Volume III

System And Program Trades

Orbital Transfer Vehicle Concept Definition And System Analysis Study 1985


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FOREWORD

This final report, Volume III-System and Program Trades, 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 one of nine documents arranged as follows:

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
Volume IX Study Extension Results

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<td>Main Propulsion Test Article</td>
<td></td>
</tr>
<tr>
<td>MSFC</td>
<td>Marshall Space Flight Center</td>
<td></td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
<td></td>
</tr>
<tr>
<td>NM</td>
<td>nautical mile</td>
<td></td>
</tr>
<tr>
<td>OMV</td>
<td>Orbital Maneuvering Vehicle</td>
<td></td>
</tr>
<tr>
<td>OPS</td>
<td>operations</td>
<td></td>
</tr>
<tr>
<td>ORB</td>
<td>Orbiter</td>
<td></td>
</tr>
<tr>
<td>OTV</td>
<td>Orbital Transfer Vehicle</td>
<td></td>
</tr>
<tr>
<td>P/L</td>
<td>payload</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>program management</td>
<td></td>
</tr>
<tr>
<td>pmp</td>
<td>pump</td>
<td></td>
</tr>
<tr>
<td>Prod.</td>
<td>Production</td>
<td></td>
</tr>
<tr>
<td>PRP</td>
<td>propellant</td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>present value</td>
<td></td>
</tr>
<tr>
<td>pwr</td>
<td>power</td>
<td></td>
</tr>
<tr>
<td>QD</td>
<td>quick disconnect</td>
<td></td>
</tr>
<tr>
<td>Reg</td>
<td>regulator</td>
<td></td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
<td></td>
</tr>
<tr>
<td>RFP</td>
<td>Request for Proposal</td>
<td></td>
</tr>
<tr>
<td>ROI</td>
<td>return on investment</td>
<td></td>
</tr>
<tr>
<td>R&amp;T</td>
<td>research and technology</td>
<td></td>
</tr>
<tr>
<td>SB</td>
<td>space based</td>
<td></td>
</tr>
<tr>
<td>SBM</td>
<td>55 klb SB man-rated vehicle</td>
<td></td>
</tr>
<tr>
<td>SBU</td>
<td>55 klb SB non-man-rated vehicle</td>
<td></td>
</tr>
<tr>
<td>SDV</td>
<td>Shuttle Derived Vehicle</td>
<td></td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>S&amp;EI</td>
<td>Systems Engineering and Integration</td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>Space Station</td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Static Test Article</td>
<td></td>
</tr>
<tr>
<td>STAS</td>
<td>Space Transportation Architecture System</td>
<td></td>
</tr>
<tr>
<td>STS</td>
<td>Space Transportation System</td>
<td></td>
</tr>
<tr>
<td>TBD</td>
<td>to be determined</td>
<td></td>
</tr>
<tr>
<td>TLM</td>
<td>telemetry</td>
<td></td>
</tr>
<tr>
<td>TVC</td>
<td>thrust vector control</td>
<td></td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

This volume documents the key system and program trade studies performed during the initial contract period (through 15 October 1985) to arrive at a preferred Orbital Transfer Vehicle (OTV) system concept and evolutionary approach to the acquisition of the requisite capabilities. These efforts were expanded to encompass a Space Transportation Architecture Study (STAS) mission model and recommended unmanned cargo vehicle in a study extension reported on in Volume IX. The basis for these initial trade studies and comparisons is the system requirements identified as part of contract SOW Task 1 and the concept synthesis and trade studies performed under contract SOW Tasks 2 and 3.

The most important factors affecting the results presented in this volume are the mission model requirements and selection criteria. The reason for conducting the OTV concept definition and system analyses study is to select a concept and acquisition approach that meets a delivery requirement reflected by the mission model. There are two potential justifications for an OTV: to compete with existing expendable upper stages, and to provide a heavy lift and man-rated capability that does not now exist. The latter reason does not support an early start of OTV development. The heavy lift requirement identified in the Revision 8 Low Mission Model (20 klb to geosynchronous Earth orbit [GEO]) falls in 1999 and the man-rated payload occurs in 2008. The one compelling reason for considering a near time OTV capability is to improve the economics of space transportation and make the NASA Space Transportation System competitive with existing and emerging foreign and commercial delivery systems. As a consequence, our system and program selection criteria has been structured to reflect economic factors such as front end cost, return on investment, and economics of the system after it is in place as well as considerations of risk and flexibility.

Figure 1.0-1 summarizes the sequence of program development followed in this study. Our pre-contract IR&D studies had developed a reference ground based Aft Cargo Carrier (ACC) configuration. By the March 1985 mid-term review, high potential cryogenic and storable concepts had been identified, and subsystem trades had selected the preferred subsystem configurations. At this time, the mission model underwent a significant change. Our concepts and subsystem decisions were reassessed and changes were incorporated. We then proceeded to identify and trade alternative acquisition strategies. The net outputs of this phase of the study were configurations capable of meeting the mission delivery requirements of the Revision 8 Low Mission Model in the most desirable way, and the program that should be pursued in this development. Only study recommendations that could be justified on the basis of the low model were made at the request of MSFC. The selection procedure is further described in the following paragraphs.
FIGURE 1.0-1 PROGRAM DEVELOPMENT SEQUENCE
1.1 Decision Summary

There are three basic viable approaches to providing orbital transfer for the high altitude missions to be conducted in the coming decades: Growth of existing cryogenic expendable vehicle; Development of a new storable, reusable, pump fed OTV; Or development of a new, reusable cryogenic OTV. The decision network in Figure 1.1-1 summarizes the evolutionary paths these approaches could follow and identifies the trade studies conducted at points along the path. We carried a program reflecting growth of the current expendable ground based vehicle fleet through the entire mission model to establish a cost comparison reflecting as little change as possible to the current way of providing space transportation. We laid out programs that reflected development of both storable and cryogenic reusable OTVs that evolved from ground based to space based operation. These propellant options were developed through the point where space basing impacts were understood before a selection was made between them. Engine selection, delivery mode for ground based vehicles (ACC vs Cargo bay), and the merit of man-rating the ground based vehicle were considered. Space base accommodations were compared, as was the preferred time for introducing man-rating in a space based vehicle. At this point, all the data required to make the propellant selection was available, and this selection was made. Final program comparisons were made to select the OTV program best able to provide the capability required by the Revision 8 OTV Low Mission Model.

Trade studies were conducted to implement the decision tree shown in Figure 1.1-1. This sequence of trades identified preferred alternatives for key program elements and served as a basis for selecting a preferred overall OTV evolutionary strategy for transitioning from an initial ground based OTV configuration to a man-rated configuration for space based operations with the availability of the Space Station in 1999.

The trade studies shown in this report include:

- Section 2.1 Aeroassist vs All-Propulsive Retrieval
- Section 2.2 IOC Cryogenic Engine Selection
- Section 2.3 Evolutionary Path to Man-Rating and Cost Effective Reliability Requirements
- Section 2.4 Space Based Propellant Acquisition
- Section 2.5 Space Based Tank Farm Selection
- Section 2.6 Cryogenic Versus Storable Upper Stages
- Section 2.7.2 ACC OTV Delivery/Scavenging Versus STS Cargo Bay OTV Delivery/Scavenging
- Section 2.7.3 Overall OTV Program Evolutionary Strategy
OTV LEO RECOVERY
- ALL PROPELLANT
- AEROCOSSIST

ENGINE (INITIAL/EVOLVED)
- RL10-11B/ADVANCED
- IOC/ADVANCED
- ADVANCED/ADVANCED
- RL10-11B/RL10-11B
- IOC/IOC

MAN RATING AND RELIABILITY
- NON-MAN RATED
- MAN RATED

PROPELLANT DELIVERY TO LEO
- STS CARGO BAY
- STS CARGO BAY AND SCAVENGING
- TANKER
- TANKER AND SCAVENGING

TANK FARM
- TETHERED
- FREE FLYER
- ON STATION

SELECT
- AEROCOSSIST
- IOC/IOC

E V O L U T I O N A R Y S T R A T E G Y

STEP 1
OTV DELIVERY/SCAVENGING

SELECT
- STORABLE
- CRYOGENIC

STEP 2
OVERALL EVOLUTION

SELECT
- CB/ACC
- CB/CB
- ACC/ACC
- ACC/CB

SELECT
- GBU/GBM/GBM
- GBU/SBU/SBM
- EXU/SBM/SBM
- GBU(S)/SBU/SBM
- GBU(CB)/SBU/SBM
- GBU(CB)/SBU/GBM

GBU = GROUND BASED, UNMANNED
SBU = SPACE BASED, UNMANNED
SBM = SPACE BASED, MAN-RATED
EXU = EXPENDABLE, UNMANNED
GBU(CB) = GROUND BASED, UNMANNED,
(CARGO BAY DESIGN)
GBM = GROUND BASED, MAN-RATED

FIGURE 1.1-1 DECISION NETWORK
1.2 Mission Model

This study was initiated with the objective of meeting the mission requirements delineated in Revision 7 of the MSFC OTV Mission Model. The major characteristics of this model are summarized in Table 1.2-1. At the midterm review, a new Revision 8 mission model, Table 1.2-2, was issued for use through the remainder of the basic study. The study contractors were instructed to make recommendations that were justifiable based on the Revision 8 Low Mission Model.

The constituency of the Revision 8 model is essentially the same as Revision 7 except for the elimination of the 14 klb/14 klb manned GEO mission. This mission was a driver for OTV but is now replaced with a more modest manned mission payload of 7.5 klb/7.5 klb. The elimination of the manned lunar mission from the low model is not significant in discounted economic terms but does impact the sizing of OTV stages.

The major revision impact is the reduction in projected annual and total traffic for OTV. Revision 7 reflected an average of 27 flights per year on the nominal model while the Revision 8 Low Mission Model has only 9. This impacts the expected economic benefits that can be accrued and, therefore, the amount of return on investment.

Even with these changes, the effective average OTV delivery requirement changed very little. The Revision 7 Nominal Mission Model had an average propellant requirement of 43 klb and the Revision 8 Low Mission Model has an average propellant requirement of 42.7 klb. This close relationship reflects the fact that multiple delivery and DOD payloads dominate both models.
<table>
<thead>
<tr>
<th>PAYLOAD NO. SERIES</th>
<th>MISSION GROUP</th>
<th>WEIGHT (LB) UP/DOWN</th>
<th>LENGTH (FT)</th>
<th>MISSION MODEL</th>
<th>IOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>13000</td>
<td>EXPERIMENTAL GEO PLATFORM</td>
<td>12000/0</td>
<td>30</td>
<td>1</td>
<td>1998/1994</td>
</tr>
<tr>
<td>13000</td>
<td>OPERATIONAL GEO PLATFORM</td>
<td>20000/0</td>
<td>35</td>
<td>11</td>
<td>2000/1996</td>
</tr>
<tr>
<td>13000</td>
<td>UNMANNED GEO PLAT. SERVICING</td>
<td>7000/4500</td>
<td>8</td>
<td>8</td>
<td>2000/1995</td>
</tr>
<tr>
<td>15000</td>
<td>MANNED GEO SORTIE</td>
<td>6500/6500 OR 14000/14000</td>
<td>15 OR 23</td>
<td>8</td>
<td>2003/1997</td>
</tr>
<tr>
<td>15000</td>
<td>UNMANNED GEO STA. LOGISTICS</td>
<td>10000/2700</td>
<td>15</td>
<td>0</td>
<td>2000/—</td>
</tr>
<tr>
<td>15000</td>
<td>MANNED GEO STA. LOGISTICS</td>
<td>16500/9000</td>
<td>27.5</td>
<td>34</td>
<td>2012/2002</td>
</tr>
<tr>
<td>17000</td>
<td>UNMANNED LUNAR</td>
<td>5000–20000/0</td>
<td>20</td>
<td>3</td>
<td>2001/2001</td>
</tr>
<tr>
<td>17000</td>
<td>MANNED LUNAR SORTIE</td>
<td>80,000/15,000</td>
<td>60</td>
<td>3</td>
<td>2007/2006</td>
</tr>
<tr>
<td>17000</td>
<td>LUNAR BASE ELEMENTS</td>
<td>80,000/0</td>
<td>53</td>
<td>3</td>
<td>2009/2008</td>
</tr>
<tr>
<td>17000</td>
<td>LUNAR BASE SORTIE/LOGISTICS</td>
<td>80,000/10,000</td>
<td>60</td>
<td>6</td>
<td>2010/2009</td>
</tr>
<tr>
<td>18000</td>
<td>UNMANNED GEO SAT. SERVICING</td>
<td>7000/4500</td>
<td>9</td>
<td>137</td>
<td>1993/1993</td>
</tr>
</tbody>
</table>

**SUBTOTALS**  
267  
426  

**10100 REFIGHTS**  
16  
26  
1994/1994  

**TOTALS**  
283  
452  
1994/1994
# Table 1.2-2 Revision B Mission Model Composition

<table>
<thead>
<tr>
<th>Payload No.</th>
<th>Mission Group</th>
<th>Weight (lb) UP/Down</th>
<th>Length (ft)</th>
<th>Mission Model LOW</th>
<th>Mission Model NOM</th>
<th>IOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>13000</td>
<td>Experimental Geo Platform</td>
<td>12000/0</td>
<td>30</td>
<td>1</td>
<td>1</td>
<td>2000/1996</td>
</tr>
<tr>
<td>13000</td>
<td>Unmanned Geo Platform Servicing</td>
<td>7000/4800</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2001/1998</td>
</tr>
<tr>
<td>15000</td>
<td>Manned Geo Sortie</td>
<td>7500/7500</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>2002/2002</td>
</tr>
<tr>
<td>15000</td>
<td>Geo Service Station Elements</td>
<td>12000/0</td>
<td>15 - 20</td>
<td>2</td>
<td>2</td>
<td>2002/1998</td>
</tr>
<tr>
<td>17000</td>
<td>Unmanned Lunar</td>
<td>5000 - 20000/8</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>2007/2001</td>
</tr>
<tr>
<td>17000</td>
<td>Manned Lunar Sortie</td>
<td>80,000 - 10,000</td>
<td>60</td>
<td>3</td>
<td>3</td>
<td>2015/2008</td>
</tr>
<tr>
<td>17000</td>
<td>Lunar Base Elements</td>
<td>85,000/6</td>
<td>63</td>
<td>3</td>
<td>3</td>
<td>2020/2009</td>
</tr>
<tr>
<td>17000</td>
<td>Lunar Base Sortie/Logistics</td>
<td>80,000/10,000</td>
<td>60</td>
<td>4</td>
<td>4</td>
<td>2021/2009</td>
</tr>
<tr>
<td>18000</td>
<td>Large Geo Satellite Delivery</td>
<td>20000/0</td>
<td>20 - 35</td>
<td>7</td>
<td>7</td>
<td>2001/1997</td>
</tr>
<tr>
<td>18000</td>
<td>DOD (Generic)</td>
<td>12000 - 20000 (EQUIV.)</td>
<td>35</td>
<td>3</td>
<td>3</td>
<td>1994/1997</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>142</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
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<td><strong>252</strong></td>
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<tr>
<td>10100</td>
<td>Reflights</td>
<td></td>
<td><strong>3</strong></td>
<td></td>
<td></td>
<td>1994/1997</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td><strong>146</strong></td>
<td></td>
<td></td>
<td>287</td>
</tr>
</tbody>
</table>
Table 1.2-3 shows the design reference missions from the nominal Revision 8 model. The one difference from the low model, aside from the change in operational dates, is the 80 klb/15 klb manned lunar mission. We used the low model in our trade studies for selection of configuration and evolutionary strategy and then noted the design and programmatic implications of going to the nominal model.

<table>
<thead>
<tr>
<th>MISSION TYPE</th>
<th>MISSION NUMBER</th>
<th>FIRST FLIGHT DATE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Payload</td>
<td>18912</td>
<td>1994</td>
<td>GB OTV Performance Driver</td>
</tr>
<tr>
<td>Unmanned GEO Missions</td>
<td>13002</td>
<td>1996</td>
<td>First Long Duration Mission - 10 Days</td>
</tr>
<tr>
<td>GEO Delivery</td>
<td>18040</td>
<td>1997</td>
<td>Rendezvous to Perform Servicing</td>
</tr>
<tr>
<td>Manned GEO Sortie</td>
<td>15700</td>
<td>2002</td>
<td>Mission Duration - 18 Days</td>
</tr>
<tr>
<td>GEO Platform</td>
<td>13700</td>
<td>1998</td>
<td>Low g Requirement</td>
</tr>
<tr>
<td>Manned Lunar Sortie</td>
<td>17203</td>
<td>2006</td>
<td>Multiple Configuration Requirement</td>
</tr>
</tbody>
</table>

Tables 1.2-4 and 1.2-5 compare the design reference missions derived from the low Revision 7 and Revision 8 models.

The multiple payload mission stayed approximately the same. The MOLNIYA (and GPS missions) were not individually specified and the low g mission was added. The mission duration of 18 days was added although this was also a reliability driver under Revision 7.
#### TABLE 1.2-4 DESIGN REFERENCE MISSION, REVISION 7 LOW MISSION MODEL

<table>
<thead>
<tr>
<th>MISSION TYPE</th>
<th>SELECTED DRM MISSION MODEL</th>
<th>FIRST FLIGHT DATE</th>
<th>REASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Payload Delivery</td>
<td>Remanifested 18903</td>
<td>1993</td>
<td>Performance Driver for ground-based OTV</td>
</tr>
<tr>
<td>12876 Up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2166 Down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molniya and GPS Missions</td>
<td>Unique Delivery Missions</td>
<td>1993</td>
<td>Mission Operation Difficulty for Space-Based Operation</td>
</tr>
<tr>
<td>Unmanned Service 7K Up</td>
<td>13002</td>
<td>1995</td>
<td>1st Rendezvous and Docking, Autonomous Rendezvous and Docking</td>
</tr>
<tr>
<td>4.51K Down</td>
<td></td>
<td></td>
<td>Drives Flight Operations and Equipment Complexity</td>
</tr>
<tr>
<td>GEO Delivery 20K Up 0 Down</td>
<td>13003</td>
<td>1996</td>
<td>Earliest Required Mission, Most Frequent Mission</td>
</tr>
</tbody>
</table>

#### TABLE 1.2-5 DESIGN REFERENCE MISSION, REVISION 8 LOW MISSION MODEL

<table>
<thead>
<tr>
<th>MISSION TYPE</th>
<th>MISSION NUMBER</th>
<th>FIRST FLIGHT DATE</th>
<th>REASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Payload Delivery 12000/2000</td>
<td>18912</td>
<td>1994</td>
<td>GB OTV Performance Driver</td>
</tr>
<tr>
<td>Unmanned GEO Missions 7000/4510</td>
<td>13002</td>
<td>2001</td>
<td>First Long Duration Mission - 10 Days, Rendezvous to Perform Servicing</td>
</tr>
<tr>
<td>GEO Delivery 20000/0</td>
<td>18040</td>
<td>2001</td>
<td>Performance Driver</td>
</tr>
<tr>
<td>Manned GEO Sortie 7500/7500</td>
<td>15700</td>
<td>2008</td>
<td>Mission Duration - 18 Days</td>
</tr>
<tr>
<td>GEO Platform 20000/0</td>
<td>13700</td>
<td>2004</td>
<td>Low g Requirement</td>
</tr>
</tbody>
</table>

1.3 Selection Criteria

The selection criteria to be used in differentiating among alternative OTV system and program options depends on the environment in which the system operates. A competitive environment, one where capital for investment is scarce, influences how the decision is made for a new venture. The OTV is in a competitive environment and is being considered for development on the basis of the attractiveness of reducing the cost of payload delivery. The effectiveness of OTV in reducing the recurring cost of payload delivery must be balanced against acquisition cost in terms of several economy factors. If its advantage is significant, it makes the STS and OTV more attractive to users.
Non-economic factors are also important. The mission model is a projection of the expected OTV marketplace and should not be viewed as a fixed or absolute opportunity. The potential growth and flexibility of each option is important, i.e., the ability to adjust to possible requirement changes or to be used for future missions. It provides a measure of the capability to evolve or grow to satisfy changes in the market. Also, the risks attendant with candidate OTV options and acquisition strategies are important because they reflect the possibility of increased cost. Key external risk factors to be assessed are those that cannot be mitigated or controlled by the OTV design.

Cost data projected for OTV systems development is compared against the cost of competitive systems which exist or possess proven technology. The economic advantage of the OTV system over its competition must be present to provide a measure of its viability.

In the trade studies, the cost data in 1985 constant and discounted dollars is provided and the economic factors are derived and presented. Economic decisions are made using Present Value (PV) dollars. Present value is a time projection of the value of money when inflation and the discounted value of the dollar are taken into account. In accordance with the ground rules, the PV used in the studies incorporates a zero percent inflation rate and a ten percent discount rate.

Several economic factors are used to help determine the best alternative. Depending on the nature of the study, different economic factors may be selected for the analysis. Three principal economic factors used for all studies, except the Man Rating and Reliability Trade Study, are Design Development Test and Engineering (DDT&E), Benefit, and Return on Investment (ROI). The nature of the Man Rating and Reliability study is different in that reliability values are determined for use on all OTVs rather than making a selection among a number of proposed alternatives.

The economic factors used in the trade studies are described below. These factors are used individually and in combination with one another to help provide an indication of the best alternative. As can be seen, some of the factors are nested in others. For example, DDT&E is used as a subfactor in the ROI analysis. It should also be noted that any single factor may not be sufficient to reach a valid conclusion by itself. For instance, the ROI may identify an alternative as the best buy, but the DDT&E cost of the alternative may not be affordable in view of available budget.

Once the economic factors of the alternatives have been determined, a score is provided. The preferred alternative for each economic factor is given a score of 10 and the other alternatives are given a score relative to the alternative marked with a 10.
An explanation of the economic factors used in this report is shown below:

a. **Design, development, test and evaluation (DDT&E).** DDT&E is a representation of the investment cost to develop a product.

b. **Benefit.** Benefit determines the value or profit of an alternative vis-a-vis the competition (which is generally not taking any action at all), it is determined by finding the difference between the cost of the competition doing the task and the cost of a particular alternative doing the task. For example, the benefit of a particular OTV alternative would be represented by finding the difference between the cost per flight of competing \( \text{CPF}_{c} \) systems and this cost per flight of the OTV \( \text{CPF}_{o} \). The total benefit would be represented by multiplying this difference by the number of flights \( N_{c} \) and \( N_{o} \) projected in the mission model.

\[
\text{Benefit} = \text{CPF}_{c} \times N_{c} - \text{CPF}_{o} \times N_{o}
\]

c. **Return on Investments (ROI).** ROI is a measure of the best buy. It is determined by dividing benefit (described in b above) by DDT&E to produce a best profit to cost ratio. To normalize the equation, one is subtracted from the result. If the ratio is negative, the option is not a viable economic venture. If the ratio is zero, the venture retrieves the investment but is not profitable. A positive ratio indicates the venture is profitable, i.e., worthwhile vis-a-vis not undertaking the venture and relying on existing capabilities.

The algorithm for ROI is:

\[
\text{ROI} = \frac{\text{CPF}_{c} \times N_{c} - \text{CPF}_{o} \times N_{o}}{\text{DDT&E}} - 1
\]

All costs used for the benefit and ROI equations are 1985 discounted dollars.

d. **Life Cycle Cost (LCC).** LCC is a representation of total costs over the life of a system. Martin Marietta uses a LCC computer model developed with company funding. The model calculates all phases of cost based on the technical description of the OTV, the operational scenarios, and the requirements of any supporting program, e.g., Space Station, Aft Cargo Carrier.

Typical inputs to the LCC model include the following:

- OTV stage weight for the subsystem component level;
- Test hardware requirements;
- Annual mission and propellant requirements;
- Operational turnaround times;
- Intravehicular activity (IVA) and extravehicular activity (EVA) requirements;
o Key implementation schedule dates;

o Supporting program data; and

o Specific payload transportation requirements.

e. Cost per flight, competition (Cpf_c). Cpf_c represents the per flight operations cost of the competing system(s).

f. Cost per flight, option (Cpf_o). Cpf_o represents the per flight operations cost of the option under consideration, i.e., OTV or program option.

g. Payback. Payback represents the amount of projected economic advantage realized after the implementation of the system. It provides a measure of how quickly the investment is captured in revenues. It is typically plotted along with the investment cost (DDT&E) to determine the cross over point where the advantage of going to the new system is first realized. Several alternative systems may be plotted together for the purpose of comparison.

h. Growth and flexibility. Growth and flexibility is the ability to adjust to possible requirements changes or to continued use for future missions.

i. Risk. Risk is an assessment of what cost related factors might go wrong in the future if an alternative is selected. It considers both the probability and the potential seriousness of something going wrong.

j. Uniform vs Discrete Discount Methodologies. Within these trade studies, two different ways of determining discounted costs were employed. The first method involves spreading the costs year by year (using 1985 dollars as the base year). Mathematically this is represented as follows. Let

\[ C_i = \text{Costs incurred in Year } i \]

\[ P_i = \text{Discount factor for Year } i \]

\[ D_i = \text{Discounted costs for year } i, \text{ then} \]

\[ D_i = P_i \times C_i, \text{ and} \]

\[ D = \text{Sum (} P_i \times C_i \text{) for all } i \]

For the case of uniform funding distributions:

\[ C_i = C_{i-1} \text{ for all } i \text{ where } i-1 \text{ does not equal 0, and} \]

\[ C = C_i \text{ for all } i \]

\[ D = C \times \text{Sum (} P_i \text{), thus} \]

\[ P = \text{Sum (} P_i \text{) can be expressed as a constant factor}. \]
2.0 TRADE STUDIES

2.1 All-Propulsive Versus Aeroassist Trade Study.

The purpose of this trade study is to evaluate the economic factors of recovering the OTV at low Earth orbit (LEO) from high altitude missions using the all-propulsive and aeroassist recovery concepts and to identify which of the two concepts provides the best economic solution.

Earlier Phase A studies conducted from 1979-1981 by Boeing and General Dynamics show the viability of returning upper stage vehicles and their payloads from high orbit to LEO. These studies were based mainly on the all-propulsive concepts. Current concepts using an aeroassist device to take out the delta velocity of an OTV or OTV-and-payload upon return to LEO have been examined. An analysis produced for our first quarter report showed the potential advantage the aeroassist recovery concept holds over the all-propulsive concept. This analysis is summarized in Figure 2.1-1. The curves on the figure show the percentage of propellant the aeroassist concept can save over the all-propulsive concept as a function of the aerobrake weight/recovery weight rated. In a 20K delivery mission, an aerobrake weight/recovery weight ratio of 0.22 is realized, i.e., brake wt. 1885 / (return stage wt. 8404 + prop. wt 200) = 0.22. For a 14K roundtrip mission, a ratio of 0.08 is realized, i.e., brake wt 1885 / (return stage wt. 8880 + prop wt 250 + PL wt 14,000) = 0.08. As can be seen on Figure 2.1-1, extension of these aerobrake weight/recovery weight ratios show a 14 and 45 percent aeroassist propellant savings over the all-propulsive concept for the 20K delivery and 14K roundtrip missions, respectively.

2.1.1 Approach

Costing of the all-propulsive and aeroassist concepts is made based upon OTV mission traffic identified in the Revision 7 Nominal Mission Model. An analysis is made for both ground and space based modes of operation to determine if OTV design concepts are capable of accomplishing the missions as well as identifying the economic viability of the concepts. Cost figures are compared against the competition which is represented by a Centaur upper stage vehicle. The Centaur is chosen as the currently available vehicle most capable of accomplishing missions contained in the mission model.

Derived cost figures for the all-propulsive and aeroassist concepts and the competition are run through an economic analysis to help determine the advantages one concept holds over the other.
2.1.2 Ground Rules and Assumptions

Ground Rules and assumptions used for the study are shown below.

0 The following ground rules are constant for both options

- Constant fiscal year 1985 dollars excluding fee & contingency
- Space based cryogenic configurations: IOC is 1994
- No evolution over the 17 year operations period
- Ground test hardware includes Ground Vibration Test Article (GVTA), Static Test Article (STA), Main Propulsion Test Article (MPTA), and Functional Test Article (FTA)
- Space station requirements are assumed similar for both concepts. Therefore, cost impacts are not included
- Initial OTV production requirements: 2 units
- Flight test article and GVTA refurbished for operational stages
- 2 OMV uses per mission
- Ground mission operations at 35 man-yr/yr
- IVA & mission Ops costs: $16,000/hr; EVA cost: $48,000/hr
- IVA/mission = 80 hrs; EVA/mission = 4 hrs
- 2 STS deliveries per OTV: 0.2 STS deliveries per engine set

0 Reference all-propulsive

- 29.2 mlb of propellant for 389 missions
- 4 hrs/mission for space based mission operations
- 20 equivalent operations spares (excluding engines)
- Engine life = 15 missions (460K isp Pratt & Whitney)

0 Reference aeroassisted OTV

- 19.9 mlb of propellant for 389 missions
- 6 hrs/mission for space based mission operations
- 20 equivalent operations spares (w/o engine or aerobrake)
- Engine life = 20 missions (460K isp Pratt & Whitney)
- Aerobrake life = 5 flights
- 0.33 STS deliveries per aerobrake

2.1.3 Alternatives

Two basic alternatives are evaluated in this study: the all-propulsive concept and the aeroassist concept. The all-propulsive concept employs the upper stage engine to slow the OTV or OTV and payload for LEO. The vehicle evaluated for the all-propulsive alternative uses a liquid oxygen/liquid hydrogen engine with an Isp of 460 seconds.

The aeroassisted alternative uses a device to perform an aeroassist maneuver to slow the OTV (or OTV and return payload) for low Earth orbit. The aeroassist maneuver uses the earth's atmosphere to reduce the vehicle's velocity, thereby reducing the rocket burn required to enter low earth orbit when returning from GEO or other high orbits. This aeromaneuver is accomplished by grazing the upper atmosphere and converting the vehicle's
kinetic energy to heat. To correct for density variations and navigational uncertainties during the aeropass, precise aerodynamic control is required. We have evaluated a vehicle that uses vehicle lift for control. This vehicle uses the deployable conical fabric lifting brake. (Reference: Subsystem Trade Studies, Volume II, Book 3, Section 2.2).

2.1.4 Cost of Alternatives

An evaluation of the all-propulsive concept in both the ground based and space based modes was made. The all-propulsive ground base mode is not feasible when flown against Revision 8 of the MSFC Low Mission Model. This was shown by running a 12 klb GEO delivery payload through a flight simulation model. This simulation uses an OTV with a 55 klb propellant capacity and with no aerobrake. The following results were produced:

- Propellant required: 59,037 lb (ergo exceeds the OTV 55 klb tank capacity)
- Weight of OTV, propellant, and payload: 77,472 lb (ergo exceeds the STS 72 klb payload capacity)

This analysis alone does not eliminate the all-propulsive alternative. As an evolutionary option, expendable upper stage vehicles could be used during the ground based mode of the mission model. The all-propulsive operation could be begun during the space based mode of the mission model. However, this approach is at more of a disadvantage relative to aeroassist than is the case in the space based operational mode. Due to the greater propellant requirements of certain payloads, an all-propulsive GBOTV would require separate STS manifesting of payload and stage/propellants, thus incurring transportation costs well beyond the single STS requirement of an aeroassist concept. For this reason, we elected to complete the all-propulsive versus aeroassist trade in the space based mode. If aeroassist wins in this mode, it will also be a winner in the ground based mode.

Life cycle costs for DDT&E, production and operations are shown on Table 2.1-1. AFE costs are included in DDT&E. Note the principal delta under operations cost is propellant. Additionally, different stage sizes caused higher airframe refurbishment and IVA costs for the all-propulsive candidate.

The cost per flight for each alternative and the competition is shown in Table 2.1-2. The cost per flight for the all-propulsive and aeroassist concepts are derived by dividing the operations cost by the number of missions flown and adding the cost for delivering the payload to LEO. Payload delivery is included to make OTV costs comparable with the competition.

The Centaur, which is used to represent the competition, represents the vehicle which could best be upgraded to accommodate the mission model requirements. The cost per flight of this vehicle is figured at $123M based on the following:

- Centaur unit cost $50M
- STS delivery to LEO 73 M
### TABLE 2.1-1 ALL-PROPULSIVE VS AEROASSIST LCC (CONSTANT $)

<table>
<thead>
<tr>
<th></th>
<th>ALL PROP.</th>
<th>AEROASSIST</th>
<th>DELTA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($1245.60M)</td>
<td>($1316.50M)</td>
<td>($-70.80M)</td>
</tr>
<tr>
<td>DDT&amp;E Stage</td>
<td>891.30</td>
<td>949.60</td>
<td>($-58.30)</td>
</tr>
<tr>
<td>Stage Systems</td>
<td>354.40</td>
<td>366.90</td>
<td>($-12.30)</td>
</tr>
<tr>
<td>Production</td>
<td>58.10</td>
<td>61.50</td>
<td>($-3.40)</td>
</tr>
<tr>
<td>Operations</td>
<td>20086.60</td>
<td>16574.60</td>
<td>3512.00</td>
</tr>
<tr>
<td>Miss Ops. SB</td>
<td>211.60</td>
<td>317.60</td>
<td>($-106.00)</td>
</tr>
<tr>
<td>Miss Ops. GB</td>
<td>35.90</td>
<td>35.90</td>
<td></td>
</tr>
<tr>
<td>Launch Ops. SB</td>
<td>235.70</td>
<td>235.70</td>
<td></td>
</tr>
<tr>
<td>Launch Ops. GB</td>
<td>3151.00</td>
<td>3973.00</td>
<td>($-822.00)</td>
</tr>
<tr>
<td>Program Support</td>
<td>381.90</td>
<td>453.00</td>
<td>($-71.30)</td>
</tr>
<tr>
<td>Propellant</td>
<td>14617.50</td>
<td>9937.00</td>
<td>4680.50</td>
</tr>
<tr>
<td>Stage Ops:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airframe Refurbish</td>
<td>880.30</td>
<td>818.70</td>
<td>61.60</td>
</tr>
<tr>
<td>IVA/EVA Air Frame (AF)</td>
<td>572.60</td>
<td>491.70</td>
<td>80.90</td>
</tr>
<tr>
<td>Brake Refurbish</td>
<td>230.90</td>
<td>80.90</td>
<td>($-150.00)</td>
</tr>
<tr>
<td>IVA/EVA (Brake)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total LCC</td>
<td>$21390.40M</td>
<td>$17952.60M</td>
<td>$3437.80M</td>
</tr>
</tbody>
</table>

### TABLE 2.1-2 COST PER FLIGHT

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost Per Flight (Constant $)</th>
<th>Cost Per Flight (Discounted $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-propulsive</td>
<td>$97M</td>
<td>$15.8M</td>
</tr>
<tr>
<td>Aeroassist</td>
<td>$86M</td>
<td>$14.4M</td>
</tr>
<tr>
<td>Competition</td>
<td>$123M</td>
<td>$22.7M</td>
</tr>
</tbody>
</table>

If the two OTV concepts prove to be cost effective over the existing Centaur configuration, they certainly will be cost effective over a more expensive upgraded Centaur configuration required for some of the missions in the OTV mission model.

A benefit analysis is shown in present value in Table 2.1-3. The value shown for this analysis represents the cost advantage, or benefit, the alternative concepts hold over the competition.
TABLE 2.1-3 BENEFIT ANALYSIS (PV)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost Per Flight Competition (Discounted $)</th>
<th>Cost Per Flight Option (Discounted $)</th>
<th>No Flights</th>
<th>Benefit (Disc.$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-propulsive</td>
<td>(22.7M)</td>
<td>- 15.8M</td>
<td>x 389</td>
<td>2684</td>
</tr>
<tr>
<td>Aeroassist</td>
<td>(22.7M)</td>
<td>- 14.0M</td>
<td>x 389</td>
<td>3384</td>
</tr>
</tbody>
</table>

A return on investment (ROI) calculation is shown in Table 2.1-4 which factors in DDT&E to provide a benefit to investment ratio.

TABLE 2.1-4 RETURN ON INVESTMENT (PV)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost Per Flight Competition (Discounted $)</th>
<th>Cost Per Flight Option (Discounted $)</th>
<th>No Flights</th>
<th>DDT&amp;E (Disc $)</th>
<th>Adj. ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-propulsive</td>
<td>((22.7M)</td>
<td>- 15.8M</td>
<td>x 389 /</td>
<td>1775.8M</td>
<td>-1.2</td>
</tr>
<tr>
<td>Aeroassist</td>
<td>((22.7M)</td>
<td>- 14.0M</td>
<td>x 389 /</td>
<td>1819.9M</td>
<td>-3.1</td>
</tr>
</tbody>
</table>

2.1.5 Alternative Comparison

An alternative comparison is shown in Table 2.1-5. To aid in evaluating each economic factor, a score is provided at the bottom of the table. A value of 10 is given to the best option for each economic factor and a proportionate value is given to the other option.

Figure 2.1-2 provides a graphic view showing the payback difference between the two alternatives. The aeroassist option provides both an earlier break even point and a greater benefit over the postulated life of the mission model.
TABLE 2.1-5 ALL-PROPULSIVE VS AEROASSISTED COMPARISON (PV)

<table>
<thead>
<tr>
<th>Economic Factor</th>
<th>All-Propulsive</th>
<th>Aeroassist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefit (Discounted $)</td>
<td>2684</td>
<td>3384</td>
</tr>
<tr>
<td>ROI</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Investment (Discounted $)</td>
<td>775.8</td>
<td>819.9</td>
</tr>
<tr>
<td>Score</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit</td>
<td>7.9</td>
<td>10</td>
</tr>
<tr>
<td>ROI</td>
<td>8.1</td>
<td>10</td>
</tr>
<tr>
<td>Investment</td>
<td>10</td>
<td>9.5</td>
</tr>
</tbody>
</table>

2.1.6 Conclusion

The aeroassisted concept provides the greatest economic advantage of the two options in both the ground based and space based modes of operation. In the ground base mode of operation, the all-propulsive concept is not feasible in that propellant required to fly a GEO mission both exceeds the OTV 55,000 lb capacity of the OTV tanks and the STS 72 klb payload lift capacity. The additional STS flights required to service payloads exceeding the Shuttle lift capability would drive all-propulsive costs well beyond the aeroassist operations costs.

In the space based mode of operations, the investment cost of both options is reasonably affordable. The economic analysis for both benefit and return on investment show aeroassist to be the winner. A payback analysis also shows the aeroassist concept to have an earlier payback and greater overall return over the full term of the mission model.

The conclusion of the trade study is therefore to select the aeroassist concept over the all-propulsive concept.
2.2 OTV Engine Trade Study

The purpose of this trade study is to select an Orbital Transfer Vehicle (OTV) cryogenic engine which provides optimum benefits under Revision 8 of the Marshall Space Flight Center (MSFC) Mission Model. At mid-term, when cost analysis were based upon the 453 flights of the Revision 7 Nominal Mission Model, study results showed that a $350M investment cost was justified to develop an advanced engine with an Isp of 483 seconds. This study reexamines the economic impact of the engine trade using the much more modest Revision 8 Low Mission Model which postulates only 145 flights over the 12 year life of the mission model.

2.2.1 Approach

The following steps are used in conducting this trade study.

- Identify engine alternatives
- Identify propellant costs by year for each alternative
  - Compute propellant consumption
  - Compute propellant cost in constant and present value dollars
- Identify engine replacement cost by year for each alternative
  - Compute the number of engine replacements required
  - Compute engine replacement cost in constant and present value dollars
- Compute combined propellant and engine replacement costs
- Compute cost of existing engine (competition)
- Compare engine alternative with the competition and with one another

2.2.2 Groundrules and Assumptions

The following ground rules and assumptions are used for this trade study:

- 1985 dollars
- Propellant cost delivered to LEO is $1,500 per pound
- Present value:
  - Inflation: 0 percent
  - Discount: 10 percent
- Cost to deliver engine to LEO: $6.8M (54" Cargo Bay length charged per ground rules at time trade conducted)

Engine competition:
- RL 10A-3-3A
  - ISP: 440 seconds
  - Life: One hour
  - Unit cost: $1.5M

- Typical mission
  - To GEO: 12.4 klb payload
  - Return: 2.4 klb payload
2.2.3 Alternatives

Three developmental engines are used to form different engine strategies that serve as the alternatives used in this study. First the engine types will be discussed followed by the alternative strategies.

The three developmental engines are the RL10-IIB, an initial operational capability (IOC) engine, and an advanced engine. The existing RL10A-3-3A engine is also used as the "competition" to serve as the baseline to determine the profitability of each developmental engine. Basic cost and performance information on these engines is shown in Table 2.2-1.

The RL10-IIB engine represents a low risk development which improves the performance of existing engine technology (i.e., the technology used by the RL10A-3-3A engine).

The IOC engine uses an advanced technology, new cycle engine which possesses an Isp approximately equal to the practical limit of the existing technology engines (e.g. RL10A-3-3A and RL10-BII engines). The IOC engine in reality is an intermediate step. It provides improved efficiency without requiring full development to the expected potential of the new cycle engines.

The advanced engine possesses an Isp near the expected limit of the new cycle engines. This engine will be the most efficient in terms of propellant consumption.

The alternatives selected for this study are formed by using these engines in different combinations for ground based (GB) and space based (SB) operations. These alternatives are:

- Alternative 1. RL10-IIB engine GB to advanced engine SB.
- Alternative 2. IOC engine GB to advanced engine SB.
- Alternative 3. Advanced engine for both GB and SB.
- Alternative 4. RL10-IIB for minimum certification for both GB and SB.
- Alternative 5. IOC engine for both GB and SB.
TABLE 2.2-1  ENGINE COST AND PERFORMANCE DATA

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>THRUST (KLB FORCE)</th>
<th>ISP (SEC)</th>
<th>DDT&amp;E (CONSTANT $M)</th>
<th>UNIT COST (CONSTANT $M/ENG)</th>
<th>LIFE (HRS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL10-IIB</td>
<td>15</td>
<td>460</td>
<td>98.2</td>
<td>1.9</td>
<td>5</td>
</tr>
<tr>
<td>Initial</td>
<td>7.5</td>
<td>475</td>
<td>175</td>
<td>2.85</td>
<td>5</td>
</tr>
<tr>
<td>Operational</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>7.5</td>
<td>483</td>
<td>350</td>
<td>3.0</td>
<td>10</td>
</tr>
<tr>
<td>RL 10A-3-3A</td>
<td>16.5</td>
<td>440</td>
<td>0</td>
<td>1.5</td>
<td>1.25</td>
</tr>
</tbody>
</table>

2.2.4 Cost of Alternatives

2.2.4.1 Propellant Cost

Propellant requirements are determined for each engine by flying an average GEO mission on a simulation model using a 12.4 klb up payload and a 2400 lb down payload. A 45 klb propellant tank capacity is used for ground based missions and a 55 klb propellant tank capacity is used for space based missions. Burnout weight for the 45 klb vehicle is 5,689 lb and for the 55 klb vehicle is 8,090 lb.

Propellant requirements for this mission, as calculated by a flight simulation model, are shown for each type of engine in Table 2.2-2. Table 2.2-3 provides a summary of propellant weights and delivery costs for each engine. The propellant requirements are extended over the duration of the Revision 8 Low Mission Model. Propellant delivery is figured at $1,500/lb.

2.2.4.2 Engine Replacements

Engine replacement cost calculations are based upon the unit cost of the engine. Cost for engine installation and checkout are included in the unit cost price. The frequency of engine replacement is based upon the burn time requirement of the missions and the life expectancy of the engine. Table 2.2-4 summarizes engine replacement costs.

2.2.4.3 Total Costs

Engine replacement and propellant costs from Tables 2.2-3 and 2.2-4 are summarized in Table 2.2-5. DDT&E costs are shown in Table 2.2-6.

Total cost for the competition engine, RL10A-3-3A, are calculated to be as follows:

- Total Cost (Constant $) $10,662.0M
- Total Cost (PV $) $ 2,302.4M
- Cost per Flight (PV $) $ 73.5M

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The competition cost estimates, along with the engine operations cost summarized in Table 2.2-5 and engine DDT&E costs shown in Table 2.2-6 are used in the economic analysis calculations in paragraph 2.2.4.4 below. Note that the DDT&E cost of Alternative 1, in constant $, is the sum of Alternatives 3 and 4. The DDT&E cost of Alternative 2, in constant $, is increased $65M over Alternative 3 because of the stretched out, two step nature of the program.

TABLE 2.2-2 PROPELLANT REQUIREMENTS

<table>
<thead>
<tr>
<th>ENGINE PERFORMANCE</th>
<th>PROPELLANT REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLE TANK SIZE</td>
<td>45,000 (LB)</td>
</tr>
<tr>
<td>1</td>
<td>55,000 (LB)</td>
</tr>
<tr>
<td>RL 10-IIB 460 Isp</td>
<td>44,997</td>
</tr>
<tr>
<td>IOC</td>
<td>43,615</td>
</tr>
<tr>
<td>475 Isp Advanced</td>
<td>41,370</td>
</tr>
<tr>
<td>RL 10A-3-3A 440 Isp</td>
<td>50,104*</td>
</tr>
</tbody>
</table>

* Used to price 'competition', not a viable candidate

TABLE 2.2-3 PROPELLANT COST (REVISION 8 LOW MISSION MODEL)

<table>
<thead>
<tr>
<th>Alternative/Engine Engine</th>
<th>Propellant in GB MLB</th>
<th>Propellant Del Cost ($M PV) GB</th>
<th>Total Combined Cost ($M PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative 1 RL 10-IIB</td>
<td>1.6</td>
<td>835</td>
<td>1844</td>
</tr>
<tr>
<td>Advanced</td>
<td>4.3</td>
<td>4.3</td>
<td>1009</td>
</tr>
<tr>
<td>Alternative 2 IOC</td>
<td>1.5</td>
<td>809</td>
<td>1818</td>
</tr>
<tr>
<td>Advanced</td>
<td>4.3</td>
<td>4.3</td>
<td>1009</td>
</tr>
<tr>
<td>Alternative 3 Advanced</td>
<td>1.4</td>
<td>758</td>
<td>1767</td>
</tr>
<tr>
<td>Advanced</td>
<td>4.3</td>
<td>4.3</td>
<td>1009</td>
</tr>
<tr>
<td>Alternative 4 RL 10-IIB</td>
<td>1.6</td>
<td>835</td>
<td>2126</td>
</tr>
<tr>
<td>RL 10-IIB</td>
<td>5.5</td>
<td>1291</td>
<td></td>
</tr>
<tr>
<td>Alternative 5 IOC</td>
<td>1.5</td>
<td>809</td>
<td>2009</td>
</tr>
<tr>
<td>IOC</td>
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<td>1200</td>
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<tr>
<td>Alternative</td>
<td>Engine Replacements</td>
<td>Engine Costs ($M PV)</td>
<td>Total Combined Costs ($M PV)</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>GB</td>
<td>SB</td>
<td>GB</td>
</tr>
<tr>
<td>Alternative 1</td>
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<td>1.95</td>
</tr>
<tr>
<td>RL10-IIB Advanced</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Alternative 2</td>
<td></td>
<td></td>
<td>2.93</td>
</tr>
<tr>
<td>IOC Advanced</td>
<td>3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Alternative 3</td>
<td></td>
<td></td>
<td>2.93</td>
</tr>
<tr>
<td>Advanced Advanced</td>
<td>2</td>
<td>6</td>
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<tr>
<td>Alternative 4</td>
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</tr>
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<td>RL10-IIB</td>
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<td>10</td>
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<tr>
<td>Alternative 5</td>
<td></td>
<td></td>
<td>2.93</td>
</tr>
<tr>
<td>IOC</td>
<td>3</td>
<td>12</td>
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</tr>
<tr>
<td>IOC</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative/Engine</td>
<td>Propellant Cost</td>
<td>Engine Replacement Cost</td>
<td>Total Costs</td>
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<tr>
<td>-------------------</td>
<td>-----------------</td>
<td>--------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Alternative 1</td>
<td>1844</td>
<td>9.18</td>
<td>1853</td>
</tr>
<tr>
<td>RL10-IIB (GB)</td>
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</tr>
<tr>
<td>Advanced (SB)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative 2</td>
<td>1818</td>
<td>10.21</td>
<td>1828</td>
</tr>
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</tr>
<tr>
<td>Advanced (SB)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Alternative 3</td>
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<td>10.21</td>
<td>1767</td>
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</tr>
<tr>
<td>Advanced (SB)</td>
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<td></td>
<td></td>
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<tr>
<td>Alternative 4</td>
<td>2126</td>
<td>17.15</td>
<td>2143</td>
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<td>RL10-IIB (GB)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>RL10-IIB (SB)</td>
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</tr>
<tr>
<td>Alternative 5</td>
<td>2009</td>
<td>19.63</td>
<td>2029</td>
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<td>IOC (GB)</td>
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</tr>
<tr>
<td>IOC (SB)</td>
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<td></td>
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TABLE 2.2-6 ENGINE DDT&E ($M PV)

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<th>ALTERNATIVE</th>
<th>DDT&amp;E</th>
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<tr>
<td></td>
<td>Const $</td>
</tr>
<tr>
<td>Alternative 1</td>
<td>$448.2M</td>
</tr>
<tr>
<td>RL10-IIB (GB)</td>
<td></td>
</tr>
<tr>
<td>Advanced (SB)</td>
<td></td>
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<tr>
<td>Alternative 2</td>
<td>415.</td>
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<tr>
<td>IOC (GB)</td>
<td></td>
</tr>
<tr>
<td>Advanced (SB)</td>
<td></td>
</tr>
<tr>
<td>Alternative 3</td>
<td>350.</td>
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<td>Advanced (GB)</td>
<td></td>
</tr>
<tr>
<td>Advanced (SB)</td>
<td></td>
</tr>
<tr>
<td>Alternative 4</td>
<td>98.2</td>
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<tr>
<td>RL10-IIB (GB)</td>
<td></td>
</tr>
<tr>
<td>RL10-IIB (SB)</td>
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</tr>
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<td>Alternative 5</td>
<td>175.</td>
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<td>IOC (GB)</td>
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<td>IOC (SB)</td>
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</tr>
</tbody>
</table>

2.2.4.4 Economic Analysis

A benefit analysis is shown in Table 2.2-7 for each engine option. This analysis is based upon the algorithm: Competition Operations Cost - Engine Operations Cost = Benefit. Table 2.2-7 shows the greatest operational benefit, not including development cost, comes from the use of the advanced engine.

A Return on Investment (ROI) analysis is shown in Table 2.2-8 for each engine option. This analysis provides a best buy rates by dividing the benefit by the investment (DDT&E) costs. This algorithm is:

\[
\text{Competition Operations Cost} - \text{Engine Operations Cost} - 1 = \text{ROI}
\]

The greatest ROI is offered by the RL-10 engine, with the IOC engine second.

The pay back economics factor represents the number of missions required to amortize the DDT&E investment for each engine option (Table 2.2-9). Table 2.2-10 identifies the number of missions required before the payback is realized. The algorithm used is:

\[
\frac{\text{DDT&E Cost}}{\text{CPF}_C - \text{CPF}_O} = \text{Number of flts to pay back}
\]

where CPF\(_C\) = cost/fit, competition CPF\(_O\) = cost/fit, engine option

The earliest investment pay back is achieved with the RL10 derivative engine, with the IOC engine second.
### Table 2.2-7 Engine Trade Benefits ($M PV)

<table>
<thead>
<tr>
<th>OPTION</th>
<th>COMPETITION OPS COST - OPTION OPS COST = BENEFIT</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>(2302 - 1853) = 449</td>
</tr>
<tr>
<td>RL10/ADV</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(2302 - 1828) = 474</td>
</tr>
<tr>
<td>IOC/ADV</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(2302 - 1767) = 535</td>
</tr>
<tr>
<td>ADV/ADV</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(2302 - 2143) = 159</td>
</tr>
<tr>
<td>RL10/RL10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(2302 - 2029) = 273</td>
</tr>
<tr>
<td>IOC/IOC</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.2-8 Engine Trade ROI

<table>
<thead>
<tr>
<th>OPTION</th>
<th>BENEFITS (PV) / DDT&amp;E (PV) - 1 = ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(449 / 258.7) - 1 = 0.73</td>
</tr>
<tr>
<td>RL10/ADV</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(474 / 254.8) - 1 = 0.86</td>
</tr>
<tr>
<td>IOC/ADV</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(535 / 251.1) - 1 = 1.13</td>
</tr>
<tr>
<td>ADV/ADV</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(159 / 70.2) - 1 = 1.26</td>
</tr>
<tr>
<td>RL10/RL10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(273 / 125.1) - 1 = 1.18</td>
</tr>
<tr>
<td>IOC/IOC</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 2.2-9 PAYBACK - MAIN ENGINE

<table>
<thead>
<tr>
<th>OPTION</th>
<th>MISSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 RL10/ADV</td>
<td>83</td>
</tr>
<tr>
<td>2 IOC/ADV</td>
<td>78</td>
</tr>
<tr>
<td>3 ADV/ADV</td>
<td>68</td>
</tr>
<tr>
<td>4 RL10/RL10</td>
<td>64</td>
</tr>
<tr>
<td>5 IOC/IOC</td>
<td>66</td>
</tr>
</tbody>
</table>

Figure 2.2-1 provides a graphic portrayal of each engine's payback vis-a-vis the competition. It also shows a comparison of the payback among the engine options. This figure shows the advanced engine providing the most benefit over the 145 mission planning horizon. It also shows the RL10-IIB engine having a quicker payback but providing the least advantage over the 145 mission scenario.
FIGURE 2.2-1 ENGINE PAYBACK FOR VARIOUS OTV ENGINES
2.2.5 Alternative Comparison

Table 2.2-10 provides a comparison of the economic analysis factors. Each factor provides a different measurement of economic merit. All factors should be weighted individually and together to determine the best engine alternative. To aid this comparison, a scoring is provided where the most favorable alternative is given a 10 and the other alternative a value in relation to the alternative scored 10.

**TABLE 2.2-10 ENGINE TRADE RESULTS**

<table>
<thead>
<tr>
<th>ECONOMIC FACTOR</th>
<th>RL10/ADV 1</th>
<th>IIOC/ADV 2</th>
<th>ADV/ADV 3</th>
<th>RL10/RL10 4</th>
<th>IIOC/IOC 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROI (PV)*</td>
<td>0.73</td>
<td>0.86</td>
<td>1.13</td>
<td>1.26</td>
<td>1.18</td>
</tr>
<tr>
<td>Benefits (PV)*</td>
<td>449.0</td>
<td>474.0</td>
<td>535.0</td>
<td>159.0</td>
<td>273.0</td>
</tr>
<tr>
<td>Investment (DDT&amp;E) (PV)*</td>
<td>258.7</td>
<td>254.8</td>
<td>251.1</td>
<td>70.2</td>
<td>125.1</td>
</tr>
<tr>
<td>LCC (PV)*</td>
<td>2112.0</td>
<td>2083.0</td>
<td>2018.0</td>
<td>2213.0</td>
<td>2154.0</td>
</tr>
<tr>
<td>Payback Missions</td>
<td>83</td>
<td>78</td>
<td>68</td>
<td>64</td>
<td>66</td>
</tr>
<tr>
<td>Cost per Flight (PV)*</td>
<td>59.1</td>
<td>58.4</td>
<td>55.1</td>
<td>66.2</td>
<td>62.2</td>
</tr>
</tbody>
</table>

* Millions of dollars (M)

<table>
<thead>
<tr>
<th>SCORE</th>
<th>RL10/ADV 1</th>
<th>IIOC/ADV 2</th>
<th>ADV/ADV 3</th>
<th>RL10/RL10 4</th>
<th>IIOC/IOC 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROI</td>
<td>5.8</td>
<td>6.8</td>
<td>9.0</td>
<td>10.0</td>
<td>9.4</td>
</tr>
<tr>
<td>Benefits</td>
<td>8.4</td>
<td>8.9</td>
<td>10.0</td>
<td>3.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Investment</td>
<td>2.7</td>
<td>2.8</td>
<td>2.8</td>
<td>10.0</td>
<td>5.6</td>
</tr>
<tr>
<td>LCC</td>
<td>9.6</td>
<td>9.7</td>
<td>10.0</td>
<td>9.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Payback Missions</td>
<td>7.7</td>
<td>8.2</td>
<td>9.4</td>
<td>10.0</td>
<td>9.7</td>
</tr>
<tr>
<td>Cost per Flight</td>
<td>9.3</td>
<td>9.4</td>
<td>10.0</td>
<td>8.3</td>
<td>8.9</td>
</tr>
</tbody>
</table>

2.2.6 Conclusion

The engine trade scores in Table 2.2-10 show mixed results. Alternative 4 [RL10-IIB (GB)/RL10-IIB (SB)] scores high on investment and payback missions. ROI is also scored high for alternative 4, but this figure is tempered by the relatively low benefit. The benefits score for alternative 4 is disproportionately low vis-a-vis the other alternatives.

Alternative 3 [ADV (GB)/ADV (SB)] scores high on benefits, cost per flight, and life cycle cost, however the risk associated with this alternative is greater than the other alternatives since it calls for the highest Isp (483) and embarks on a new technology high performance engine.
Alternative 5 [IOC (GB)/IOC (SB)] represents a good compromise. All economic factors except LCC fall between alternatives 3 and 4 in scoring. Alternative 5 does not have as great a risk as alternative 3 and can serve as a stepping stone to the more efficient advanced engine. By starting out with the same engine for ground based operations, experience and greater confidence will be realized in the engine for initial space based operations and later for man-rated operations.

The conclusion of this study is that the IOC engine should be developed for both ground based and space based OTV operations.
2.3 Man Rating and Reliability Trade Study

The objective of this study is to establish data to permit the selection of a man-rating policy and then to implement that policy in the OTV configurations. The mission model is dominated by unmanned missions so it is also the objective of the study to define the redundancy configuration of unmanned OTV concepts. This step in the OTV concept definition is crucial since it establishes the equipment lists and thereby has major influence of design and weight.

2.3.1 Approach

The following approach is used in the analysis.

- Establish cost data to permit definition of a man-rating policy.
- Incorporate redundancy needed to meet the policy in the manned OTV.
- Configure the unmanned OTV redundancy to be consistent with current expendable stages.

The first step in the approach established the sensitivity of life cycle cost to various failure policies. The failure policies considered are shown in Table 2.3-1. In this analysis, 368 GEO delivery mission are used and the space based cryogenic reference configuration serves as the basis for characterizing the configurations for each failure policy. The equipment complement of the reference configuration is adjusted through a functional Failure Modes Effects Analysis (FMEA) to be consistent with the failure policies. This means examining the Failure Modes in each flight phase, determining if a failure met the policy and, if not, adding redundancy until the policy is satisfied.

Step two reexamines the reference configuration through a FMEA to specifically meet the stated man-rating policy.

Step three determines the consistency of the redundancy policy with current expendable reliability capability.

<table>
<thead>
<tr>
<th>TABLE 2.3-1 MAN-RATING POLICY CONCEPTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
</tr>
<tr>
<td>Single String</td>
</tr>
<tr>
<td>Fail Safe</td>
</tr>
<tr>
<td>Fail Operational/Fail Safe</td>
</tr>
<tr>
<td>Fail Operational/Fail Safe</td>
</tr>
</tbody>
</table>
2.3.2 Ground Rules

The following ground rules are used in the man-rating analysis:

- **Reference Missions (Rev 7 Nominal Mission Model)**
- 14 manned 14 klb up, 14 klb down GEO servicing missions.
- 354 unmanned 12,445 lb up, 4,711 lb down GEO servicing missions.
- **Mission duration:** 480 hours manned missions
  51 hours unmanned missions
- **Reference OTV design**
  - Space based cryo - (Figure 2.3-1)
    - Single engine configuration 15 klb thrust 478.6 Isp
    - Dual engine configuration 7.5 klb thrust 471.3 Isp
    - Three engine configuration 5 klb thrust 475.8 Isp

2.3.3 Analysis

This section documents the results of the investigations to establish manned and unmanned redundancy for the candidate OTV concepts.

2.3.3.1 Man Rating Policy

The redundancy required to implement the four failure policies is shown in Table 2.3-2 together with the computed reliabilities. These data form the basis for characterizing conceptual cryo stages. Feasible layouts were sketched and weight statements (Table 2.3-3) were developed. These data are used for performance analysis to determine propellant required to capture the GEO missions. The resulting performance data is presented in Tables 2.3-4 and 2.3-5. The performance and the design data form the basis of the life cycle cost analysis shown in Table 2.3-6 and Figure 2.3-2. It is noted that propellant requirements resulting from stage weight dominates the LCC difference and that progression from single string to Fail Operational, Fail Operational, Fail Safe is exponential in cost of mission capture.
MULTI-LAYER NICALON, Q FELT AND SEALED NEXTEL ON GRAPHITE POLYIMIDE FRAME AEROBRACE

ULTRA LIGHT 2090 TANKS

AVIONICS MODULE DESIGNED FOR SPACE REPLACEMENT

GRAPHITE POLYIMIDE HONEYCOMB COVERED WITH CERAMIC FOAM TILES

WEIGHTS
(SINGLE STRING)

AEROBRACE 1552
TANKS 1647
STRUCTURE 731
ENVIRONMENTAL CONTROL 478
MAIN PROPULSION 1015
ORIENTATION CONTROL 299
ELECTRIC POWER 443
AVIONICS 353
CONTINGENCY (15%) 978

DRY WEIGHT 7496
PROPELLANTS, ETC 84000

LOADED WEIGHT 91496

CAPABILITY: 14000 LB ON GEO SORTIE

FIGURE 2.3-1 SPACE BASED CRYO REFERENCE CONFIGURATION
### TABLE 2.3-2 FAILURE POLICY EQUIPMENT/RELIABILITY ALLOCATION

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>RELIABILITY DATA OTV SINGLE STRING</th>
<th>RELIABILITY DATA OTV FAIL SAFE</th>
<th>RELIABILITY DATA OTV OPS SAFE</th>
<th>RELIABILITY DATA OTV OPS OPS SAFE</th>
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<tr>
<td>Structure</td>
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<td>0.9995680930</td>
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<td>0.9995680930</td>
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<td>QD's</td>
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</table>

| TOTALS                     | 0.7200587420                       | 0.8636410530                    | 0.977398000                    | 0.9819766330                     |

37
### TABLE 2.3-3 CONFIGURATION RELIABILITY VS WEIGHT

SPACE BASED CRYO - 84 KLB PROPELLANT LOAD
(Weight Lb)

<table>
<thead>
<tr>
<th>Description</th>
<th>Single String</th>
<th>Fail Safe</th>
<th>FO/FS</th>
<th>FO/FO/FS</th>
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<td>Mtg. Provisions - REMs &amp; Acc.</td>
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<td>10</td>
<td>10</td>
<td>10</td>
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<td>106</td>
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<td>48</td>
<td>48</td>
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<td>Support Struct. &amp; Attach</td>
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<td>LH₂ Tank</td>
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<td>Boom - Avionics</td>
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<th>FO/FO/FS</th>
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<td>58</td>
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<td>0</td>
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<td>LH₂ Tank</td>
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<td>0</td>
<td>0</td>
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<td>Dry Weight</td>
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<td>Contingency (15%)</td>
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<td>1006</td>
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<td>Total Dry Weight</td>
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<td>7713</td>
<td>8868</td>
<td>9711</td>
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### TABLE 2.3-4 MANNED MISSION PERFORMANCE DATA

**Configuration:** SB Cryo Ref (Fig 2.3-1)

**Mission:** Manned GEO Servicing

**Payload:** Up 14 klb; Down 14 klb

<table>
<thead>
<tr>
<th>Failure Policy</th>
<th>Dry Weight (lb)</th>
<th>Isp (@ = 640:1) (sec)</th>
<th>Thrust Engine (lb)</th>
<th>No. Engine</th>
<th>Propellant Weight (lb)</th>
<th>Gross Weight (lb)</th>
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</thead>
<tbody>
<tr>
<td>Single String</td>
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<td>478.6</td>
<td>15000</td>
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<td>77381</td>
<td>101092</td>
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</table>

### TABLE 2.3-5 UNMANNED MISSION PERFORMANCE DATA

**Configuration:** SB Cryo Ref (Fig 2.3-1)

**Mission:** Unmanned GEO Servicing

**Payload:** Up 12445; Down 4711

<table>
<thead>
<tr>
<th>Failure Policy</th>
<th>Dry Weight (lb)</th>
<th>Isp (@ = 640:1) (sec)</th>
<th>Thrust Engine (lb)</th>
<th>No. Engine</th>
<th>Propellant Weight (lb)</th>
<th>Gross Weight (lb)</th>
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<td>5000</td>
<td>3</td>
<td>45816</td>
<td>63261</td>
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</table>
### TABLE 2.3-6 OTV RELIABILITY OPTIONS LCC (USING DELIVERED PROPELLANT) (1985 $B)$

<table>
<thead>
<tr>
<th></th>
<th>Single String</th>
<th>Fail Safe</th>
<th>Fail Op Safe</th>
<th>Fail Op/ Fail Op Safe</th>
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<td>DDT&amp;E</td>
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<td>PRODUCTION</td>
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<td>0.3</td>
<td>0.4</td>
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</tr>
<tr>
<td>REFURB</td>
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<td>5.6</td>
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</tr>
<tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<td>4.7</td>
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<td>0.1</td>
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<td><strong>TOTAL COST</strong></td>
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<td><strong>40.3</strong></td>
<td><strong>46.1</strong></td>
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</table>
These data resulted in the NASA establishing the following manned safety policy:

No single credible failure shall preclude the safe return of the crew.

2.3.3.2 Man-Rating Policy Implementation

The Failure Modes Effects Analysis to implement the man-rating policy resulted in the redundancy shown in Table 2.3-7. It is noted that for a 480 hour mission the reliability of the manned configuration falls between the Fail Safe and the Fail Operational, Fail Safe concepts shown in Figure 2.3-2. This redundancy configuration meets the failure policy and provides a mission success probability that is judged to be acceptable based on expected loss costs. Table 2.3-8 summarizes the reliabilities of the manned and single string concept which meets the criteria of being as good as current expendable stages. The unmanned 51 hour mission has good probability (0.966) of mission success. A comparison of the equipment compliment for the manned and unmanned concepts is shown in Table 2.3-9.

<table>
<thead>
<tr>
<th>TABLE 2.3-8 RELIABILITY</th>
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<td>Configuration</td>
</tr>
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<td>Manned</td>
</tr>
<tr>
<td>Unmanned (Single String)</td>
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</table>

2.3.3.3 Man Rating Costs

The cost of man-rating is of course of interest. It is estimated at this point in the development of the OTV concept that the cost differences between all unmanned and manned operations are based on the LCC data in Table 2.3-6 as follows:

- **Investment**
  - (DDTE & Production) $400M

- **Operations**
  - 368 Missions $4370M

Operations costs ignore the reduced losses resulting from a higher reliability. The expected losses for single string and the man-rated concepts is given by

\[
(1-R)N \times \text{Expected Loss Cost}
\]
<table>
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<th>COMPONENT</th>
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<th>RELIABILITY</th>
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</tr>
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<td>Lines &amp; Fit</td>
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<td>2</td>
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<td>Radiators</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>FC Pwr Cond</td>
<td>2</td>
<td>1</td>
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</tr>
<tr>
<td>Star Tracker</td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>IMU</td>
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<td>1</td>
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<tr>
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</tr>
<tr>
<td>Cmd &amp; Data Hdlr</td>
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<td>Sequencer</td>
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<tr>
<td>Wiring</td>
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</table>
The expected cost for an average loss was obtained as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Payload Value</td>
<td>$194M</td>
</tr>
<tr>
<td>Payload Delivery to GEO (20 klb x $2K)</td>
<td>$40M</td>
</tr>
<tr>
<td>OTV Fuel to GEO (64.5 klb x $2K)</td>
<td>$129M</td>
</tr>
<tr>
<td>Operations</td>
<td>$5M</td>
</tr>
<tr>
<td>Worst Case Cost</td>
<td>$368M</td>
</tr>
<tr>
<td>Expected Loss Cost (W/C x 50%)</td>
<td>$184M</td>
</tr>
</tbody>
</table>

The reduction of worst case loss cost by 50% reflects an average loss cost across all the missions. Computing the losses for simple string and man-rated we get:

<table>
<thead>
<tr>
<th>Description</th>
<th>Manned</th>
<th>Unmanned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single String:</td>
<td>$720M</td>
<td>$2210M</td>
</tr>
<tr>
<td>Man Rated:</td>
<td>$139M</td>
<td>$261M</td>
</tr>
</tbody>
</table>

Now it is clear that in combination of these cost factors the cost of man-rating is:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>$400M</td>
</tr>
<tr>
<td>Operations</td>
<td>$4370M + 400M - 2930M = 1840M, which is equivalent to about $5M per manned mission (operations cost/missions)</td>
</tr>
</tbody>
</table>

These data should be viewed as only indications of the cost of man-rating. However, based on this relative immature concept data, the increased flexibility of manned mission capability is achieved for a modest increase in cost per flight.

2.3.4 Conclusion

Reliability figures are based upon the NASA policy that "no single credible failure shall preclude the safe return of the crew". The resulting reliability requirement for a manned 28 day mission is 0.946 and for a manned 51 hour mission is 0.996. The resulting unmanned single string reliability requirement for a 28 day mission is 0.72 and for an unmanned 51 hour mission is 0.966. The cost of upgrading from unmanned to man-rated is $2.2B.

The question of evolutionary strategy is not answered by this analysis; whether to start single string and then transition by block change to a man-rated OTV or start out man-rated. These decisions are properly a part of the evolution strategy trades in Section 2.7.
2.4 Propellant Delivery Trade Study

The purpose of this trade study is to select a preferred method for delivering cryogenic propellant to LEO for use in space based OTV operations. At issue are two questions: would a new propellant delivery system be more economically viable than using the existing Space Transportation System (STS) cargo bay; and, if so, what new system would be the most economically viable.

This study is a necessary prerequisite for the evolutionary strategies for the acquisition of an OTV that captures the mission model. (Ref paragraph 2.7.3, Preferred Overall Evaluation). The selection of the preferred propellant delivery approach is a key issue in the economics of establishing OTV as a viable venture. The single most costly factor is delivering propellant to LEO and therefore the cost per pound of the delivery system has a major influence on whether the OTV will be competitive with existing stages and existing LEO delivery methods.

The study addresses only cryogenic propellant and considers only the Aft Cargo Carrier (ACC) for use in propellant scavenging. If storable propellant had been selected over cryogenic propellant, then a follow-on propellant delivery trade would have been required using storable propellant as a basic consideration. (Ref paragraph 2.6, Storable versus Cryogenic Trade Study). Likewise, if the cargo bay had been selected over the ACC for propellant scavenging, then a follow-on propellant delivery trade would have been required using cargo bay scavenging as a basic consideration (Ref paragraph 2.7.2, ACC versus Cargo Bay for OTV Delivery/Scavenging).

2.4.1 Approach

The approach used in this trade is to create a simplified delivery problem and evaluate the economic benefits of the delivery concepts. The fundamental decision involved in the trade is whether it is justified to embark on an acquisition of a tanker, a scavenging system, or both; or whether to use the STS as a delivery system. The following cost benefit [i.e., Return on Investment (ROI)] ratio will be the principle measure.

\[
\frac{\text{STS PROPELLANT DEL. COST} - \text{OPTION PROPELLANT DEL. COST}}{\text{OPTION INVESTMENT COST}} = \text{ROI}
\]

If the ratio is negative, the option is not a viable economic venture. If the ratio is zero, the venture retrieves the investment but is not profitable. A positive ratio indicated the venture is profitable.

2.4.2 Ground Rules and Assumptions

The ground rules and assumptions listed below are used in the trade study. Costs are in millions of constant 1985 dollars, unless otherwise indicated as present value [PV] dollars.
OTV

- Mission Traffic: 10 missions per year, 1999-2010
- Configuration: 55 klb stage with 483 sec Isp
- Payload: 12.4 klb to GEO
  - 24 klb return
- Propellant: LH2/LO2
- Propellant Rqmt: 41.37 klb per mission
- Total Prop. Rqmt
  - (41370 x 120 missions): 4.9644 mlb

Scavenging

- Scavenging System: STS ACC
- STS Scavenging Flights: 328
- Prop. Scavenged/Flight: 14 klb
- Total prop. Scavenged: 4.592 mlb
- DDT&E: $212M
- DDT&E [PV] ($212M x 2.16 / 4 yrs): $114.5M
- Propellant Delivery Cost: $1167M
- Cost per flight ($1167M / 328): $3.6M
- Propellant Delivery Cost [PV] ($1167M x 1.97 / 12 yrs): $191.6M (see Section 1.3 for uniform discounting)

STS Cargo Bay

- DDT&E: $4M
- DDT&E [PV]: $2.2M
- Prop. Delivery Rqmt. 4.9644 mlb
- STS Delivery Capacity: 65 klb
- STS Flights
  - (4.9644M/65 klb): 76.4
- STS cost per flight: $73M
- Propellant Delivery Cost
  - (76.4 x $73M): $5577
- Propellant Delivery Cost [PV]
  - ($5577M x 1.97 / 12 yrs): $915.4M

SDV Tanker

- SDV Tanker Acquisition: 1995-1998
- DDT&E: $2200M
- DDT&E [PV]
  - ($2200 x 2.16 / 4 yrs): $1188M
- Propellant Delivery Rqmt: 4.9644 mlb
- SDV Delivery Capacity: 181 klb
- SDV Flights
  - (4.9644M / 181 klb): 27.4
- SDV Cost per Flight: $75M
- Propellant Delivery Cost
  - (27.4 x $75M): $2055M
- Propellant Delivery Cost [PV]
  - ($2055 x 1.97 / 12 yrs): $337.4M
0 STS Cargo Bay/Scavenging

0 DDT&E ($4M + $212M): $216M
0 DDT&E [PV] ($2.2M + $114.5M): $116.7M
0 Scavenge Prop. Delivery: 4.592 mlb
0 STS CB Prop. Del.
(4.9644M - 4.592M): 0.372 mlb
0 STS Flights (0.372M/65 klb) 5.7
0 STS CB Del Cost (5.7 x $73M): $416M
0 ACC Scavenging Prop. Del. Cost: $1167M
0 Total Prop. Delivery Cost
($416 + $1167): $1583M
0 Total Prop Delivery Cost [PV]
($1583M x 1.97 / 12 yrs): $260.2M

0 SDV Tanker/Scavenging

0 DDT&E ($2200 + $212M): $2412M
0 DDT&E [PV] ($1188M + $114.5M): $1302.5M
0 Scavenge Prop. Delivery 4.592 mlb
0 SDV Tanker Prop. Delivery
(4.9644M - 4.592M): 0.372 mlb
0 SDV Tanker Flights
(0.372M/181,000): 2.1
0 SDV Tanker Del. Cost
(2.1 x $75M): $157M
0 ACC Scavenging Prop. Delivery Cost: $1167M
0 Total Prop Delivery Cost
($157 + $1167): $1324M
0 Total Prop. Delivery Cost [PV]
($1324M x 1.97 / 12 yrs): $217.0M

2.4.3 Alternatives

The following alternative methods for propellant delivery to LEO are considered in the trade study.

0 Alternative 1 - STS/scavenging.

This option provides cryogenic propellant for use at LEO by combining two propellant delivery methods. One, excess propellant, left over from STS launches, is acquired through a scavenging system contained in the ACC. This propellant, in turn, is off loaded at the Space Station.

The second method uses tanks carried in the STS cargo bay to carry additional propellant to the Space Station to complete the on-orbit propellant availability requirements.
Alternative 2 - Shuttle Derived Vehicle (SDV) Tanker.

The tanker used for this alternative is a vehicle specifically designed to launch heavy payloads into orbit. This vehicle, when configured as a tanker, is capable of delivering large amounts of propellant (181 klb) to the Space Station.

Alternative 3 - Tanker and Scavenging.

This alternative combines the scavenging concept with a tanker to provide propellant at the Space Station.

Competition

The competition for the alternatives used in this study is propellant tanks carried in the STS cargo bay. This option is selected as the competition since technology for the concept is presently available.

2.4.4 Cost of Alternatives

An economic analysis for each alternative is shown for benefit in Table 2.4-1 and for ROI in Table 2.4-2. The data in these tables are extracted from the list of ground rules and assumptions in paragraph 2.4.2 and converted to discounted dollars.

The present value calculations for discounted dollars assumes a constant distribution of cost and therefore can be simplified to a single factor for propellant delivery and for investment (i.e., DDT&E).

- Propellant delivery factor: 1.97
- Investment factor: 2.16

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<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 STS/Scavenging</td>
<td>$915.4</td>
<td>$260.2</td>
<td>$655.2</td>
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<tr>
<td>2 SDV Tanker</td>
<td>$915.4</td>
<td>$337.4</td>
<td>$577.0</td>
</tr>
<tr>
<td>3 Tanker/Scavenging</td>
<td>$915.4</td>
<td>$217.0</td>
<td>$698.4</td>
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</table>
TABLE 2.4-2 RETURN ON INVESTMENT (Discounted $M)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Benefit</th>
<th>Investment (DDT&amp;E)</th>
<th>Adj.</th>
<th>ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 STS/Scavenging</td>
<td>(655.2/116.7)</td>
<td>-1</td>
<td>1</td>
<td>4.6</td>
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<tr>
<td>2 SDV Tanker</td>
<td>(577.0/118.0)</td>
<td>-1</td>
<td>1</td>
<td>-0.5</td>
</tr>
<tr>
<td>3 Tanker/Scavenging</td>
<td>(698.4/1302.5)</td>
<td>-1</td>
<td>1</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

2.4.5 Alternative Comparison

The results of the propellant delivery analysis are summarized in Table 2.4-3. Alternative 1, scavenging combined with STS cargo bay propellant delivery, is clearly the most advantageous option. The ROI analysis shows a negative value for both Alternatives 2 and 3 indicating that they are not economically viable ventures. The relatively low investment cost of Alternative 1, has a significant effect on the trade study results since it is also a factor used in the ROI and LCC calculations.

The benefit analysis shows a fairly even score among the alternatives with the greatest advantage lying with Alternative 3, SDV/Scavenging. Scavenging, utilized by Alternatives 1 and 3, boosts the benefit score of these alternatives over that of Alternative 2.

The difference in scores between Alternatives 1 and 3 are due to the bulk delivery modes of the options, i.e., cargo bay versus SDV Tanker. As can be seen the SDV Tanker provides the greater benefit of the two.
TABLE 2.4-3  PROPELLANT DELIVERY RESULTS
(Discounted $M)

<table>
<thead>
<tr>
<th>Economic Factor</th>
<th>OPTION</th>
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<th>2</th>
<th>3</th>
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<tbody>
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<td></td>
<td>STS/Scavenging</td>
<td>SDV/Tanker</td>
<td>Tanker/Scavenging</td>
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</tr>
<tr>
<td>ROI</td>
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<td>-0.5</td>
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<tr>
<td>Benefits</td>
<td>$655.2</td>
<td>$577.0</td>
<td>$698.4</td>
<td></td>
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<tr>
<td>Investment (DDT&amp;E)</td>
<td>$116.7</td>
<td>$1188</td>
<td>$1302.5</td>
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<td>LCC (DDT&amp;E Ops Cost)</td>
<td>$376.9</td>
<td>$1525.4</td>
<td>$1519.5</td>
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<td>ROI</td>
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<td>.9</td>
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<tr>
<td>LCC</td>
<td>10</td>
<td>2.5</td>
<td>2.5</td>
</tr>
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</table>

2.4.6 Conclusion

Alternative 1, scavenging combined with STS Cargo Bay propellant delivery, provides the most favorable economic means of delivering propellant to LEO for use in OTV operations. The investment costs associated with the development of SDV tanker makes the use of Alternatives 2 and 3 uneconomical when applied to the Revision 8 Low Mission Model.

It shall be noted that Alternatives 2 and 3 would become more attractive if a greater demand for bulk delivery of propellant to LEO existed, or if the SDV tanker DDT&E was shared with another program (e.g., Space Station). As shown in the study, scavenging provides the most economical means of delivering propellant to LEO, however, the amount of propellant acquired by the scavenging is limited. Space based OTV propellant requirements under the Revision 8 Low Mission Model are mostly satisfied by the scavenging concept. Delivery of the relatively small amount of propellant remaining to meet the on-orbit demand can be satisfied by the STS for less than the cost of developing a new more efficient propellant delivery vehicle. If mission requirements change whereby greater quantities of propellant must be delivered to LEO in bulk, then the use of the SDV tanker becomes more attractive.
The bulk delivery requirement can be affected in two ways. One by a greater demand for propellant at LEO to satisfy OTV operational needs; and, two by the percentage of this demand supplied through scavenging decreasing. In essence, the economic benefit received from a greater number of bulk propellant delivery missions would be needed in order to offset the investment cost of a new tanker vehicle.
2.5 Tank Farm Trade Study

The purpose of the tank farm trade study is to determine the most advantageous means for storing propellant in the vicinity of the Space Station. A free-flying propellant farm, a tethered propellant farm, and a propellant farm located on the Space Station were considered. The technical trades conducted are reported in Volume IV, Section 8.2, of this Final Report. A scoring based on objective and subjective considerations was conducted and the Space Station location was a clear winner for both storable and cryogenic propellants.

We baselined the on-station tank farm as the lowest cost and lowest risk solution, and this approach is reflected in subsequent analyses.
2.6 Storable versus Cryogenic Propellant Trade Study

The purpose of this trade study is to select between storable propellant and cryogenic propellant for use by the OTV.

2.6.1 Approach

This trade includes an analysis of DDT&E, production, and operations costs. These costs are converted from constant dollars to present value dollars and run through return on investment, benefit, and investment analyses in order to provide discriminators useful for making a selection.

2.6.2 Ground Rules and Assumptions

Data used for this trade study were developed under the Revision 7 Nominal Mission Model. The cost of propellant when the mission calculations were run was $500/lb for cryogenic and $600/lb for storable. This cost includes production and delivery to LEO. Although these data were developed using Revision 7, we believe they provide a realistic enough representation of Revision 8 propellant cost to make a selection between the cryogenic and storable propellant options.

Other ground rules and assumptions used in the study follow:

- All costs are in 1985 dollars and exclude fees.
- All cost estimates reflect midterm data (weight, mission model, etc) generated for the cryogenic and storable stage families.
- DDT&E

Maximum sharing of engineering & tooling efforts between stages was assumed where applicable.

Ground test hardware includes Static Test Article (STA), Ground Vibration Test Article (GVTA), Main Propulsion Test Article (MPTA) and Functional Test Article.

Dedicated flight tests required for the ground based OTV; no space based configuration flight test assumed.

Flight test articles refurbished to operations spares.

Space Station assessment limited to tank farm impacts.
Production

Each unique stage assumes an initial production run of 2 units (1 operation, 1 spare (flight test/GVTA Article refurbished for ground based).

92% Wright learning curve assumed; learning shared across stages.

Transportation charges for space based production hardware included in production (68.5M/STS flt) (1.5 flts/full SB stage)

Operations

Payload delivery costs assumed the same, transportation costs not included; no reflights included.

Propellant usage based on 421 missions extracted from the midterm, nominal mission model (32 GB, 389 SB)

Eastern Test Range Launch only; STS Cost Per Flight (CPF) = $68.5M; Aft Cargo Carrier CPF = 2.3M

Mission operations at 35 man-yrs/yr

Full STS user charge for GB OTV; return flight assumed available; storable pays additional transportation charges for the Apogee Kick Motor.

Space Based

- IVA = 80 hrs/mission @ $16K/hr; EVA = 4 hrs/mission @ $48K/hr.
- 2 OMV uses per SB mission per MSFC guidelines (propellant use approx. 500 lb per mission)
  Mission Ops = $16K/hr
  Hardware delivery assumed at 1 STS flight per stage (less brake).

Aerobrake Life = 5 flights; transportation at 0.33 STS flts./brake
Engine Life = 20 flights; 0.1 STS flight/engine
Avionics, Environmental Protection System, structural life = 40 flights; 1 STS flt/replacement

Facilities

As clear discriminators for ground based facility cost estimates were not identified at this time, the same requirements were assumed for both items.
2.6.3 Alternatives

The two alternatives identified for this study are storable propellant and cryogenic propellant. The storable propellant considers the combination of N₂O₄/MMH. The cryogenic propellant considered the combination of liquid hydrogen and liquid oxygen.

2.6.4 Cost of Alternatives

The life cycle cost of storable and cryogenic propellants is summarized in Table 2.6-1 and shows the cost for DDT&E, production, and operations in both constant and discounted dollars. It should be noted that cryogenic costs are lower than storable by a factor of 21 percent in constant dollars and 13 percent in discounted dollars. This indicates that the advantage cryogenics hold over storable is reduced as the cost of providing propellants at LEO is reduced. This is significant since the primary cost of the OTV is propellant. If propellant were free, the DDT&E and production costs would be the discriminators and, as indicated in Table 2.6-1, the two alternatives would be essentially equal.

Table 2.6-2 provides a breakout of DDT&E and shows the delta costs for each element. Note that tank farm costs are included. Conceptual designs and equipment lists were developed for the tank farms to determine if this element, along with propellant costs, is a major discriminator. As can be seen, this is not the case since there is only a $21M difference in favor of cryogenic propellants.

Table 2.6-3 provides a breakout of operations cost and shows the delta cost for each element. The table also provides a cost per flight for using storable propellant ($61.24M) and for using cryogenic propellant ($45.50M).

Placed at the end of this trade study section are Tables 2.6-7 and 2.6-8 which contain spread sheets that show greater detail on how LCC were developed for the OTV using both storable and cryogenic propellants. Table 2.6-9, also placed at the back of this section, provides a spread sheet of OTV competition costs. Competition costs represent costing of the mission model using the STS with existing upper stage vehicles or derivatives thereof. The competition cost totals shown at the bottom of the spread sheet are also placed on Tables 2.6-7 and 2.6-8 for ease of comparison.

Table 2.6-4 shows the calculations for a benefit analysis. Calculations for return on investment are shown in Table 2.6-5.

A payback computation is graphically shown in Figure 2.6-1. This computation is based upon a propellant cost of $500/lb for cryogenic and $600/lb for storable-propellant. The delta propellant cost per pound for onorbit propellant is due to the difference in STS delivery requirements and scavenging opportunity. The delta reflects a conservative estimate of the additional storable propellant requirements and subsequent higher propellant unit cost of the scavenging/delivered mix. As shown in the Figure, the cryogenic propellant holds an advantage over storable propellant. This advantage will change proportionally with the amount of propellant required, thus a more optimistic mission model would show a proportionally greater advantage for cryogenic propellants.
### TABLE 2.6-1  STORABLE VS CRYOGENIC STAGE TOP LEVEL COMPARISON

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<th>STORABLE</th>
<th>CRYO</th>
<th>DELTA</th>
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<tr>
<td>DDT&amp;E</td>
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<td>PRODUCTION</td>
<td>314.28</td>
<td>237.84</td>
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<td>OPERATIONS</td>
<td>8879.45</td>
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<td>2281.30</td>
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<td>TOTAL</td>
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<td>8200.72</td>
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Cryo % Reduction = 21

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<td>DDT&amp;E</td>
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<tr>
<td>Production</td>
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<tr>
<td>Operations</td>
<td>1956.60</td>
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<td>404.60</td>
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<td>TOTAL LCC</td>
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<td>339.30</td>
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</table>

Cryo % Reduction = 13

Competition LCC* 25365 (Constant $M)
4974 (Discounted $M) (See Table 5.7.3-23)

*Does not include DDT&E
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<td>D&amp;D/SE&amp;I</td>
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<td>-4.30</td>
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<td>Test Ops/Fixtures</td>
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<tr>
<td>DDT&amp;E Total</td>
<td>1238.20</td>
<td>1364.70</td>
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### TABLE 2.6-3 STORABLE VS CRYOGENIC STAGE OPERATIONS COMPARISON (CONSTANT $M)

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<thead>
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<th>STORABLE</th>
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<td>PROP OPS/GB DELIVERY</td>
<td>7363.80</td>
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<td>Mission OPS</td>
<td>44.10</td>
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<td>145.30</td>
<td>145.30</td>
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<td>EVA</td>
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<td>21.10</td>
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<td>Aero Replacement</td>
<td>100.70</td>
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<td>Prog Management</td>
<td>72.00</td>
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<td>Sustaining Eng</td>
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<td><strong>TOTAL</strong></td>
<td>7916.70</td>
<td>5822.0</td>
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<td>STS Del of Eng &amp; Str &amp; Prod Hdw</td>
<td>309.90</td>
<td>220.80</td>
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<td>STS Del of Aerobrake</td>
<td>607.30</td>
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<td>Tank Farm Ops</td>
<td>45.60</td>
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<td>*Compressor Repair</td>
<td>6.10</td>
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<td>*Major Overhaul</td>
<td>22.30</td>
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<td><strong>TOTAL OPS</strong></td>
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<td>CPF COMPOSITE</td>
<td>61.24</td>
<td>45.50</td>
<td>15.73</td>
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*Includes related EVA/IVA

### TABLE 2.6-4 STORABLE/CRYOGENIC BENEFIT (DISCOUNTED $M)

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<tr>
<th>Alternative</th>
<th>Competition Cost</th>
<th>Propellant Cost</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Storable</td>
<td>4974</td>
<td>-</td>
<td>2356</td>
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<tr>
<td>Cryogenic</td>
<td>4974</td>
<td>-</td>
<td>2696</td>
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<tr>
<td>Alternative</td>
<td>Competition Cost</td>
<td>Propellant Cost</td>
<td>DDT&amp;E</td>
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<td>-------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>-------</td>
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<tr>
<td>Storable</td>
<td>((4974 - 2618) / 586.9) - 1</td>
<td>= 3.01</td>
<td></td>
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<tr>
<td>Cryogenic</td>
<td>((4974 - 2278) / 670.4) - 1</td>
<td>= 3.02</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 2.6-1 STORABLE VS CRYOGENIC PAYBACK COMPARISON

BILLIONS 1986 PV DOLLARS

STOR @ $600 - CRYO @ $500 / LB

STORABLE
CRYOGENIC

YEAR

2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
89 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10

61
2.6.5 Alternative Comparison

Table 2.6-6 provides a comparison of the principal economic factors. It also provides a score ranking the most favorable alternative 10 and the other alternative with a value relative to the better option.

Table 2.6-6 OTV Storable Versus Cryogenic Propellant Trade Results

<table>
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<tr>
<th>Economic Factor</th>
<th>Storable</th>
<th>Cryogenic</th>
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<td>Return on Investment</td>
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<td>2356.0</td>
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<td>670.4</td>
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2.6.6 Conclusion

The cryogenic alternative is recommended as the preferred OTV propellants. The return on investment between the two options is essentially the same, however the cryogenic alternative advantage becomes greater as propellant requirements increase. This option therefore provides greater flexibility for growth.

The benefit analysis places the advantage on the side of the cryogenic propellant. The main disadvantage for cryogenic when comparing the two options lies in DDT&E costs. This difference, however, is not significant and both options can be considered to be affordable.

It should also be noted that, if OTV requirements change to include extended dwell time on orbit, the use of storable propellants should be revisited.
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**MULTIPLE PAYLOAD DELIVERY SCENARIO**

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<th>STAGE COST TO LEO (MB)</th>
<th>STS DEL TOTAL (MB)</th>
<th>COST PER YEAR (MILLION 1985 DOLLARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10912 A</td>
<td>12000</td>
<td>25 STS/PAW-02</td>
<td>11253</td>
<td>6.5</td>
<td>11.37</td>
<td>20.7</td>
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<tr>
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<td>12000</td>
<td>25</td>
<td></td>
<td>0</td>
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<td>0</td>
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<tr>
<td>P/L DN</td>
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**EXPERIMENTAL GEO PLATFORM SERVICING DEL**

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<th>P/L</th>
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<th>STAGE WEIGHT LENGTH (POLAR/FEET)</th>
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<th>STS DEL TOTAL (MB)</th>
<th>COST PER YEAR (MILLION 1985 DOLLARS)</th>
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</thead>
<tbody>
<tr>
<td>13002 S/C</td>
<td>1670</td>
<td>15 STS/CEXTAUR 6</td>
<td>44390</td>
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<tr>
<td>P/L up</td>
<td>2000</td>
<td>15</td>
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**GEOD SERVICE STATION LOGISTICS SCENARIO**

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<th>STAGE WEIGHT LENGTH (POLAR/FEET)</th>
<th>STAGE COST TO LEO (MB)</th>
<th>STS DEL TOTAL (MB)</th>
<th>COST PER YEAR (MILLION 1985 DOLLARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15099</td>
<td>13159</td>
<td>15 STS/CEXTAUR 6</td>
<td>51800</td>
<td>29.1</td>
<td>55.4</td>
<td>73</td>
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<tr>
<td>MOBILE GEO SERVICE STATION</td>
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<td></td>
<td></td>
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<table>
<thead>
<tr>
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<th>P/L</th>
<th>P/L REPORT LENGTH (POLAR/FEET)</th>
<th>STAGE WEIGHT LENGTH (POLAR/FEET)</th>
<th>STAGE COST TO LEO (MB)</th>
<th>STS DEL TOTAL (MB)</th>
<th>COST PER YEAR (MILLION 1985 DOLLARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15099</td>
<td>13150</td>
<td>20 STS/CEXTAUR 6</td>
<td>51800</td>
<td>29.1</td>
<td>55.4</td>
<td>73</td>
</tr>
<tr>
<td>GEO MAINT/WORK STATION</td>
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<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
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<table>
<thead>
<tr>
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<th>P/L</th>
<th>P/L REPORT LENGTH (POLAR/FEET)</th>
<th>STAGE WEIGHT LENGTH (POLAR/FEET)</th>
<th>STAGE COST TO LEO (MB)</th>
<th>STS DEL TOTAL (MB)</th>
<th>COST PER YEAR (MILLION 1985 DOLLARS)</th>
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</thead>
<tbody>
<tr>
<td>15701 S/C</td>
<td>12000</td>
<td>25 STS/CEXTAUR 6</td>
<td>51800</td>
<td>29.1</td>
<td>55.4</td>
<td>73</td>
</tr>
<tr>
<td>MOBILE GEO SERVICE STATION</td>
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<td></td>
<td></td>
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### Table 2.6-9 Competition Mission Model Capture (Continued)

<table>
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<tr>
<th>Mission Number</th>
<th>P/L</th>
<th>P/L</th>
<th>Stage</th>
<th>Stage</th>
<th>Stage</th>
<th>Stage</th>
<th>Total Cost (Million 1985 Dollars)</th>
<th>Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUNAR BASE PROGRAM SEQUENTIAL</td>
<td>12000</td>
<td>S/C</td>
<td>5000</td>
<td>20</td>
<td>STS/100-MT</td>
<td>37412</td>
<td>16.5</td>
<td>48</td>
</tr>
<tr>
<td>LUNAR COMMUNICATIONS RELAY</td>
<td>12000</td>
<td>UP</td>
<td>20000</td>
<td>18</td>
<td>STS/CEAUR 6°</td>
<td>63336</td>
<td>29.1</td>
<td>55.4</td>
</tr>
<tr>
<td>LUNAR SURFACE EXPLORER</td>
<td>12000</td>
<td>UP</td>
<td>30</td>
<td>STS/CEAUR 6°</td>
<td>51000</td>
<td>29.1</td>
<td>55.4</td>
<td>73</td>
</tr>
<tr>
<td>GENERIC 2</td>
<td>20000</td>
<td>25</td>
<td>STS/CEAUR 6°</td>
<td>63336</td>
<td>29.1</td>
<td>55.4</td>
<td>130</td>
<td>185.4</td>
</tr>
</tbody>
</table>

REFLIGHTS

| 10100 | 20000 | 20 | STS/CEAUR 6° | 63336 | 29.1 | 55.4 | 105.8 | 160.8 | 0 | 0 | 161 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 161 | 0 | 0 | 161 | 407 | SAME AS MSH 13700 |

**TOTALS:**

- **$956,1150,1010,1058,1055,1119,1157,1290,1425,1782,1451,1675,1583,2276,2147,2198,2536**
- **0.42, 0.37, 0.35, 0.32, 0.29, 0.26, 0.24, 0.22, 0.20, 0.18, 0.16, 0.15, 0.14, 0.12, 0.11, 0.10, 0.09**
- **406, 446, 254, 335, 278, 385, 382, 292, 291, 216, 254, 245, 220, 202, 437**

**PV Factor (2% Inflation, 20% Discount)**

**PRESENT VALUE IN 1985 DOLLARS**

**AVERAGE COST PER FLIGHT:**

- **CONSTANT DOLLARS $120.8**
- **PRESENT VALUE DOLLARS $23.7**
2.7 Evolutionary Strategy Trade Study

The purpose of the evolutionary trade study is to select an Orbital Transfer Vehicle (OTV) development path that will accommodate all missions set forth in Revision 8 of the Marshall Space Flight Center (MSFC) Low Mission Model. The options cover both ground based and space based operations as well as unmanned and manned missions. Six options which provide the strategies studied are illustrated in Figure 2.7-1. These same options are shown with time phasing in Figure 2.7-2.

Options 2 and 6 are identical except that during ground based operations Option 2 employs an Aft Cargo Carrier (ACC) to deliver the OTV to Low Earth Orbit (LEO) and Option 6 uses the cargo bay. Selecting between these two options becomes more complex in that the investment cost for developing the ACC should be shared with the scavenging operation if scavenging is to also use the ACC.

Due to the similarities and complexities associated with Options 2 and 6, they are addressed first in a subtrade study to eliminate one or the other from contention. This subtrade is designated as Step 1. Step 2 of the trade study evaluates the surviving option from Step 1 along with the other remaining trade study options. From this group, the option representing the preferred overall evolutionary strategy is selected.
<table>
<thead>
<tr>
<th></th>
<th>GROUND BASED OTV</th>
<th></th>
<th>SPACE BASED OTV</th>
<th></th>
<th>LUNAR MISSION OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>45K</td>
<td>45K</td>
<td>55K</td>
<td>55K</td>
<td>55K</td>
<td>LUNAR MISSION OPTIONS</td>
</tr>
<tr>
<td></td>
<td>EXPENDABLE</td>
<td>ACC</td>
<td>INTERMEDIATE</td>
<td>MANNED</td>
<td>2 STG 81K</td>
</tr>
<tr>
<td></td>
<td>CARGO BAY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45K</td>
<td>55K</td>
<td>55K</td>
<td>55K</td>
<td>LUNAR MISSION OPTIONS</td>
</tr>
<tr>
<td></td>
<td>I: DIRECT EVOLUTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>II: LIMITED SPACE IOC</td>
<td></td>
<td></td>
<td></td>
<td>2 STG 81K</td>
</tr>
<tr>
<td></td>
<td>IV: INITIAL DEVELOPMENT IS SPACE FOC</td>
<td></td>
<td></td>
<td></td>
<td>2 STG 81K</td>
</tr>
<tr>
<td></td>
<td>V: INITIAL DEVELOPMENT IS SPACE IOC</td>
<td></td>
<td></td>
<td></td>
<td>2 STG 81K</td>
</tr>
<tr>
<td></td>
<td>VI: GND BASED IN CARGO BAY</td>
<td></td>
<td></td>
<td></td>
<td>2 STG 81K</td>
</tr>
<tr>
<td></td>
<td>VII: NO SPACE BASING</td>
<td></td>
<td></td>
<td></td>
<td>3 STG 55K</td>
</tr>
<tr>
<td>OPTION</td>
<td>GB IOC</td>
<td>SB IOC</td>
<td>MAN-RATED</td>
<td></td>
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</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>GBU</td>
<td>SBM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>GBU</td>
<td>SBU</td>
<td>SBM-------</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EXU</td>
<td>SBM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>EXU</td>
<td>SBU</td>
<td>SBM-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>GBU (CB)</td>
<td>SBU</td>
<td>SBM-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>GBU</td>
<td>GBU (55K)</td>
<td>GBM-------</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**LEGEND:**
- GBU: 45 klb Ground Based Nonman-rated
- SBU: 55 klb Space Based Nonman-rated
- SBM: 55 klb Space Based Man-rated
- GBM: 55 klb Ground Based Man-rated
- EXU: Expendable Nonman-rated
- CB: STS Cargo Bay
- ACC: Aft Cargo Carrier

**NOTE:**
1. All space based OTVs are delivered in the STS cargo bay.
2. All ground based OTVs are delivered in the ACC except as noted in Option 6.

**FIGURE 2.7-2 OTV CONFIGURATION EVOLUTION**
2.7.1 Ground Rules and Assumptions

Ground rules and assumptions which apply to the trade study are shown below. They are consistent with the OTV ground rules provided by the MSFC.

- **GENERAL**
  - Constant fiscal year 1985 dollars excluding fee and contingency
  - Discount rate of 10% per year

- **Research and Technology (R&T)**
  - Assumed $100M for Aeroassist Flight Experiment (AFE) flight and $59M for advanced engine technology base for both candidates

- **Design Development Test and Evaluation (DDT&E)**
  - Ground test hardware includes Static Test Article (STA), Ground Vibration Test Article (GVTA), Main Propulsion Test Article (MPTA), and functional test article: Follow-on stages include ground test hardware as required.
  - Dedicated flight test required for initial stage: includes Space Transportation System (STS) delivery and propellants.
  - Flight test article and GVTA of initial stage refurbished to meet operational requirements.
  - Ground Based (GB) ACC version includes ACC DDT&E ($163M); CB version includes $27M impact for orbiter bay modifications
  - All options include DDT&E for payload (P/L) clustering structure
  - Maximum sharing of engineering and tooling effort between stages assumed where applicable (evolutionary approach).
  - Supporting program DDT&E included per ground rules where applicable (e.g., Space Station accommodations and tank for ACC and propellant scavenging).

- **PROVISIONS**
  - Each evolutionary stage requires two stages at Initial Operational Capability (IOC) (1 operations unit, 1 spare)
    -- Refurbished DDT&E hardware credited to initial option stage
    -- No learning on stages assumed due to small production run
    -- Each evolutionary option stage requires 2 P/L clustering structures (1 operations unit, 1 spare)
    -- Transportation charges of production hardware allocated to operations

- **OPERATIONS**
  - P/L transportation costs included for all options according to STS program user charge guidelines
    -- 1994-1998 P/L's and GB OTV stages were considered an integral P/L unit and charged accordingly
    -- Space Based Payloads (1999-2010) were charged according to user charge guidelines.
    -- Option 7 (GB evolutionary option) P/L's were charged in the same manner as 1999-2010 Space Based (SB) payloads (less than 6% of the missions may potentially be manifested with the stage hardware on a single shuttle)
OPERATIONS (Continued)
- STS user charge of $73M per flight, ACC charge of $2.3M where applicable.
- Low Mission Model (145 flights)
- Ground based Mission operations at 35 Man-yrs/yr throughout operations period
- Expendable stages (Options 4 & 5, 1994-1998)
  -- Operations (OPS) cost includes stage Cost per Flight (CPF) and
     STS delivery of stage hardware and mission payload
- Ground Based OTV
  -- Operations costs consistent with ACC - CB GB OTV Trade Study
  -- CB OTV stages for Option 7 (1999-2010) assume 1 shuttle flight
     per mission for hardware delivery
- Space Based OTV
  -- Space Station Intra Vehicular Activity (IVA) calculated on a per
     mission basis at $15K/hr
  -- 2 Orbital Maneuvering Vehicle (OMV) uses per mission cost
     according to study ground rules at 2 hrs out, 1.5 hrs back and
     average of 500 lb propellant per mission
  -- No Space Based Mission OPS or Extra Vehicular Activity (EVA)
     required
  -- STS costs include delivery of initial operational unit and spares
     as required
  -- On-orbit propellant costs are composite average of scavenged and
     STS tanker costs, determined by option usage ($330 to $360/lb)
- Operations Spares
  -- STS transportation applicable only to SB stages
  -- Aerobrake Life = 5 flights; 0.34 STS flt/brake
  -- Engine Life = 10 flights; 0.1 STS flt/engine
  -- Avionics, EPS, STR Life = 40 flights; 1 STS flt/replacement

PRODUCTION
- Production for both options includes 2 P/L clustering structures (1
  operations, 1 spare)
- No stage production is required due to refurbishment of DDT&E
  hardware and low flight rates.

FACILITIES
- Facilities costs include
  -- Provisions for manufacturing facility for initial stage and
     refurbishment hardware
  -- Dedicated OTV Launch Processing Facility [Kennedy Space Center
     (KSC)]
  -- Mission operations area at existing KSC facility

BENEFITS
- STS benefits are based on 50% of the calculated weight and volume
  potential after the ground based OTV and STS payloads are manifested.
  Each of the P/Ls were manifested with stage for both an ACC and a
  cargo bay OTV concept. The amount of total volume and weight per-
  formance remaining represented potential STS P/L capability that
  could be utilized for other non-OTV P/Ls. The 50% factor represents
  a rough probability of how much of this additional potential might
  be used.
2.7.2 Step 1: ACC versus Cargo Bay for OTV Delivery/Scavenging.

As discussed in the introduction to this trade study the purpose of this subtrade analysis is two fold. One is to select either Option 2 (OTV in ACC) or Option 6 (OTV in STS Cargo Bay) as the preferred evolutionary OTV development strategy (Figure 2.7-2). The other is to select between the ACC and the STS cargo bay the most economic way to deliver the OTV to LEO during ground based operations and to deliver scavenged propellant to LEO during space based operations. OTV delivery and scavenging are correlated and the preferred delivery mode depends on the combined economics of the two systems. This selection, in turn, will provide the answer to the first part of the analysis and thus select either the ACC (Option 2) or the STS cargo bay (Option 6) as the preferred OTV evolutionary developmental strategy. The following therefore addresses the economy of OTV delivery and scavenging.

2.7.2.1 OTV Delivery/Scavenging Alternatives

Four possible combinations exist for delivering the OTV or scavenged propellant to LEO. The matrix in Figure 2.7.2-1 shows how the alternatives listed below were derived. The first designation listed represents the OTV delivery mode and the second represents scavenging.

- Alternative 1 CB/ACC
- Alternative 2 CB/CB
- Alternative 3 ACC/ACC
- Alternative 4 ACC/CB

<table>
<thead>
<tr>
<th>OTV DELIVERY</th>
<th>SCAVENGING SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACC</td>
</tr>
<tr>
<td>OTV DELIVERY</td>
<td>CARGO BAY</td>
</tr>
<tr>
<td>ACC</td>
<td>3</td>
</tr>
</tbody>
</table>

FIGURE 2.7.2-1 CARGO BAY VS ACC SCAVENGING

2.7.2.2 Cost of OTV Delivery/Scavenging Alternatives

The cost of the OTV delivery/scavenging alternatives is done in four parts. First is the OTV delivery computations for both the ACC and CB modes, next is the scavaging computations in both the ACC and CB modes, third is the computations for the OTV delivery and scavaging competition, and finally the computation for the STS benefit factor.
2.7.2.2.1 OTV Delivery Computations

Computations for OTV delivery to LEO are based upon the configurations for the ACC and CB as shown in Figures 2.7.2-2 and 2.7.2-3 respectively. A synopsis of a typical Geostationary Earth Orbit (GEO) payload delivery mission using these configurations is shown in Figure 2.7.2-4 for the ACC and Figure 2.7.2-5 for the CB. As can be seen, the cargo bay scenario is significantly less complex both in terms of OTV operations and on-orbit integration. This issue is traded against the increased benefits derived from freeing additional STS cargo bay space by placing the OTV in the ACC.

The Martin Marietta Life Cycle Cost (LCC) Model was used to derive the OTV delivery cost data for the ACC and CB configurations shown in Tables 2.7.2-1 through 2.7.2-4. These data are used to form the basis for the OTV economic analysis described in paragraph 2.7.2.3 below. Tables 2.7.2-1 and 2.7.2-2 show the LCC associated with each configuration in constant dollars and present value (PV) dollars respectively.
FIGURE 2.7.2-2  GROUND BASED ACC OTV (NONMAN-RATED)
GROUND BASED CARGO BAY OTV

VEHICLE DATA

<table>
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<tr>
<th>Description</th>
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<td>TANK SIZE</td>
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</tr>
<tr>
<td>DRY WEIGHT</td>
<td>8642 lbs</td>
</tr>
<tr>
<td>LOADED WEIGHT</td>
<td>57076 lbs</td>
</tr>
<tr>
<td>ASE</td>
<td>5000 lbs</td>
</tr>
<tr>
<td>PAD WEIGHT</td>
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</tr>
<tr>
<td>SINGLE ENGINE THRUST</td>
<td>7500 lbs</td>
</tr>
<tr>
<td>ISP</td>
<td>475 sec</td>
</tr>
<tr>
<td>AVIONICS: SINGLE</td>
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</tr>
<tr>
<td>FAULT TOLERANT</td>
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</table>

FIGURE 2.7.2-3 GROUND BASED CARGO BAY OTV
<table>
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</tr>
<tr>
<td>00:08:2</td>
<td>MECO</td>
</tr>
<tr>
<td>00:08:350</td>
<td>OTV SEPARATION</td>
</tr>
<tr>
<td>00:09:35</td>
<td>DEPLOY AEROBRAKE</td>
</tr>
<tr>
<td>00:12:20</td>
<td>ORBITER OMS-1</td>
</tr>
<tr>
<td>00:33:290</td>
<td>OTV BOOST-1</td>
</tr>
<tr>
<td>00:44:20</td>
<td>ORBITER OMS-2</td>
</tr>
<tr>
<td>01:25:140</td>
<td>OTV BOOST-2</td>
</tr>
<tr>
<td>21:30:00</td>
<td>ORBITER RENDEZVOUS WITH OTV</td>
</tr>
<tr>
<td>22:00:00</td>
<td>GRAPPLE OTV</td>
</tr>
<tr>
<td>23:05:00</td>
<td>MATE PAYLOAD TO OTV</td>
</tr>
<tr>
<td>24:20:00</td>
<td>RELEASE OTV/PAYLOAD</td>
</tr>
<tr>
<td>24:35:00</td>
<td>ORBITER SEPARATION TO SAFE DIS.</td>
</tr>
<tr>
<td>25:43:000</td>
<td>OTV BOOST-3</td>
</tr>
<tr>
<td>26:15:000</td>
<td>OTV/PAYLOAD SEPARATION</td>
</tr>
<tr>
<td>27:50:000</td>
<td>OTV DEBOOST BURN</td>
</tr>
<tr>
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<tr>
<td>36:22:00</td>
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</tr>
<tr>
<td>36:25:00</td>
<td>JETTISON AEROBRAKE</td>
</tr>
<tr>
<td>36:49:00</td>
<td>OTV LEO REBOOST - 1</td>
</tr>
<tr>
<td>38:18:00</td>
<td>OTV LEO REBOOST - 2</td>
</tr>
<tr>
<td>43:17:00</td>
<td>ORBITER RENDEZVOUS</td>
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<tr>
<td>43:47:00</td>
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<tr>
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<td>OTV STORAGE</td>
</tr>
<tr>
<td>TBD</td>
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</table>

**FIGURE 2.7.2-4** ACC GB GEO DELIVERY OPERATIONAL SCENARIO
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</tr>
<tr>
<td>00:08:20</td>
<td>MECO</td>
</tr>
<tr>
<td>00:12:20</td>
<td>ORBITER OMS-1 (130 NM)</td>
</tr>
<tr>
<td>00:44:20</td>
<td>ORBITER OMS-2 (140 NM)</td>
</tr>
<tr>
<td>04:15:00</td>
<td>RELEASE OTV/PAYLOAD</td>
</tr>
<tr>
<td>04:20:00</td>
<td>DEPLOY AERO BRAKE</td>
</tr>
<tr>
<td>04:30:00</td>
<td>ORBITER SEPARATION TO A SAFE DISTANCE</td>
</tr>
<tr>
<td>05:37:00</td>
<td>OTV BOOST</td>
</tr>
<tr>
<td>06:15:00</td>
<td>OTV/PAYLOAD SEPARATION</td>
</tr>
<tr>
<td>07:44:00</td>
<td>OTV DEBOOST BURN</td>
</tr>
<tr>
<td>16:13:00</td>
<td>ATMOSPHERIC ENTRY</td>
</tr>
<tr>
<td>16:17:00</td>
<td>ATMOSPHERIC EXIT</td>
</tr>
<tr>
<td>16:20:00</td>
<td>JETTISON AERO BRAKE</td>
</tr>
<tr>
<td>16:44:00</td>
<td>OTV LEO REBOOST - 1</td>
</tr>
<tr>
<td>18:13:00</td>
<td>OTV LEO REBOOST - 2</td>
</tr>
<tr>
<td>23:12:00</td>
<td>ORBITER RENDEZVOUS</td>
</tr>
<tr>
<td>23:42:00</td>
<td>GRAPPLE OTV</td>
</tr>
<tr>
<td>23:57:00</td>
<td>OTV STOWAGE</td>
</tr>
<tr>
<td>TBD</td>
<td>ORBITER DEBOOST</td>
</tr>
</tbody>
</table>

FIGURE 2.7.2-5 CARGO BAY GB GEO DELIVERY OPERATIONAL SCENARIO
<table>
<thead>
<tr>
<th></th>
<th>ACC OTV</th>
<th>CARGO BAY</th>
<th>DELTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;T</td>
<td>153.00</td>
<td>153.00</td>
<td>0.00</td>
</tr>
<tr>
<td>DDT&amp;E</td>
<td>1033.40</td>
<td>1056.40</td>
<td>-23.00</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>29.90</td>
<td>29.90</td>
<td>0.00</td>
</tr>
<tr>
<td>OPERATIONS</td>
<td>2998.30</td>
<td>2886.50</td>
<td>111.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>4214.60</td>
<td>4125.80</td>
<td>88.80</td>
</tr>
<tr>
<td>CB % REDUCTION</td>
<td></td>
<td></td>
<td>2.1</td>
</tr>
</tbody>
</table>

ACC-ORB MODS  163.00  27.00  136.00
TOTAL LCC      4377.60 4152.80 224.80
TOTAL INVESTMENT (Total LCC minus operations) 1379.30 1266.30 113.00
<table>
<thead>
<tr>
<th></th>
<th>ACC OTV</th>
<th>CARGO BAY</th>
<th>DELTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;T</td>
<td>117.20</td>
<td>117.20</td>
<td>0.00</td>
</tr>
<tr>
<td>DDT&amp;E</td>
<td>592.80</td>
<td>606.80</td>
<td>-14.00</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>12.70</td>
<td>12.70</td>
<td>0.00</td>
</tr>
<tr>
<td>OPERATIONS</td>
<td>1060.30</td>
<td>1020.70</td>
<td>39.60</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1783.00</td>
<td>1757.40</td>
<td>25.60</td>
</tr>
<tr>
<td></td>
<td>CB % REDUCTION = 1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC-ORB MODS</td>
<td>92.70</td>
<td>13.20</td>
<td>79.50</td>
</tr>
<tr>
<td>TOTAL LCC $</td>
<td>1875.70</td>
<td>1770.60</td>
<td>105.10</td>
</tr>
<tr>
<td>TOTAL INVESTMENT (Total LCC minus operations)</td>
<td>815.40</td>
<td>749.90</td>
<td>65.50</td>
</tr>
<tr>
<td>Description</td>
<td>ACC OTV</td>
<td>CARGO BAY</td>
<td>DELTA</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>GB MISSION OPS</td>
<td>10.50</td>
<td>10.50</td>
<td>0.00</td>
</tr>
<tr>
<td>GB LAUNCH OPS</td>
<td>2806.70</td>
<td>2726.20</td>
<td>80.50</td>
</tr>
<tr>
<td>PRP OPS</td>
<td>1.10</td>
<td>0.60</td>
<td>0.50</td>
</tr>
<tr>
<td>PROGRAM SUPPORT</td>
<td>42.40</td>
<td>41.20</td>
<td>1.20</td>
</tr>
<tr>
<td>P/L CLUST STR</td>
<td>7.60</td>
<td>6.20</td>
<td>1.40</td>
</tr>
<tr>
<td>PROPELLANTS</td>
<td>0.40</td>
<td>0.50</td>
<td>-0.10</td>
</tr>
<tr>
<td>AIRFRAME SPARES</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>AIRFRAME IVA</td>
<td>0.60</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>ENGINE SPARES</td>
<td>5.00</td>
<td>5.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ENGINE IVA</td>
<td>0.10</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>BRAKE SPARES</td>
<td>70.00</td>
<td>42.70</td>
<td>27.30</td>
</tr>
<tr>
<td>BRAKE IVA</td>
<td>0.10</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>GROUND REFURB</td>
<td>11.80</td>
<td>12.80</td>
<td>-1.00</td>
</tr>
<tr>
<td>EXPECTED LOSS</td>
<td>38.60</td>
<td>38.60</td>
<td>0.00</td>
</tr>
<tr>
<td>P/L IVA</td>
<td>3.40</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>TOTAL OPS</td>
<td>2998.30</td>
<td>2886.50</td>
<td>111.80</td>
</tr>
<tr>
<td>CPF</td>
<td>85.7</td>
<td>82.5</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>ACC OTV</td>
<td>CARGO BAY</td>
<td>DELTA</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>D&amp;D</td>
<td>372.30</td>
<td>378.30</td>
<td>-6.00</td>
</tr>
<tr>
<td>SOFTWARE</td>
<td>61.10</td>
<td>59.30</td>
<td>1.80</td>
</tr>
<tr>
<td>TOOLING *</td>
<td>24.40</td>
<td>31.50</td>
<td>-7.10</td>
</tr>
<tr>
<td>SE&amp;I</td>
<td>87.20</td>
<td>88.10</td>
<td>-0.90</td>
</tr>
<tr>
<td>TEST HARDWARE *</td>
<td>145.10</td>
<td>152.40</td>
<td>-7.30</td>
</tr>
<tr>
<td>TEST OPS</td>
<td>20.70</td>
<td>21.30</td>
<td>-0.60</td>
</tr>
<tr>
<td>TEST FIXTURES</td>
<td>3.60</td>
<td>3.70</td>
<td>-0.10</td>
</tr>
<tr>
<td>PROG. MANAGE.</td>
<td>42.80</td>
<td>44.10</td>
<td>-1.30</td>
</tr>
<tr>
<td>STAGE DDT&amp;E (INC P/L STR)</td>
<td>757.20</td>
<td>778.70</td>
<td>-21.50</td>
</tr>
<tr>
<td>LEVEL II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM,SE&amp;I,TEST</td>
<td>176.00</td>
<td>179.80</td>
<td>-3.80</td>
</tr>
<tr>
<td>TEST FLTS</td>
<td>80.20</td>
<td>77.90</td>
<td>2.30</td>
</tr>
<tr>
<td>FACILITIES</td>
<td>20.00</td>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>DDT&amp;E TOTAL</td>
<td>1033.40</td>
<td>1056.40</td>
<td>-23.00</td>
</tr>
<tr>
<td>ACC</td>
<td>163.00</td>
<td>0.00</td>
<td>163.00</td>
</tr>
<tr>
<td>CB MODS</td>
<td>0.00</td>
<td>27.00</td>
<td>-27.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1196.40</td>
<td>1083.40</td>
<td>113.00</td>
</tr>
</tbody>
</table>

*The main cost discriminators include the tradeoff of the heavier tankage/structure of the cargo bay concept vs the more sophisticated ACC option aerobraking concept.
Operations cost and the Design, Development, Test, and Engineering (DDT&E) costs shown in Table 2.7.2-1 are further detailed in Tables 2.7.2-3 and 2.7.2-4. In each of these figures, the cost of acquiring the ACC and cargo bay capabilities are shown separately.

2.7.2.2.2 Scavenging Computations

2.7.2.2.2.1 Requirements and Assumptions

Costs of scavenging were also computed for both the ACC and CB modes. Additional requirements and assumptions used as a basis for arriving at the scavenging costs are shown below.

- **REQUIREMENT**
  - 5.5M lb propellant required
  - Delivery 1999 - 2010 (12 years)
  - Investment 1995 - 1998 (4 years)
  - 110 missions

- **ASSUMPTIONS**
  - Constant flight rate (9 missions/yr)
  - Constant investment distribution
  - Constant 1985 dollars
  - Cargo bay scavenging
    -- 181 scavengable flights
    -- 2.53M lb propellant scavenged
    -- Development, Production & Operations Cost $151M
      (Investment $40M + Production & Operations $111M)
  - ACC Scavenging
    -- 328 scavengable flights
    -- 4.59M lb propellant scavenged
    -- Development, Production & Operations Cost $1250M (Investment $83M + Production & Operations $1167M)
  - Composite Discount Factor
    -- Investment = 1.34
    -- Operating = 1.97
    -- STS Delivery Cost = $1014/lb

In this trade, the discount factor is treated as a constant to simplify computations. This can be done since we use a constant number of flights per year and a constant cost per flight. This same procedure is applied to the DDT&E costs by assuming costs are distributed equally over a five year period.

The amount of propellant required, 5.5 mlb, was derived from a performance simulation using the ground mission profile contained in Revision 8 of the MSFC OTV Mission Model.
We believe the investment (DDT&E) cost shown in the MSFC ground rules was high and consequently reduced the figure to $83M from $212M. A revision of the ACC study final report and the ACC scavenging study final report showed a discrepancy in charging. Table 2.7.2-5 shows where the discrepancies occurred in the original scavenging DDT&E costing.

**TABLE 2.7.2-5 PROPELLANT SCAVENGING DDT&E COST REVISION**

<table>
<thead>
<tr>
<th>GROUND RULE ELEMENT</th>
<th>REVISED COST</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROPELLANT SCAVENGING DDT&amp;E</td>
<td>$65M</td>
<td>---</td>
</tr>
<tr>
<td>DDT&amp;E for STS MODS and Integration</td>
<td>$101M</td>
<td>$12M</td>
</tr>
<tr>
<td>o ACC DDT&amp;E</td>
<td>60.9M</td>
<td>12M</td>
</tr>
<tr>
<td>o Facility</td>
<td>34.9M</td>
<td>-</td>
</tr>
<tr>
<td>o GSE</td>
<td>6.4M</td>
<td>-</td>
</tr>
<tr>
<td>STS DDT&amp;E</td>
<td>$46M</td>
<td>$6M</td>
</tr>
<tr>
<td>o Level II Integration</td>
<td>30.5M</td>
<td>6M</td>
</tr>
<tr>
<td>o Orbiter MODS</td>
<td>9.5M</td>
<td>-</td>
</tr>
<tr>
<td>o ET MODS</td>
<td>6.3M</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>$212M</td>
<td>$83M</td>
</tr>
</tbody>
</table>

Reductions due to DDT&E Expendable for OTV DACC

2.7.2.2.2 Propellant Delivery Costs

The amount of propellant recovered under the scavenging concept is dependent, in part, on the number of STS missions suitable for scavenging operations. A significantly greater number of flights for scavenging are available using the ACC concept, (328 ACC versus 181 CB missions) since the full cargo bay space remains available for mission payloads whereas this is not the case under the cargo bay concept.

Calculations used to compare the costs of providing propellant at LEO using the ACC and cargo bay methods are shown in Tables 2.7.2-6, 2.7.2-7, and 2.7.2-8. These calculations are made in constant dollars. The figures used to arrive at this cost are extracted from the OTV Concept Definition and System Analysis Studies ground rules issued by the MSFC in May 1985 with the exception of the total amount of propellant required (5.5 mlb) which is described above, and modifications to the ACC scavenging system DDT&E (Table 2.7.2-5).
The results of this constant dollar evaluation show nearly a billion dollar spread favoring the ACC over the cargo bay scavenging method.

**TABLE 2.7.2-6 PROPELLANT SCAVENGED**

<table>
<thead>
<tr>
<th>No. of Available Scavenging Flights</th>
<th>Average Propellant Scavenged (lb)</th>
<th>Propellant Scavenged (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC Version</td>
<td>328</td>
<td>14,000 × = 4.59M</td>
</tr>
<tr>
<td>Cargo Bay</td>
<td>181</td>
<td>14,000 × = 2.53M</td>
</tr>
</tbody>
</table>

**TABLE 2.7.2-7 STS PROPELLANT DELIVERY COST**

<table>
<thead>
<tr>
<th>Total Propellant Required (lb)</th>
<th>Scavenged Propellant (lb)</th>
<th>STS Delivery to LEO ($ per lb)</th>
<th>Delivery Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>(5.5M - 4.59M)</td>
<td>$1014</td>
<td>$923M</td>
</tr>
<tr>
<td>Cargo Bay</td>
<td>(5.5M - 2.53M)</td>
<td>$1014</td>
<td>$3012M</td>
</tr>
</tbody>
</table>

**TABLE 2.7.2-8 TOTAL PROPELLANT COST AT LEO**

<table>
<thead>
<tr>
<th>Development Cost</th>
<th>STS Delivery Cost to LEO</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>$1250M</td>
<td>+ $923M</td>
</tr>
<tr>
<td>Cargo Bay</td>
<td>$ 151M</td>
<td>+ $3012M</td>
</tr>
</tbody>
</table>

Tables 2.7.2-9 and 2.7.2-10 provide a scavenging cost comparison between the ACC and cargo bay which show a significantly different picture. Because of the time value of money, the magnitude of the difference is reduced. It should be noted that an approximation method was used in that the yearly distribution of costs were assumed in order to simplify computations.

The investment (DDT&E) costs, shown in Table 2.7.2-9 represent the total constant dollar investment spread over four years and reduced by a discount factor.
The operations costs equation, shown in Table 2.7.2-10 contain three terms. The first term is the cost of production and operations per year. The second term is the cost of delivery by the STS and is the difference between the propellant required per year and the amount scavenged. The third term is the cost of transportation of the scavenging system.

The cost of the ACC scavenging system is considerably higher because it is a "smart stage" having propulsion and guidance and, as a consequence, is heavier. The weight of this system is estimated to be 8.6 klb. This weight, in turn, translates into a cost for delivery to LEO. The results of the present value dollar evaluation shows a $153M spread favoring the ACC over the cargo bay scavenging method.

The cost of the ACC scavenging system is considerably higher because it is a "smart stage" having propulsion and guidance and, as a consequence, is heavier. The weight of this system is estimated to be 8.6 klb. This weight, in turn, translates into a cost for delivery to LEO. The results of the present value dollar evaluation shows a $153M spread favoring the ACC over the cargo bay scavenging method.

TABLE 2.7.2-9 INVESTMENT COSTS (PV)

<table>
<thead>
<tr>
<th></th>
<th>Scavenged</th>
<th>Discount</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DDT&amp;E Per Year</td>
<td>Factor (10%/year)</td>
<td>Value</td>
</tr>
<tr>
<td>ACC</td>
<td>83 4</td>
<td>x 1.34</td>
<td>= 27.8M</td>
</tr>
<tr>
<td>Cargo Bay</td>
<td>40 4</td>
<td>x 1.34</td>
<td>= 13.4M</td>
</tr>
</tbody>
</table>

TABLE 2.7.2-10 OPERATIONS COST (PV)

<table>
<thead>
<tr>
<th>Cost of Scav./year</th>
<th>Cost of STS Propellant Delivery/Year</th>
<th>Cost of Scavenging/Yr.</th>
<th>Composite Site Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prod &amp; Ops Years</td>
<td>[Total Scav- Prop. - enged Del + Req'd Prop x Cost] / Years</td>
<td>Wt. Pen. STS Ave. (ACC) Cost STS or x per x Flts. x 1.97 = Cost</td>
<td></td>
</tr>
<tr>
<td>ACC 1167M 12 2 + (5.5 - 4.59)M x 1014 + 8600 x 73M x 8 / 72000</td>
<td>x 1.97 = $480M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cargo Bay 111M 12</td>
<td>(5.5 - 2.5)M x 1014 + [0.1 x 73M x 8] / 12</td>
<td>x 1.97 = $633M</td>
<td></td>
</tr>
</tbody>
</table>

(See Section 1.3 for an explanation of uniform discounting.)
2.7.2.2.3 Computation for OTV Delivery and Scavenging Competition

The competition for the OTV delivery/scavenging concept is to neither develop an ACC or cargo bay for delivery of OTV to LEO nor develop a scavenging system (expendables 1994-1994; SBOTV 1999-2010 without propellant scavenging). All missions would be accomplished with expendable vehicles and with a propellant tank located in the cargo bay of the STS. The trade assumes conservatively that no DDT&E cost will be expended by the competition for a propellant tank in the cargo bay. Since this trade was designed to include the impact of the type of reusable GBOTV (cargo bay or ACC) as well as the subsequent evolution of a space based propellant delivery system, the competition consisted of the following program components:

a) Use of existing expendables from 1994-1998
b) Subsequent propellant delivery of space based propellants via STS tanker (5.5 mlb over 12 years, 1999-2010, see Table 2.7.2-11).

The cost of the competition to the scavenging system, STS delivered propellant, is summarized in Table 2.7.2-11. The cost for ground based operations from 1994-1998 with expendable stages is computed to be $1874M (Table 2.7.3-23, 1994-1998). This amount was derived by the Martin Marietta LCC computer model. The total competition cost is the sum of the scavenging competition (STS tanker) ($916M) and the expendable stage delivery ($1874M) for a total competition cost of $2790M.

<table>
<thead>
<tr>
<th>Propellant per year</th>
<th>STS Delivery to LEO ($ per pound)</th>
<th>Composite Discount Factor</th>
<th>STS Propellant Delivery Cost ($M PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5M/12</td>
<td>x 1014</td>
<td>x 1.97</td>
<td>916</td>
</tr>
</tbody>
</table>

2.7.2.2.4 STS Cargo Bay Benefit Factor Computation

The difference in manifesting cargo under the ACC and cargo bay modes of operation shows that additional volume and weight is made available to the STS for other payloads when the ACC mode is used. In order to make a fair assessment of this benefit, credit is awarded to the ACC concept for the benefit the STS receives. This is justified to offset ACC development costs since cost is added to the OTV system when expenditures are made on collateral systems for OTV support. In order to compensate for anomalies that may exist, the benefit is reduced to 50 percent of the calculated amount.

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The calculations involve examination of the 35 ground based missions in both the ACC and cargo bay modes. Due to differing payload weights and volumes, missions have payload weight and volume less than the 60 linear feet and 72 klb STS capacities. A large volume benefit is realized by moving the OTV out of the cargo bay into the ACC. Adjustments are made, accordingly, if either the weight or volume benefits exceeded the capacity of the STS, e.g., if the payload weight is the maximum 72 klb and the cargo bay linear volume is 50 feet, zero credit is given for the remaining 10 linear feet since adding additional payload will exceed the STS weight capacity.

Examination of the 35 ground based missions produced the ACC and cargo bay total weights and volumes cost benefit for OTV delivery shown below.

Available capacity in the cargo bay mode:

Volume: $50M
Weight: $130M

Available capacity in the ACC mode:

Volume: $500M
Weight: $170M

These figures are used in the algorithms shown in Table 2.7.2-12 to produce the STS derived benefit of $245M.

<table>
<thead>
<tr>
<th>Benefit Reduction Factor</th>
<th>Volume Benefit</th>
<th>Weight Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>CB</td>
<td>Benefit</td>
</tr>
<tr>
<td>Volume</td>
<td>Volume</td>
<td>Reduction</td>
</tr>
<tr>
<td>0.5 x (500M - 50M)</td>
<td>+</td>
<td>0.5 x (170M - 130M)</td>
</tr>
</tbody>
</table>

(See Section 2.7.1, pages 73-74, for an explanation of STS benefits.)

The cost components that comprise the trade alternatives and hypothesized competition are summarized in Table 2.7.2-13. These figures are grouped together in Table 2.7.2-14 to show the combined cost for OTV delivery and scavenging for investment and operations under each of the trade alternatives. The total shown on this table are used in the analyses of the alternatives contained in the next paragraph below.
TABLE 2.7.2-13 COST DATA SUMMARY

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST (PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTV Delivery Cost</td>
<td></td>
</tr>
<tr>
<td>ACC Investment</td>
<td>$815.4M</td>
</tr>
<tr>
<td>ACC Operations</td>
<td>$1060.3M</td>
</tr>
<tr>
<td>Cargo Bay Investment</td>
<td>$749.9M</td>
</tr>
<tr>
<td>Cargo Bay Operations</td>
<td>$1020.7M</td>
</tr>
<tr>
<td>Scavenging Costs</td>
<td></td>
</tr>
<tr>
<td>ACC Investment</td>
<td>$27.8M</td>
</tr>
<tr>
<td>ACC Operations</td>
<td>$480.0M</td>
</tr>
<tr>
<td>Cargo Bay Investment</td>
<td>$13.4M</td>
</tr>
<tr>
<td>Cargo Bay Operations</td>
<td>$633.0M</td>
</tr>
<tr>
<td>Competitive Costs</td>
<td></td>
</tr>
<tr>
<td>GB Delivery</td>
<td>$1874M</td>
</tr>
<tr>
<td>STS Propellant Delivery</td>
<td>$916M</td>
</tr>
<tr>
<td>STS Derived Benefit for OTV Delivery</td>
<td>($245.0M/OTV Credit)</td>
</tr>
</tbody>
</table>

TABLE 2.7.2-14 ALTERNATIVE COST SUMMARY

<table>
<thead>
<tr>
<th>ALTERNATIVE</th>
<th>OTV DELIVERY</th>
<th>SCAVENGING</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB/ACC (Alternative 1)</td>
<td>$749.9M</td>
<td>$27.8M</td>
<td>$777.7M</td>
</tr>
<tr>
<td>Investment</td>
<td>$1020.7M</td>
<td>$480.0M</td>
<td>$1500.7M</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB/CB (Alternative 2)</td>
<td>$749.9M</td>
<td>$13.4M</td>
<td>$763.3M</td>
</tr>
<tr>
<td>Investment</td>
<td>$1020.7M</td>
<td>$633.0M</td>
<td>$1653.7M</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC/ACC (Alternative 3)</td>
<td>$815.4M</td>
<td>$27.8M</td>
<td>$843.2M</td>
</tr>
<tr>
<td>Investment</td>
<td>$1060.3M</td>
<td>$480.0M</td>
<td>$1540.3M</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC/CB (Alternative 4)</td>
<td>$815.4M</td>
<td>$13.4M</td>
<td>$828.8M</td>
</tr>
<tr>
<td>Investment</td>
<td>$1060.3M</td>
<td>$633.0M</td>
<td>$1693.3M</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(To track numbers, see Tables 2.7.2-2, 2.7.2-9 and 2.7.2-10.)
2.7.2.3 Alternative Comparison.

The aggregate benefits for each of the delivery and scavenging combinations are shown in Tables 2.7.2-15 and 2.7.2-16. The data used in these tables have been brought forward from the Cost Data Summary (Table 2.7.2-13) and the Alternative Cost Summary (Table 2.7.2-14).

The benefit, shown in Table 2.7.2-15, indicates that all alternatives provide an advantage over not undertaking any development for STS delivery or scavenging.

The return on investment, shown in Table 2.7.2-16, factors in investment cost. This calculation supports the finding that all alternatives provide a viable solution.

A comparison of alternatives against the principal selection criteria is shown in Tables 2.7.2-17. This comparison shows the alternative of using the ACC for both the OTV delivery and the scavenging system provides the greatest advantage. This is largely due to the freeing of revenue bearing cargo bay space leaving additional weight and volume for other payloads. This is a significant advantage since the available capacity can be used for logistics cargo destined for the space station or for other payloads that may be orbited during the same time frame.

**TABLE 2.7.2-15 BENEFITS (PV)**

<table>
<thead>
<tr>
<th>OTV DELIVERY/SCAVENGING</th>
<th>COMPETITION COST</th>
<th>OTV DELIVERY &amp; SCAVENGING COST</th>
<th>STS DELIVERED BENEFIT</th>
<th>TOTAL BENEFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB/ACC</td>
<td>$2790.0M</td>
<td>- $1500.7M</td>
<td>+ 0.0</td>
<td>= $1289.3M</td>
</tr>
<tr>
<td>CB/CB</td>
<td>$2790.0M</td>
<td>- $1653.7M</td>
<td>+ 0.0</td>
<td>= $1136.3M</td>
</tr>
<tr>
<td>ACC/ACC</td>
<td>$2790.0M</td>
<td>- $1540.3M</td>
<td>+ $245.0M</td>
<td>= $1494.7M</td>
</tr>
<tr>
<td>ACC/CB</td>
<td>$2790.0M</td>
<td>- $1693.3M</td>
<td>+ $245.0M</td>
<td>= $1341.7M</td>
</tr>
</tbody>
</table>

(See Section 2.7.1, pages 73-74, for an explanation of STS benefits.)
### TABLE 2.7.2-16 RETURN ON INVESTMENT (1985 $M [PV])

<table>
<thead>
<tr>
<th>OTV DELIVERY/SCAVENGING</th>
<th>OTV DELIVERY &amp; SCAVENGING COST</th>
<th>STS DELIVERY &amp; SCAVENGING COST</th>
<th>INVESTMENT (DDT&amp;E)</th>
<th>TOTAL ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB/ACC</td>
<td>((2790.0 - 1500.7 + 0.0) / 777.7) -1</td>
<td>65.8%</td>
<td>CB/ACC</td>
<td>65.8%</td>
</tr>
<tr>
<td>CB/CB</td>
<td>((2790.0 - 1653.7 + 0.0) / 763.3) -1</td>
<td>48.9%</td>
<td>CB/CB</td>
<td>48.9%</td>
</tr>
<tr>
<td>ACC/ACC</td>
<td>((2790.0 - 1540.3 + 245.0) / 843.2) -1</td>
<td>77.3%</td>
<td>ACC/ACC</td>
<td>77.3%</td>
</tr>
<tr>
<td>ACC/CB</td>
<td>((2790.0 - 1693.3 + 245.0) / 828.8) -1</td>
<td>61.9%</td>
<td>ACC/CB</td>
<td>61.9%</td>
</tr>
</tbody>
</table>

### TABLE 2.7.2-17 OTV DELIVERY/SCAVENGING TRADE RESULTS

<table>
<thead>
<tr>
<th>ECONOMIC FACTOR</th>
<th>CB/ACC</th>
<th>CB/CB</th>
<th>ACC/ACC</th>
<th>ACC/CB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return on Investment</td>
<td>65.8%</td>
<td>48.9%</td>
<td>77.3%</td>
<td>61.9%</td>
</tr>
<tr>
<td>Benefits</td>
<td>$1289.3M</td>
<td>$1136.3M</td>
<td>$1494.7M</td>
<td>$1341.7M</td>
</tr>
<tr>
<td>Investment</td>
<td>$777.7M</td>
<td>$763.3M</td>
<td>$843.2M</td>
<td>$828.8M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SCORE</th>
<th>Return on Investment</th>
<th>Benefits</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.5</td>
<td>8.6</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>7.7</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>10.0</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.2</td>
</tr>
</tbody>
</table>
2.7.2.4 Conclusion

We conclude from this study that all alternatives considered provide a benefit worthy of acquisition. Of the alternatives considered, using an ACC for delivering the OTV to LEO during ground based operations and using the ACC for a scavenging system during space based operations provide the greatest economic advantage. This is clearly indicated as the best alternative through a comparison of return on investment with benefits and through a comparison of return on investment with investment (DDT&E).

A major element in providing the ACC advantage is the increase in available payload volume and weight by moving the OTV and scavenging system out of the revenue producing STS cargo bay and into the ACC.

It is important to note that this conclusion is based upon a relatively low STS flight rate. If a more optimistic rate is assumed, the benefits of the ACC scavenging concept would increase and thus make it even more attractive.

Finally, as noted at the beginning of this step of the trade report, the selection of the ground based OTV delivery mode in the first part of the analysis will eliminate one of two OTV evolutionary configuration options in the second part of the analysis. Selection of the ACC for OTV delivery thereby eliminates Option 6, OTV cargo bay delivery during ground basing, and retains Option 2, ACC delivery, for further consideration.

2.7.3 Step 2, Preferred Overall Evolution

The purpose of this subtrade study analysis is to select the most economical OTV evolution strategy from the remaining five trade study options shown in Figure 2.7.3-1. The remaining options include one ground based option (Option 7) and four space based options. The ground based option avoids the high investment cost for Space Station accommodations and for a scavenging system. The space based options have merit in avoiding a high delivery cost to LEO for all but the vehicles initial delivery to the Space Station. Space based configurations are also less constrained by the envelope dimension of the STS cargo bay/ACC.

Economics are a principal discriminator in the selection of the development strategy. Since there are no near term mission delivery requirements cited in the mission model which cannot be accomplished by existing upper stages, the selected OTV system must be able to improve the cost of delivering payloads over the current STS/expendable systems.

Economic data gathered for each option are derived from simulated missions flown against Revision 8 of the MSFC OTV Low Mission Model. Economic data for the competition, represented by existing upper stage payload delivery systems, is also gathered in the same way. Using these data, the options are compared with one another and the competition. Any costs associated with the development and operation of interfacing systems such as the ACC, scavenging, etc., are assigned to the option(s) that use them.
Figures 2.7.3-3 through 2.7.3-7, placed at the back of this section of the report, pictorially illustrate the configurations and evolutionary steps of each of the remaining options. Configuration alterations may take place at two basic block changes. One is from ground basing to space basing and the other is from nonman-rated to man-rated. Ground based configurations are designed for packaging within the ACC whereas space based configurations are not as restricted by a constraining envelope. Changes from ground to space basing include moving the avionics from an integral packaging within the structure to a ring design to facilitate on-orbit maintenance. Changes from a nonman-rated configuration to a manrated configuration involve added redundancy to preclude any single credible failure from preventing the safe return of the crew. A prime example is moving from a single engine to dual engines. The aerobrake is unique to each configuration.

<table>
<thead>
<tr>
<th>OPTION</th>
<th>GB IOC</th>
<th>SB IOC</th>
<th>MAN-RATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-----</td>
<td>-------</td>
<td>-----------</td>
</tr>
<tr>
<td>2</td>
<td>-----</td>
<td>-------</td>
<td>-----------</td>
</tr>
<tr>
<td>RE-SERVED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-----</td>
<td>-------</td>
<td>-----------</td>
</tr>
<tr>
<td>5</td>
<td>-----</td>
<td>-------</td>
<td>-----------</td>
</tr>
<tr>
<td>RE-SERVED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-----</td>
<td>-------</td>
<td>-----------</td>
</tr>
</tbody>
</table>

LEGEND:
- GBU 45 klb Ground Based Nonman-rated
- SBU 55 klb Space Based Nonman-rated
- SBM 55 klb Space Based Man-rated
- GBM 55 klb Ground Based Man-rated
- EXU Expendable Nonman-rated
- CB STS Cargo Bay
- ACC Aft Cargo Carrier

NOTE:
1. All space based OTVs are delivered in the STS cargo bay.
2. All ground based OTVs are delivered in the ACC except as noted in Option 6.

FIGURE 2.7.3-1 REMAINING OTV CONFIGURATION EVOLUTION OPTIONS
2.7.3.1 Cost of Remaining Alternatives

Aggregate program costs for each of the remaining options are summarized in Table 2.7.3-1 in constant dollars and in Table 2.7.3-2 in discounted dollars. These tables include collateral costs associated with each option's interface requirements, i.e. option's interface cost for Space Station, ACC, propellant scavenging, and payload transportation. The tables also address research and technology, DDT&E, production, and operations costs. A more detailed breakdown for DDT&E, production and operations cost for each option is contained in Tables 2.7.3-8 through 2.7.3-22 located at the back of this section.

The life cycle cost totals between options are quite close. The difference between the highest and lowest option in discounted dollars is only 14% (Table 2.7.3-2). This indicates that other factors such as risk, flexibility, and growth play a greater role in discriminating between options.

Life cycle costs calculations for the competition represented by existing upper stage vehicles are shown in Table 2.7.3-23 located at the back of this section. Information extracted from the totals shown on this table is used in the discussions below.

The cost per flight to capture 145 missions of the Revision 8 Low Mission Model are shown in Table 2.7.3-3. Two values are shown for the competition cost per flight. When flown against the Revision 8 Low Mission Model, the expendable upper stages take more STS flights and more upper stages to deliver the payloads. The real cost per flight is determined by the total cost divided by the number of transportation actions, i.e. 220 flights. For comparative purposes the cost per flight is adjusted to 145 missions thereby raising the cost per flight to an equivalent of $155.0M. A comparison of this figure with the cost per flight of each option shows the options with a significant advantage.
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>OPTIONS</th>
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<th>2</th>
<th>4</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Station</td>
<td>GBU/GBU/</td>
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<td>936.</td>
<td>936.</td>
<td>936.</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>SBM</td>
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</tr>
<tr>
<td>ACC</td>
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<td>163.</td>
<td>163.</td>
<td>163.</td>
<td>163.</td>
<td>163.</td>
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<td>83.</td>
<td>83.</td>
<td>83.</td>
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<td>4995.</td>
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<tr>
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<td>6177.</td>
<td>5158.</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>DDT&amp;E</td>
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<td>1414.</td>
<td>1218.</td>
<td>1257.</td>
<td>1223.</td>
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<tr>
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<tr>
<td>OPS</td>
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<td>6098.</td>
<td>8754.</td>
<td>8443.</td>
<td>12332.</td>
</tr>
<tr>
<td>Subtotal</td>
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<td>8058.</td>
<td>7916.</td>
<td>10155.</td>
<td>9998.</td>
<td>13951.</td>
</tr>
<tr>
<td>TOTAL</td>
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<td>14235.</td>
<td>14094.</td>
<td>16332.</td>
<td>16176.</td>
<td>19109.</td>
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</tr>
<tr>
<td>INTERFACING SYSTEM</td>
<td>OPTIONS</td>
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<td>4</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Space Station</td>
<td>GBU/SM/SM</td>
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<td>315.50</td>
<td>315.50</td>
<td>315.50</td>
<td>0.00</td>
</tr>
<tr>
<td>ACC</td>
<td></td>
<td>92.60</td>
<td>92.60</td>
<td>57.53</td>
<td>57.53</td>
<td>92.66</td>
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<td>Prop Scav</td>
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<td>30.75</td>
<td>30.75</td>
<td>30.75</td>
<td>0.00</td>
</tr>
<tr>
<td>P/L Trans</td>
<td></td>
<td>790.00</td>
<td>790.00</td>
<td>790.00</td>
<td>790.00</td>
<td>790.00</td>
</tr>
<tr>
<td>Subtotal</td>
<td></td>
<td>1228.85</td>
<td>1228.85</td>
<td>1193.78</td>
<td>1193.78</td>
<td>882.66</td>
</tr>
</tbody>
</table>

| OTV                |         |         |         |         |         |         |
| R&T                |         | 116.94 | 116.94 | 72.61 | 72.61 | 116.94 |
| DDT&E              |         | 692.07 | 686.32 | 435.42 | 421.93 | 639.90 |
| Prod.              |         | 47.28 | 59.07 | 8.66 | 23.33 | 57.23 |
| OPS                |         | 1596.57 | 1543.63 | 2416.02 | 2363.09 | 2527.33 |
| Subtotal           |         | 2452.86 | 2405.96 | 2932.71 | 2880.96 | 3341.40 |
| TOTAL              |         | 3181.71 | 3634.81 | 4126.49 | 4076.74 | 4224.06 |
### Table 2.7.3-3  Cost Per Flight (Constant $M)

<table>
<thead>
<tr>
<th>OPTION</th>
<th>Operations + P/L Trans / 145 Flts = Cost/Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GBU/SBM/SBM</td>
<td>6408 + 4995 / 145 = 79</td>
</tr>
<tr>
<td>2 GBU/SBU/SBM</td>
<td>6098 + 4995 / 145 = 77</td>
</tr>
<tr>
<td>4 EXU/SBM/SBM</td>
<td>8754 + 4995 / 145 = 95</td>
</tr>
<tr>
<td>5 EXU/SBU/SBM</td>
<td>8443 + 4995 / 145 = 93</td>
</tr>
<tr>
<td>7 GBU/GBU/GBM</td>
<td>12332 + 4995 / 145 = 119</td>
</tr>
</tbody>
</table>

**Competition Cost per Flight:**
- 220 required missions cost: $120.8
- 145 equivalent mission cost: $155.0

The investment cost, shown in discounted dollars in Table 2.7.3-4, includes the cost of acquiring the OTV and the cost of interfacing systems. Ground based Option 7 shows the lowest investment cost largely because it does not use either space station or scavenging systems. Options 4 and 5 also show a low investment because they do not have a ground based OTV configuration and can defer development costs of space based OTV configurations to a later time where they are discounted more. Options 1 and 2 show the highest investment costs due to earlier expenditures for ACC accommodations, research and technology, and DDT&E.
A benefit analysis is shown in Table 2.7.3-5 for each option. Benefit represents the difference between the cost of the competition and the OTV option to accomplish the mission model. Where applicable, the STS benefit (described in 2.7.2.2.4 above) is added to provide the total benefit the option holds over the competition to do the job.
The investment cost is added into the equation in Table 2.7.3-6 to produce a return on investment (ROI) ratio. The ROI difference among options is small with Options 1, 2 and 7 virtually falling into a tie. Option 7 favorable value is principally due to its relatively low investment cost.

TABLE 2.7.3-6 OTV OPTION RETURN ON INVESTMENT (PV)

<table>
<thead>
<tr>
<th>OPTION</th>
<th>(Benefit / Investment) - 1 = ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GBU/SBM/SM</td>
<td>(2832.4 / 1295.2) - 1 = 1.19</td>
</tr>
<tr>
<td>2 GBU/SBU/SBM</td>
<td>(2885.4 / 1301.2) - 1 = 1.22</td>
</tr>
<tr>
<td>4 EXU/SBM/SM</td>
<td>(1768.0 / 920.3) - 1 = 0.92</td>
</tr>
<tr>
<td>5 EXU/SBU/SM</td>
<td>(1820.9 / 921.4) - 1 = 0.98</td>
</tr>
<tr>
<td>7 GBU/GBU/GBM</td>
<td>(1989.4 / 906.7) - 1 = 1.19</td>
</tr>
</tbody>
</table>

Figure 2.7.3-2 shows the payback and accumulation of benefits the five remaining options hold over the competition. The all ground based option, Option 7, provides the earliest payback because of the lower investment cost. The rate of benefit accumulation for Option 7 decreases when the mission complexity increases and a greater number of STS flights are required to support mission operations.

Options 4 and 5, which use existing expendable vehicles for the ground portion of the model, effectively delay the large space based investment. This delay also reduces the time available for benefit accumulation thereby increasing the number of missions before payback is realized and lessening the net benefit accumulation vis-a-vis the other options. The number of missions required before payback of an option is realized as follows:

- Option 1: 48 Missions
- Option 2: 48 Missions
- Option 4: 80 Missions
- Option 5: 81 Missions
- Option 7: 25 Missions
FIGURE 2.7.3-2 OTV EVOLUTIONARY STRATEGY COMPARISON
2.7.3.2 Alternative Comparison

Table 2.7.3-7 shows the principal economic factors for the candidate options along with scoring. As before, the best candidate is awarded a score of 10 and the other options a score relative to that awarded the best candidate. The table shows Options 1 and 2 rank high with virtually the same scores. Option 7 scores high an investment which also raises the score for ROI. Option 7 benefits are disproportionately low vis-a-vis Options 1 and 2. Options 4 and 5 score high on investment cost but low in the other two categories. The payback comparison, Figure 2.7.3-2, along with the ROI and benefits comparison place Options 4 and 5 below the other options considered.

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Scores

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Option 7 remains attractive only if the low investment costs are real. In order for the attractiveness of this option to be sustained, the STS user fee of $73M per flight or less must be achieved. For example, if the STS user charge were to increase to $100M, the Option 7 benefit would be reduced to $756M (discounted $) making it economically undesirable in that the investment would not be paid back in 145 mission. The STS lift capacity is another consideration. When using the groundruled 72 klb STS payload capacity, we find that 1.6 shuttle flights per OTV mission is required. If this capacity should be reduced to 65 klb, for example, the benefit would decrease to $1625M (discounted $) with a resulting ROI of 0.79. It also should be noted that Option 7 competes with revenue producing payloads for cargo space thereby reducing STS profitability.

Options 1 and 2 differ only in the space based unmanned phase of the mission model in that Option 2 specifies an intermediary space based nonman-rated vehicle whereas Option 1 moves initially to a space based man-rated vehicle. Costs for Option 2 are slightly higher principally due to the costs of acquiring a different vehicle for the space based nonman-rated phase.
There are four principal non-economic factors that favor Option 1 over Option 2. First, Option 1 maximizes early verification of man-rated reliability. Second, Option 1 reduces Space Station operational complexity in that it is only involved with one program cycle (space based man-rated). Third, Option 1 provides greater flexibility in that the earlier experience with the vehicle can promote confidence for accelerating the schedule for more advanced missions earlier, i.e. heavier payloads, manned missions, and lunar mission. Fourth, Option 1 has a lower cost risk than Option 2 because it has only two major program cycles rather than 3, involves no space based avionics repackaging, and remains with only one engine type rather than two engine types.

2.7.4 Conclusion

All OTV options provide an economic advantage over the continued use of existing expendable vehicles for accomplishing the missions postulated in Revision 8 of the MSFC Low OTV Mission Model.

Step 1 of the trade study shows that it is better during ground based operations to deliver the OTV via the STS Aft Cargo Carrier (Option 2) rather than in the cargo bay (Option 6). Step 2 of the trade study shows that Option 1 and 2 costs are essentially equal and both options hold an economic advantage over the remaining options. Option 1 provides several non economic advantages over Option 2. These include maximizing early verification of man-rated reliability, reducing space station operations complexity, providing greater flexibility by making it possible to do more advanced missions earlier, and reducing risk by eliminating the need to change vehicle configurations midway through the space based phase of the mission model.

Based upon the ground rules and assumptions used in this study, Option 1 is recommended as the preferred evolutionary strategy for OTV development. This option progresses from a nonman-rated OTV carried in the ACC during ground based operations to a man-rated OTV based at the space station during space based operations.

The conclusions reached for the preferred overall evolution are largely based upon the postulated ground rules and assumptions and the results of other trade studies contained in this report. Any changes in the underlying ground rules and assumptions may have a bearing upon the conclusions reached in this study. Some key issues that may alter these results include: mission model length and activity level, utilization of scavenging for propellant recovery at LEO, operations risk of the ACC, STS cost per flight changes -- up or down, STS payload lift capability -- up or down, availability of the STS, accommodation of DOD requirements including no Space Station utilization and access to molniya orbits, and restrictions on Space Station utilization due to interference with other operations.
AVIONICS: INTEGRAL
STRUCTURE: GRAPHITE EPOXY
AEROBRAKE: 40 FT
REDUNDANCY: NON-MAN RATED
PROP CAP: 45,000 Lb
LOADED WT: 50,363 Lb
ENGINE: 475 lsp/7500 Lb (1)

AVIONICS: RING
STRUCTURE: GRAPHITE EPOXY
AEROBRAKE: 44 FT
REDUNDANCY: MAN RATED
PROP CAP: 55,000 Lb
LOADED WT: 62,169 Lb
ENGINES: 475 lsp/7500 Lb (2)

GROUND BASED ACC DELIVERY

SPACE BASED CB DELIVERY

FIGURE 2.7.3-3 OPTION 1 CONFIGURATION GBU/SBM
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GROUND BASED ACC DELIVERY | SPACE BASED ACC DELIVERY | SPACE BASED CB DELIVERY

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**Multiple Payload Delivery Scenario**

1. **1012 A U**
   - 12000
   - STS/105-AMS: 37437
   - 12000 25
   - Up: 1200 25
   - Dn: 2000 5
   - Max GEO P/L: 21000 lbs
   - Max GEO P/L: 101 lbs
   - MAX GEO P/L: 2030 lbs
   - DIA: 10.0

2. **1012 B U**
   - 12000
   - STS/105-AMS: 37437
   - 12000 25
   - Up: 1200 25
   - Dn: 2000 5
   - Max GEO P/L: 21000 lbs
   - Max GEO P/L: 101 lbs
   - MAX GEO P/L: 2030 lbs
   - DIA: 10.0

**GEO Servicing**

1. **1002 A U**
   - 1600
   - STS/105-AMS: 46790
   - 1600 25
   - Up: 1600 25
   - Dn: 200 15
   - P/L: 7000 15
   - Max GEO P/L: 10,000 lbs

**Experiments and Reception Station**

1. **1570 U**
   - 7500
   - STS/105-AMS: 2035
   - 7500 10
   - Max GEO P/L: 10,000 lbs

**GEO Service Station Logistics Scenario**

1. **1500 A**
   - 15159
   - STS/105-AMS: 51000
   - 15159 15
   - GEO Service Station

2. **1500 B**
   - 15159
   - STS/105-AMS: 51000
   - 15159 15
   - GEO Station

3. **1570 A**
   - 12000
   - STS/105-AMS: 51000
   - 12000 15
   - GEO Service Station
**TABLE 2.7.3-23  COMPETITION MISSION MODEL CAPTURE (CONTINUED)**

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<td>1/200 UP</td>
<td>20000</td>
<td>10</td>
<td>STS/GENIUS 6'</td>
<td>6335x</td>
<td>29.1</td>
<td>55.4</td>
<td>102.2</td>
<td>157.6</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>158</td>
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<td>158</td>
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</tbody>
</table>

**DOC**

| 10031 | 12000 | 30 | STS/GENIUS 6' | 51800 | 29.1 | 55.4 | 73 | 120.4 | 514 | 514 | 514 | 514 | 514 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2095 | Single STS Delivery | Max GEO P/L 12000 |
| 10035 | 20000 | 35 | STS/GENIUS 6' | 6335x | 29.1 | 55.4 | 130 | 105.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 742 | 742 | 742 | 742 | 742 | 742 | 742 | 742 | 742 | Same as DOC 13700 |

**Refight**

| 10100 | 20000 | 20 | STS/GENIUS 6' | 6335x | 29.1 | 55.4 | 103.4 | 160.0 | 0 | 0 | 161 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 402 | Same as DOC 13700 |

**Refight (1/14)**

**Totals:**

- Constant 1985 Dollars
- PV Factor (2% Inflation, 10% Discount)
- Present Value 1985 Dollars

<table>
<thead>
<tr>
<th>Average Cost Per Flight:</th>
<th>Constant Dollars</th>
<th>$120.8</th>
<th>(210 Flights with Multiple P/L Revisions)</th>
<th>Present Value Dollars</th>
<th>$23.7</th>
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<tr>
<td>956 1150 1062 1158 1055 1191 1757 1290 1625 1792 1451 1675 1583 2276 2147 2100 25365</td>
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<td>0.42 0.39 0.35 0.32 0.29 0.26 0.24 0.22 0.20 0.18 0.16 0.14 0.12 0.11 0.10 0.09</td>
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