting emphasis. The Revision 8 low and nominal mission models can be met with a single operational ground based vehicle and the space based mission can be readily met with a single space based OTV with significant margin. A future model review could indicate that mission sequencing requires additional vehicles to meet overlapping time phased specific user requirements. A second stage and additional vehicle is required to meet the lunar return missions identified in the nominal model. We recommend a ground standby spare to assure continued operations in case of an inoperative OTV, or when the actual schedule of launches is unable to be met with a single vehicle, as the current low model permits.

8.0 SPACE STATION ACCOMMODATIONS

The user benefits of a space based OTV operating in conjunction with the growth Space Station are not well understood by the potential payload user community. The growing NASA effort to publicize and establish a user constituency is necessary to obtain the nation's support to establish this improved, lower cost, faster response OTV system. Our analyses and recommendations are based on providing the environment, response, positive control, flexibility and operator efficiencies that must be achieved for a "turn of the century" capability. The individual payload size is no longer limited by single orbiter bay delivery limitations. Low-g transfer with a thoroughly prechecked payload is readily available. Multiple payload operation with manifesting performed either at KSC or at the station is easily achievable. On-orbit retrieval of all or portions of a payload for return to the station or to earth is possible. Increased confidence in the payload readiness and lowered risk after checkout should bring current high premium insurance rates down for the end users.

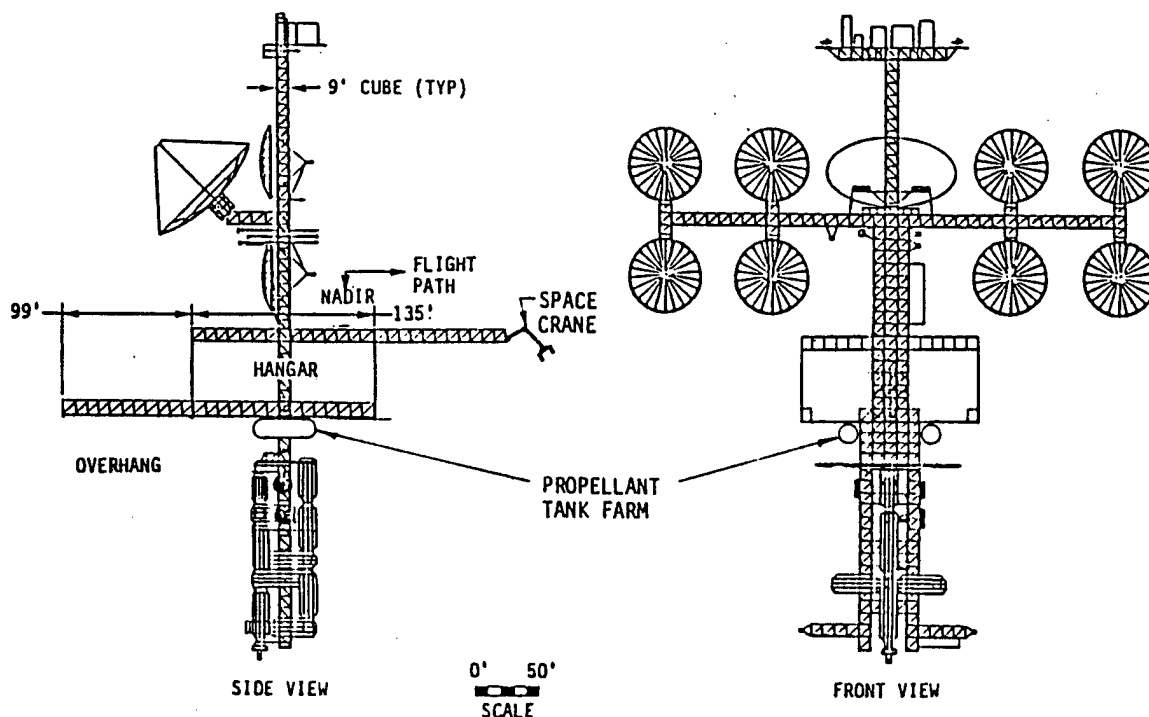


Figure 12 FOC Space Station With OTV Accommodations

8.1 OTV REQUIREMENTS/APPROACHES

Space station accommodations for OTV must provide: propellant storage; large volumes for assembly, maintenance and storage functions; meteoroid and debris protection; mechanisms to handle long and large masses as well as dexterous manipulation of small ORUs; non-destructive inspection; and associated ground support functions. The resulting spaceborne functional elements are the hangar system, and the propellant farm. We conducted functional and design analyses to define the requirements, physical nature, location on the power tower Space Station configuration and evolution of these elements. Figure 12 shows the overall arrangement of our preferred approach. Our major overall conclusions are as follows:

- 1) OTV assembly, integration, flight preparation, inspection and maintenance operations should be conducted in a meteoroid and debris protected environment. This approach minimizes the protection scar that must be borne by the OTV design, and contains any debris created during assembly and maintenance operations.
- 2) These functions should be planned for robotic, automated or remote, operation with extra vehicular activity limited to contingency backup in the event of anomalies. This proved necessary to minimize involvement of the limited space station crew in personnel intensive EVA activities.
- 3) Hangar and farm should be located near each other to facilitate propellant loading operations, and near the mass center of the station to minimize deviations in the micro-g environment.
- 4) System evolution should be phased to support mission model requirements with minimized initial expenditures - but a space tended mode appears economically unsound and a misutilization of space station capabilities.

We concluded that the requirements to be imposed on the IOC space station for OTV accommodations capable of supporting the low Revision 8 mission model, in consonance with the overall conclusions just stated, are as follows:

- 1) The space station should be able to accept a total accommodations mass of 370,000 pounds. Mass excursions as great as 180,000 during propellant resupply and 70,000 pounds during OTV operations must be accommodated.

- 2) The basic space station structure should be designed to permit attachment of this mass, considering associated forces and torques, and provisions should be made for appropriate attachment hardware.
- 3) Space station should provide for addition of power, signal and fluid interfaces to support an OTV propellant farm or, if space station is designed to use cryogenics for reboost/attitude control, should provide for expansion of this facility to support OTV.
- 4) The space station's Mobile Remote Manipulator System must be designed to operate in conjunction with the space crane required at the OTV hangar for transfer of articles. Provisions must be made for transfer locations, arm lengths, swept volumes, masses and inertias.
- 5) The IOC space station design should make provision for adding hangar power, signal and video servicing interfaces and OTV power, signal and fluid interfaces.
- 6) Space station power systems should be designed to accommodate an average daily OTV support power consumption that grows from approximately 5 kilowatts in 1997 to 8 kilowatts in 2010. Peak usage is estimated to be 50 kilowatts.
- 7) The space station layout should accommodate a hangar whose volume is 85,000 cubic feet in support of the low Rev 8 mission model (220,000 cubic feet for the nominal model).

8.2 EVOLUTIONARY PLAN

We have identified, prioritized and defined five major elements of space based accommodations. The first three elements, the propellant tank farm, the servicing and maintenance hangar, and launch site ground support, comprise the initial operational capability package. The propellant tank farm consists of the cryogenic fluid LO_2 and LH_2 storage tankage, supports, fluid management system, subcoolers, and tanking/detanking lines, hoses and umbilicals. The servicing and maintenance hangar includes, trusses, robotic arms, cabling, optical support bench, carriage rails, crane rails, and orbital replacement units (ORUs). Launch site ground support comprises communications, logistic resupply, and the several comprehensive data bases required for configuration control of the propellant tank farm and the servicing and maintenance hangar, and associated robotic arms; functional test/checkout; non destructive inspection and test; consumables

management; servicing and maintenance. The last two elements are extensions of the preceding elements that are required to evolve to greater space base mission support capability. They are a storage hangar (or a duplicate servicing and maintenance hangar), and a servicing and maintenance hangar extension needed for the multi-stage OTVs and their attached long payloads. Both reflect on-orbit facilities growth capability as a function of the increased size and complexity of the time phased mission model needs. The required schedule for provision of these five elements of space based accommodations is shown in Figure 13. The first three elements must be in place and operational by the time the space based OTV is operational. The last two must be in place and operational before the first scheduled 80,000 pound lunar delivery mission.

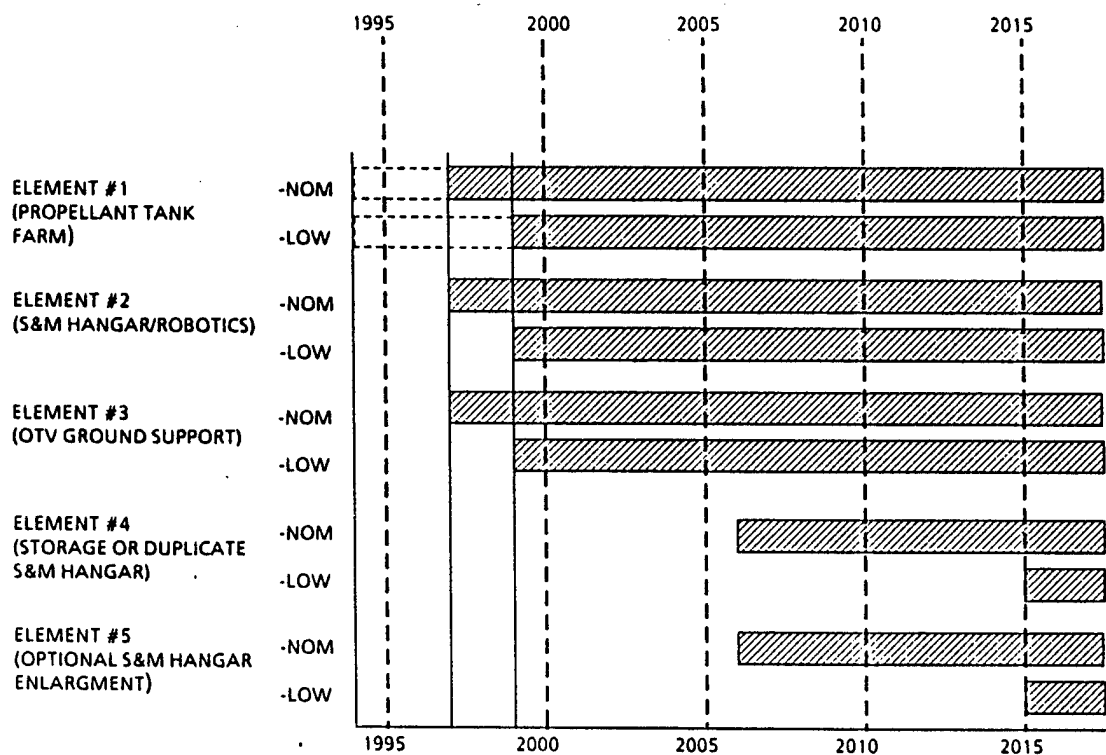


Figure 13 OTV Accommodations Phasing By Element

9.0 PROGRAMMATICS

9.1 SCHEDULE

The top level schedule for the ground and space based OTVs, ACC, and propellant scavenging system shown in Figure 14 meets the time phased requirements of the Revision 8 mission model. The contractor ATP for the ground based unmanned vehicle design, development, test and engineering (DDT&E) is Jan 1988. The cryogenic IOC advanced main engine program is initiated simultaneously with PDR in Oct. 1988. NASA advanced technology efforts supporting the advanced engine, advanced ceramic materials, cryogenic fluid management, and Space station technologies are assumed to continue according to current planning. The Aeroassist Flight Experiment initial flight is assumed to be completed by October 1989. OTV CDR is July 1989 with the vehicle delivery to KSC in the third quarter 1993 for flight in early 1994. The space base man-rated vehicle development would proceed in parallel but be phased to meet the 1999 (low model) space based IOC. ATP in the first quarter of 1993 with PDR at 12 months and CDR at 24 months provides for a maximum learning curve from the ground based program and efficient use of a building block modification program. The DDT&E period provides for delivery of the space

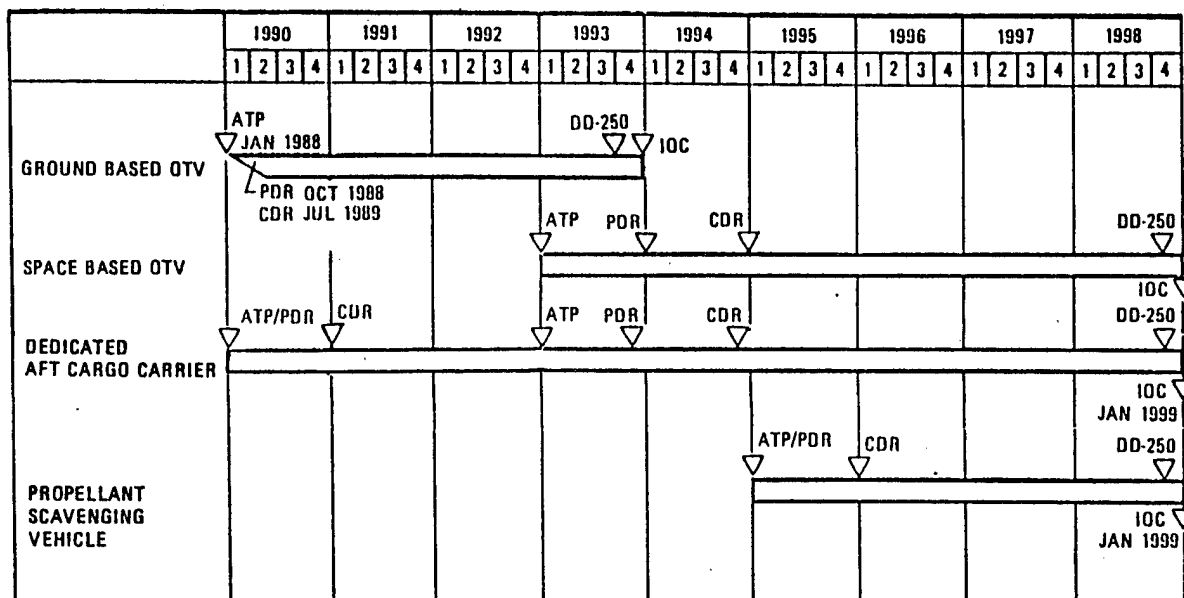


Figure 14 OTV Master Schedule

based vehicle to NASA in 1998 and the initial revenue flight in 1999 from Space Station. The Space Station accommodations for general purpose shared usage would be developed as

independent NASA projects with PDR and CDR time phased to support both OTV and Payload user requirements, communication, and to facilitate cross talk for efficient design of the general purpose software and hardware elements. The dedicated ACC with required ET modifications would be initiated in Jan 1990 and the related orbiter impacts and KSC STS related modifications would be initiated as required through the well established STS element contractor-to-NASA interfaces. The propellant scavenge and tanker vehicle would be initiated in 1994 to meet the delivery and flight schedules of the other space based elements.

9.2 COST

Our recommended vehicle program comprises a supporting Research and Technology program, a ground based OTV development, a space based OTV development, logistics support development, space base support development and, finally, ground based and space based operations. The recommended development spans the years 1988 through 1999 starting with the ground based development through 1993, transitioning to space based development through 1999. Note that the following cost data is presented in 1985 \$ without prime contractor fee and program contingency.

The major elements in the recommended R & T program are \$100M for an Aeroassist Flight Experiment that will verify the unique aerothermal and control parameters associated with aeroassisted OTV retrieval, and a \$53m investment in advanced cryogenic engine technology. The total vehicle DDT&E includes vehicle contracts for a \$599M ground based development plus a \$229M delta to develop a space based vehicle, \$175M in development of an IOC advanced capability engine, \$30M to develop a multiple payload carrier system, and a total of \$345M in Level II project activity. Acquisition of the required ground based operational vehicles, an operational stage and a spare, will be based on the refurbishment of the GVTA and flight test articles. Production of four multiple payload carriers is estimated at \$30M. The production cost of two space based flight vehicles and associated payload support hardware is estimated at \$145M.

The total cost of developing an aft cargo carrier dedicated to the OTV program has been estimated to be \$163M, including ACC hardware, ET modification, orbiter impact and facilities/GSE modification. The development of the OTV dedicated ACC in conjunction with development of the ACC scavenging system is estimated to reduce the total cost for both programs by \$130M.

The total cost associated with providing space based accommodations for the OTV is

estimated to be \$936M. The major ingredients of this figure are \$165M for robotics hardware, \$285M for associated software, \$100M for imaging systems needed for nondestructive inspection of OTV, \$76M for the hangar, \$170M for the propellant farm, and \$140M for transportation of systems to the space station. Of these elements, the robotics, supporting software, the hangar and the imaging systems also support mission spacecraft operations. Their cost should be shared with other programs, perhaps to a total amount of \$400M.

Operations cost of ground based missions is \$85.6M per flight including shuttle launch cost. The space based mission operational cost is \$76.4M per flight including the cost of propellant delivery to the space station and all supporting space base operations. The resulting space based cost of payload delivery to GEO is \$3820/pound.

OTV SUMMARY OPTION 1

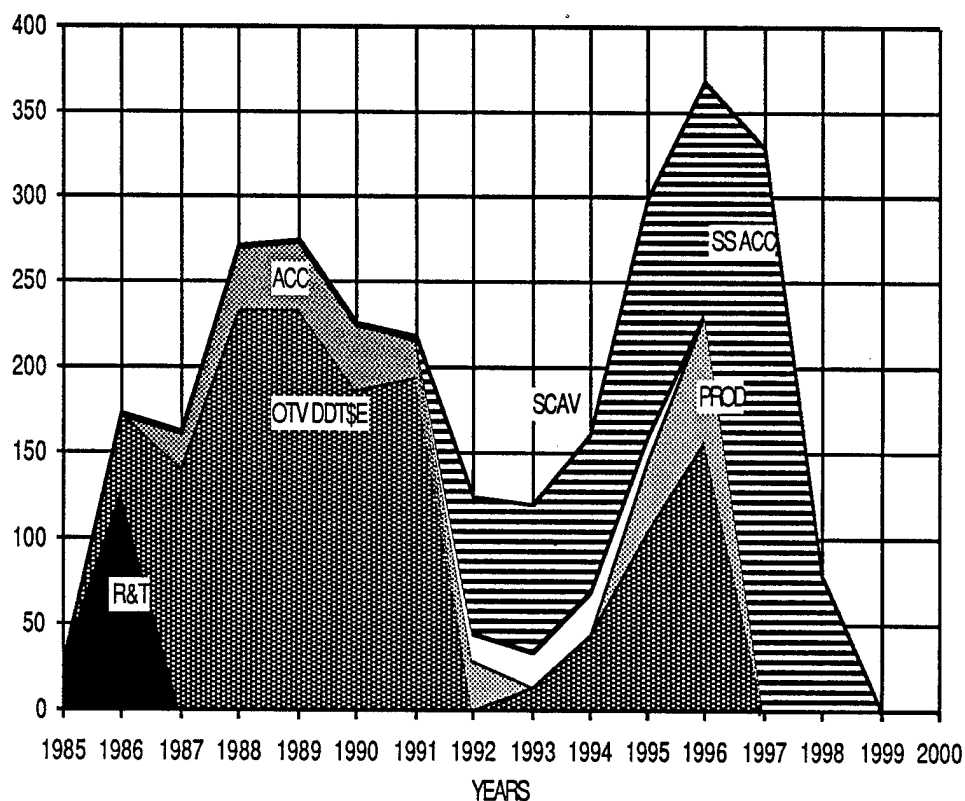


Figure 15 OTV Spend Plan

Figure 15 shows the peak funding level during the ground based program is \$250M during the first two years of the program (1988 and 1989) and the Space based program, including dedicated accommodations, would reach a \$275M peak in 1996. In conjunction with the general purpose Space Station accommodations, peak funding would reach \$365M including the appropriate share of space station funding.

9.3 TECHNOLOGY

The Orbital Transfer Vehicle will incorporate the state-of-the-art advanced technology available at the time of development in all subsystem areas. Avionics, structures and operations technology items required for OTV are anticipated to be available under planned R&T programs. The specific items anticipated are a solid state star tracker, advanced ring laser gyros, a magnetically coupled cryogenic pump, avionics network interface devices, distributed processing executive software, avionics expert system hardware, cryogenic fluid quick disconnects and non-destructive tank and structure cracking, fatigue and erosion detection devices.

In the propulsion area, OTV engine development specifically for the OTV application is required. The required OTV peculiar R&T program has been estimated to be \$53M. In the area of zero-g propellant transfer, R&T activity is under way in the form of the Cryogenic Fluid Management Facility (CFMF). It should be noted that this development should be kept on a schedule consistent with OTV program requirements. Developments under way in the area of RCS propellant feed from main tank storage should be continued.

In the aerobrake area, the Aeroassist Flight Experiment (AFE) and associated R&T development of appropriate heat shield materials needs to be pursued. The cost of the AFE is estimated to be \$100M. The data provided from this experiment relative to non-equilibrium flow and other aerothermal characteristics cannot be acquired short of large scale flight testing.

GLOSSARY

ACC	Aft Cargo Carrier
AFE	Aeroassist Flight Experiment
AKM	Apogee Kick Motor
AMS	Apogee and Maneuvering Stage
ASE	Airborne Support Equipment
ATP	Authority to Proceed
CAM	Collision Avoidance Maneuver
CDR	Critical Design Review
CELV	Complementary Expendable Launch Vehicle
CFMF	Cryogenic Fluid Management Facility
CISS	Centaur Integrated Support System
DDT&E	Design, Development, Test, & Engineering
DOD	Department of Defense
ET	External Tank
EVA	Extra Vehicular Activity
FOC	Full Operational Capability
FRCI	Fiber Reinforced Ceramic Insulation
FY	Fiscal Year
GBOTV	Ground Based Orbital Transfer Vehicle
GEO	Geostationary Orbit
GN&C	Guidance, Navigation & Control
GPS	Global Positioning System
GSE	Ground Support Equipment
GVTA	Ground Vibration Test Article
IOC	Initial Operational Capability
Isp	Specific Impulse
IVA	Intra Vehicular Activity
KSC	Kennedy Spaceflight Center
LEO	Low Earth Orbit
MECO	Main Engine Cut Off
MLI	Multi-Layer Insulation
MMH	Mono Methyl Hydrazine
MMSE	Multi-use Mission Support Equipment
MMU	Manned Maneuvering Unit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics & Space Administration
nmi	Nautical Miles
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
OPF	Orbiter Processing Facility
ORU	Orbital Replacement Unit
OTV	Orbital Transfer Vehicle
PDR	Preliminary Design Review
PIDA	Payload Installation Deployment Aid
Psf	Pounds per square foot
Psi	Pounds per square inch
Psia	Pounds per square inch absolute
RCS	Reaction Control System
RMS	Remote Manipulator System

RPL	Rocket Propulsion Laboratory
R&T	Research and Technology
RTS	Remote Tracking Station
RTV	Room Temperature Vulcanizing Sealant
SBOTV	Space Based Orbital Transfer Vehicle
S&M	Servicing and Maintenance
SOFI	Spray on Foam Insulator
STS	Space Transportation System
TABI	Tailorable Advanced Blanket Insulation
TDRS	Tracking & Data Relay Satellite
TOS	Transfer Orbit Stage
TPS	Thermal Protection System
USAF	United States Air Force
VAB	Vertical Assembly Building
VAFB	Vandenberg Air Force Base
VPF	Vertical Processing Facility