ENHANCING THE ORBITAL UTILIZATION OF EXPENDABLE LAUNCH VEHICLES

by

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(1983)

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Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the Degrees of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

and

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1988

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ABSTRACT

A new space infrastructure is being planned and designed, and is expected to be in place within the next 10 to 15 years. Political, economic, and technical factors will drive its development. The cost of propellant supply for space based reusable orbital transfer vehicles has long been considered a significant factor in the development of the new space infrastructure. There are two primary approaches to this problem: minimize propellant requirements or reduce propellant costs.

This thesis investigated the utilization of expendable launch vehicle (ELV) capabilities in roles beyond Earth-to-orbit transportation. A framework was introduced for looking at what ELVs can offer the new infrastructure, and what the associated demand might be. Many opportunities for enhanced orbital utilization of ELVs were identified. Reduction of orbital propellant costs through propellant reclamation was established as having the greatest near term potential.

An orbital propellant supply infrastructure simulation (OPSIS) was developed. Through parametric simulation, data on quantity and cost of delivered propellant for different scenarios was generated. Sensitivity analyses were performed on selected infrastructure scenarios. An ELV utilization scenario was identified which provides propellant for orbital needs at less than one third of the cost proposed by methods currently under consideration.

The political feasibility of propellant reclamation was researched through evaluation of current policies. Technical feasibility was investigated through review and status of relevant development programs. A scenario for implementation was introduced calling for accelerated technology development, international participation, and private operation.

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to Verla and Edith

ACKNOWLEDGEMENTS

Many thanks go to my Thesis Advisor, Professor Walter Hollister, for his guidance and support through the development and focus of this thesis. His suggestions throughout the past year and a half have been helpful and enlightening.

A special thanks to Professor Leon Trilling who has provided thoughtful guidance on many topics.

To Professor Richard de Neufville and the Technology and Policy Program, many thanks for a heightened understanding of how and why.

Grateful thanks to General Dynamics Space Systems Division for financial support and to Dan Heald and Mike Felix in particular, who were instrumental in making it possible.

For assistance in many administrative manners, thank you to Liz Zotos in Cambridge and Mitzi McCrary in San Diego.

Much appreciation to Mike Massimino, Imtiaz Rahaman, and Caleb King, who have shared much more than an office with me (no, I don't mean my microwave).

Finally, special thanks to my family whose love and support, encouragement and confidence has been a guiding light.

BIOGRAPHY

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Publication: Improving the Efficiency of Expendable Launch Vehicles in the Future Space Transportation System, in Proceedings of the 8th Princeton Conference on Space Manufacturing, May, 1987.

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AACB	Aeronautics and Astronautics Coordinating Board
ABMA	Army Ballistic Missile Agency
ABU	Asian Broadcasting Union
ACC	Aft Cargo Carrier
ACS	Attitude Control System
AEC	Atomic Energy Commission
AFSC	Air Force Systems Command
AIAA	American Institute of Aeronautics and Astronautics
ALS	Advanced Launch System
ARPA	Advanced Research Projects Agency
ASEB	Aeronautics and Space Engineering Board
ASME	American Society of Mechanical Engineers
ASTP	Apollo-Soyuz Test Project
AXAF	Advanced X-Ray Astrophysics Facility
BEAR	Beacon Explorer / Auroral Research
CAST	Committee on Advanced Space Technology
CELV	Complementary Expendable Launch Vehicle
CEPT	Conference Europeene de Postes et Telecommunications
CER	Cost Estimating Relationship
CETS	Committee on Engineering and Technical Systems
CFMFE	Cryogenic Fluid Management Flight Experiment
CFMPO	Cryogenic Fluid Management Program Office
CO2	Carbon Dioxide
COMSTAC	Commercial Space Transportation Advisory Committee
CONUS	Continental United States
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research
COSTCALC	Cost Calculation subroutine
CRAF	Comet Rendezvous / Asteroid Flyby
DARPA	Defense Advanced Research Projects Agency
DDT&E	Design, Development, Test and Evaluation
DOT	Department of Transportation
DSP	Defense Support Program
DoD	Department of Defense
EBU	European Broadcasting Union
ELV	Expendable Launch Vehicle
EOS	Earth Observing System
EOSAT	Earth Observing Satellite Company
ESA	European Space Agency
ET	External Tank
ETCO	External Tanks Corporation
EVA	Extra-Vehicular Activity
FAO	Food and Agricultural Organization (UN)
FY	Fiscal Year
GDR	German Democratic Republic
GEO	Geosynchronous Orbit
GHz	Giga-Hertz
GLOW	Gross Lift-Off Weight
GNP	Gross National Product
GP-D	Gravity Probe-D
GRO	Gamma Ray Observatory
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
H2O	Water
HLLV	Heavy Lift Launch Vehicle
IAA	International Academy of Astronautics

IAEA	International Atomic Energy Agency
IAF	International Astronautical Federation
IB-COESS	Interagency Board on Civil Operational Earth-Observing Satellite Systems
ICBM	Inter-Continental Ballistic Missile
ICSC	International Council of Scientific Unions
IGI	Industrial Guest Investigator
IISL	International Institute for Space Law
ILA	International Lawyers Association
IMCO	International Maritime Consultative Organization
INMARSAT	International Maritime Satellite Organization
INTELSAT	International Telecommunications Satellite Consortium
IRBM	Intermediate Range Ballistic Missile
ISF	Industrial Space Facility
I_{sp}	Specific Impulse
ITU	International Telecommunications Union
JEA	Joint Endeavor Agreement
JSC	Johnson Space Center
LAD	Liquid Acquisition Device
LANDSAT	Land remote sensing satellite program
LaRC	Langley Research Center
LCC	Life Cycle Cost
LDR	Large Deployable Reflector
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
LVGEN	Launch Vehicle Generator Program
MECO	Main Engine Cut-Off
MIR	Soviet Space Station "Peace"
MIT	Massachusetts Institute of Technology
MLI	Multi-Layer Insulation
MOU	Memorandum of Understanding
MRBM	Medium Range Ballistic Missile
MSFC	Marshall Space Flight Center
MT	Mega-Ton
NACA	National Advisory Committee for Aeronautics
NAS Act	National Aeronautics and Space Act of 1958
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NTO	Nitrogen Tetroxide
OCST	Office of Commercial Space Transportation
OMB	Office of Management and Budget
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
OPSIS	Orbital Propellant Supply Infrastructure Simulation
ORS	Orbital Refueling System
OSAD	Outer Space Affairs Division
OSCRS	Orbital Spacecraft Consumable Resupply System
OTA	Office of Technology Assessment
OTV	Orbital Transfer Vehicle
PAM	Payload Assist Module
PMD	Propellant Management Device

PRC	Peoples Republic of China
PRCALC	Propellant Requirements Calculation subroutine
PRM	Propellant Reclamation Matrix
RFP	Request For Proposal
RTG	Radio-isotope Thermoelectric Generator
SAC	Strategic Air Command
SAE	Society of Automotive Engineers
SAMS	Space Assembly, Maintenance, and Servicing Study
SBOTV	Space Based Orbital Transfer Vehicle
SCORE	Signal Communications by Orbit Relay Experiment
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Office
SDV	Shuttle Derived Vehicle
SEB	Source Evaluation Board
SFHT	Super Fluid Helium Tanker
SFMD	Storable Fluid Management Demonstration
SIG	Senior Interagency Group
SIRTF	Shuttle Infrared Telescope Facility
SLBM	Submarine Launched Ballistic Missile
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSI	Space Studies Institute
STAS	Space Transportation Architecture Study
STIG	Space Technology Interdependency Group
STS	Space Transportation System
TEA	Technical Exchange Agreement
TFU	Theoretical First Unit
TVS	Thermodynamic Vent System
UARS	Upper Atmosphere Research Satellite
UDMH	Unsymmetrical Dimethylhydrazine
UK	United Kingdom
UN	United Nations
UNESCO	United Nations Education Science and Cultural Organization
US	United States of America
USA	United States of America
USAF	United States Air Force
USN	United States Navy
USSR	Union of Soviet Socialist Republics
VCS	Vapor-Cooled Shields
WHO	World Health Organization
WIPO	World Intellectual Property Organization
WMO	World Meteorological Organization (UN)
WWII	World War II

Chapter 1 INTRODUCTION

The U.S. is preparing to embark on its second generation of space exploration activities. The first generation began with the early satellite launches and climaxed with the manned lunar landings. There was a strong link with mother Earth in that first generation, and space was a place to visit, but not to live and to work. The missions were independent and self contained, carrying everything with them when they were launched. All were dedicated missions, designed to be used once for a singular purpose. Missions were limited in scope by the equipment and supplies a spacecraft could carry on its journey. Manned missions were of limited duration, and satellites would 'live' only so long as their supplies held out. Skylab began to extend man's stay in orbit and was the first step to the next generation.

The second generation will be one of interdependence. There will be an infrastructure of several components, each performing critical functions which in turn enable the other components to perform their functions. Instead of a lone spacecraft strictly on its own, new spacecraft will interact with each other. Interaction will include routine maintenance, propellant and consumables resupply, and emergency repair. Reusability will become an important characteristic in the second generation, particularly for orbital operations. Commercial operations will strengthen and grow as costs of transportation are reduced. Ties to Earth will still be significant, but not directly so. Spacecraft will have the ability to operate in orbit indefinitely and man will begin to live and work in space.

Far on the horizon is a third generation of space operations. In this vision, earth to orbit transportation will be routine with fully reusable vehicles. Space travel will become an experience for more of the population, and space will have an impact on our daily lives. Commercial operations will support a large industry and manufacturing in space will make use of extraterrestrial resources enabling complete independence from earth. A schematic illustrating this progression is shown in Figure 1.1.

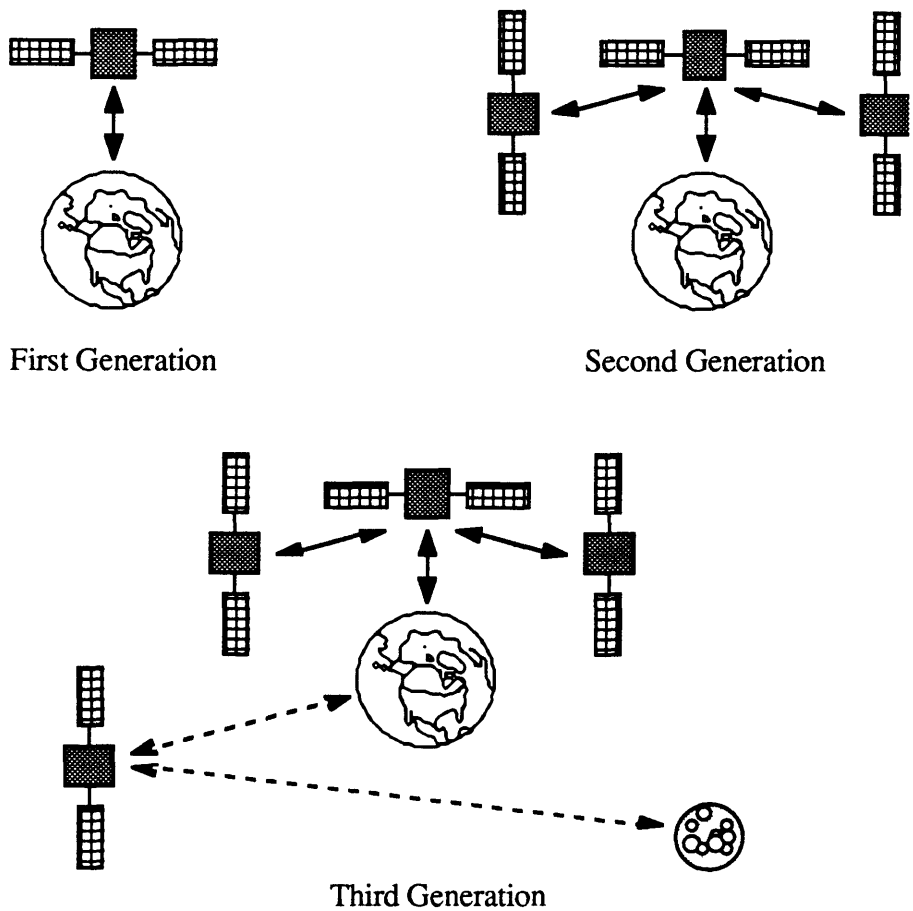

Figure 1.1
Schematic indicating three generations of space program evolution .

The space shuttle brought the dream of reusable spacecraft into reality in 1981 when it first flew, and the planned space station will begin to establish a permanent manned presence in space for the U.S. when it becomes operational in the mid-1990's. Spacecraft are being designed and built incorporating consumables resupply capability and will shortly enter operation. The dawn of the second generation is upon us, but many of its characteristics are still vague and uncertain.

Some things are generally settled upon. The infrastructure of the next generation will contain earth to orbit transportation vehicles, both reusable and expendable. Orbital operations will be centered around the space station. Reusable upper stages known as Orbital Transfer Vehicles (OTVs) based at the space station will provide transportation for high energy missions to geosynchronous orbit and beyond. There will be maintenance and supply satellites such as the Orbital Maneuvering Vehicle, and there will be a supply of propellant and other consumables to support this array of operations. That these will be the basic components of a new space infrastructure is agreed upon in principle. What the details will be, how the program will be funded and administered are as yet unclear.

The cost of orbital propellants for space based reusable orbital transfer vehicles has long been considered a very significant factor in the development of a new space infrastructure. There have been two primary approaches to this problem. The first is to improve the efficiency of the orbital operations so that the propellant requirement is minimized.[1] This solution has been approached through the use of aerobraking for reusable OTVs to minimize return ΔV requirements[2], or through a combination of high-thrust chemical OTVs and low-thrust electrical OTVs.[3] The second approach is to reduce the cost of propellants to the user spacecraft. This has been primarily associated with

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[1] Sponable, J.M., DeWispelare, A.R., USAF, Optimizing the Space Transportation System with a Space Fueling Station & Tug, AIAA/SAE/ASME 20th Joint Propulsion Conference, 11-13 June 1984, Cincinnati, Ohio, AIAA Paper 84-1324.

[2] General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986.

[3] Dunn, B.P., "High-Energy Orbit Refueling for Orbital Transfer Vehicles", Journal of Spacecraft and Rockets, Vol. 24, No. 6, November-December 1987, pp. 518-522.

propellant scavenging from the shuttle.[4,5] An area for propellant cost reduction that has not been addressed is the utilization of expendable launch vehicles through propellant reclamation to deliver large amounts of propellant to orbit.

The primary concern of this thesis is the utilization of ELV capabilities in roles beyond the historical one of earth to orbit transportation. A framework is introduced for looking at ELVs in terms of what they have to offer to this new infrastructure. There are many areas for enhanced orbital utilization of ELVs, but the primary one initially is to provide propellants for orbital activities in a cost effective manner as part of the new infrastructure. A significant reduction in cost of propellants delivered to orbit can be achieved through the enhanced orbital utilization of ELVs through propellant reclamation. There are many policies which affect this concern, many questions which must be answered and many events that must occur if the enhanced orbital utilization of ELVs is to occur. Some of these questions are:

- Will ELVs be a part of the new space infrastructure?
- Will new ELVs be developed for this role?
- What will be the nature and capabilities of these new ELVs?
- Will there be a requirement for propellants in orbit?
- What will those propellants be (cryogenics or storable)?
- Can ELVs provide those propellants?
- Can the propellant be provided by other sources such as the space shuttle?
- Will the infrastructure be international or U.S. only?
- What will the military and civil roles be in this infrastructure?

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4 Heinz, V.M., MIT Space Systems Laboratory, Analysis of a Space-Based Fuel Station, AIAA 14th Aerospace Sciences Meeting, Washington, D.C., 26-28 January 1976, AIAA Paper 76-196.

5 Rockwell International Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume I, Technical Report, NASA -CR-171848, January 1985.

- Where will the funding for development of the infrastructure come from?
- To what degree will there be commercial involvement?
- How will the infrastructure be operated: will it be run by military, civil or private organizations, and on a national or international level?

This thesis will establish a framework for addressing these questions through simulation of different infrastructure scenarios, assessment of current policies, and review of relevant studies and technology development. A set of recommendations will then be made for guiding the development and implementation of an orbital propellant supply infrastructure which utilizes ELVs through propellant reclar ation.

1.1 Background

The space program in the United States is in a period of transition that will be of significance for many years to come. The events of the past several years have led to a perception that the U.S. space program does not enjoy the preeminence it once did. This has been highlighted by the Challenger disaster plus Titan, Atlas and Delta launch vehicle failures. The western space program experienced further setbacks with the failure of Ariane , which resulted in a virtual hiatus in space launches over a period of 2 years. During this time, the Soviet Union continued to launch rockets into space at the rate of nearly 100 per year.[6] They successfully tested their new Energia heavy lift booster[7], they

[6] Smith, Marcia, The First Quarter Century of Spaceflight, Futures, October 1982, Pages 353-373.

[7] Clark, Phillip S., Energia: Soviet Superbooster, SPACE, Volume 3, Number 4, September-October 1987, Page 36.

provided routine orbital resupply and refueling operations to their 'MIR' (Peace) space station[8] as their cosmonauts set endurance records for time spent in space.

The primary reason for the western failures and Soviet successes centers on space transportation. The stable of launch vehicles in the west has been plagued with failure while those of the Soviet Union have continued to provide reliable, assured access to space. The reason for this current state of affairs in the U.S. program is primarily the fallout of space transportation policies which were set in the late 1960's and early 1970's. According to James Bennett and Phillip Salin of the Reason Foundation,

> The underlying causes of the crisis lie in the policy-making process, in which confused, short-sighted decisions dominated by political expediency have been made about space development over the past 30 years.[9]

A conscious decision was made to develop the shuttle system as the primary source of transportation to Earth orbit, phasing out expendable launch vehicles entirely. In 1976, Dr. James Fletcher as Administrator of NASA prophesied to congressional committees the routine operation of 60 shuttle launches per year with an order of magnitude cost reduction over then current launch costs.[10] As history has shown, this dream never became reality. The Shuttle has launched at most 9 times in a year, the actual costs are higher than expendables, although the price charged to customers for launch services is less. Expendables have not been phased out and are in fact enjoying a renaissance of sorts.

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[8] Mills, P., REFUELLING SALYUT SPACE STATIONS BY PROGRESS TANKERS, Journal of the British Interplanetary Society, August 1985, pp. 381-384.

[9] Bennett, J., Salin, P., "The Private Solution to the Space Transportation Crisis", SPACE POLICY, August 1987, pp. 181-204.

[10] Simon, Michael C., Keeping the Dream Alive: Putting NASA and America Back in Space, Earth Space Operations, San Diego, California, July, 1987.

Expendable launch vehicles (ELVs) have had a varied and colorful history in the development of space exploration and exploitation. They are direct descendants of ballistic missiles which were developed in the late 1950's as delivery systems for nuclear warheads. The power of these ballistic missiles was harnessed to place satellites in space, initially by the Soviet Union and followed closely by the United States. Satellite launching progressed from the near earth domain to other heavenly bodies and deep space. Soon, ELVs were launching men into space and providing the transportation for men to walk on the moon. Through all these developments, the basic scenario was to use the ELV as a workhorse, delivering its payload to orbit. After achieving their missions the launch vehicles were destroyed, burning up in the earth's atmosphere during re-entry. This historic role is varied by mission but singular in the task of delivering payloads from earth to orbit. ELVs have the potential to contribute much more than this to the overall space operations scenario.

The most advantageous location for utilization of launch vehicles (beyond their primary task of earth to orbit transportation) is in space, to utilize more fully the energy that went into placing not only the payload but the rest of the launch vehicle in orbit. To date, there has been talk of using the external tank (ET) of the shuttle in orbit for a variety of purposes, many of which are applicable to an ELV. However, there is an inherent advantage to using ELVs in addition to ET's. This is that the ELV is a self contained vehicle, with avionics, guidance, and propulsion. This can allow the ELV to fly itself to a desired orbital position (limited of course, by the amount of propellant available).

There has been no established need for the materials that compose an ELV after payload delivery in the history of space operations. This is beginning to change. There are several needs that can be fulfilled by orbital ELVs presently and in the future. Some of these can be seen in Table 1.1 below.

ORBITAL NEED	ELV RESOURCE	UTILIZATION METHOD
• Propellant Supply	• Residual Propellant/ Fluids	• Reclaimed and Stored for Reuse
• Avionics Components	• Modular Avionics Components	• Reuse on Orbital Spacecraft/ Return to Earth for Reuse
• Propulsion Components	• Modular Propulsion Components	• Reuse on Orbital Spacecraft/ Return to Earth for Reuse
• Orbital Transfer	• Entire ELV	• Refuel and Use as Orbital Transfer Vehicle
• Storage Vessels	• Propellant Tankage	• Refuel and Disburse as Required
• Experimental/ Habitation/ /Manufacturing Modules	• Propellant Tankage	• Partial Disassembly and Modification
• Supply Stock for Orbital Manufacturing Facility	• Tankage Materials	• Material Recovery and Reconfiguration

Table 1.1
Uses for ELVs in orbit.

The first one is the use of residual propellant in the tanks of the ELV after it has delivered its payload. Residual propellant is the result of reserves for the flight propellant, ullage in the tanks, and off-loaded tanks from missions requiring less than rated payload capacity. The use of this residual propellant will lie in resupply of propellant for satellites and space stations, and most significantly orbital transfer vehicles.

Currently the limiting factor on the life of many satellites is the amount of propellant they can carry on board. This is of course limited by the launch capacity of the vehicle that places them in orbit. Some satellites are being designed with inherent resupply capability which will extend the life of the satellites significantly over their current counterparts.

Plans now call for the development of special logistical servicing satellites which will travel to the satellites needing refueling and servicing to perform these tasks. However, this means that a separate satellite will need to be built and launched. ELVs which are modified and used for this purpose could provide a more cost effective and efficient use of resources.

After achieving orbit, ELVs could be refueled and reused as orbital transfer vehicles. Envision a deep space probe which requires a significant amount of velocity for its mission. It is placed in LEO by its ELV, then its ELV is effectively refueled by a co-orbiting ELV tanker which has collected residual propellant from several previous ELV missions to LEO. The ELV in effect, could function as both lower and upper stage.

A parts inventory could be maintained in orbit through modular design for 'plug in' and 'plug out' utilization of ELV components. The components could range from structural material to avionics or propulsion. Uses for their material could begin with components which could be removed in space and used directly for orbital applications. An example would be propellant tank stiffeners being removed from the tanks and used as structural members for truss construction. Other uses could include modular avionics or propulsion components which could be taken from ELVs and used on satellites, or orbital transfer vehicles. The key to these types of uses lies in the design of the components and the ease with which that design lends itself to modularization and 'plug in/plug out' capability. Complicated procedures for removing and installing components would likely require manned involvement or very sophisticated remote manipulator systems. If the designs emphasized simplicity, these uses have the potential to be cost effective.

Beyond the use of materials from the launch vehicle as they are when placed in orbit, the materials could be reconfigured and used as supply stock for an orbiting manufacturing facility. The materials used for this would principally be structure and tankage. Ultimately, the common vision for space manufacturing is to utilize extraterrestrial materials from the moon, the asteroids, and other heavenly bodies. In the interim however, ELVs could provide the initial supply stock to orbiting facilities. This would allow for an evolutionary path of development for the technology required for manufacturing in space.

The modes of utilization of expendable launch vehicles will be paced by the demand for what the ELVs can offer. Some of these demands are beginning to emerge, while others are further off. The most significant demand for any of the resources which ELVs have to offer in the near future is that of propellant for space based reusable orbital transfer vehicles (OTV). The demand has been estimated by many sources in industry and government, and will be a minimum of 200,000 lb per year beginning with OTV operations expected to start in mid to late 1990's. The demand could grow to several million pounds per year, given certain factors such as SDI deployment, a robust civil space program (Moon bases or Mars missions), and burgeoning commercial space development.

The need for propellant resupply for OTV operations is an integral part of the space transportation infrastructure for the next several decades. Many studies have addressed the issue, arriving at recommendations which involve the shuttle as the focal point of the transportation system. With the Challenger disaster, the role of the shuttle as the only mode of space transportation has been dispelled and ELVs have regained a firm position in space transportation. Following the cancellation of the shuttle Centaur program for safety reasons, it is doubtful whether the shuttle bay can be used to carry cryogenic propellants on resupply missions. This adds to the notion that unmanned expendables should play a central role in the provision of resupply propellants for OTV operations in the future, which is the focal point of the thesis.

The utilization of ELVs can be divided into two distinct phases. The first phase is the historical utilization of ELVs as providers of earth to orbit transportation. The second phase is that which will come in the next decades, answering the demand for orbital resources with resources which are available in the ELVs themselves. This second phase will be provide additional utilization beyond earth to orbit transportation. The relationship between the areas of utilization of ELVs in the past and projected for the future can be seen in Figure 1.2.

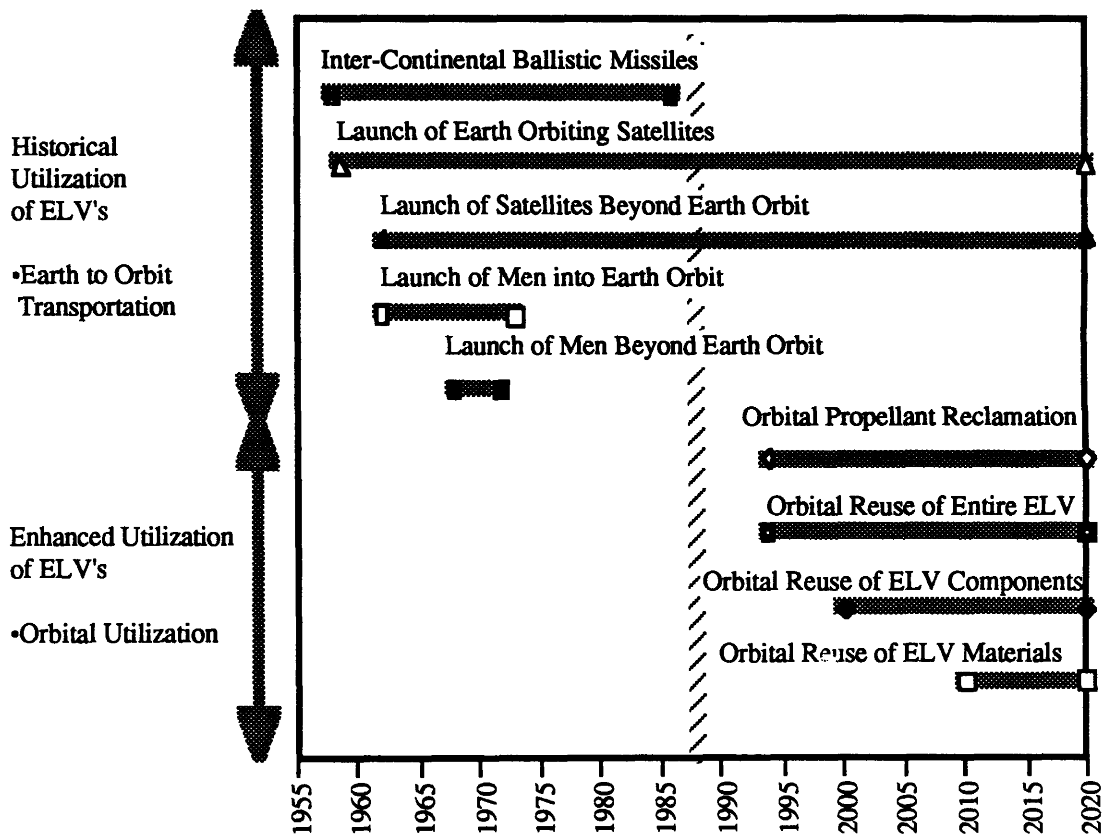

Figure 1.2
Historical and projected utilization of ELVs by the United States.

1.2 Thesis Organization

This thesis looks in some detail at the background and future utilization of ELVs, and at the technological, economic and political factors involved in the development of propellant reclamation capability. The following two chapters will address the roles that ELVs have played and may play in the space program of the United States. Chapter 2 will address the historical utilization which began with the development of ICBMs to the launching of the Apollo Moon missions atop the giant Saturn V booster. Chapter 3 will address the potential areas of development for enhanced orbital utilization of ELVs. The establishment of demand for various avenues of utilization will be addressed as will the ways in which ELVs can fulfil such demand.

In Chapter 4 the current policy environment surrounding ELVs will be examined regarding its effect on enhanced utilization. Impacts of the administration's policies on space development and commercialization, and the impact of legislation will be assessed. A political assessment will be made to determine the forces in industry, government, and other institutions which may help or hinder enhanced utilization of ELVs. The emergence of a commercial launch capability and the potential for enhanced utilization to provide a competitive advantage for U.S. producers will be assessed. Issues of international competition as a policy driver will be raised, as will conflicts that may arise in the tradeoffs between competition and cooperation with foreign producers.

Chapter 5 will describe the technologies required to utilize ELV propellant reclamation for orbital propellant resupply. Current launch vehicles will be assessed to determine the degree to which they may fulfill the objectives of enhanced utilization. Additionally, proposed vehicles which are under design and consideration for development will be assessed. The assessment will include capability to fulfill projected demands in the appropriate time period, as well as the presence of the necessary technology.

Chapter 6 will describe a simulation called OPSIS (Orbital Propellant Supply Infrastructure Simulation) of the orbital propellant supply infrastructure which has been developed as an analytical tool. Cost figures will be assessed for the processes of resupply from ELV propellant reclamation, and 'conventional' resupply from dedicated resupply missions. These different methods will provide a comparison. The model is set up parametrically, allowing sensitivity analyses for a number of parameters defining the various characteristics of the system.

Results of the OPSIS simulation will be given in Chapter 7. These will include the economic advantages of ELV propellant reclamation over other alternatives, and sensitivities of various simulation parameters to deviation from the baseline values. Discussions of the implication of the results such as identification of trends and threshold levels of certain parameters will also be included.

Conclusions will be drawn and recommendations made in Chapter 8 for policies which will allow for and encourage the enhancement of ELV utilization. Recommendations will be made for governmental as well as private institutions. The intended effects of those recommendations will be discussed, as will expectations of implementation methods and obstacles. The result of the research will be the outline of a program for orbital utilization for ELVs over time. This will include recommendations for organizational responsibility for performing particular tasks, which technologies should be developed and when, and policies that should be implemented or changed.

Chapter 2 HISTORICAL UTILIZATION OF ELVs

Expendable launch vehicles have played a central role in the space program in the United States. They have been the sole source of Earth to orbit transportation prior to the development of the Space Shuttle, and continue to be the backbone of the space transportation infrastructure after the tragedy of the Challenger disaster. There are three primary expendable launch vehicles currently in the stable of the United States space program. These vehicles, with their principal manufacturer, are indicated in the table below:

ELV	Manufacturer
Atlas	General Dynamics
Delta	McDonnell Douglas
Titan	Martin Marietta

ELVs have fulfilled many roles in the course of their development and utilization in the history of the U.S. space program. All of the roles performed the same task of delivering a payload from the surface of the Earth into space, but the payloads varied as did the purpose of the missions. The uses of ELVs thus far in the U.S. space program can be broken into five categories as shown below:

- Inter-Continental Ballistic Missile (ICBM)
- Launch of Earth Orbiting Satellites
- Launch of Satellites Beyond Earth Orbit
- Launch of Men into Earth Orbit
- Launch of Men Beyond Earth Orbit

The development of the launch vehicles for each of these tasks was a very complicated and intricate process. The history of each of the uses of ELVs is in many ways interconnected and interdependent on at least one of the other uses. In order to understand how the launch vehicles that are in existence today got here, and how others were developed but used for only a short period of time, it is important to understand the history and interaction of launch vehicle development over the past several decades. The following sections are synopses of the history associated with the development of expendable launch vehicles for each of the functions which have been indicated above.

2.1 Inter-Continental Ballistic Missile (ICBM)

The first use for modern day ELVs was that of a ballistic missile, providing an inter-continental delivery system for nuclear warheads. The development of the modern expendable launch vehicle was primarily a result of the military desire after WWII to develop a delivery system for nuclear warheads. The basic technology necessary for this development grew from the WWII era when German A4 missiles were used as delivery systems for conventional warheads over distances greater than 200 miles. Over time through the development process, the modest range of the A4 would increase to 500 miles with the development of medium range ballistic missiles (MRBM), then approach 2000 with the development of intermediate range ballistic missiles (IRBM). The goal of this train of development, the inter-continental ballistic missile (ICBM) would be capable of delivering nuclear warheads to targets more than 6000 miles away from their launch site. What follows is a description of the early development of rockets in the United States for use as ballistic missiles. Only missiles which had further use as space launch vehicles are discussed, but this includes all the early missile development programs which developed the technology and paved the road to space.

The Germans were the leaders in rocketry during WWII, having developed the A4 (or V-2) rocket which they used to bombard London. The A4 was developed by a group of German scientists working at research establishments at Kummersdorf-West and

Peenemunde. Robert Goddard had done significant research in the development and use of liquid rockets prior to WWII, and his interest was primarily scientific. He neither sought nor received very much military interest. However, the Germans were aware of his work and borrowed much of it in the development of propellant delivery systems and basic engineering details.[1]

The first successful test flight of the A-4, which was conceived in 1936, occurred on 3 October 1943. The A-4 then went into production for use as a strategic weapon and on 8 September 1944, the first A-4 fell on England. More then 3,700 A4 rockets were fired after that, the last being on 27 March 1945. The thousands of scientists and engineers in Peenemunde working on this new rocket saw it not only as a weapon, but as a stepping stone to space travel. In March 1944, Wernher von Braun who was the director of engineering at Peenemunde, was arrested by the German Gestapo with two of his leading colleagues. They were placed in jail for talking too much about space travel and not about the A4 rocket as a weapon. They were released only after convincing Hitler that they were indispensable to the rocket program.[2]

The A4 had come two years too late to turn the tides for Germany, and as the war came to an end, military interest in rocket technology took on a new light. The Americans had developed the capability of producing nuclear weapons as demonstrated in August of 1945 which could, and would, become significant strategic weapons in combination with rockets capable of placing them almost anywhere on the Earth. The Soviet Union was also developing nuclear weapons with a keen interest in developing the technology to deliver

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[1] Baker, David, THE ROCKET: The History and Development of Rocket & Missile Technology, Crown Publishers, Inc., New York, 1978.

[2] Dornberger, Walter R.,Emme, Eugene M., ed., The History of Rocket Technology: German V-2, Wayne State University Press, Detroit, 1964.

those weapons. This military interest in rocketry placed a high value on the technology which the Germans had developed in the A-4.

At the end of the war, the Americans and the Soviets were very interested in acquiring the German scientists which had been the masterminds of this rocket. By August 1945 under Operation Overcast, the U.S. Army had secured 350 of the top German scientists. Over a hundred were rocket scientists and many were from Peenemunde including Wernher von Braun. The Soviets received a larger number of the German rocket scientists, but it was generally felt that those most influential in the development of the A4 were secured by the Americans. The German scientists were later brought to the United States where they began work on the development of ballistic missiles at Fort Bliss in El Paso and at the White Sands proving ground in New Mexico.[3]

This group of German researchers aided the U.S. Army in performing test launches of the 100 A4s which were captured in Germany. The testing was performed at the White Sands proving ground in New Mexico. Several improvements were made and information was gathered on upper atmospheric conditions using the captured A4s as sounding rockets. The group of researchers, led by Wernher von Braun, moved to Redstone Alabama with the Ordinance Guided Missile Center when it moved there in 1950. in Redstone, which would later become the Marshall Space Flight Center, this group began the design of a medium range ballistic missile for the U.S. Army.

After 18 months of design work on 8 April 1952, the project of developing a U.S. MRBM was officially named Redstone. With a gross lift-off weight (GLOW) of 61,000 lb, the Redstone was to deliver its payload over a distance of more than 200 miles. The

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[3] Ordway, F.I.III, Sharpe, M.R., The Rocket Team, MIT Press, Cambridge, Massachusetts, 1982.

Redstone missile was heavily dependent on the practical experience of the German A4 engineers, and used many concepts similar to those used in the A4. The first successful launch of the Redstone occurred on 20 August 1953 and over the next 5 years, 37 research and development flights would be made. The initial Redstone rockets were built at Redstone Arsenal, until Chrysler Corporation won a contract to began manufacturing the missiles. The Redstone entered field service in Germany in 1958 and fulfilled this role until 1965 when it was replaced by the Pershing.

A derivative of the Redstone was the basis for the Jupiter Intermediate Range Ballistic Missile (IRBM) which began with a joint Army/Navy decision in 1955 to develop the first U.S. IRBM. With a range of over 1500 miles and a gross lift-off weight (GLOW) of 110,000 lb, the Jupiter was twice the size, with more than seven times the range capability of its predecessor the Redstone. The Jupiter had its first test launch on 1 May 1957, was declared operational in 1958, and underwent operational deployment to Italy and Turkey in 1960. By the mid-1960's, the Jupiter was retired as an IRBM in favor of ICBMs based on the continental United States (CONUS) and Submarine Launched Ballistic Missiles (SLBM).

The Air Force began a program for development of an Intermediate Range Ballistic Missile (IRBM) in December of 1955, which was similar in many respects to the Army/Navy Jupiter program. They contracted with the Douglas Aircraft Company in Santa Monica (which would become McDonnell Douglas Corporation) for hardware design, development and fabrication of the Thor missile which would have a range capability of 1500 miles. The Thor was a single stage liquid propellant missile which was first successfully launched on 20 September 1957. The Thor IRBM was declared operational in June of 1958, and about 60 Thor missiles were deployed in the United Kingdom. The role as an IRBM for the Thor launch vehicle ended in 1962 when it was retired from service.

In the United States, initial studies were begun in 1946 for Inter-Continental Ballistic Missile (ICBM) development. The MX-774 was the initial development program for a U.S. ICBM. The contractor for this program was the Consolidated-Vultee Aircraft Corporation, which later became the Convair Division of General Dynamics Corporation. The MX-774 incorporated many technologies from the German A4 but pioneered several revolutionary concepts as well. This program was competing as a delivery system with the B-50 superfortress bomber which was in full production. At the time the Department of Defense saw little reason for continuing research on ICBM development with the development and production of the B-50 going so well. The MX-774 was effectively cancelled in 1947 and support for ICBM development was low until the early 1950's, when the Atomic Energy Commission (AEC) developed smaller nuclear weapons and there came to be a general realization that the Soviet Union was involved in similar research. This threat of a Soviet capability for delivering a nuclear warhead from their soil to U.S. soil was of paramount concern in the 1950's. The result was a tremendous push to develop a vehicle capable of such a mission.

A massive program was then launched to develop an intercontinental delivery vehicle for nuclear warheads. In order to do this, the vehicle had to escape the earth's atmosphere with near orbital velocities, and maneuver itself into a precise trajectory for delivery. In January 1951, the Air Force began Project MX-1593, which was basically a continuation of the MX-774 project which had begun in 1946. Again the contractor for this program was the Convair Division of General Dynamics in San Diego, which had performed the work on the MX-774 project. The United States exploded its first Hydrogen bomb on 1 November 1952, which brought the notion of using ICBMs with nuclear warheads squarely into reality. Hydrogen bombs were much smaller and lighter than the early atomic bombs, requiring a missile of relatively modest performance. The Soviet Union shocked the United States by following suit with the explosion of their own

Hydrogen device less than 9 months later on 12 August 1953. This fact, coupled with intelligence reports that the Soviets had been developing their own capability for ICBMs had a significant impact on the ICBM program in the United States.

By 1954 the ICBM program, which was named ATLAS in 1951 (after the Greek God who supported the world on his shoulders), was gaining a great deal of momentum. By mid-1955, it had the highest of national priorities. The first successful launch occurred with an Atlas B version on 2 August 1958, with a range of 2500 miles. The Atlas was tested more and improved, then the D version of the Atlas was implemented as the first operational U.S. ICBM system on 9 September 1959. Additional improvements in the system led to a range of over 9000 miles in 1960, which was more than doubled the original design goals of the program.[4] New versions of the Atlas, versions E and F were designed to be placed in underground silos for increased survivability in the event of a Soviet attack on the launch site. The Atlas continued to serve its military strike role until 1965, when the Atlas ICBMs began to be replaced by a second generation ICBM system, the Minuteman.

Early in the development of the Atlas program, the Air Force was concerned with the complexity of the design and felt it should undertake the parallel development of an alternate vehicle to ensure the successful development of a U.S. ICBM. In 1955, the Air Force awarded the Martin Company (now Martin Marietta) a contract to design and develop a two staged liquid rocket as an alternative and backup to the Atlas missile. The program was named Titan in reference to mythological Greek giants that once roamed the Earth, and was given official approval to begin production in 1957. The first flight of the Titan launch vehicle occurred on 6 January 1959 and the Titan entered service with the Strategic Air

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[4]Von Braun, Werhner, et. al., Space Travel: A History, Harper & Row, Publishers, New York, 1985.

Command (SAC) in 1962. The initial Titan was flawed with the same problem as the Atlas in that it used non-storable liquid propellants which required an exposed launch site and had long fuelling and preparation times. This was contrary to what SAC was looking for regarding preparedness, and a preemptive Soviet attack would destroy the missiles before they could make retaliatory strikes. Because of this situation, SAC pressed for the development of a storable propellant ICBM which was named the LGM-25C, or the Titan II. It was introduced into service with SAC in 1963, and by 1965 the storable propellant Titan II had replaced the non-storable Titan I which was withdrawn from service as an ICBM. The Titan II served for many years as the big gun for SAC, providing the longest range at nearly 10,000 miles and the highest destructive capability at 20 MT.[1] It continued in service until very recently when on 5 May 1987 the last of the Titan IIs in service as an ICBM was deactivated at Little Rock, Arkansas. As the Titan IIs have been phased out of service, they are being replaced with the new MX, or Peacekeeper missile.[5]

Repeatedly, the story of ELVs and their role as warhead delivery systems ends as they are replaced by rockets better suited for that task. There are two primary reasons for this. First, the ELVs are all liquid propelled rockets. In the case of the Atlas and the Titan I, non-storable propellant had to be loaded into the rocket immediately prior to launch. This rendered them ineffective in a retaliatory strike because they would be destroyed before they could be launched. In the Titan II and the Thor (Delta), the propellants are storable, in that they can be loaded into the launch vehicle substantially prior to launch, but they involve complicated systems which hamper their launch readiness. The alternative to liquid rockets for warhead delivery is solid propellants. Solids are storable, and require no

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[5]Ropelewski, Robert R., Soviet Weapons Gains Spur U.S. Strategic Modernization, Aviation Week & Space Technology, 18 March 1985, Page 29.

loading of propellant. In addition, they are readily adaptable to silo launch and are transportable in a launch mode.

The second reason for solids rockets over liquid rockets as ballistic missiles is that the liquid rockets have a payload capability which is much more than required for delivery of nuclear warheads. A strategic decision was made to go with a large number of missiles, each delivering a relatively modest warhead of 1 MT yield. This would force the Soviets to silo-target their missiles, in hopes of diverting attacks on civil and industrial targets. Based on this strategy, the liquid rockets were too large. Smaller liquid rockets could have been developed, but would have been much more costly than solid rockets of the same capability. The Titan II was kept in service for many years to preserve the U.S. retaliatory threat of a big gun which was capable of destroying an entire city, but with the deployment of the Peacekeeper the Titan II was eventually replaced by a solid fueled rocket as were all the other liquid rockets.

A summary of the ballistic missiles which have been described, and their performance and operational characteristics can be seen in Table 2.1.

Name	Class	GLOW [lb]	Length [ft]	Dia [ft]	Stages	Range [n.mi.]	Yield [MT]	Year Deployed	Year Retired
Atlas D	ICBM	254000	76	10	1.5	9200	2	1959	1964
Atlas E	ICBM	267000	82	10	1.5	10400	2	1960	1965
Atlas F	ICBM	260000	82	10	1.5	10400	4	1961	1965
Jupiter	IRBM	110000	60	9	1	1740	1.5	1958	1961
Redstone	MRBM	61000	69	6	1	230	H.E.	1958	1965
Thor	IRBM	105000	65	9	1	1730	1.5	1958	1962
Titan I	ICBM	220000	90	10	2	6000	4	1962	1963
Titan II	ICBM	330000	103	10	2	9300	10	1963	1987

Table 2.1

Characteristics of Ballistic Missiles which evolved into ELVs.[6]

The general developmental relationships for these vehicles which has been described is summarized in Figure 2.1. The summary indicates the general relationships between the development of the different programs, and give the date of the conception and the date of their first successful flight.

[6] Baker, David, THE ROCKET: The History and Development of Rocket & Missile Technology, Crown Publishers, Inc., New York, 1978, page 270.

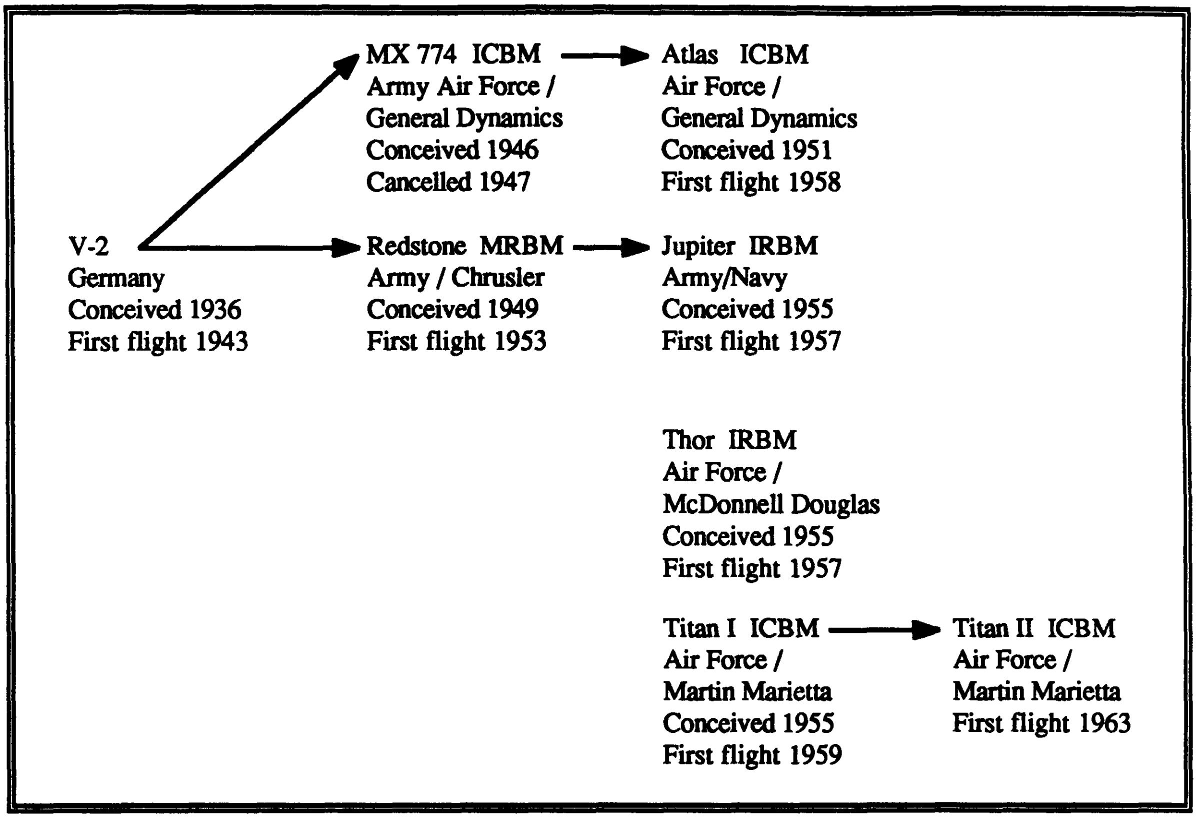

Figure 2.1

Developmental flow of ballistic missiles which evolved into ELVs.[7]

As the capabilities of rockets began to mature, and the nature of requirements for warhead delivery systems such as MRBMs and ICBMs became better defined, the rockets which had been initially developed to fulfill those tasks became obsolete in those roles. Nonetheless there were many other roles for which these rockets, bred as weapons of destruction, were much better suited.

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[7] Collected from information in:
Baker, David, THE ROCKET: The History and Development of Rocket & Missile Technology, Crown Publishers, Inc., New York, 1978.

2.2 Launch of Earth Orbiting Satellites

The primary role of ELVs in the process of their evolution has been the launching of satellites which orbit the Earth and provide space-based platforms for communication, surveillance, and remote sensing. The placement of satellites in Earth orbit had been a long held dream of many people, particularly those involved in the development of rocket systems. The push to develop ballistic missiles for warhead delivery in the mid to late 1950's provided the technology which made the dream of achieving the necessary Earth orbiting velocities a reality. All of the early rockets developed as ballistic missiles contributed directly to the placement of satellites in orbit. There was much interest in orbiting satellites, for military as well as civil endeavors.

There was a conscious separation of civil and military space programs by President Eisenhower in the 1950s. It is argued that these policies may have prevented the U.S. from being in space before the Soviet Union. President Eisenhower would not allow technology from the IRBM Thor to be used for placement of a satellite in orbit until after the Soviets had launched Sputnik. The Thor reportedly could have orbited a satellite as early as 1956, and it was in fact a Thor derivative, the Juno 1 which place the first U.S. satellite in orbit.[8] An explanation for this policy is that the U.S. was concerned with Soviet response to overflight of their territory by satellites. By holding back from orbiting a satellite until after the Soviets had done so, the concern was mitigated. The Soviets could not dispute the rights of the U.S. to overfly Soviet soil, if they had done so over U.S. soil.[9]

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[8] Smith, Marcia, The First Quarter Century of Spaceflight, Futures, October 1982, Pages 353-373.

[9] McDougall, Walter A., The Heavens and the Earth, A Political History of the Space Age, Basic Books, Inc., Publishers, New York, 1985, pp. 120-124.

The policy of separation between civil and military space programs was formalized when the National Aeronautics and Space Act of 1958 created NASA. In section 102(b) of the act, NASA is given responsibility for aeronautical and space activities with the exception that:

> ...activities peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States (including the research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and shall be directed by, the Department of Defense...[10]

Any disputes over jurisdiction between NASA and DoD is to be settled by the National Aeronautics and Space Council, which is composed of the Vice President who is chairman, the Secretaries of State and Defense, the NASA Administrator, and the Chairman of the Atomic Energy Commission (AEC). It is also the responsibility of the Council to "advise and assist the President, as he may request, with respect to the performance of functions in the aeronautics and space field." In the original version of the act, Section 204 created a Civilian-Military Liaison Committee which was to serve as a link between the activities of the civil and military space programs, and as a forum for dispute resolution. The committee was abolished in 1965, with its functions transferred to the President.

After the NAS act was passed, some of the new NASA facilities were directly taken from operations that were previously military. A prime example of this is the George C. Marshall Space Flight Center in Huntsville, Alabama, which was part of the Army's Redstone Arsenal run by the Army Ballistic Missile Agency (ABMA). After the creation of NASA, the facilities and personnel of the ABMA in Huntsville became part of NASA.

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[10] United States Congress, National Aeronautics and Space Act of 1958, Public Law 85-568, 29 July 1958.

The Army, Navy and Air Force all were involved in power struggles for their shares of the military space effort. In spite of these power struggles, there was cooperation between the services and in particular between the civil and military space programs. A brief history of the development of launch vehicles as orbital satellite delivery systems will indicate the amount of cross-fertilization that was occurring, and the degree to which each successive step in the launch vehicle evolutionary process built upon previous ones.

Sounding rockets have been used since the 1945 when the Wac Corporal first flew, for scientific missions such as atmospheric research. They were effective in their purpose, but were incapable of achieving the velocities required for placing a satellite in Earth orbit. When satellites became operational, sounding rockets seemed at first obsolete, but have continued to play an important role in space science. They have remained in use because of their low cost, simplicity, and short lead time. Sounding rocket technology and components were directly as part of satellite launchers such as the Vanguard.[11]

The development of ballistic missiles provided the capability of placing satellites in Earth orbit, although this capability had much lower priority than did that of missile delivery. However, when on 4 October 1957 the Soviets orbited the world's first artificial satellite, the U.S. response was to raise the priority of developing satellite launching capability to match the Soviet achievement. Not only was it a political embarrassment for the U.S. to be outdone by the Soviets, but it was a clear demonstration of their capability to launch warheads which could attack the U.S. mainland.

Following the Russian exploits of the Sputnik launch, there was a heated rush in the United States to orbit a satellite. The efforts centered on the Vanguard project which

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[11] Corliss, V.R., NASA Sounding Rockets, 1958-1968, A Historical Summary, Scientific and Technical Information Office, NASA, Washington, D.C., 1971.

had been initiated by the Navy on 5 July 1955 when the Naval Research Laboratory issued a report titled A Scientific Satellite Program. This report discussed the advantages, and problems associated with placing a small satellite in orbit. On 29 July 1955 President Eisenhower approved plans for the U.S. to launch Earth orbiting satellites, in support of the 1957-58 Geophysical Year. By March 1956 the design was finalized, the first stage being derived largely from the Viking atmospheric sounding rocket which was also a Navy program. The first Vanguard prototype launch on 23 October 1957 came after Sputnik had been orbiting the Earth for nearly three weeks, but was only a suborbital test flight with inert second and third stages. In its first launch attempt at placing a satellite in orbit, Vanguard TV-3 exploded after rising 3 feet from the launch pad then losing thrust. Vanguard TV-4 was successful in placing a four pound payload, the Vanguard 1, in orbit on 17 March 1958. Ending in late 1959, the Vanguard program had made 11 attempts to orbit payloads of which 3 were successful. Elements of this program lived on however, finding applications as upper stages of the Delta, Atlas, and Scout launch vehicles.[12]

As an alternate vehicle to the Navy Vanguard project, the Army Ballistic Missile Agency (ABMA) was directed on 8 November 1957 to develop a launch vehicle capable of placing a satellite in orbit. The idea behind having two parallel programs was to enhance the probability of success. The rocket under development by the Army was the Jupiter C, which was modified by the addition of a fourth stage and renamed the Juno I. The Jupiter C had previously been used as a test vehicle for the development nose cone material needed for atmospheric re-entry. The Jupiter C was based on the Redstone MRBM, with upper stages added to gain enough velocity to subject the nose cones being tested to re-entry conditions. On 31 January 1958, the Juno I launch vehicle successfully placed the first

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12 McLaughlin Green, C., Lomask, M., Vanguard, A History, Scientific and Technical Information Office, Office of Technology Utilization, NASA, Washington, D.C., 1970.

U.S. satellite in orbit. The satellite was Explorer 1 which weighed 30 lb. The Juno I was launched six times of which three were successes. The last successful Juno 1 launch placed Explorer 4 in orbit on 26 July 1958, making the Juno I the only space launcher to retire from successful service before the creation of NASA.[13]

The Juno II space launch vehicle was derived from the Jupiter IRBM which was used as the first stage. The Juno II was a four stage vehicle with the three upper stages comprised of eleven, three, and one solid propellant Baby Sergeant rockets. The first successful launch of a Juno II came on 13 October 1959, placing the Explorer 7 satellite into Earth orbit. In 1961 after 10 flights of which only 3 were successful, the Juno II was cancelled. However, the first stage of the Juno II went on to become the central propellant tank in the Saturn 1 and 1B launch vehicles, and the S-3 engine used in the Juno II led to the design of the H-1 engine used in the Saturn 1, 1B, and Delta launch vehicles.

After achieving success at meeting its specified performance goals as an ICBM in November 1958, the Atlas was called upon to go into Earth orbit. Under the name of Project SCORE (Signal Communications by Orbital Relay Experiment), an Atlas B placed itself and 120 lb of communications equipment in orbit on 24 December 1958. The Atlas broadcast a recorded Christmas message from President Eisenhower to the world for 13 days. While the mission was of scientific value, it was more significantly a signal that the U.S. had matched the Soviet capability to launch nuclear warheads between continents as was demonstrated with Sputnik. In 1959, the Air Force began to develop the true potential of the Atlas as a satellite launcher by combining it with the Able upper stage which had been developed in 1958 as an upper stage to provide nose cone re-entry tests for the Thor IRBM . None of the three flights with this combination was a complete success. The Atlas

[13] Baker, David, THE ROCKET: The History and Development of Rocket & Missile Technology, Crown Publishers, Inc., New York, 1978, page 237-238.

was then paired with another Thor upper stage, the Agena in support of the Samos and Midas programs being run by the Air Force. On 24 May 1960 the first successful Atlas-Agena flight placed a payload of 5,000 lb in orbit.

Developments progressed in 1961 with a new Agena stage being combined with the new Atlas E and F versions. The new Atlas-Agena B emerged, and on 12 July 1961 placed the Air Force Midas satellite in orbit. Most significant in the development of the Atlas as a satellite launcher was its combination with the Centaur high energy upper stage. The Centaur is powered by liquid oxygen and liquid hydrogen, and when combined with the Atlas can place payloads of up to 10,000 lb in low Earth orbit (LEO). The first successful flight of the Atlas-Centaur occurred on 8 May 1962. Over seventy flights later, the basic Atlas-Centaur is still flying today and will continue to launch satellites as one of the first commercial launch vehicles in the United States.

Early in 1958, NACA began studies aimed at providing a low cost launch vehicle for orbiting small payloads. The Langley Research Center was responsible for this project which was named Scout, and remained in control of project Scout after NACA was absorbed by NASA in late 1958. The Scout was seen as a four stage rocket using solid propellants which were proven and relatively simple in construction, storage, and operation. The four stages for the Scout were borrowed from three other rocket programs. The first stage coming from the Navy's Polaris missile, the second from the Army's tactical Sergeant rocket, and the third and fourth stages coming from the third stage of the Navy's Project Vanguard. The Scout was first launched on 1 July 1960, but did not successfully place a satellite in orbit until 16 February 1961 when the 15 pound Explorer 9 was placed in orbit. The Scout has provided launch services with steadily improving capabilities and performance for NASA the past 27 years and will continue to do so in the future.

In 1960 the Air Force became interested in NASA's Scout program for ballistic as well as orbital flight experiments and developed four versions of the Scout. This was done under the Air Force Systems Command of the Space Systems Division. The first launch was on 7 January 1961.

The Army was interested in providing a satellite launching capability of its own, and proceeded to use the Thor IRBM for this purpose. Using the upper stages of the Navy Vanguard rocket as upper stages for their Thor, they created a satellite launcher and called it the Thor-Able. The new agency for administration of civil space programs also wanted to develop a launcher of its own. NASA created a launch vehicle nearly identical to the Thor-Able of the Army using the same Vanguard upper stages and Thor first stage, and they called it the Thor Delta. The NASA Thor Delta was intended to provide civil launch capability in the interim until a more advanced launcher was available. Thus from the same components, the Air Force launch vehicle for military missions kept the name Thor, and the NASA version for civil missions came to be known as the Delta.[1]

The first successful Delta flight was on 12 August 1960, placing an inflatable Echo 1 passive communications satellite in orbit. This first version of the Delta was launched 12 times by 1962, placing the Echo communications satellites, Tiros weather satellites, scientific research satellites, as well as the first satellite of the United Kingdom (the Ariel 1), into orbit. In 1962 the uprated Delta versions were introduced, and there continued to be a proliferation of new Delta versions, each with more capability than the previous. The Delta D was introduced on 10 August 1964 with three Castor 1 solid propellant rockets attached, which brought it to resemble more closely the modern Delta. The move by NASA to augment the Delta thrust with solid rocket motors followed suit with the Air Force which had introduced virtually the same improvement in their Thor-Agena D nineteen months earlier. The series of improvements in the Delta improved its launch capability to LEO by more than an order of magnitude, from 600 lb in 1960 to 7,610 lb with the currently operational Delta 3920 PAM-D which is being marketed commercially by McDonnell Douglas.

The Titan launch vehicle has been an integral part of the U.S. satellite launch capability for over 25 years. There have been four primary configurations of the Titan vehicle. The first was the Titan I which lived a short life as a ballistic missile, after which the retired ICBMs were used to launch military satellites. The Titan II was a storable propellant derivative of the Titan I, developed by the need for a storable propellant ICBM to increase readiness. It was used to launch the Gemini spacecraft but was not used as a satellite launcher until missiles commissioned as ICBMs began to come out of service and be refurbished as satellite launchers. There are at least 60 decommissioned Titan II ICBMs currently planned for refurbishment as military satellite launchers.

The Titan III was developed by the Air Force as a satellite launcher. This was done by adding a third stage called Transtage of storable bi-propellants using nitrogen tetroxide (NTO) as the oxidizer and unsymmetrical dimethyl hydrazine (UDMH) as the fuel. The first successful flight of a Titan III-A came on 10 December 1964 and was followed on 18 June 1965 with the Titan III-C which was the heaviest lift vehicle launched to that date. The Titan III-C was a Titan III-A with two large solid rocket motors attached to the liquid core vehicle. The solids acted as the first stage, and the liquid engines were ignited at altitude after SRB burnout. The effect was a four stage vehicle with a lift capability of nearly 30,000 lb.

On 29 July 1966 the Titan III-B was introduced with its first successful launch. This launch vehicle had an enhanced upper stage using the Agena D rather than the Transtage of the Titan III-A and would become the standard launch vehicle for medium weight military satellites. The Titan III-D was an enhanced version of the III-C which began service in 1971.

The first non-military use of Titan rockets as satellite launchers came with the development under NASA of the Titan III-E/Centaur in 1974. Other than the Saturn V, this was the most powerful launch vehicle ever developed in the U.S. Its primary task has been to launch planetary missions and space probes.

The stable of expendable launch vehicles that has been used over the past thirty years by the U.S. to place satellites in orbit were direct descendants of the early ballistic missiles. There is a considerable degree of shared technology and hardware between the various programs, and between organizations. Perhaps the most vivid illustration of this is the Thor IRBM which became a primary satellite launcher for the Army as well as for NASA.

2.3 Launch of Satellites Beyond Earth Orbit

Once the door to space had been opened and the first steps had been taken into orbit about the Earth, efforts expanded to begin the exploration of the solar system and beyond. To satisfy this area of scientific inquiry, expendable launch vehicles began to launch satellites beyond the gravitational influence of the Earth, on missions to the Moon, the planets, and into deep space.

Early attempts at sending satellites beyond Earth orbit were centered on the Moon as either lunar orbit or impact missions. However the early missions were plagued with failure. The U.S. launched 9 Pioneer satellites between August 1958 and December 1960 aboard the Thor Able 1, Juno II and Atlas Able launch vehicles to the Moon and none them was fully successful. Meanwhile the Soviets achieved the first lunar impact on 12 September 1959. The U.S. achieved the first successful planetary fly-by with the Mariner 2 mission to Venus which was launched aboard an Atlas Agena-B on 27 August 1962.

The Atlas Agena-B and Atlas Agena-D vehicles launched almost all U.S. interplanetary probes from 1962 to 1965. This included the Ranger missions to the Moon and the Mariner missions to Mars and Venus. The Thor-Agena Delta launched Pioneer 6 to lunar orbit on 16 December 1965 and served as a launcher until 1969. The Atlas Agena-D continued in service until 1967. In 1966 the Atlas Centaur was introduced as the launch vehicle for the Surveyor lunar landing missions, launching all seven missions successfully. The Atlas Centaur continued as the primary launcher of interplanetary probes until the Titan III-E/Centaur entered service with the 10 August 1975 launch of the Viking 1 Mars landing mission. The Titan III-E Centaur had significantly greater capability than the Atlas Centaur and has been the standard launcher for heavy probes while the Atlas Centaur has continued to fulfill its role as the launcher of medium weight interplanetary probes.[14]

2.4 Launch of Men into Earth Orbit

Initial manned launch programs in the United States began with project Mercury which was initiated in October 1958. The beginnings of project Mercury can be traced back to July 1952 and a National Advisory Committee for Aeronautics (NACA) resolution aimed at devoting effort to the problems of manned flight to high altitudes, escaping from earth's gravity. The U.S. Air Force initiated a study in March 1956 entitled Manned Ballistic Rocket Research System, which was known as project 7696.

In the 1950's, several aerospace companies presented proposals for a manned orbital flight. These proposals were largely based on multi-stage launch vehicles which were still in the study stage and far away from operational development. By early 1958,

[14] Wilding-White, T.M., Jane's Pocket Book II, Space Exploration, MacDonald and Janes, London, 1976.

NACA personnel had come to favor the use of ballistic missile boosters for manned orbital flight. These boosters were already in advanced stages of development, particularly the Atlas which had been given the highest of national priorities in early 1957. Atlas was selected as the launcher for the Mercury orbital flights in late 1958, and nine missiles were ordered for the program in December.[15]

In addition to the Atlas, two other rockets were used in the Mercury program. The Little Joe rocket was a cluster of Castor and Recruit solid rocket motors used as a testbed for measuring ascent factors such as dynamic pressure, and evaluating spacecraft systems with Rhesus monkeys on board. The Little Joe rocket was incapable of placing the Mercury spacecraft in orbit, as was the Redstone. However, the Redstone was capable of placing the Mercury capsule in an exo-atmospheric ballistic flight and it was decided to use the Mercury-Redstone as another test vehicle prior to orbital launch with the Atlas.

A Chimpanzee named 'Ham' was launched on a suborbital flight aboard a Mercury-Redstone rocket on 31 January 1961, and after five further test launches of Mercury capsules Alan B. Shepard became the first U.S. man in space on 5 May 1961 aboard the Mercury-Redstone Freedom 7. The Mercury-Atlas launched John Glenn into orbit on 20 February 1962 aboard the Friendship 7 for three revolutions about the Earth. In all there were six manned Mercury missions, two suborbital flights on the Mercury-Redstone and four orbital flights on the Mercury-Atlas. The launch vehicles performed flawlessly in all manned flights, although of the total 25 Mercury launches there were seven failures.

The successes of the Mercury program had paved the way for the next step in U.S. manned space activities which was the Gemini program. Project Gemini was conceived

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[15] Emme, Eugene M., ed., The History of Rocket Technology: Project Mercury, Wayne State University Press, Detroit, 1964.

and approved as an intermediate step to Apollo in 1961. The Gemini (initially called the Mercury Mark II) was a two man capsule which required a higher performance launch vehicle than the Atlas. The Titan II was selected as the only proven launch vehicle capable of launching the Gemini program on schedule. The first Gemini-Titan launch was on 8 April 1964 with a boilerplate spacecraft, and the first manned Gemini-Titan launch was on 23 March 1965 with Grissom and Young. The last of twelve Gemini-Titan flights (10 were manned) ended on 15 November of 1966 and all were successful. The Gemini program provided data on the prolonged effects of weightlessness on the human body, and orbital rendezvous and docking operations between spacecraft in orbit.[16]

The Apollo program was the culmination of the series of early manned space launches of the U.S. A planned sequence of developments in manned exploration was leading to the goal which President Kennedy stated in his 25 May 1961 address to congress of 'landing a man on the Moon and returning him safely to the Earth'. A series of Saturn vehicles was envisioned, with the capability of ultimately launching the Apollo Moon mission.

The Saturn launch vehicle began in April 1957 when the U.S. Army Ballistic Missile Agency (ABMA) studied the possibility of achieving a large lift capability by clustering existing rockets. On 15 August 1958 the plans for this development were authorized by the Advanced Research Projects Agency (ARPA) under the project name of Juno V. The name was changed to Saturn on 3 February 1959 at the urging of Wernher von Braun. The Saturn program was then transferred to the new National Aeronautics and Space Administration (NASA) from the ABMA on 21 October 1959. This was done because the Saturn program had no direct military role as an ICBM and was applicable to

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[16] Hacker, B.C., Grimwood, J.M., On The Shoulders of Titans. A History of Project Gemini, Scientific and Technical Information Office, NASA, Washington, D.C., 1977.

the launching of satellites and space probes which fell under the auspices of NASA. Along with the Saturn program went the Development Operations Division of the ABMA. The first successful Saturn launch came with the 27 October 1961 launch of a Saturn SA-1. This vehicle was basically eight Redstone propellant tanks clustered around a Jupiter tank which was the core, using eight engines. A high energy S-IV cryogenic upper stage was used as well for the early Saturn 1, which provided a payload delivery capability of 20,000 lb to low Earth orbit, but was never used for manned missions. The Saturn 1B used essentially the same first stage as the Saturn 1 but a larger and more powerful cryogenic upper stage, the Saturn IVB which doubled the payload capability to 40,000 lb. This was enough to place manned Apollo capsules in orbit for testing. The first Saturn 1B was launched on 26 February 1966, and the initial manned flight was delayed when a flash fire in the capsule during tests killed astronauts Grissom, White, and Chaffee on 27 January 1967.

The first manned Saturn flight was aboard a Saturn 1B on 22 October 1968, placing Schirra, Eisele and Cunningham in orbit for 10 days. This was the last Saturn 1B flight for four and a half years, until a Saturn 1B was used to launch men to Skylab. The final Saturn 1B flight was in support of the Apollo-Soyuz Test Project on 15 July 1975. Nineteen vehicles of the Saturn 1 family were launched from 1961 to 1975, five of which were manned.

The Saturn V was developed as the launch vehicle for the Moon mission, and after considerable debate as to its configuration the basic design as we now know it was approved in January 1962. The Saturn V was largely a vehicle made from scratch, not directly using any significant hardware elements from previous launch vehicles with the exception of its Saturn IVB third stage which was the second stage of the Saturn 1B. It was design to serve a single purpose: placing a man on the Moon and returning him safely to the Earth.

AS-501 was the first Saturn V mission. It was unmanned and launched on 9 November 1967. The third Saturn V launch placed Apollo 8 with Borman, Lovell and Anders on a trip to the Moon and back in preparation for the first lunar landing. Apollo 11 was launched by a Saturn V on 16 July 1969 to enable Neil Armstrong to be the first man on the Moon. A total of 6 lunar landings were made, the final one launched on 7 December 1972.[17]

The Apollo program was very successful, requiring only five Saturn V launches prior to the first Moon landing when it was initially expected that as many as 15 preliminary flights might be needed.

The Saturn V was modified to launch Skylab into orbit on 5 May 1973. Skylab was built in a reconfigured S-IVB third stage of a Saturn V. This was the last of 13 Saturn V launches and left hardware for two completed launch vehicles unused.[18]

Manned activity in space for the U.S. experienced a hiatus of over 7 years between the Apollo-Soyuz Test Project (ASTP) of July 1973 and the first Shuttle flight of 12 April 1981. Shuttle flights placed men and women in orbit on 23 successful flights, but the Challenger disaster of 28 January 1986 has again created a hiatus in U.S. manned space activity. The shuttle is expected to fly again in late 1988, and will remain the only source of manned launch capability in the U.S. for the foreseeable future. There is no serious consideration in the U.S. of restoring the role of manned launch activities to expendable launch vehicles.

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[17] Turnill, R., The Observers Book of Manned Spaceflight, Frederick Warne, London, 1978.

[18] Bilstein, R.E., Stages to Saturn, A Technological History of the Apollo/Saturn Launch Vehicles, Scientific and Technical Information Branch, NASA, Washington, D.C., 1980.

However, the Soviet Union continues to launch manned missions to their MIR space station aboard the manned expendable launch vehicle Salyut.

2.5 Launch of Men Beyond Earth Orbit

The Apollo Moon missions are the only manned missions which have gone beyond the bounds of Earth orbit. The first to do so was the first manned Saturn V mission in which Borman, Lovell and Anders orbited the Moon and returned back to Earth. There were a total of nine manned missions beyond Earth orbit , all of them to the Moon. Six resulted in lunar landings, with Apollo 13 the only failure. An oxygen tank explosion en route to the Moon resulted in a loss of propellant which aborted the lunar landing. There are no definite plans for future manned missions beyond Earth orbit, however it seems likely the there will be a return to the moon or a mission to Mars after the turn of the century.

2.5 Summary

The expendable launch vehicles which have been developed and used in the history of space transportation in the U.S. are shown in the Table 2.2.

Name	Agency	GLOW [lb]	Stages	Payload [lb to LEO]	Year of First Launch
Atlas	NASA	260000	1.5	2200	1959
Atlas-Agena A	USAF	275000	2.5	5500	1960
Atlas-Agena D	USAF/NASA	275000	2.5	8800	1963
Atlas Centaur	NASA	326000	2.5	10000	1962
Delta	NASA	115000	3	600	1960
Delta D	NASA	143000	3.5	1280	1964
Delta E	NASA	150000	3.5	1500	1965
Delta M	NASA	227000	3.5	2800	1970
Delta 900	NASA	276000	3.5	3700	1972
Delta 1000	NASA	295000	3.5	4000	1972
Delta 2914	NASA	295000	3.5	4400	1974
Delta 3914	NASA	419000	3.5	4850	1975
Delta 3916	NASA	423000	3.5	5000	1979
Juno I	ABMA	64000	4	40	1958
Juno II	NASA	122000	4	100	1958
Saturn I	NASA	1100000	2	22000	1961
Saturn IB	NASA	1318000	2	40000	1966
Saturn V	NASA	6526000	3	330000	1967
Scout	NASA	37000	4	400	1960
Shuttle	NASA/DoD	4400000	1.5	65000	1981
Thor-Able	USAF	115000	4	280	1958
Thor-Able Star	USAF	118000	2	900	1960
Thor-Agena A	USAF	117000	2	310	1959
Thor-Agena B	USAF/NASA	123000	2	1500	1960
Thor-Agena D	USAF	123000	2	1500	1962
LTTAT-Agena D	USAF	138000	2.5	2500	1963
Titan II	NASA	300000	2	8100	1964
Titan III-A	USAF	309000	3	7900	1964
Titan III-B	USAF	395000	3	8800	1966
Titan III-C	USAF	1400000	3.5	28000	1965
Titan III-D	USAF	1400000	2.5	30000	1971
Titan III-E	NASA	1410000	3.5	30000	1974
Titan 34D	NASA/USAF	1742530	4.5	32800	1982
Vanguard	USN	22600	3	26	1958

Table 2.2

Summary of ELV performance characteristics.[19]

Over the past 30 years, many launch vehicles have come and gone. From the tiny Vanguard to the awesome Saturn V, there are many launch vehicles that are no longer in service. However, there are a few launch vehicles that have survived through an

[19] Baker, David, THE ROCKET: The History and Development of Rocket & Missile Technology, Crown Publishers, Inc., New York, 1978, page 267. Updates made from various sources.

evolutionary development process that has allowed them to be flexible and provide a variety of services. The survivors, particularly the Atlas, Delta, and Titan are all proceeding to the new market for commercial space launches.

There are common elements between the ELVs that have survived. Each of them has possessed the following characteristics:

- Flexible / Adaptable
- Successful / Reliable
- Cost Effective

The next generation launch vehicle will progress beyond the capabilities of the old reliable stable of Atlas, Delta and Titan. To be as successful as these vehicles have been must, it must retain these characteristics.

Chapter 3 ENHANCED UTILIZATION OF ELVs

In the past thirty years of space activity, orbiting systems have been materially autonomous once in space. Some spacecraft have been dependent on ground control for telemetry, but none have relied on any material resource for effective operation. As the infrastructure of space operations begins to mature, dependencies are beginning to develop between systems that will be placed in orbit. Spacecraft will require maintenance and refueling to extend their operational lifetime. Reusable orbital transfer vehicles will provide transportation services, and they will require servicing, refueling and refurbishment. The space station will be a focal point of the space operations infrastructure, and it will require replenishment of expendables and regular maintenance and servicing. As space operations begin to mature, the dependencies between the elements of the space infrastructure begin to grow, and new functions, services, and resources are required that were never previously required.

There are several visions of what the future infrastructure of space operations might look like.[1,2,3] The Space Transportation Architecture Study (STAS) has been addressing the issue of what the best mix of space transportation vehicles might be for the space infrastructure. STAS is a study being cosponsored by NASA and the Air Force and is

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1 Waltz, D., TRW Military Space Systems Division, TRW Space & Technology Group, Design and Support of Serviceable Spacecraft, Satellite Servicing Workshop III, NASA/Goddard Space Flight Center, 9-11 June 1987.

2 Rockwell International., Space Transportation Systems Division, Space Platform Expendables Resupply Concept Definition Study, Final Report, NASA-CR-178819, December 1985, page 13.

3 Office of Technology Assessment, United States Congress, Civilian Space Stations and the U.S. Future in Space, OTA-STI-241, November 1984, pp. 49-102.

being performed by four contractors. There are certain elements to all of the proposed infrastructures which are basically common. These elements are:

- An Unmanned Heavy Lift Launch Vehicle (Shuttle class or larger)
- A Space Station (Current baseline for International Space Station)
- An Orbital Transfer Vehicle (Reusable, initially unmanned but manned potentially)
- Spacecraft Servicing Satellites (Orbital Maneuvering Vehicle (OMV) and future more sophisticated systems)
- Propellant Storage and Transfer (Space Station based or free-flying)

The efficacy of an infrastructure utilizing these basic components has been studied extensively. However, in order to establish an infrastructure which incorporates each of these functions, it is not necessary to have separate hardware items for each of the functions. A schematic of these basic functions of the future space operations infrastructure and hardware elements that can provide them can be seen in Figure 3.1.

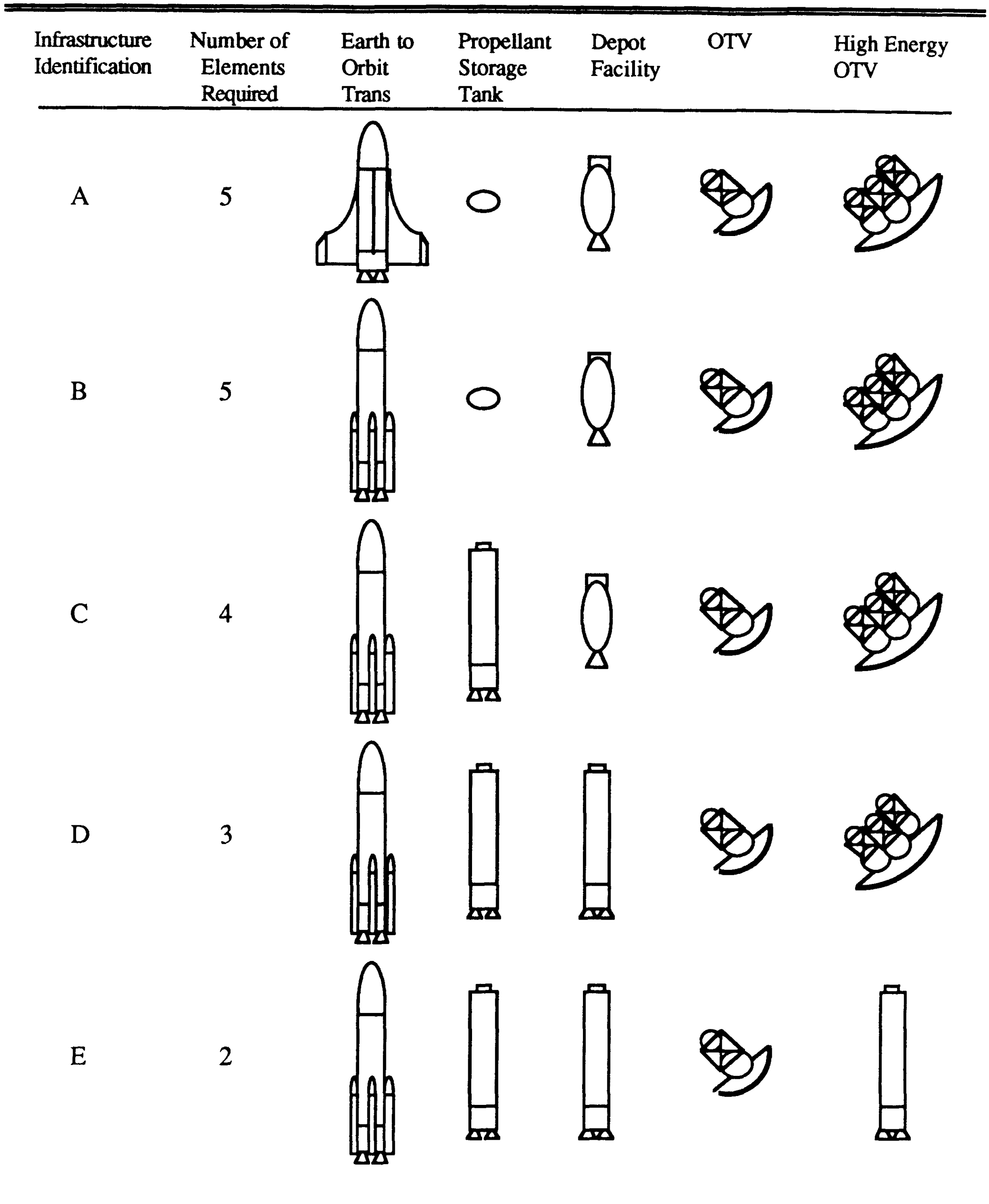

Figure 3.1
Basic elements of the future space operations infrastructure options.

Infrastructure A incorporates the standard elements which are being considered currently. The shuttle is to be the primary propellant delivery vehicle, with propellant scavenging used to take advantage of low shuttle load factors which are projected to be from forty to seventy five percent. The scavenging missions will be augmented by a mix of dedicated missions which utilize more of the shuttle payload capability than is allowed by taking advantage of a low load factor.[4] Propellant will be loaded into a tank located either in the payload bay or in an aft cargo carrier (ACC) for transportation and delivery. The use of scavenging will provide a significant portion of the propellants required, but dedicated flights will be required to match projected demand.[5]

Infrastructure B incorporates an ELV as the transportation vehicle for propellant delivery. The shuttle is replaced in this scenario, but similar operations are used for propellant delivery. A separate tank is used as part of the payload, and used to provide propellant by taking advantage of the unused payload capability due to a load factor less than one.

Infrastructure C uses the ELV of B in an additional role beyond that of transportation only. The separate tanks used for propellant storage are not needed because the propellants are transferred from the propellant tanks of the ELV itself once in orbit. Some additional technology for propellant transfer must be added to the ELV tanks, but this eliminates the need for development of a separate hardware element to perform the propellant storage function during delivery.

Infrastructure D builds on the concept used in C by using the ELV not only as a transportation and propellant storage vehicle for delivery, but as a long term propellant

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[4] Fester, D., Martin Marietta Denver Aerospace, Earth-to-Orbit Propellant Transportation Overview, NASA Report N85-17002, 1985.

[5] Rockwell International Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume I, Technical Report, NASA -CR-171848, January 1985.

storage depot in orbit. This reduces the total number of hardware elements of the system from five to three.

The final infrastructure in the figure is E. This infrastructure incorporates maximum use of the ELV by adding to the uses in D an additional role as high energy upper stage for large payloads. This scenario finds the ELV fulfilling four different functions that in the original A and B infrastructures were performed by four separate hardware elements.

Expendable launch vehicles have the potential to contribute much more to the space operations infrastructure than merely earth to orbit transportation. There are many ways which they can contribute resources which they are composed of, which are already in orbit, and can be economically utilized if there is sufficient demand. The feasibility of any proposed utilization is dependant on matching the resource with a demand for that resource. Identification of some areas of future demand which can be fulfilled by ELV resources was seen in Chapter 1 in Table 1.1.

The development of the demand for resources in space is a process which takes place over a considerable time period. The time period at which various resources of an ELV might satisfy orbital demand is a function of the maturity of the infrastructure, thus the type of demand, and the complexity of deriving that resource from the ELV. These distinctions will become more clear as this discussion progresses, but let assume us for now that certain categories of utilization will become manifest with the maturity level of the space operations infrastructure. Therefore the utilization of ELV resources will be a time phased process. As seen in the introduction, the categories for utilization can be generally categorized into four groups. These groups are identified in Figure 3.2, with the primary resources to be used by each group, the sources of demand for those resources, and the author's estimate of the year when those resources might begin to be used in space.

USE	DEMAND	YEAR
PROPELLANT/LIQUID RECLAMATION		
- Cryogenics	- Orbital Transfer Vehicles	1994
- Storables/Water	- Space Stations	1992
	- Satellites	1989
REUSE OF ENTIRE ELV		
- Propellant Depot	- Propellant Resupply Infrastructure	1994
- High Energy Upper Stage	- Large Lunar / Martian Missions	2000+
REUSE OF ELV COMPONENTS		
- Tankage	- Pressure Vessels	2000
	• Storage	
	• Habitat	
- Structure	- Satellites / Stations	2000
- Avionics	- Satellites / Stations	2000
- Propulsion	- Satellites / Stations	2000
RECOVERY OF ELV MATERIALS	- Raw Material Stock	
- Metals	• Materials Processing	1996
- Non-Metals	• Space Manufacturing	2010+

Figure 3.2
Orbital utilization is driven by the demand for resources in orbit.

The following discussion will address the resources which can be provided by the ELV and the demand which may develop to utilize the resources. The time factor is critical to match the technological maturity and availability for economic provision of the ELV resource with the infrastructure maturity which develops the demand for the resource. Various sources of demand will be addressed for each of the categories, along with the feasibility or expected likelihood of a potential match between demand and supply.

3.1 Orbital Propellant Reclamation

The need for resupply of propellants in orbit for spacecraft and OTVs is well established and will be an operational reality in the near future. The Soviets are routinely performing refueling and resupply missions to the MIR space station with their Progress tanker. NASA has performed propellant transfer flight experiments aboard the space shuttle prior to the Challenger disaster and has plans for several propellant transfer experiments in the near future. As Rockwell pointed out in a recent study,

> NASA has recognized that the capability for remote resupply of space platform expendable fluids will help transition space utilization into a new era of operational efficiency and cost/effectiveness.[6]

Expendable launch vehicles have propellants in their tanks when they achieve orbit, which is destroyed with them as they burn up in the atmosphere. Orbital facilities will be in need of propellant supplies for their own propulsion system, for resupply of other compatible consumables (for LOX and LH2 systems) and for supply of propellant for orbital maneuvering and transfer vehicles. The specifics of the resources which can be supplied and the demand for utilization of those supplies is addressed in the next sections.

3.1.1 Propellant Supply

On a nominal mission to LEO for satellite deployment, a launch vehicle will have propellant left over in its tanks that is equivalent to ten or twenty percent of its payload

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Rockwell International Corporation, Space Platform Expendables Resupply Concept Definition Study, Final Report, NASA-CR-178819, December 1985, page 9.

weight. This leftover propellant on nominal missions is the result of residuals and flight reserves. Propellant residuals are the propellant that the propulsion system is unable to remove from the tanks during the normal ascent phase of the mission. The amount of residual propellants varies between launch vehicles and their tanks, but is generally in excess of one percent of the propellant handling capability of the tank.

Flight propellant reserves are the other component of the nominal propellant which is leftover on a typical flight. The reserves are a contingency built into the launch vehicle that allow for a flight which requires more than the nominal amount of velocity to achieve orbit. Additional velocity requirements can arise for several reasons. The basic components which constitute the total velocity requirement of a launch vehicle are as follows:

- Orbital velocity
- Velocity losses due to the earth's gravitation
- Velocity losses due to atmospheric drag
- Velocity losses due to atmospheric expansion of engine exhaust
- Velocity losses due to steering

The orbital velocity is constant for a particular mission, so that does not deviate and cause use of propellant reserves. Gravitation losses can increase if there is a loss in thrust level, or if there is a deviation from the nominal ascent trajectory. Drag losses can increase if atmospheric conditions are stormy with increased wind velocities, or with non-standard variations in the atmospheric density. Expansion losses from the engine exhaust are fairly constant but can vary with deviations in the nominal atmospheric pressure. Steering losses are basically the losses associated with a thrust vector that is not parallel to a velocity vector, and can be increased by anything that creates greater deviation in the thrust vector. Such deviations might be caused by loss of thrust, changes in the nominal ascent trajectory, and wind conditions.

The amount of propellant which is set aside as reserve is typically one or two percent of the propellant to be used, so it is on the same order as the residuals. Therefore, when the residuals and the reserves are taken into account, there should be nominally at least two percent of the propellant capability of the tanks left in them after they are in orbit. As mentioned previously, this amount of weight in orbit is at least ten to twenty percent of the payload capability of the launch vehicle. Simply put, if there is a need for this propellant in orbit, a significant portion of payload capability is being wasted when the launch vehicles are destroyed.

There is another source for propellant in orbit which is more substantial than the residuals and the reserves. This is the propellant that can be placed in orbit to take advantage of a load factor that is less than one hundred percent. The load factor is simply the percentage of the payload capability that is being used for the particular mission. For the majority of launch vehicles which are currently in service, the load factor normally approaches one hundred percent because the payload capability is relatively small and the payloads are usually a single satellite that is specially designed and sized to match the capability of its launcher. However, with the space shuttle and with launch vehicle or payload capability comparable to the shuttle or larger, load factor decreases.

Load factors decrease from one hundred percent for larger payload vehicles because as the payload capabilities increase, multiple manifesting is used. Most satellites are not large enough to require the entire launch capability of the shuttle or one of the proposed heavy lift launchers. Therefore several payloads are launched at once, and they are packaged within the cargo bay or payload shroud to accomplish multiple deployments. There are two limits for multiple manifesting, the first being volume and the second being weight. Volume limited payloads take the entire volume of the cargo bay or the payload shroud but do not match the total payload weight of the launcher thereby leaving some of the launch capability unused. When multiple manifesting is limited by the payload limit, there is still often excess capability. A simple example would be a vehicle with 65,000 lb payload capability such as the shuttle, which is launching four 15,000 lb satellites. There is 5,000 lb available but there may not be a satellite of 5,000 lb or less that is ready at that launch date or is compatible with the deployment requirements of the other satellites. Because of these limitations, the load factor is less than one hundred percent for larger capability launcher. Load factors generally average on the order of sixty to eighty percent, which means that on the average twenty to forty percent of the lift capability of a launcher is being wasted.

Utilization of the load factor can be achieved by adding more payload to the vehicle somehow, or by flying the nominal trajectory with full tanks and having excess propellant in the tanks after achieving orbit. Typically for a mission which uses less than the maximum payload capability, the propellant tanks will be off-loaded so that they are not completely full and only carry the propellant necessary to satisfy the mission requirements. By always flying with the tanks full rather than partially full, the losses to the system which are brought on by having an average load factor which is inevitably less than one hundred percent can be mitigated.

Launch vehicles perform most effectively at their design conditions. There is not a full recovery of payload by flying with full tanks and less than full payload. The recovery is roughly ninety percent, depending on the particulars of the vehicle and the mission.[7] As an example, if a launch vehicle with 100,000 lb nominal payload capability is manifested with a load factor of eighty percent, the excess propellant placed in orbit should be 18,000 lb. With the addition of propellant available from reserves and residuals in the tankage, the

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[7] Rockwell International, Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study, Final Report, Volume 1, Technical Report, NASA-CR-171848, January 1985, page 2.

amount of propellant available on orbit from a 100,000 lb payload class launch vehicle is seen in Figure 3.3.

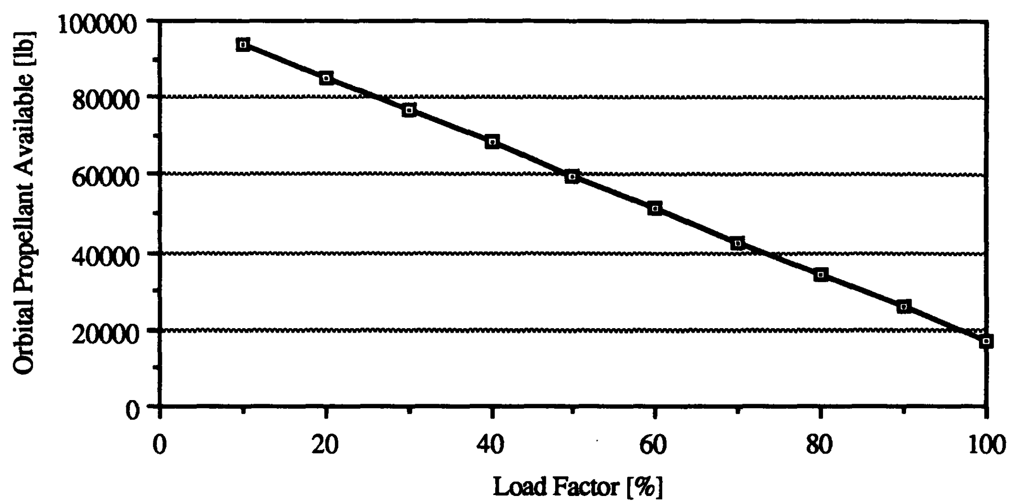

Figure 3.3
Orbital propellant available as a function of load factor for a 100,000 lb lift capability ELV using liquid oxygen and liquid hydrogen propellants.

A more detailed discussion of the relation between load factor and the amount of propellant available on orbit is in chapters 5 and 7.

Once in orbit, the propellant would be transferred to an orbital propellant depot for storage until it is needed by an OTV or some other use. An example of a nominal trajectory which outlines this basic scenario of propellant reclamation and gives an idea of the amount of reclaimable propellant delivered to orbit as a function of load factor is shown in Figure 3.4.

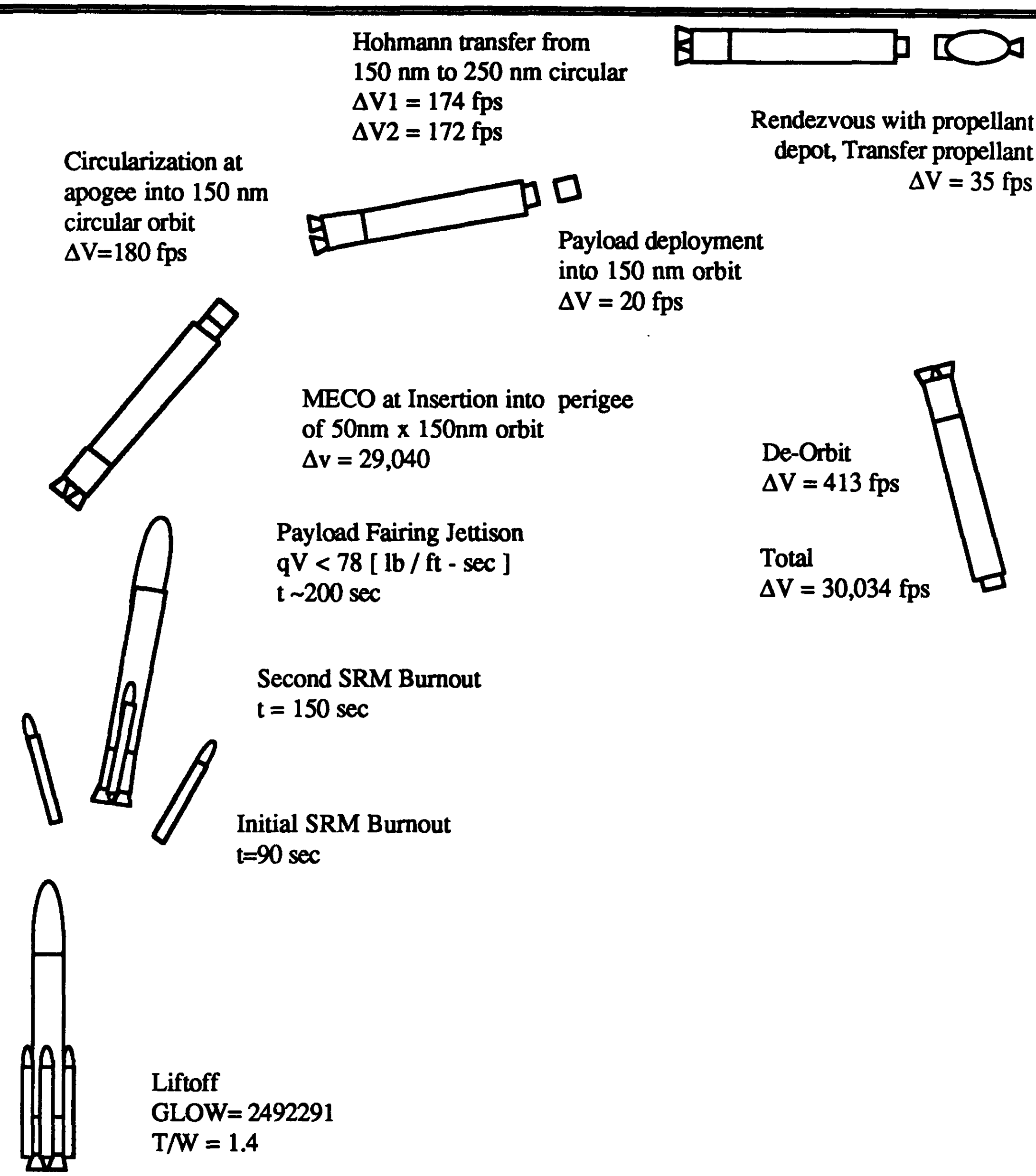

Figure 3.4

Operational Flight Scenario for Propellant Reclamation.

3.1.2 Propellant Demand

Resupply of consumables for spacecraft, particularly propellants has been recognized by NASA as providing tremendous benefits in terms of satellite life and life cycle costs. Because of this recognition, the necessary technologies for liquid transfer in orbit are being developed.[8] An infrastructure is being designed which will provide the means for providing consumables resupply to user spacecraft. There are several spacecraft sitting on the ground waiting to be launched, in the production phase, or in the funded design phase which are dependent on servicing and consumables resupply for their operation.[9] Some of these spacecraft are indicated in Table 3.1.

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8 Aydelott, J.C., NASA Lewis Research Center, and Rudland, R.S., Martin Marietta Denver Aerospace, Technology Requirements to be Addressed by the NASA Lewis Research Center Cryogenic Fluid Management Facility Program, NASA-TM-87048, 1985, pp. 1-3.

9 Waltz, D., TRW Space & Technology Group, Military Space Systems Division, Design and Support of Serviceable Spacecraft, NASA GFSC Satellite Servicing Workshop III, Session III - Serviceable Spacecraft Designs, 9-11 June 1987.

Satellite	Life [Yrs]	Alt [nmi]	Inc [deg]	Mass [lb]	Launch Date	Consumables (Type)
Advanced X-Ray Astrophysics Facility (AXAF)	15	324	28.5	18,950	1992	Liquid He, Argon, Zenon, CO^2
Earth Observing System (EOS)	10	381	98.25	22,030	1992	Cryogens
Gamma Ray Observatory (GRO)	5	270	28.5	31,000	1990	Hydrazine
Gravity Probe-D (GP-D)	1	520	90.0	4,000	1990's	Liquid Helium
Large Deployable Reflector (LDR)	10	500	28.5	121,170	1997	Superfluid Helium
Proteus Platform	10	216	28.5	2,203	1992	Hydrazine
Shuttle Infrared Telescope Facility (SIRTF)	5	378	28.5	8,812	1994	Cryogens, Superfluid Helium
Upper Atmosphere Research Satellite (UARS)	2	320	57.0	11,000	1991	Solid Hydrogen

Table 3.1

Satellites utilizing consumables resupply.[10]

The evidence of these satellite programs which are waiting to be launched or are under way is testimony to the fact that consumables resupply in space will be a reality. Several estimates have been made as to the propellant supply requirements of satellites and the space station over the decades to come.[11] Most of the estimates are consistent and as a

[10] Data from:
Rockwell International Corporation, Space Platform Expendables Resupply Concept Definition Study, Final Report, NASA-CR-178819, December 1985, page 33.
Committee on Advanced Space Technology, Aeronautics and Space Engineering Board, Commission on Engineering and Technical systems, National Research Council, Space Technology to Meet Future Needs, National Academy Press, Washington, D.C., 1987, pp. 20-42.

[11] Rockwell International Corporation, Space Platform Expendables Resupply Concept Definition Study, Final Report, NASA-CR-178819, December 1985, pp. 28-35.

representative sample of expected demand for consumables resupply, Figure 3.5 is a NASA estimate based on projections of several other sources.[12]

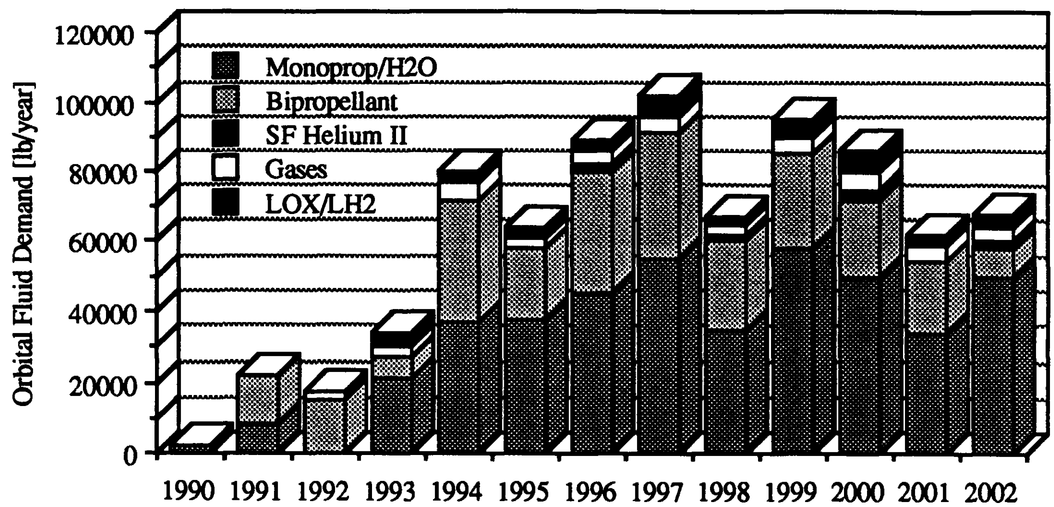

Figure 3.5
Orbital Fluid Resupply quantities demanded per year.[13]

As demand develops in the mid-1990's, the primary fluids required are bipropellants and monopropellants (hydrazine) and water. The demand for bipropellants is for twenty to thirty thousand pounds per year, declining after the turn of the century. Monopropellants and water are needed at the rate of about forty thousand pounds per year from 1994 on. These demands are significant, but at a total of between sixty and one hundred thousand pounds per year would require only one or two shuttle equivalent flights per year. Particularly the demand for cryogenics is but a few thousand pounds a year. The type of heavy lift ELV that would be used for propellant reclamation will almost surely use cryogenic rockets.

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12 Griffin, J.S., NASA, Johnson Space Center, Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers, AIAA Paper 86-1601, 1986, pp. 4-5.

13 Griffin, J.S., NASA, Johnson Space Center, Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers, AIAA Paper 86-1601, 1986, Page 4.

The most significant demand for fluids in orbit comes from the reusable orbital transfer vehicle. This vehicle will provide transportation for payloads from low earth orbit to high energy orbits, primarily geosynchronous. The OTV will almost certainly be a cryogenic vehicle in order to maximize its performance, although other propellants have been considered, including electrical propulsion for some missions which are not time-sensitive. On a typical flight the OTV may use 40,000 lb or cryogenic propellants to deliver a 13,500 lb payload to geosynchronous orbit. With even ten flights per year this is a significant requirement for cryogenic propellants in orbit. When comparing the demand for cryogenic propellants from the OTV with the demand for liquid consumables and propellant from other sources, the OTV demand is overshadowing. This can be seen in Figure 3.6 which is the same data as that in Figure 3.5 with the demand from the OTV added.

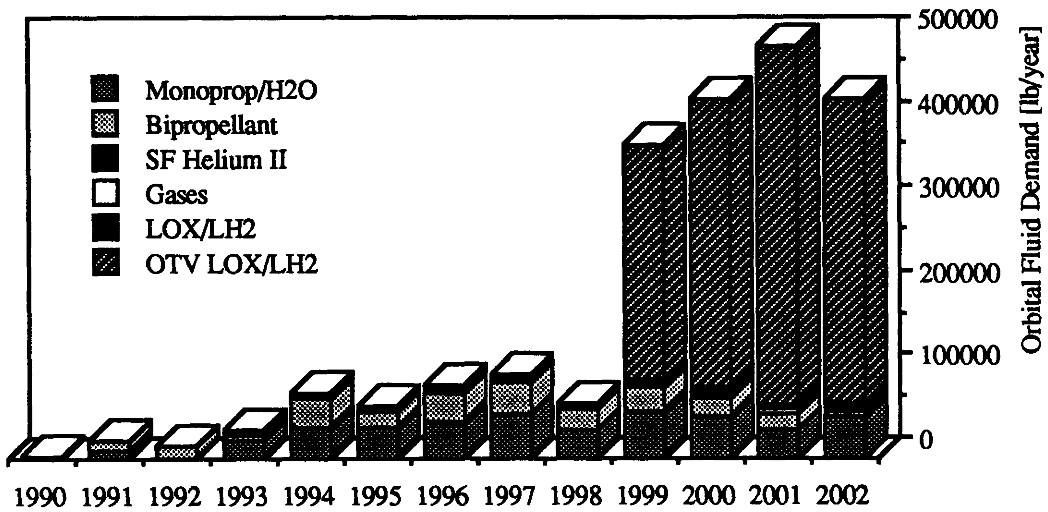

Figure 3.6
Orbital fluids resupply requirement including OTV demand.[14]

[14] Griffin, J.S., NASA, Johnson Space Center, Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers, AIAA Paper 86-1601, 1986, Page 4.

The demand for propellants in orbit increases significantly with the advent of the reusable space based orbital transfer vehicle, which occurs in 1999 in this case. The estimates from this NASA source are for civil missions only, and when military missions with the possibility of SDI deployment are also considered, the demand can increase dramatically to more than a million pounds a year. An example of this can be seen in Figure 3.7 which shows three General Dynamics estimates. These estimates are based on the NASA-MSFC OTV mission model (Rev. 9) which includes five scenarios that were used in STAS. The data is for a modular space based orbital transfer vehicle (SBOTV) which uses cryogenic hydrogen and oxygen, and aerobraking.

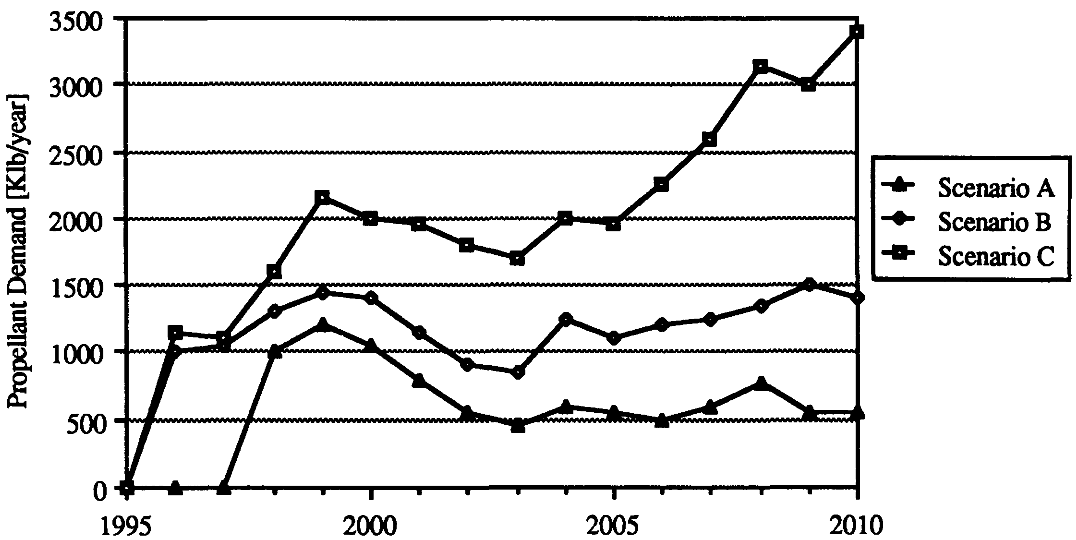

Figure 3.7
OTV propellant requirements.[15]

The three scenarios for this propellant demand estimate are as follows: scenario A is the low estimate for both civil and DoD use. Scenario B is the baseline scenario which has an increase in civil GEO activities and an increase in DoD use. The third scenario, C is a

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[15] General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986, pp. 2.1-2.4.

further increase in civil use, particularly in GEO, no increase in DoD use from scenario B, and the introduction of Nuclear waste disposal using OTVs which accounts for the majority of the increase. A summary of these scenarios by mission is shown in Table 3.2.

Mission group	Scenario A	Scenario B	Scenario C
Experimental GEO Platform	1	1	1
Operational GEO platforms	0	0	0
GEO shack elements	0	2	2
Manned GEO sortie	0	16	22
GEO shack logistics	0	37	51
Unmanned planetary	14	14	25
Unmanned lunar orbit	0	3	4
Unmanned lunar surface	0	5	1
Lunar orbit station	0	0	1
Manned lunar sorties/logistics	0	0	8
Multiple GEO payload delivery	84	84	88
Large GEO satellite delivery	10	10	19
GEO satellite retrieval	2	2	2
Nuclear waste disposal	0	0	391
DoD (generic)	176	240	240
Subtotal	287	414	855
Reflights	5	8	17
Total	292	422	872

Table 3.2
OTV mission model comparison.[16]

The demand for propellants in orbit is evident, as is the domination of OTV refueling in the demand. There is little question that OTVs will one day be developed and operational in space. There are however, many questions remaining as to where the

[16] General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986, page 2.3.

propellant for resupply will come from and how it will get there. The next generation of ELVs provides a resource supply that matches well with the demand, and can be provided at a low cost relative to other sources.

3.2 Orbital Reuse of Entire ELV

Once an ELV has delivered its payload, it is orbiting the earth with all of its tanks, avionics, propulsion systems, and remaining propellant. There are uses for such vehicles in orbit which can be realized if certain elements of the future infrastructure are in place. Two primary uses are evident. The first is to use the orbital ELV as a propellant depot facility, and secondly as a large upper stage for large payload high energy missions.

3.2.1 Demand

The demand for an orbiting propellant storage depot is clearly established by the requirements of the new space infrastructure.[17] The specific characteristics of the demand are not well known, but the general characteristics are. These characteristics will of course be determined by the types of spacecraft that will be accessing an orbital propellant facility, their rates of access, and the amount of propellants they require. Propellant requirements have been estimated in section 3.1 to be on the order of a few hundred thousand pounds per year beginning in the mid to late 1990s. The primary user spacecraft will be reusable orbital transfer vehicles, probably requiring 25,000 to 50,000 pounds of propellant per

[17] Office of Technology Assessment, United States Congress, Civilian Space Stations and the U.S. Future in Space, OTA-STI-241, November 1984, pp. 49-82.

mission.[18] Sizing studies for an orbital propellant depot have indicated that its propellant storage capability should be 100,000 pounds, which is a size consistent with orbital delivery in the shuttle cargo bay.[19] Larger sizes are possible, when delivered by a launch vehicle with large lift capability other than the shuttle.

The need for large upper stages is dependent on the type of missions being planned and the size of the payloads that will be used for those missions. High energy missions envisaged include[20]:

- Geosynchronous transfer
- Planetary probes
- Deep space probes
- Lunar manned missions
- Lunar unmanned (exploration or cargo/supply) missions
- Mars manned missions
- Mars unmanned (exploration or cargo/supply) missions
- High energy plane changes

These missions will be served in large part by the reusable orbital transfer vehicle. For missions that require large payloads and high ΔVs, a vehicle with larger capabilities may be required. Studies have addressed the issue of the occasional large, high ΔV

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[18] General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986, page 2.2.

[19] Schuster, J.R., Bennett, F.O., Liggett, M.W., and Torre, C.N., General Dynamics Space Systems Division, and Brown, N., NASA MSFC, Evaluation of On-Orbit Cryogenic Propellant Depot Options For the Orbital Transfer Vehicle, Paper 88c, 6th Intersociety Cryogenics Symposium, 2-7 November 1986, Miami Beach, Florida, pp. 1-4.

[20] Pioneering the Space Frontier: The Report of the National Commission on Space, Bantam Books, New York, May 1986, pp. 12-15.

payload by using multiple staging of OTVs or of attaching several propellant modules to a core OTV.[21] These solutions are feasible, and so is the use of orbital ELVs.

3.2.2 Supply

Orbital ELVs will have the basic components necessary to provide the service of a propellant depot facility: storage tanks, propellant transfer capability, propulsion system, avionics, and capability for guidance and control. There is little question of the availability of ELVs in orbit for this type of utilization. If ELVs are built and flown, they will be in orbit. There are two concerns about use of ELVs as propellant depots. First is their limited insulation and inherent design for short term propellant storage and second is their size, which is for roughly 800,000 pounds of propellant.

Adequate insulation to prevent boiloff of the cryogenic propellants being stored in orbit is critical. Without adequate insulation, heating rates to propellant tanks can create serious boiloff problems.[22] Methods have been studied for eliminating boiloff losses by incorporating refrigeration or reliquifaction technologies. Passive systems can reduce boiloff to less then 0.2 percent per month through incorporation of multilayer insulation (MLI) and vapor-cooled shields (VCS).[23] The standard insulation of a launch vehicle has a

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21 General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986, pp. 3.1-3.5

22 Rockwell International, Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume I, Technical Report, NASA-CR-171848-Vol-1, January 1985, pp. 57-64.

23 Schuster, J.R., Bennett, F.O., Liggett, M.W., and Torre, C.N., General Dynamics Space Systems Division, and Brown, N., NASA MSFC, Evaluation of On-Orbit Cryogenic Propellant Depot Options For the Orbital Transfer Vehicle, Paper 88c, 6th Intersociety Cryogenics Symposium, 2-7 November 1986, Miami Beach, Florida, pp. 5-9.

much lower performance than do these specially designed systems for long term cryogenic storage. Therefore if the ELV were to be used as an orbital propellant depot, it would require additional insulation. The insulation could be integrated with the vehicle on the ground, or once the vehicle is in orbit. Ground applications of additional insulation would have to be able to withstand the ascent of the launch vehicle, and would diminish performance of the ELV due to their added weight. Space operations for application of additional insulation would be a time consuming task for EVA, and would likely not be tailored to automation.

The size of the ELV tanks, with an 800,000 pound capacity is much larger than is required for the expected demand. Because of this oversize, boiloff problems would be exacerbated. Surface area of the tanks would be much larger than that of a more optimally sized facility therefore taking on more solar radiation. The tankage and structural mass which must be cooled to cryogenic temperatures would also be greater. Because of the complications associated with conversion of an ELV to use as an orbital propellant depot, this mode of utilization is not feasible for the demand which is being assumed.

Utilization of orbital ELVs as high energy upper stages is less complicated than that of long term propellant storage and is quite feasible. A particular scenario for use of the ELV in this manner is described in Figure 3.7. The payload for this scenario is one that required substantial ΔV for a high energy mission, and is a large payload that requires the full payload capability of the launch vehicle. The ELV ascends with its payload to orbit, then to rendezvous with a propellant depot. Propellant from the depot is transferred to the ELV tanks until there is sufficient propellant to achieve the ΔV required for the mission (this may require propellant from more than one depot, depending on the size of the depot). When the ELV is properly filled, it proceeds from LEO to wherever the payload is destined. In doing so it acts essentially as both the first and second stage for the rocket, thereby reducing the need for a separate upper stage.

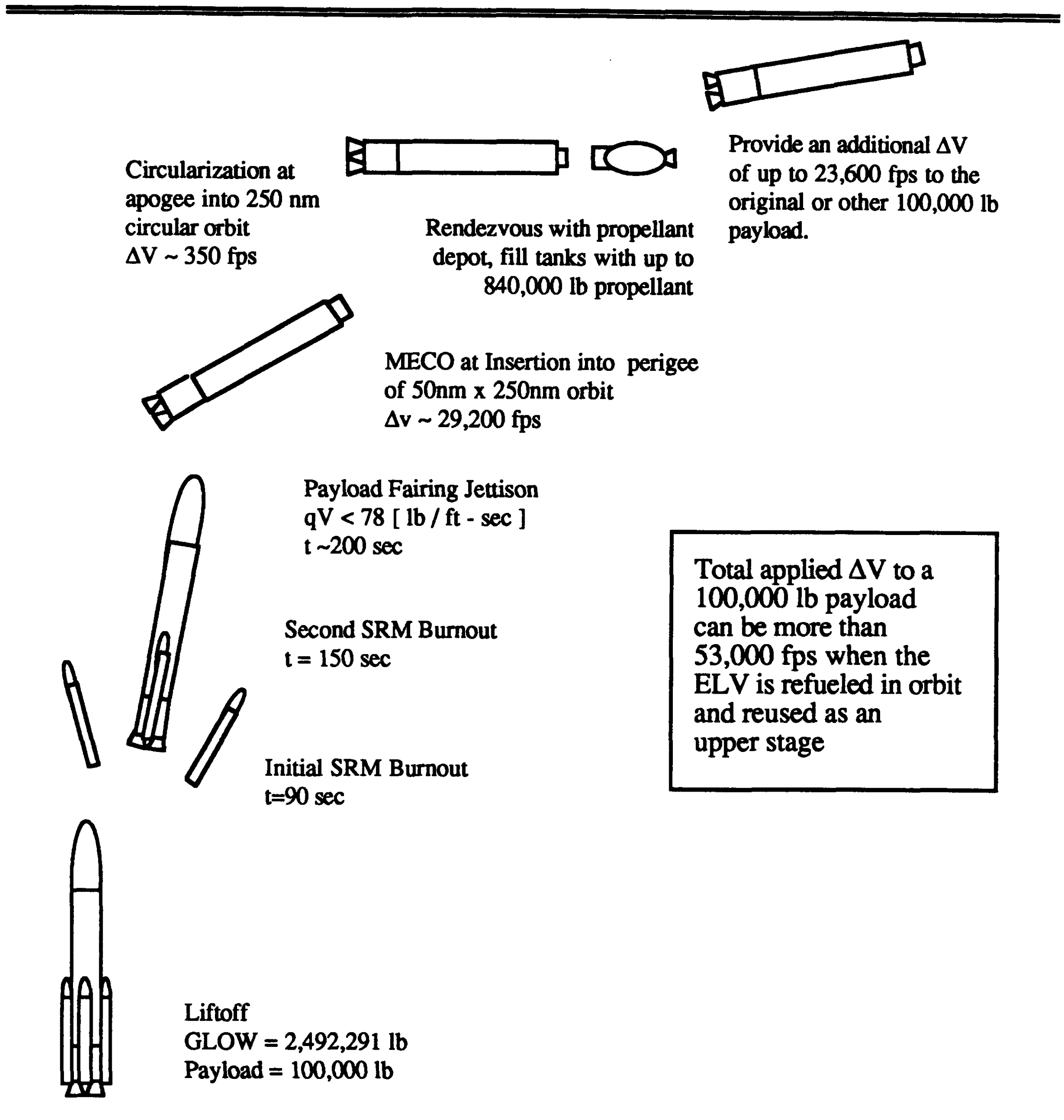

Figure 3.8
Scenario for reuse of entire ELV as high energy upper stage.

ELVs have the potential to be used for this purpose for smaller payloads as well, but for smaller payloads they become less and less efficient. This is because of their huge size. If an ELV from the previous scenario is delivering a 12,000 pound payload one way to GEO it will require 206,000 lb of propellant. If the same task is being performed by a reusable OTV with aerobraking, the propellant requirement will be only 41,500 pounds and this is a round trip with 2,000 pounds returned to LEO.[24]

Orbital reuse of entire ELVs is possible as high energy upper stages and as propellant depots. Due to the expected nature of the demand for such services however, it will be practical to use entire ELVs only as high energy upper stages for large payloads. The expected time period for the onset of such missions is the turn of the century.[25] Prior to that time, the infrastructure will be getting established in preparation for support of these advanced missions.

3.3 Orbital Reuse of ELV Components

An ELV is composed of several different subsystems such as propulsion, avionics, tankage, and structure. Any spacecraft is composed of these basic subsystems. For spacecraft that are to be built in space, or to be repaired through maintenance operations there is a need for components to these basic subsystems. If there is modularization and standardization of components between the various space systems, then there is potential for reuse of components from ELVs in orbit.

Spacecraft components have been used for multiple purposes previously, but never before has the work been done in space. Some reuses of components include: rechargeable Nickel-Cadmium batteries used in British UoSAT satellites were surplus NASA cells from

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[24] General Dynamics Space Systems Division, Orbital Transfer Vehicle Concept Definition and System Analysis Study, Final Report, NASA-CR-179055, December 1986, page 2.2.

[25] Pioneering the Space Frontier: The Report of the National Commission on Space, Bantam Books, New York, May 1986, Page 15.

the ITOS program; a Polar Bear (Beacon Explorer/Auroral Research) satellite was made from a surplus Transit navigation satellite that had spend eight years in a museum; ICBMs such as the Atlas and Titan II being refurbished as ELVs; seats and instrument panels reused in Gemini and Apollo programs; Skylab built from Saturn IVB rocket stage; sharing of parts between shuttle orbiters; use of Progress freighters by the Soviets as garbage trucks - they have taken garbage from Salyut and MIR with them after they leave the space station to burn up in the atmosphere; spare RTGs from Galileo to be used on the proposed Comet Rendezvous/Asteroid Flyby (CRAF) mission; and many other examples.[26]

The basic scenario involved for orbital reuse of ELV components is for the ELV to rendezvous with a spaceport which has the capability of disassembling the ELV into its component parts. The disassembly could be an automated process or involved manned operations through EVA, or potentially in pressurized work habitats. The disassembled components could then be placed in an inventory from which they would be taken as a need arose, or they could be disassembled in response to a need.

There have been numerous studies which have addressed orbital uses for the external tank (ET) of the space shuttle, and many of the uses for the tankage and structure of an ELV are similar to those under consideration for the ET. One of the most complete is the study done by Gimarc for the Space Studies Institute. Some of the uses envisaged by this study for ET components in orbit are shown below.[27]

- Cryogenic storage
- Storage of water and gases

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[26] Lorenz, Ralph D., "Born Again! Second-hand Spacecraft are Sometimes Given a New Lease of Life", Spaceflight, Volume 30, March 1988, pp. 93-95.

[27] Gimarc, Alex J., Report on Space Shuttle External Tank Applications, Space Studies Institute, Princeton, New Jersey, 1 December 1985.

- Storage containers for orbital debris
- Storage containers for orbital assets
- Habitation modules
- Hangars or service platforms for spacecraft
- Manned Space Station / Platform
- Landing / re-entry module
- Orbital wake shield
- Variable gravity facility using tethers
- Momentum exchange using tethers
- Structural base for observational satellites

These uses are equally applicable to an ELV and its components in orbit, and in fact they would likely be easier to achieve with an ELV. The primary reason for this is that the ET is just a set of tanks, whereas an ELV has its own propulsion system, guidance capability, and attitude control system. The ET, to rendezvous with a facility for disassembly and use would require the dedicated use of the shuttle orbiter, or some other orbital maneuvering system.

There is in fact a company which has plans to convert ETs into an orbiting laboratory. External Tanks Corporation (ETCO) has been conducting discussions with NASA for the project and is seeking private investment to finance their venture. They project annual profits of more than $ 30 million in the 1990s after operation of the laboratories has begun.[28] NASA is interested in the project and has indicated that it is within the current state of the art. However they have pointed out several difficulties associated with it:

- Reduction of the shuttle payload capability.
- Propellant requirements to prevent early reentry of the ET.

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28 "Company Seeks Funds for Orbiting Laboratory", Aviation Week & Space Technology, 12 January 1987, pp. 102-103.

- Additional propulsion and guidance equipment to orient the tank properly.
- Accessibility of the orbiting tank.
- Probability of micrometeoroid or space debris damage to the tank or potential impact of the tank with useful satellites.
- Cost of tank modifications and operations.[29]

If conceived during the design process, uses for ELVs such as those envisioned for the ET could be incorporated in the design. They could eliminate some of the difficulties that are being faced in ET redesign for orbital use such as additional fittings, handholds and grips, hatch relocation, and tank interface.[30]

The use of components from ELVs for constructing space habitats has been done previously, but the spacecraft was constructed on ground rather than in space. The Skylab spacecraft, the first space station, was constructed from the empty tanks of the third stage of the Saturn V ELV. The use of the empty tanks for the structural shell of Skylab, as well as common hardware from other programs was summarized in a NASA publication which chronicled the Skylab program:

> Many factors influenced the final design configuration of Skylab. However, one of the most important was an economic necessity to use components and equipment, where possible, that had been developed for other programs.[31]

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[29] "Company Plans Conversion of Shuttle Tanks to Orbiting Research Platforms", Aviation Week & Space Technology, 29 February 1988, page 38.

[30] Price, Robert L., Martin Marietta Aerospace, "A Plan to Make Space Shuttle External Tanks Reusable", Space-faring gazette: A Journal for Space Development, Vol. 3 No. 7, July 1987, pp. 1,8,12.

[31] Belew, L.F., George C. Marshall Space Flight Center, Skylab, Our First Space Station, Scientific and Technical Information Office, NASA, Washington D.C., 1977, Page 17.

The concept of commonality between system components and modular design has been studied and implemented in the space shuttle and space station programs as a cost saving method. Commonality of spacecraft subsystems and elements is a key to utilization of ELV components in orbit. The type of commonality required to effect this type of utilization must be farsighted. This point was made in a recent paper on commonality which stated the number one rule to follow when implementing commonality:

> Implement commonality early in the program to effect major cost savings.[32]

The avionics and propulsion systems of an ELV have the potential to be of use to other spacecraft in orbit. If they are designed in conjunction with other spacecraft programs and commonality is in the minds of the designers, then these systems could be composed of modular building blocks. The modules could be designed to have a 'plug in' and 'plug out' capability, which would allow easy disassembly from the source vehicle (an ELV) to the user spacecraft. This design approach could make ground assembly operations easier, and would lend itself to automation both in space and on the ground.

In laying out the infrastructure of a future space operations system, commonality should not only be considered for hardware items, but for functions within the infrastructure. The utilization of ELVs in orbit has the potential to provide both types of commonality.

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[32] Waiss, R.D., Boeing Aerospace Co., Cost Reduction on Large Space Systems Through Commonality, AIAA Paper 87-0585, AIAA 25th Aerospace Sciences Meeting, 12-15 January 1987, Reno, Nevada, Page 2.

3.4 Orbital Reuse of ELV Materials

Space based manufacturing facilities have been studied which would require large amounts of material in orbit.[33] Such facilities could be used for manufacture of solar power satellites and other large projects. However, the cost of placing in orbit the material necessary for such projects is prohibitive. This is why they turn to extraterrestrial bodies for material resources, such as the moon and the asteroids. Technology development of space based manufacturing will surely be done with smaller scale projects. Terrestrial resources will likely be used early in the development as opposed to extraterrestrial resources.

There are two primary requirements involved in beginning extraterrestrial manufacturing. The first is in providing the manufacturing facility itself, and the second is in providing materials for the manufacturing process. There have been numerous papers on advanced manufacturing facilities in LEO, utilizing lunar resources, or asteroid resources, either of which is in raw form.[34] These manufacturing facilities must first create useable material from the raw resources, then transform the material to whatever application is desired. These proposals are exciting and ambitious, but admittedly beyond the immediate horizon. The President's National Commission on Space has indicated that the expected time period for onset of such activities is 2010 to 2020. The Commission recently recommended that:

> The augmented technology program we propose for NASA specifically include vigorous development of the

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[33] MIT, Space Systems Laboratory, Extraterrestrial Processing and Manufacturing of Large Space Systems, NASA-CR-161293, September 1979.

[34] Space Manufacturing 4, 5, & 6, Proceedings of the Fifth, Seventh, and Eighth Princeton/AIAA/SSI Conference, 18-21 May 1981, 8-11 May , 1985, and 6-9 May 1987.

technologies for robotic and tele-operated production of shielding, building materials, and other products from locally-available raw materials.[35]

The ELV can provide those raw materials to a space manufacturing facility as an intermediate step, in the short term, prior to the use of materials from the Moon, Mars, or asteroids. This intermediate step can provide valuable experience and knowledge, leading to those ambitious goals in a phased approach as seen in Figure 3.8.

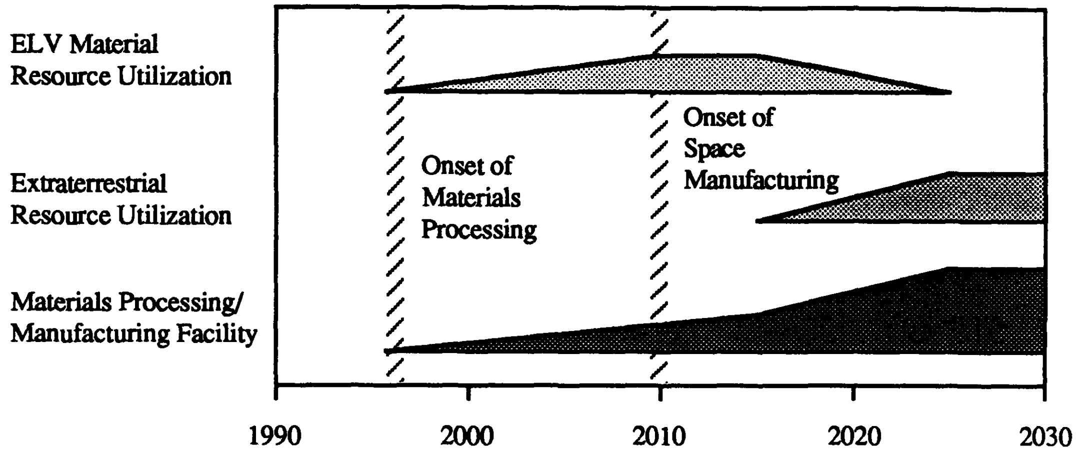

Figure 3.9
A phased approach to resource supply for space manufacturing.[36]

The ELV, if used as a resource in this intermediate role, can eliminate the process of creating useable materials from raw materials by providing useable materials directly to the manufacturing facility. This is a simplifying step which requires one rather than two stages of transformation. This could be done by including the materials as part of the traditional

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[35] Pioneering the Space Frontier: The Report of the National Commission on Space, Bantam Books, New York, May 1986, Page 105.

[36] Comstock, D.A., Improving Efficiency of Expendable Launch Vehicles in the Future Space Transportation System, Space Manufacturing 6, Nonterrestrial Resources, Biosciences, and Space Engineering, Proceedings of the Eighth Princeton/AIAA/SSI Conference, 6-9 May 1987, pp. 283-290.

payload manifest of missions servicing the manufacturing facility. Alternatively through ELV utilization, the manufacturing materials are provided in the transportation vehicle itself. This would effectively improve the performance of the transportation system by including its structure and other on-orbit mass as part of its payload. We can then take advantage of the energy that goes into placing not only the payload but the delivery vehicle in orbit.

The potential synergy between these two systems can arise from designing the launch vehicle in conjunction with the manufacturing facility. The launch vehicle should be designed to use materials which are desirable for the types of products proposed for the manufacturing facility. This may result in a design that is slightly off-optimal from a pure launch vehicle engineering standpoint, but which is much closer to optimal from the perspective of the overall system. Conversely, manufacturing techniques should be developed which can utilize the components and materials from the launch vehicle.

The types of uses for the ELV materials by an orbiting manufacturing facility are similar to uses that have been studied for ET use. Some of these uses are shown in Table 3.3. The majority of the materials to be used would come from the tankage and structure of the launch vehicle, which will likely be aluminum alloy.

- Intact tankage
- Reworked or modified tankage
- Sectional tankage
- Reworked tankage materials
- Metals recovery
- Non-metallic volatiles
- Compositionally indifferent materials
- Metallic structures
- Non-metallic structures
- Composite structures and systems
- Non-metallic volatile products

Table 3.3

Materials & Structures opportunities afforded by recoverable ETs in orbit.[37]

[37] Workshop on Utilization of the External Tanks of the Space Transportation System, cosponsored by the National Aeronautics and Space Administration and the California Space Institute, San Diego, CA 8-9 March 1982.

CHAPTER 4 RELEVANT POLICY ENVIRONMENT

There are several motivations to the space program, many of which are political. They vary in level of importance according to individual or group and the political circumstances of the time. In his book Pride and Power, Van Dyke summarized the motivations for a space program as follows:

- Military Security: "Immediate Missions" in Space
- Military Security: Potentialities
- Peace
- Progress in Science and Technology
- Economic and Social Progress
- National Prestige
- National Pride: The Achievement Motive
- Special Interests and Ulterior Motives[1]

Each of these motives has played a role in shaping space policy in the past and will continue to do so in the future. As the space program matures, visions of where it is going change for reasons that can be derived from a lack of technological capability, but largely the space program has been driven by policy decisions. Decisions at the highest levels of government have provided the impetus and the funding to realize the many accomplishments that have already been made. These decisions have largely been made for political reasons, many of them international in scope. A primary factor has been the space race with the Soviets. A significant area of departure from the pattern of government dominance over space policy, is the development of a commercial space industry. Regulatory policies will remain, but in part the direction of space development will be in the

[1] Van Dyke, Vernon, Pride and Power: The Rationale of the Space Program, University of Illinois Press, Urbana, 1964.

hands of the private sector. However, until a significant commercial space industry is established, the government will remain the dominant policy maker for all space activities.

This chapter will address the relevant policy concerns which have a significant impact on the new infrastructure, and set up a framework for addressing the questions raised in Chapter 1.

4.1 ELV RESURGENCE

The ELV in the U.S. was recently an endangered vehicle. ELVs enjoyed preeminence in the Soviet space program, and service with ESA, the Japanese and the Chinese. However, these programs did not possess the space shuttle, which promised to make ELVs obsolete. Until the Challenger disaster it was NASA policy that the Space Shuttle provide all earth to orbit transportation capabilities for the space infrastructure of the United States. However in the wake of the Challenger disaster, this policy has been replaced with a policy advocating a mixed fleet of shuttle and ELVs. This is to provide assured access to space and to fulfil demand for launch services which the shuttle cannot match alone. Following the path opened by new legislation, a commercial launch vehicle industry is beginning to emerge. In addition, there are new launch vehicle programs which address the need for lower cost and higher capability.

4.1.1 A Shift in Policy

After the Apollo program, the civil space program in the U.S. needed another goal to set its sights on. President Nixon appointed a Space Task Group (STG) which was to define this new goal.[2] In September 1969, the STG recommended that the country pursue one of three programs: a manned Mars mission, a Space Station, or a Space Shuttle.[3] NASA was in a period of decreasing funding, and congressional support for substantial new space programs was low. The shuttle was a building block for a space station and the space station was a building block for a manned Mars mission. The shuttle program was the only choice which had a chance of getting funded, and it needed approval not only from Congress, but from the DoD and the Office of Management and Budget (OMB) as well. NASA was basing its justification for the shuttle program on the savings that could be realized by the shuttle, claiming that it would not only pay for itself but would someday make a profit. In 1976, Dr. James Fletcher as Administrator of NASA prophesied to congressional committees the routine operation of 60 shuttle launches per year with an order of magnitude cost reduction over then current launch costs.[4] As history has shown, this dream never became reality. The Shuttle has launched at most 9 times in a year, the actual costs are higher than expendables, although the price charged to customers for launch services is less. There were doubts in Congress as NASA was making its claims, as Congressman Joseph Karth said:

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[2] Roland, A., "Priorities in Space for the USA", SPACE POLICY, May 1987, pp. 104-111.

[3] Space Task Group, The post-Apollo Space Program: Directions for the Future, Space Task Group Report to the President, September 1969.

[4] Simon, Michael C., Keeping the Dream Alive: Putting NASA and America Back in Space, Earth Space Operations, San Diego, California, July, 1987.

> NASA must consider the Members of Congress a bunch of stupid idiots. Worse yet, they may believe their own estimates - and then we really are in bad shape.[5]

While these comments seem harsh if not extreme, they are indicative of the problems inherent in obtaining funding for any high cost, high risk, high technology program. In order for Congress to accept the high risk and cost associated with such a program, the perceived benefits must be substantial. NASA needed the shuttle program and in their zeal to win over supporters with the potential virtues of the new space transportation system, they laid claim to capabilities that even NASA engineers felt could not be accomplished.[6]

Cost projections for shuttle operations were much less than ELV costs. Visions of the shuttle as an inexpensive reusable system painted a picture of space transportation in which ELVs were obsolete. When NASA made the policy decision to rely totally on the shuttle for earth to orbit transportation, they began to reduce funding from their ELV programs. The trends in ELV funding can be seen in figure 4.1.

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[5] Hechler, K., The Endless Space Frontier: A History of the House Committee on Science and Aeronautics, 1959-1978, AAS History Series, Vol. 4, American Astronautical Society, San Diego, CA, 1982, page 246.

[6] Tischler, A.O., "A Commentary on Low-Cost Space Transportation", Astronautics & Aeronautics, August 1969, pp. 50-64.

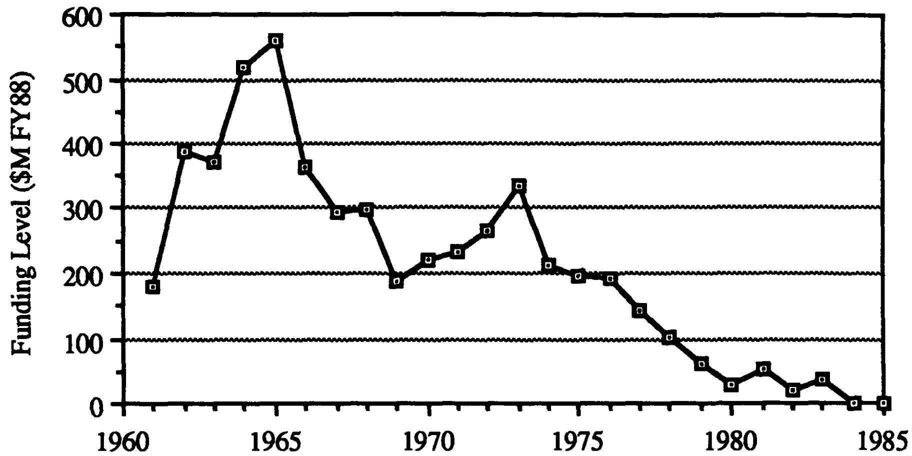

Figure 4.1
NASA funding of R&D for ELVs.[7]

This funding profile is consistent with the former NASA policy, which was aimed at phasing out ELVs leading to total reliance on the shuttle for space transportation. The production of launch vehicles in the U.S. has undergone a significant reduction as a result of this policy. As shown in Figure 4.2, launch vehicle production had almost been reduced to nothing by 1986.

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[7] Budget of the United States Government, U.S. Government Printing Office, Washington, D.C., 1960-1989.

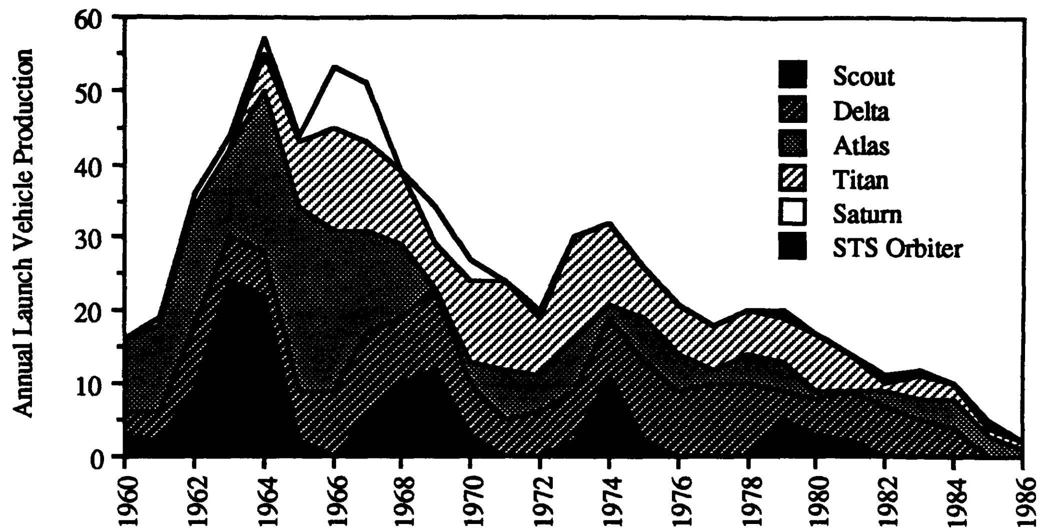

Figure 4.2
U.S. Space launch vehicle production.[8]

The DoD was not as optimistic as NASA regarding the operational capabilities of the shuttle. They were wary of relying on a single system for assured access to space. Resolute in maintaining assured access, they continued the practice of ELV procurement for satellite launch. Military concerns for control as well as availability of launch capability are high, as Air Force Secretary Hans Mark said in 1985:

> The real issue is operational control of the launch vehicles... Under current arrangements, if the space shuttle becomes the only launch vehicle for putting U.S. payloads in space, then the Air Force loses all control of launch vehicle capability... It is unacceptable that the people in charge of the most

[8] Note: Upper stages and weapon systems (Atlas E,F, Thor, Titan I, II) not included.

CETS, NRC, Assessment of Candidate Expendable Launch Vehicles for Large Payloads, NASW-3511, September 1984, page 8.

important space payloads we fly do not have operational control over their own space launch vehicles.[9]

In 1984 the Air Force began their complementary expendable launch vehicle (CELV) as a hedge against limited annual shuttle flight rates and capacity, particularly for polar launches. Martin Marietta won the CELV competition with their Titan IV in February 1985. The contract is worth $ 2.1 billion for 23 launches beginning in 1988 and continuing at a rate of 5 or 6 per year.[10] In addition the Air Force is converting at least 14 Titan II ICBMs that have recently been retired from service into ELVs.

The space science community was displeased with the NASA policy of total reliance on shuttle as well. In May 1986, the Space Science Board of the National Research Council emphasized that in the mid-1960s the U.S. launched five to six science missions a year, and since the Voyager launches of 1977 not any major science payloads had been flown. The board also said that the policy mandating use of the shuttle has "deprived the nation of launch vehicles for major scientific payloads for almost a decade [and has] been devastating for space science."[11]

The explosion of shuttle mission 51-L on 28 January 1986 left no doubt but that total reliance on the space shuttle sacrificed assured access. NASA therefore had to adopt the concept of a mixed fleet of launchers. A few months after the accident, NASA

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[9] A quote from the following article:
Gordon, J.K., "USAF Foresees Need for Launch Vehicle to Replace Shuttle in 1990s", Aviation Week & Space Technology, 29 July 1985, page 18.

[10] Wilson, A., "Titan Grows Stronger", SPACE, September-October 1987, pp. 8-11.

[11] A quote from the following article:
Foley, Theresa M., "House Panel Considers Canceling Shuttle/Centaur Due to Safety Concerns", Aviation Week & Space Technology, 23 June 1986, pp. 18-19.

associate administrator for space science, Burton Edelson, said that NASA will use the shuttle exclusively "for manned spaceflight, for Spacelab-type missions and space station".[12] The use of shuttle as a commercial launch vehicle was ended officially on 15 August 1986 when President Reagan issued a new policy. He stated that "NASA will no longer be in the business of launching private satellites". This policy was established after lobbying by Martin Marietta, General Dynamics, McDonnell Douglas and the Transportation Department. All of these interests urged the new policy on the basis that continued use of the shuttle for launching commercial satellites would limit the prospects of a commercial space launch industry.[13]

The costs of shuttle flight in relation to its annual launch rate are seen in Figure 4.3. The data is taken from a 1983 Rockwell study, and indicates that if indeed the flight rates are high, launch costs drop significantly.

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[12] A quote from the following article:
Foley, Theresa M., "NASA Planning Use of Expendables To Launch Science Spacecraft", Aviation Week & Space Technology, 23 June 1986, pp. 18-19.

[13] Foley, T.M., "Reagan Bars Shuttle From Competing For New Satellite Launch Contracts, Aviation Week & Space Technology, 25 August 1986, page 22.

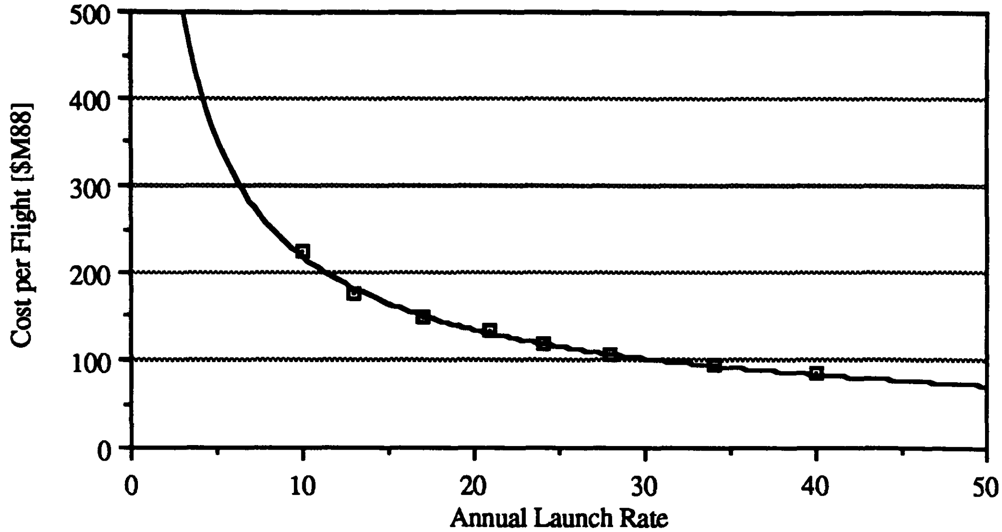

Figure 4.3
Effect of annual launch rate on shuttle flight costs.[14]

Launch rates for the shuttle will likely never reach the levels forecast early in the program. There have been no shuttle launches for over two years, and once flights resume the flight rate will be low in relation to early projections. The House Committee on Appropriations requested an assessment of shuttle flight rates and utilization following the Challenger accident. In the assessment done by the Committee on NASA Scientific and Technological Program Reviews of the National Research Council, it was determined that:

> Three Orbiters can sustain a rate of 8 to 10 flights per year after an initial buildup period of approximately 2 years providing: (1) no Orbiter is lost or becomes inoperable, (2) adequate logistics support exists, and (3) no problems exist that require extensive downtime. A surge rate of 12 flights

[14] Rockwell International Space Transportation and Systems Group, Economic Comparison: Shuttle-Only Fleet vs Shuttle/Commercial ELV Mixed Fleet, 17 May 1983.

per year should be possible for short periods of time for simple payloads and flight plans.

With a 4-Orbiter fleet the sustainable flight rate would be 11-13 per year with a surge rate of 15 flights per year only if appropriate ground support facilities are acquired.[15]

There is a need for a mixed fleet of launch vehicles in order to provide an assured access to space for this country, and to meet the demand that is in excess of shuttle capability. This fact was recognized in the NRC assessment of shuttle flight rates and utilization, and is recognized by NASA. ELVs are again considered essential to the U.S. space program. Some of the reasons for having ELVs in addition to the shuttle in a mixed fleet concept are indicated below.

- Assured access to space
- Meeting launch demand
- Potential for cost reduction
- Better schedule guarantees
- Potential heavy lift capability
- Simplification with unmanned systems

Recently there has been established in the United States a viable commercial launch industry which will sell the services of launch vehicles having proven records in hundreds of launches over 30 years. These expendables will continue to play important roles in the U.S. space program, particularly in light of the shuttle disaster.[16] However, they possess relatively small payload delivery capabilities and are expensive to launch with costs to LEO

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[15] National Research Council, Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization, National Academy Press, Washington, D.C., October 1986, page 15.

[16] Rector, W.F.III, Scherer, L.R., General Dynamics Space Systems Division, Expendable Launch Vehicles as a Complement to the Space Shuttle, Space Commerce '86, 16-20 June 1986, Montreux, Switzerland, Conference Proceedings, pp. 428-431.

of about 3,000 dollars per pound. The vehicles are the commercial Atlas, Delta, and Titan. They are all products of ballistic missile development and have all served the U.S. space program in a number of capacities.

In a recent report by the NRC outlining future technology needs of the space program, several space transportation needs were brought forth. Among these needs are:

- Modern expendable launch systems of small and medium capacity
  - Payload weight: 20,000 to 50,000 lbs to LEO
  - Reliable
  - Low operational cost
  - Improved payload-to-lift mass
- Unmanned heavy-lift launch capability to LEO
  - Payload weight: greater than 100,000 lbs
  - Payload envelope: as unrestricted as feasible
  - Cost: substantial reduction over current systems (full or partial reusability will be determined by economic trade-off)
- Reusable orbital transfer system to raise payloads from LEO to higher altitude sun-synchronous or geostationary orbit and return them
  - Geostationary payload weight: greater than 20,000 lb
  - Payload envelope: as unrestricted as feasible
  - Robotics: capable of interfacing with an intelligent front-end for routine servicing operations[17]

There are currently new programs in the U.S. for development of a new class of launch vehicle to provide a lift capability which exceeds those of current ELVs. The new launch vehicle will be of shuttle class or larger payload capability, to provide low cost

[17] Committee on Advanced Space Technology (CAST), Aeronautics and Space Engineering Board (ASEB), Commission on Engineering and Technical Systems (CETS), National Research Council (NRC), Space Technology to Meet Future Needs, National Academy Press, Washington, D.C., 1987, page 18.

transportation for a variety of missions. Such missions may include manned missions to the planet Mars, the return of men to the Moon to establish a lunar base, and the potential deployment of strategic defense weaponry in Earth orbit. One of the biggest objectives of a new launch vehicle is the significant reduction of Earth to orbit transportation costs. There are three primary areas which can be addressed in the cost reduction of placing payloads in space. These three areas are operations, production, and use.

4.1.2 COST REDUCTION

Operations is a significant cost item in the launch of payloads into space and involves the launch operations and flight operations. Currently many hundreds and thousands of highly trained and skilled personnel are required to launch a rocket. Many of these people sit attentively in front of computer monitors which show the vital characteristics of various systems on the launch vehicle. The observers monitor the information which is being provided to ensure that come launch time, everything is within the acceptable operational bounds. If one of the people finds some system operating in an unacceptable manner, then the launch is delayed while the problem is corrected. Hundreds of these people continuously monitor the vital statistics of the launch vehicle prior to launch. These people are in a dedicated function while they are performing this task, and each day or week that the launch vehicle is delayed, their pay is accumulating against the cost of the launch. The use of artificial intelligence and expert systems is being seriously explored as a remedy to this situation. Through automated monitoring of vital launch vehicle and payload parameters using artificial intelligence, the degree of direct human interaction that is required can be significantly reduced. The computer systems could be programmed to monitor the vital statistics of the launch vehicle and payload , within the predetermined acceptability levels, providing notification to a proper authority when the bounds of acceptable operation are exceeded.

The next area of cost reduction is production. There are many highly skilled technicians involved in the production of launch vehicles. Production methods are complicated and time consuming, as are quality assurance procedures of inspection and testing. The launch vehicles which provide the backbone of the transportation capability in the U.S. have been around for three decades. There have been evolutionary improvements in their production process over these three decades, but they are still basically produced in the same manner that they were in the late 1950's and early 1960's. Advancements made in production technology have not revolutionized launch vehicle production as they have automobile and other production. Many people feel that revolutionary new production technologies for launch vehicles are not only possible but highly desirable. Some of the production improvements include automated welding and real time automated inspection of welds[18], filament winding of large composite tanks, computer integrated paperless factories which significantly reduce the overhead costs of production, and advances in non-destructive evaluation techniques which allow for faster and more accurate quality assurance through automated processes. Production costs can also be reduced significantly through implementation of commonality in the design.[19]

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[18] Malin, V., "Designer's Guide to Effective Welding Automation - Part I: Analysis of Welding Operations as Objects for Automation", Welding Journal, November 1985, pp. 17-27.
Malin, V., "Designer's Guide to Effective Welding Automation - Part II: Flexibility and Economics", Welding Journal, June 1986, pp. 43-52.
Malin, V., "Problems in Design of Integrated Welding Automation - Part I: Analysis of Welding-Related Operations as Objects for Welding Automation", Welding Journal, November 1986, pp. 53-60.
Malin, V., "Problems in Design of Integrated Welding Automation - Part II: Integrated Welding Automation", Welding Journal, January 1987, pp. 36-44.

[19] Waiss, R.D., Boeing Aerospace Co., Cost Reduction on Large Space Systems Through Commonality, AIAA 25th Aerospace Science Meeting, 12-15 January 1987, Reno, Nevada, AIAA Paper 87-0585.

The third area which can have a significant impact on cost, and perhaps the most significant one is utilization. There are two primary categories which are involved in utilization. The first one has to do simply with how many of the launch vehicles are being used to place payloads in orbit. This has a very significant effect on both the operations and production costs by increasing the volume.[20] With operations, the costs of building and maintaining the launch facility and personnel are amortized over more launches thereby reducing the costs associated with each one. Regarding production, as more vehicles are produced learning curve improvements are made and the fixed costs of production such as facilities and overhead can be amortized over many more vehicles. This reduces the average cost of each vehicle. The second area of utilization has to do with the function of the launch vehicle and the role it performs in the space infrastructure. Historically launch vehicles have provided only the role of transportation from Earth to orbit. However, in the new infrastructure there will be the potential for launch vehicles to take on the additional roles which were described in Chapter 3. If the costs of having launch vehicles perform these functions is less than having other elements of the infrastructure provide them, then the launch vehicle will in effect reduce the cost of the overall infrastructure.

4.1.3 NEW ELV PROGRAMS

There are two launch vehicle development programs under serious consideration for the new space transportation role. The first is the Shuttle-C program under the sponsorship of NASA, with some Air Force involvement. The Shuttle-C is a shuttle derived vehicle (SDV) which replaces the orbiter with a payload canister. There have essentially been two

[20] Koelle, H.H., "The Future Big Boosters", The Journal of the British Planetary Institute, Vol. 39, No. 8, 1986, pp. 331-338.

configurations studied for an SDV. The first has been espoused by Rockwell and Martin Marietta, and is a side-mounted cargo module which would be positioned much the same as the orbiter is currently. The propulsion system would be attached to the end of the cargo module. The second configuration has been studied by Boeing, and is known as the in-line configuration. This configuration has the cargo container stacked on top of the ET in a conventional launch vehicle configuration. The propulsion in this case is attached to the aft end of the ET. Several studies for increasing the lift capability of the STS for cargo missions have been undertaken since the beginning of the shuttle program.[21]

The current contracts for the Shuttle C are sponsored by NASA's Marshall Space Flight Center. Martin Marietta, Rockwell International and United Technologies are the contractors in a study which began in August of 1987. NASA estimates that from $1 to $1.5 billion will be required for DDT&E of a 100,000 pound capability Shuttle C, and that it may begin operations by 1993.[22]

The second primary program is the Advanced Launch System (ALS). The ALS is a new launch vehicle with a payload capability on the order of 100,000 lb to LEO, which utilizes the advances in technology since the shuttle and other ELVs were developed. The stated objective of the ALS program is to reduce the costs of earth to orbit transportation by an order of magnitude over current launch costs. The ALS program is under the prime sponsorship of the Air Force. The SDIO is significantly involved in the program, and one

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[21] Many studies have been done on this subject. Three representative studies are given below.
Rockwell International, Space Division, Shuttle Growth Study, Concept Preliminary Definition and Evaluation, NASA Contract NAS8-23015, May 1977.
Martin Marietta Corporation Denver Aerospace Michoud Division, Shuttle Derived Vehicles (SDV) Technology Requirements Study, NASA-CR-170702, May 1982.
Boeing, In-Line Unmanned Launch Vehicle System Cost Study, Final Report, Contract F04701-82-C-0151, October 1984.

[22] Colucci, F., "Shuttle C Loads Up", SPACE, Vol 4 No 2, March-April 1988, pp. 20-23.

of its biggest supporters. This new class of launch vehicle is viewed as critical to provide assured access to space and to provide the lift capability required if SDI is to be deployed. NASA is also interested in the ALS program, and has provided funding for propulsion system development.

NASA would like to see the ALS developed, but feels that the Shuttle-C program can provide a good interim vehicle which will be required to meet demand until the ALS becomes operational. The ALS has been clearly designated a non-man-rated launch vehicle, whereas NASA would like to develop the Shuttle C with a man-rated capability. This places burdens on the Shuttle C design which would not exist otherwise. Space station launch requirements are cited as one of the primary reasons the Shuttle-C is needed as an interim vehicle. The NRC recently reported that if a Shuttle-C vehicle were available for use in space station deployment, it could reduce the time to full operational capability of the station by 12 to 18 months. However, the report went on to say that:

> it is presently unclear what additional uses such a vehicle would have after the four or five flights needed for deployment of the Block I Space Station because it is likely to face competition from a more economical vehicle from the Advanced Launch System Program.[23]

The ALS is currently being studied by Boeing, General Dynamics, Hughes, Lockheed, Martin Marietta, McDonnell Douglas, and United Technologies under one year contracts to the Air Force. Ultimately it is the goal of the ALS to reduce earth to orbit transportation costs by an order of magnitude. This goal will be accomplished through a phased approach, utilizing an interim and an objective configuration. The interim vehicle

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[23] National Research Council, Report of the Committee on the Space Station of the National Research Council, National Academy Press, Washington, D.C., September 1987, page 21.

will take advantage of existing technologies and develop a core vehicle which can use solid rocket motors for thrust augmentation. The interim vehicle will incorporate revolutionary approaches to launch vehicle production and operations, including such things as paperless factories (everything on computers), automated fabrication and welding with real time automated inspection, collocated manufacturing and launch facilities, and incorporation of artificial intelligence and expert systems for launch processing and checkout. It is estimated that the interim core vehicle can be operational by 1993 if full scale development begins in 1989.

The objective system of the ALS will add a fully reusable flyback booster, eliminating the need for the solids and increasing the lift capability of the core. The flyback booster is similar in concept to those studied for use with the shuttle. Because of funding and technology concerns, the flyback booster for the shuttle was eliminated in favor of the SRBs. The ALS contractors feel that the technology level for hot structures, propulsion systems, and other technologies associated with a flyback booster have improved considerably since the early shuttle studies. The objective system will follow the interim ALS system by five years, beginning operational service in 1998. Part of the rationale behind having the ALS program divided into an interim and objective phase is to distribute the funding over two peaks, and to ensure at least a vehicle with the capabilities of the interim system.[24]

U.S. policy appears clear in its commitment to a new class of vehicle to augment the shuttle in its role as the nation's space transportation system. The question of whether the Shuttle C or the ALS will be developed remains open. The situation between these two launch vehicles is similar in many respects to that between the B-1 bomber and the

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[24] Colucci, F., "ALS: The Cost Cutter", SPACE, Vol 3 No 4, September-October 1987, pp. 18-21.

advanced technology stealth bomber. While everyone would like the advances inherent in the higher technology project, the waiting period may be unacceptable. Developing a vehicle that will be obsolete when the new vehicle arrives is an argument against the lower technology program. The B-1 has been developed and the advanced technology bomber is under development.[25] It is too early to tell what will come of the ALS and Shuttle C dilemma.

The Air Force and NASA are participating in both studies, and the results of the studies are to go to a joint DoD/NASA steering committee. Funding for the Shuttle-C was deleted in the FY 1989 budget by the OMB in favor of an advanced solid rocket motor for the shuttle. However, NASA told Shuttle C contractors that it intends to award a second phase contract to all three of them.[26] If the Shuttle C is developed, the interim ALS vehicle probably will not be, and vice versa. Regardless, the plan appears to lead to the development of an objective ALS vehicle as a follow on to either early capability vehicle. It is hoped that the joint steering committee will arrive at a development strategy by the end of 1988.[27]

4.1.4 SHUTTLE CENTAUR CANCELLATION

From its inception, the space shuttle was to carry in its cargo bay high energy upper stages. This upper stage would carry liquid oxygen and liquid hydrogen propellants to

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[25] Kotz, Nick, "Money, Politics, and the B-1 Bomber", Technology Review, April 1988, pp. 30-40.

[26] "Agencies Discuss Impact of ALS On Shuttle-C Cargo Launcher", Aviation Week & Space Technology, 29 February 1988, page 25.

[27] Colucci, F., "Shuttle C Loads Up", SPACE, Vol 4 No 2, March-April 1988, pp. 20-23.

propel large payloads to GEO and provide the necessary ΔV for interplanetary missions. Known as the space tug in early studies, the shuttle compatible vehicle eventually became a derivative of the Centaur upper stage used for Atlas and Titan ELVs. The first applications for the Shuttle/Centaur as it came to be known were the Galileo and Ulysses missions that were scheduled to fly in May of 1986. The DoD was planning to use Shuttle/Centaur for at least seven launches, including Block 2 Milstar advanced military communications spacecraft and Defense Support Program (DSP) missile early warning satellites.[28]

After the Challenger disaster, concern for safety has been paramount in the minds of all involved in the space program. There had been serious concern and much attention given to the safety of the Shuttle/Centaur in the shuttle's cargo bay prior to 28 January 1986. Although the Centaur had performed reliably for 20 years with unmanned ELVs, integration with the manned shuttle introduced unique safety issues. The liquid oxygen and liquid hydrogen in the vehicle had the potential for a devastating explosion. Primary safety issues were fueling the Centaur in the orbiter payload bay, shuttle launch loads and particularly shuttle launch aborts.[29] These safely issues led NASA to cancel the program on 19 June 1986. More than $470 million had been spent by NASA and the Air Force on Shuttle Centaur development, and $411 million by NASA for flight hardware. However, it is likely that some of the hardware developed can be used on unmanned ELV programs.[30]

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28 "NASA Cancels Shuttle/Centaur Because of Safety Concerns", Aviation Week & Space Technology, 23 June 1986, page 16.

29 Covault, C., Foley, T., "Shuttle Centaur Flight Safety Issues Threaten Launch Planning", Aviation Week & Space Technology, 12 May 1986, page 18-19.

30 "NASA Cancels Shuttle/Centaur Because of Safety Concerns", Aviation Week & Space Technology, 23 June 1986, page 16.

The cancellation of Shuttle/Centaur in conjunction with the loss of the Challenger has caused a delay of at least six years in the Galileo mission. The upper stages which exist as replacements to the Shuttle/Centaur are not as powerful and their missions will require trajectory delays in addition to launch delays. The Galileo will at best have a 3.5 year launch delay and a 2.5 year trajectory delay.[31]

The implications of this NASA policy place serious doubts on the ability of the shuttle to provide cryogenic propellants to orbiting propellant depots. Studies on techniques for transportation of cryogenic propellants to orbit have concentrated on use of storage tanks in the shuttle cargo bay, or in an aft cargo carrier (ACC).[32,33] If the shuttle is to carry cryogenic propellants to orbit, the safety issues which led to cancellation of the shuttle Centaur will have to be addressed.

The use of the shuttle as a transportation vehicle for cryogenic propellants to orbit was included in the infrastructure diagram in Figure 3.1 as option A. Following cancellation of the shuttle Centaur program, the option provided by the shuttle for propellant transportation is in serious question. The new class of ELV as discussed in the previous section provides a solution to this dilemma. The ELV can provide propellant to orbit in either of the scenarios presented by infrastructure B or C.

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[31] Dornheim, M.A., "Galileo Mission Will Be Delayed Six Years by Shuttle/Centaur Loss", Aviation Week & Space Technology, 30 June 1986, pp. 18-19.

[32] Fester, D., Martin Marietta Denver Aerospace, Earth-to-Orbit Propellant Transportation Overview, NASA document N85-17002, 1985.

[33] Rockwell International, Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study, Final Report, Volume 1, Technical Report, NASA-CR-171848, January 1985, page 2.

NASA concerns for safety are primarily with the crew. Unmanned vehicles are not subject to the same safety criteria as are "man-rated" vehicles. While ELVs have been used for manned missions, including the Atlas and Titan which are currently in use, none are currently man-rated. There are no plans to make the ALS a man-rated vehicle.

4.2 SPACE POLICY MAKERS

The roles of policy making for space have been fairly distinct in the past, with government the dominant if not exclusive participant. Military programs have been assigned to the appropriate branch of the service, predominantly the Air Force, under DoD and Congressional oversight. Civilian programs have been the domain of NASA, under budget approval and oversight of the Congress. The launch tragedy that destroyed the Challenger has prompted stronger involvement in space policy by government agencies other than NASA and DoD. These tendencies were apparent prior to January 1986, but strengthened afterwards. Agencies with program and/or policy interests in the civilian space program include the Departments of Transportation, Commerce, Agriculture, Energy, Interior, and State, the Federal Communication Commission, and the National Science Foundation.[34] With the space program in a state of disarray, corporate and academic leaders are also making policy recommendations.

[34] Smith, Marcia, The First Quarter Century of Spaceflight, Futures, October 1982, Pages 353-373.

4.2.1 NASA / DoD

There was a conscious separation of civil and military space programs by President Eisenhower in the 1950s. The policy of separation between civil and military space programs was formalized when the National Aeronautics and Space Act of 1958 created NASA. In section 102(b) of the act, NASA is given responsibility for aeronautical and space activities with the exception that:

> ...activities peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States (including the research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and shall be directed by, the Department of Defense...[35]

Any disputes over jurisdiction between NASA and DoD are to be settled by the National Aeronautics and Space Council, which is composed of the Vice President who is chairman, the Secretaries of State and Defense, the NASA Administrator, and the Chairman of the Atomic Energy Commission (AEC). It is also the responsibility of the Council to "advise and assist the President, as he may request, with respect to the performance of functions in the aeronautics and space field." In the original version of the act, Section 204 created a Civilian-Military Liaison Committee which was to serve as a link between the activities of the civil and military space programs, and as a forum for dispute resolution. The committee was abolished in 1965, with its functions transferred to the President.

In response to the mutual interests of civil and military space programs, a Space Technology Interdependency Working Group was jointly initiated in December 1973 by the

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[35] United States Congress, National Aeronautics and Space Act of 1958, Public Law 85-568, 29 July 1958.

Air Force Systems Command (AFSC), and NASA. The purpose of this group was to exchange status briefings of programs that were of mutual interest to military and civil space. There are a number of committees and liaison offices which function to facilitate communication and cooperation between the civil and military space programs. Some of these are: the Senior Interagency Group / Space (SIG/Space), the Aeronautics and Astronautics Coordinating Board (AACB), NASA's Military Liaison Office, and the Space Transportation System (STS) Liaison Office at the Air Force Space Division.[36] Mutual interests in space technology between civil and military programs led to a formal AFSC/NASA Memorandum of Understanding (MOU). This memorandum was signed on 25 May 1982, creating a Space Technology Interdependency Group (STIG). The purpose of the MOU is to:

> "establish the relationships and responsibilities of the STIG. The STIG is charged with identifying candidate programs and encouraging joint AFSC/NASA dependent and interdependent technology programs and monitoring the status of these programs to help ensure successful implementation and completion."[37]

The scope of the civil and military space programs can be summarized by the budget comparison in Figure 4.4. Starting out at roughly the same level of funding, the civil program rapidly grew during the manned exploration period of Mercury, Gemini and Apollo to a peak in the mid 1960s. Funding for the civil program then decreased sharply to a roughly constant level from the mid 1970s to the present. Military spending remained

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36 CAST, ASEB, CETS, NRC, Space Technology to Meet Future Needs, National Academy Press, Washington, D.C., 1987, page 18.

37 AFSC/NASA Memorandum of Understanding: Space Technology Interdependency Group (STIG), 25 May 1982.

essentially constant through the 1960s. As the civil program spending slowed in the early 1970s, military spending declined as well. Military presence in space was essential for surveillance, communications, and early warning in the late 1970s and spending was on the rise. By 1982, Military spending had passed civil spending and the gap continues to grow. This gap will likely continue to grow as SDI progresses. This should be the case unless the program is cut or NASA is successful in securing large amounts of funding for a major program such as return to the Moon or a manned Mars mission.

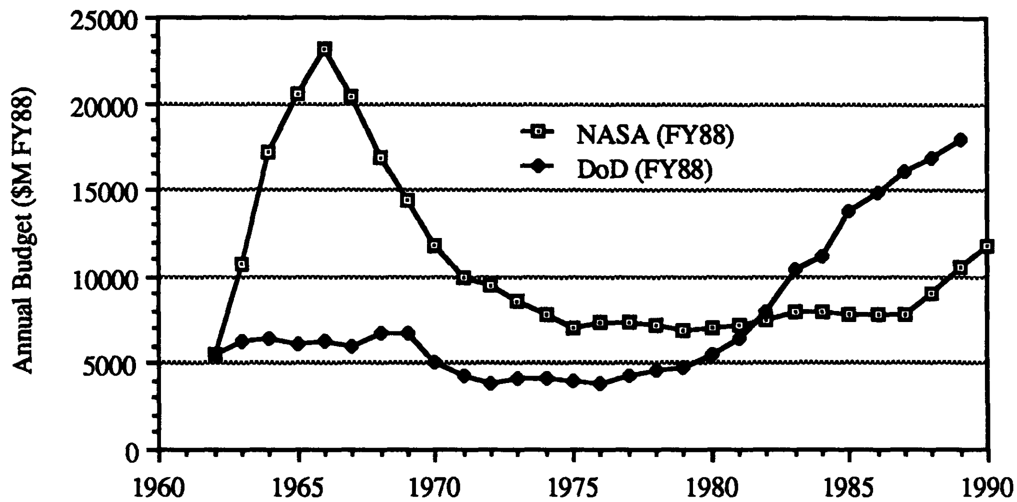

Figure 4.4
Comparison of NASA and DoD space program funding in constant FY88 dollars.[38]

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[38] Budget of the United States Government, U.S. Government Printing Office, Washington, D.C., 1960-1989.

4.2.2 DEPARTMENT OF TRANSPORTATION

In response to the development of a commercial space launch industry, the Congress passed into law the Commercial Space Launch Act of 1984 on 9 October 1984. The purpose of this bill is:

> "to establish a framework within which expendable launch vehicles (ELVs) and their associated facilities and launch services may be licensed for commercial launches."[39]

The Department of Transportation (DOT) was designated by President Reagan as the Federal Government's lead agency for commercial launch activities in November 1983, and this was more formally followed in February 1984 with Executive Order 12465. This formalized DOT as the Federal focal point for private sector space launches, and it tasked DOT with aiding commercial operators to identify and satisfy the requirements of other Federal agencies regarding commercial space activities. The Commercial Space Launch Act furthered this role by designating DOT as "the lead Federal agency to facilitate and expedite the issuance and transfer of commercial space launch licenses". In response to these tasks, the DOT created the Office of Commercial Space Transportation (OCST).

The DOT has been coming under criticism for not effectively dealing with the problems associated with a commercial launch industry. The OCST had been operating for nearly three years without in-house technical experts when Madeline Johnson, who was head of the office resigned on 30 September 1986. The Commercial Space Transportation Advisory Committee (COMSTAC), which includes representatives from the ELV industry and the financial and insurance community, had recommended to former Secretary Dole the

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[39] United States Code Congressional and Administrative News, 98th Congress - Second Session, 1984, Legislative History of Public Law 98-532, The Commercial Space Launch Act, Pages 5328-5346.

hiring of engineers familiar with ELVs into the office. The office is facing difficulties implementing the changes necessary to bolster its effectiveness in promoting commercial space transportation. It had requested an increased budget of $2.27 million for FY 87 but its budget was frozen at the 1986 level of $575,000.[40] The OCST request for FY 88 is $4 million, a significant increase from past years, with the intent of increasing staffing and performing regulatory research pertaining to the ELV industry.[41] The funding profile for the office can be seen in Figure 4.5, with the Presidential budget requests for FY 88 and 89.

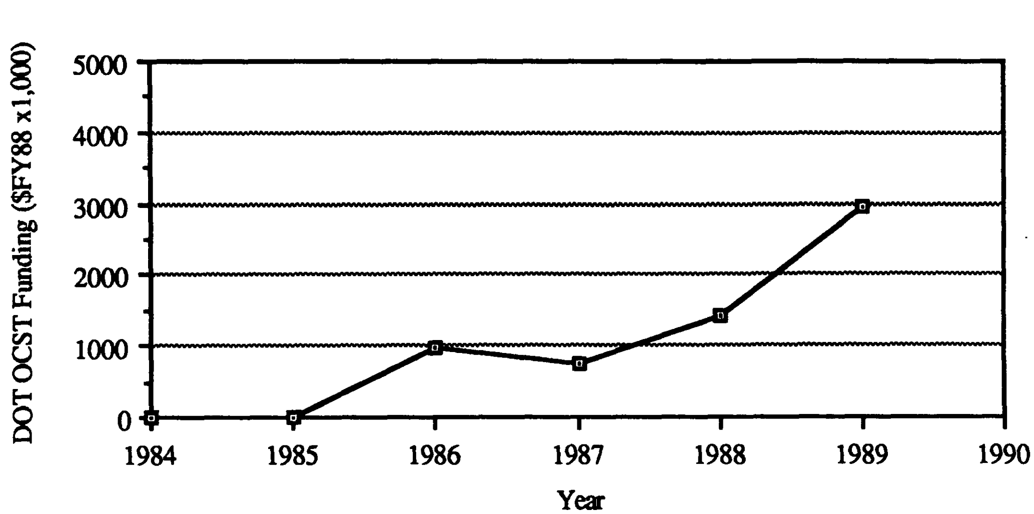

Figure 4.5.
Office of Commercial Space Transportation Funding Profile.[42]

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40 "Management of Commercial Space Transportation Office May Be Reorganized", Aviation Week & Space Technology, 29 September 1986, Page 16.

41 "Companies Submit Commercial ELV License Requests", Aviation Week & Space Technology, 16 March 1987, Page 26.

42 Budget of the United States Government, FY 1986-1989, U.S. Government Printing Office, Washington, D.C., 1984-1987.

Courtney Stadd was appointed Director of the OCST in early 1987 to replace Johnson, and has made improvements in the operations of the office. As can be seen from the figure, the funding for the office is gradually increasing. The OCST has recently received several mission review and launch license requests, indicating the rising expectations of the commercial launch industry.[43] As the industry grows, so will the OCST.

4.2.3 OTHERS

Corporate and academic leaders are concerned about the policy of the U.S. regarding space development, and in a recent forum they made some recommendations. The forum's report is titled "Space, America's New Competitive Frontier". In the report some of the recommendations include:

- Reduced space transport costs.
- More time in space for microgravity research.
- Promotion of multi-industry consortia or joint ventures.
- Greater protection for intellectual property.
- A more coherent approach to government-industry relations.

The report states that

> There is reason to be concerned about the adequacy of general federal funding for basic science. Furthermore,

[43] Foley, Theresa M., "First U.S. Commercial Sales of ELVs Expected in 1987", Aviation Week & Space Technology, 9 March 1987, Page 113.

there is a need for better linkages between science and applications across the board.[44]

Evidence of the shift from DoD and NASA dominance in U.S. space policy is found in the latest National Space Policy, released 11 February 1988 by the White House. The policy was written by the interagency White House Economic Policy Council, with heavy influence from the Commerce, Transportation and Treasury departments.[45]

4.3 FUNDING

Funding the the space program in the U.S. has been almost entirely from the Federal Government. The two significant recipients of federal funding are NASA for the civil space program and the DoD for the military space program. The DoD budget for the defense space program exceeded that of NASA for the civil program in 1982 for the first time. DoD spending for space is mostly program oriented development and operations, with the exception of the Defense Advanced Research Projects Agency (DARPA) and the Stragtegic Defense Initiative (SDI). NASA has more funding available for research and technology development than does the DoD and their role as chartered by the NAS Act of 1958 is to develop generic space technology for all U.S. space interests.[46] There has been limited private sector funding for space research and technology development in the past, but as commercial ventures begin to develop the potential for private funding of space

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44 "Corporate, Academic Leaders Recommend Space Agenda for Next 10 Years", Aviation Week & Space Technology, 16 June 1986, page 89.

45 Foley, Theresa M., "U.S. Opens Low-Earth Orbit To Commercial Development", Aviation Week & Space Technology, 22 February 1988, page 21.

46 CAST, ASEB, CETS, NRC, Space Technology to Meet Future Needs, National Academy Press, Washington, D.C., 1987, page 45.

grows considerably. These three primary sources of funding for the space program will be addressed in the following sections.

Total funding for space in the U.S. is shown in Figure 4.6. Private funding is not shown but to date it has been very small in comparison to government spending on the civil and military space programs. It is interesting to note from the figure that the total spending for space has gone through tremendous changes, and is now at the level it was in the mid 1960s when the civil space program was so strong. However, the ratios have changed and the majority of the funding is going to the military now.

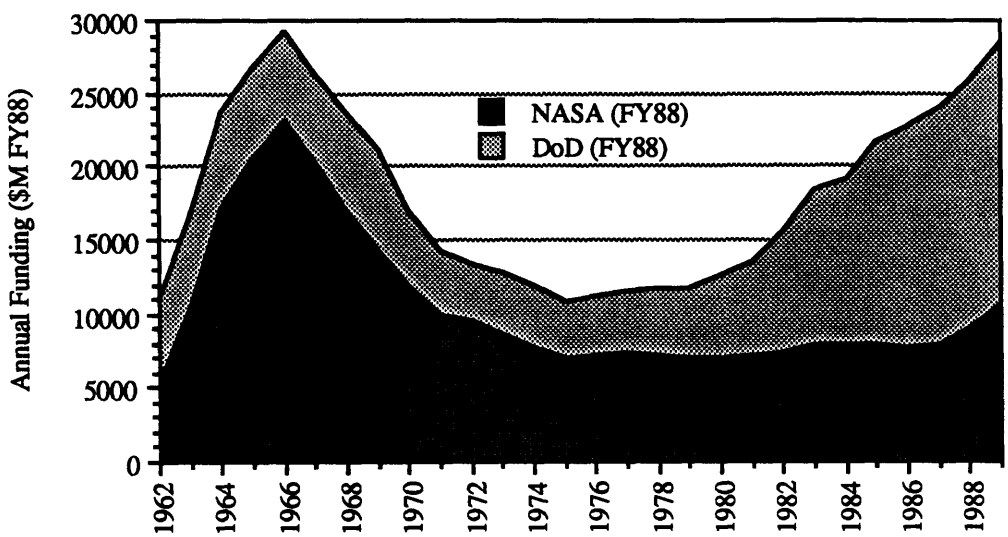

Figure 4.6
Total funding for the U.S. space program by civil and military programs in constant FY88 dollars.[47]

The level of funding appears to correspond to the degree of focus of the respective programs. The focus of the civil program was very sharp during its funding peak, namely

[47] Budget of the United States Government, U.S. Government Printing Office, Washington, D.C., 1960-1989.

to place a man on the Moon and to return him safely to Earth. Military applications in space are focused now. Various satellite programs for communications, navigation, surveillance and early warning, and the launch vehicle programs necessary to maintain and improve on existing satellite systems provide this focus. The SDI also provides a strong focus for military space. Conversely, during the funding sag between the two peaks, the focus of either program was not as clearly defined as it was at the peak.

4.3.1 CIVIL

Funding for the civil space program in the U.S. rises and falls with the political climate. This is true to some degree with any program, but the space program is particularly vulnerable in that it is viewed as discretionary spending. Unlike social programs and defense, it is not viewed as vital to the operation and security of the country. The Committee on Advanced Space Technology of the National Research Council (NRC) challenged this view in a recent report when they said:

> Space activities should be more than a discretionary element of U.S. government and private efforts: a sustained effort is essential to national defense and economic well being. Communications, navigation, and Earth observations (meteorological, oceanic, and land) are supported operationally by space systems of the public and private sectors.[48]

The historical funding patterns for NASA are indicated in Figure 4.7. The NASA budget is shown in constant FY88 millions, and as a percentage of the Federal budget.

[48] CAST, ASEB, CETS, NRC, Space Technology to Meet Future Needs, National Academy Press, Washington, D.C., 1987, page 13.

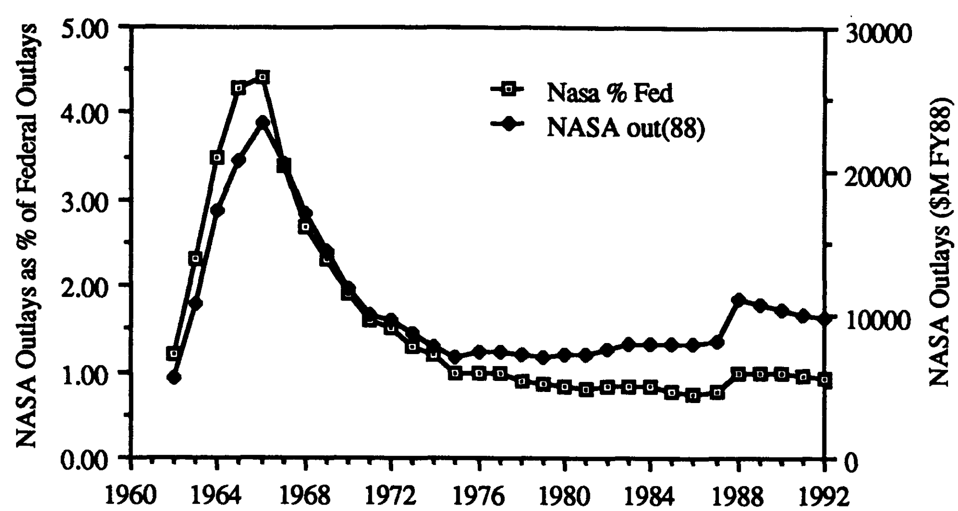

Figure 4.7
NASA funding history.[49]

The budget grew rapidly in response to the race for the moon with the Soviets. Peaking in 1966 at over 23 billion, the annual budget declined rapidly to a level between seven and eight billion. It has been at this level since 1974, the year prior to the last Apollo flight. An upward shift in the funding level for FY88 is proposed in the current budget, to fund the new shuttle orbiter and the space station. The proposed budget plan has the annual NASA funding level stabilizing at approximately $10 billion in the early 1990s. NASAs funding history for the space research and technology portion of their budget is indicated in Figure 4.8.

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[49] Historical Tables: Budget of the United States Government, Fiscal Year 1989, Executive Office of the President, Office of Management and Budget, U.S. Government Printing Office, Washington, D.C., 1987.

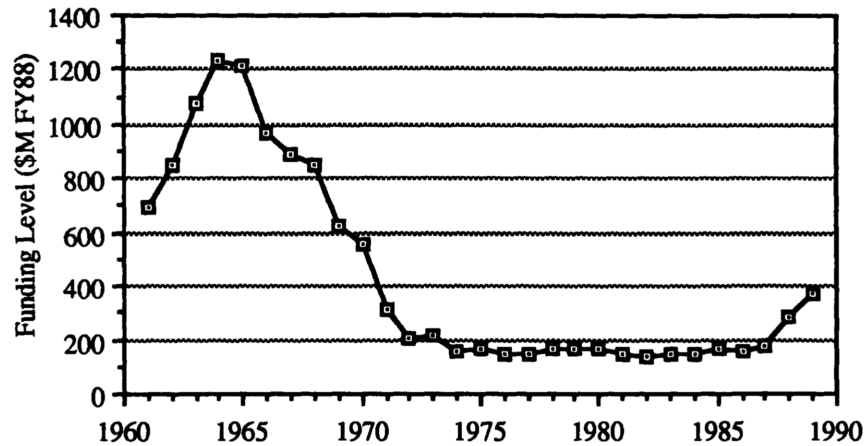

Figure 4.8
Funding history for NASA Space Research and Technology.[50]

Space research and technology funding parallels closely the patterns seen in the overall NASA budget, but the rises proposed in the future are more pronounced.

4.3.2 MILITARY

Military funding for space is less volatile and less susceptible to major changes due to political shifts than is civil funding. The military program enjoys a role of necessity for applications such as surveillance and communications. If a decision is made to deploy SDI, military operations in space will increase considerably, as will the budget. The rise in military spending for space is illustrated in Figure 4.9.

[50] Historical Tables: Budget of the United States Government, Fiscal Year 1989, Executive Office of the President, Office of Management and Budget, U.S. Government Printing Office, Washington, D.C., 1987.

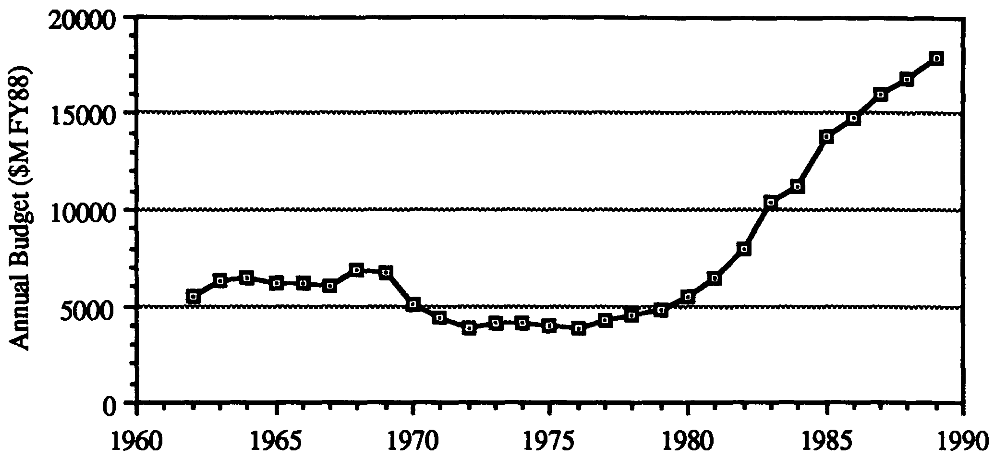

Figure 4.9
Military space funding history in constant FY88 dollars.[51]

It is evident from the figure that military spending in space is increasing steadily to high levels. The increase begins with the Reagan administration, and is reflective of the Presidents strong commitment to defense, to the military space program and to the development of the Strategic Defense Initiative.

4.3.3 PRIVATE SECTOR

Direct funding from the private sector will be made for research and development, and for construction, launching and operation of orbital systems. However, the level of funding will be relatively low in relation to government funding until the feasibility of commercial space operations has been better established.

[51] Budget of the United States Government, U.S. Government Printing Office, Washington, D.C., 1960-1989.

As the commercial space industry grows, a significant amount of indirect funding will also be provided by the private sector. Profits from commercial space activities will provide tax revenue which can eventually offset federal expenditures for a civil space program.. An OTA study addressed this issue as shown in Table 4.1.

		Government space expenditure net cost	
	Tax Revenues	A constant $7 billion/	$7 billion (1983)
Years	growth @ 15%/year	year (1983)	increasing at 1%/year
0 (1983)	0.5	6.5	6.5
5 (1988)	1.0	6.0	6.4
10 (1993)	2.0	5.0	5.7
15 (1998)	4.1	2.9	4.0
20 (2003)	8.2	(1.2)	0.3
25 (2008)	16.0	(9.5)	(7.5)

Table 4.1

Effect on tax revenues from space commerce on net Federal civil space expenditures.[52]

4.5 COMMERCIALIZATION OF SPACE

The exploration and development of space began purely as a government sponsored program. The costs were high and the paybacks were not profitable in a monetary sense. As the program progressed, some technologies emerged which had good potential for

[52] United States Congress, Office of Technology Assessment, Civilian Space Stations and the U.S. Future in Space, OTA-STI-241, U.S. Government Printing Office, Washington, D.C., November 1984, pp. 220-221.

commercialization. The Reagan administration has made several policy implementations aimed at developing the commercialization of space. Two of the biggest commercialization efforts have been for remote sensing and ELVs. On 11 February 1988, President Reagan's new National Space Policy was released. The policy has the resolute aim of developing more commercial operations in space. Regarding general commercial activities, the policy states that the government will purchase "commercially available space goods to the fullest extent feasible," and will not conduct operations on its own that impede commercial space activities.[53]

In a 1986 address before the International Conference and Exhibition on the Commercial and Industrial Uses of Outer Space, Congressman Don Fuqua, Chairman of the House Committee on Science and Technology, stated:

> The general idea of space commercialization was visionary in the early seventies, with credibility as a concept but not, by any means, as a workable arrangement. Like any new idea, it has come through the tumbling and polishing process that brings to bear the practicalities imposed by the various participants in its eventual implementation.
>
> We are beginning to see a gradual increase in the number of industries that are willing to move from the talking stage of "commercial uses of space" to a strategy for the experimentation and testing of a product or technology. It is important to understand that this evolutionary process moves at a different rate in each and every situation. The communications satellite industry has surely led the pack. There also seems to be considerable potential for specialized pharmaceuticals and certain materials.

[53] Covault, Craig, "Space Policy Outlines Program To Regain U.S. Leadership", Aviation Week & Space Technology, 22 February 1988, page 20.

> Despite commercial development in particular areas, however, I believe there has been a general frustration and disappointment in the private sector that the ideas and visions that seemed to be racing full-speed ahead in the talking stage now appear to be parked on an interim plateau.
>
> I think some of this dissillusionment comes from a discrepancy between the pace of the process versus the level of expectation. I would urge the industrial community not to abandon its initial optimism.[54]

Commercialization of products and services in space has many barriers which make it much more difficult to establish than earth based commercialization. There are five primary barriers to space commercialization that can be characterized as forms of risk. They are:

- Technical Risk: uncertainties regarding new technological developments with no guarantee of success.
- Institutional Risk: changes in government regulations and policies, and long lead times for agreements and approvals.
- Government Market Risk: funding patterns can change, and when the government is primary customer, the market for goods and services can collapse.
- Commercial Market Risk: uncertainty over what the competition will be, and the stability of unproven markets.
- Access Risk: space transportation systems are not 100% reliable, and a launch failure could be a serious setback.

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[54] Fuqua, Don, U.S. Congress, Space Commercialization Legislation, Space Commerce '86, 16-20 June 1986, Montreux, Switzerland, Conference Proceedings, page 151.

> Launch commitments are not necessarily firm, and dates may slip considerably.[55]

There are several methods the government has initiated to mitigate the risks associated with commercial ventures in space. Among the methods are:

- Research and Development Tax Credit: this credit provides the ability to deduct most of the investment against ordinary income, and allows future returns to be treated as long-term capital gains.

- Technical Exchange Agreement (TEA): technical information is exchanged between companies and NASA and parties cooperate on ground based research and analyses. Each party funds their own role.

- Industrial Guest Investigator (IGI): parties share scientific interest. Company assigns scientist at company expense to collaborate with NASA principal investigator on space flight experiment. Both parties benefit.

- Joint Endeavor Agreement (JEA): Company does studies, planning, research, development, and applications demonstrations, and agrees to make results to U.S. industry on reasonable terms. NASA provides Shuttle flight time, and some protection to JEA partner. No funds change hands.[56]

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[55] Oderman, M.R., The Center for Space Policy, Inc., The Transition to Space Commerce, Space Commerce '86, 16-20 June 1986, Montreux, Switzerland, Conference Proceedings, pp. 67-80.

[56] Viriglio, G., "Economic Aspects of Space Industrialization", Earth-Oriented Applications of Space Technology, Vol. 6, No. 1, 1986, pp. 61-63.

4.5.1 REMOTE SENSING COMMERCIALIZATION

In February 1983 President Reagan authorized the process which would lead to the transfer of the civil land remote sensing satellite program (LANDSAT) to the private sector. Secretary of Commerce Malcolm Baldrige established the Interagency Board on Civil Operational Earth-Observing Satellite Systems (IB-COESS) to oversee the competitive process. IB-COESS was tasked with setting the policy framework for the request for proposal (RFP). The Departments of Commerce, State and Defense, as well as NASA were represented on IB-COESS. A Source Evaluation Board (SEB) was created to issue the RFP and evaluate the proposals, seven of which were received by 10 March 1984. Three of the proposals were recommended by the SEB and Secretary Baldridge authorized negotiations with two of them, Eastman Kodak Company and EOSAT (Earth Observing Satellite Company), a joint venture of Hughes Aircraft Company and RCA Corporation. EOSAT was selected.[57]

The Congress was preparing the necessary legislation for the transfer of LANDSAT to the private sector during the proposal and selection process. On 17 July 1984, the Land Remote Sensing Commercialization Act of 1984 took effect. Among the findings in Title I Section 101 of the act were that:

- The private sector, and in particular the *"value-added" industry, is best suited* to develop land remote-sensing data markets
- There is *doubt that the private sector alone* can currently develop a total land remote-sensing system because of the high risk and large capital expenditure involved

[57] Marshall, H., U.S. Department of State, "US Space Commercialization - Effects on Space Law and Domestic Law", SPACE POLICY, May 1985, page 205.

- *Cooperation between the Federal Government and private industry* can help assure both data continuity and United States leadership
- certain *Government oversight must be maintained* to assure that private sector activities are in the national interest and that the international commitments and policies of the United States are honored[58]

There is a recognition by the government that private industry is better suited than government to pursue commercial development of space programs. However, there is also the recognition that support from the government is needed, and that oversight may be required to ensure policy compliance. This oversight is of particular importance to the State Department, which has the authority to ensure that commercial remote sensing activities are conducted in accordance with international agreements and international space law.

4.5.2 ELV COMMERCIALIZATION

A second major thrust for commercialization has been for expendable launch vehicles. Legislative initiatives to commercialize ELVs began in 1981, and on 16 May 1983, President Reagan issued a policy directive on commercialization of ELVs. This policy declared that the U.S. government would facilitate commercial operation of ELVs by the private sector. The policy applied to launch vehicles previously developed for government use (Atlas, Delta, Titan) as well as for newly developed commercial vehicles.

On 30 October 1984, the Commercial Space Launch Act was passed into law, designating the Department of Transportation as the focal point of the U.S. government for

[58] United States Congress, Land Remote-Sensing Commercialization Act of 1984, Public Law 98-365, 17 July 1984, (*italics* added).

commercial space transportation. Among the findings of the Congress in Section 2 of the Act were that:

> - private applications of space technology have achieved a *significant level* of commercial economic activity, and offer the potential for growth in the future, particularly in the U.S.
> - the private sector in the U.S. has the capability of developing and providing private satellite launching and associated services that would *complement* the launch associated services now available from the U.S. government
> - provision of launch services by the private sector is consistent with the national security interests and foreign policy interests of the United States and would be facilitated by *stable, minimal, and appropriate regulatory guidelines* that are fairly and expeditiously applied
> - the United States should encourage private sector launches and associated services and, *only to the extent necessary, regulate* such launch and services in order to *ensure compliance* with international obligations of the U.S. and to *protect* the public health and safety, safety of property, and national security interests and foreign policy interests of the United States.[59]

There are a number of agreements that any commercial launch venture must make with the government prior to a launch. The first is for the government to authorize use by the company of the launch vehicle commercially. The technology involved in any of the three primary commercial launch vehicles is owned by the government. In addition, any commercial launch must use government facilities, because no others exist and independent construction would be prohibitive.

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59 United States Congress, Commercial Space Launch Act of 1984, Public Law 98-575, 30 October 1984, (*italics* added).

Conditions for use of the launch facilities and the liabilities of launch are issues of concern with the new industry. The Air Force recently released a draft agreement for commercial use of the expendable launcher facilities, which was not well received by the launch industry. An open industry review of the draft was held, at which the specific complaints were aired. Some of the major complaints registered by the Commercial Space Transportation Advisory Committee (COMSTAC) were:

- The agreement is biased to the parochial interests of the government.
- The commercial operator would be exposed to very high risk due to unlimited requirements for third party liability insurance.
- Lack of definition of clear costing principles of services provided by the government.
- The agreement overburdens the government with monitor and control responsibilities.
- The agreement places demands for data disclosure which may compromise company proprietary data.
- The agreement places severe burdens on new entrants.
- The agreement does not address schedule priority for commercial users sharing government facilities.[60]

These difficulties have been settled, and General Dynamics, McDonnell Douglas and Martin Marietta have come to agreement with the government over use of launch facilities for commercial launch. McDonnell Douglas hopes to launch the first commercial launch vehicle in the U.S. in October 1988.[61] Costs are still relatively high for commercial launch services, but competition is expected to drive the cost down and create an

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60 "Industry Group Criticizes Air Force Draft Agreement on ELVs", Aviation Week & Space Technology, 16 February 1987, page 23.

61 "Industry Observer", Aviation Week & Space Technology, 27 February 1988, page 11.

environment more oriented to the user. Concerns of launch service buyers that are being addressed by manufacturers include contract terms, launch delays, payment plans, liability, and scheduling.[62]

The commercial market for space launch vehicles is international in scope. There are many countries involved in selling launch services in addition to the United States. Included in the competition for commercial space launches are the Soviet Union, China, the European Space Agency, and within the next few years, Japan. Since its inception in 1975, the European Space Agency (ESA) has been developing a launch capability that would establish the independence of a European space program from the U.S. and the Soviet Union. The Ariane launch vehicle was the fruit of this effort. First launched on 24 December 1979 an Ariane 1 made the first commercial flight for ESA on 23 May 1984.

The Chinese are rapidly entering the commercial launch market with a range of launch vehicles capable of delivering nearly 10,000 pounds to LEO.[63] The Great Wall Industry Corporation is the official representative of the Peoples Republic of China (PRC) in the commercial launch arena. They have secured several launch agreements from U.S. customers.[64]

The Soviet Union has established a civilian space agency called Gavkosmos which will manage their own, as well as cooperative commercial space ventures. They have an

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62 "Satellite Customers Call For Change in Launch Policies", Aviation Week & Space Technology, 27 February 1988, page 23.

63 Brodsky, Robert F., et. al., "Foreign Launch Competition Growing", Aerospace America, July 1986, page 38.

64 "China Wins Launch Reservations for Three More U.S. Satellites", Aviation Week & Space Technology, 24 November 1986, page 20.

"Chinese Make Inroads on Commercial Launch Market", Aviation Week & Space Technology, 9 March 1987, page 134.

operational launch system consisting of eight types of vehicles, which they use to routinely conduct about 100 space launches per year. The vehicle being marketed is the Proton (SL-12 and SL-13) launch system. Soviet efforts in commercial space launches are targeted at Eutelsat and third world countries. They are offering substantial discounts and insurance packages to developing countries. Western payloads are also being sought, but concerns over technology transfer is preventing shipment to the USSR of satellites containing U.S. parts which are considered sensitive. However, the Soviets are making customs exemptions by offering that the payloads could be shipped in sealed containers to the Soviet launch site. No agreements have yet been reached.[65]

The Japanese are aggressively pursuing the commercial launch market. They are positioning themselves to compete for a share in the global space market with the same efficiency they brought to the automobile and electronics markets. With strong backing from the Japanese government, research agencies and manufacturers in Japan have developed a fleet of launch vehicles. From their Tanegashima Space Center, the Japanese have launched 14 large vehicles since 1975. They are currently using their H-1 launch vehicle for domestic launch services, and plan to market their H-2 vehicle for commercial launches when it becomes operational in 1992.[66]

India has a developing space program with potential as a competitor in the space transportation market, but on a more modest scale than the other nations. The Indian Space

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65 "Soviets Discuss Proton Payload Exemptions", Aviation Week & Space Technology, 12 January 1987, page 33.

66 "Japan Preparing New Spaceport Facilities for H-1, H-2 Rockets", Aviation Week & Space Technology, 14 July 1986, page 51.

Research Organization has flight tested satellite launch vehicles which are expected to enter service within the decade, and has plans for a GEO launch vehicle in the 1990's.[67]

4.5.2 FUTURE COMMERCIALIZATION PROSPECTS

There are a number of areas which offer potential for commercialization in space. Administration policies have facilitated the commercialization of remote sensing and launch vehicles, and have helped to open the door for a partially commercial space station. Commercialization areas are many. Those with potential for private investment are summarized in Table 4.2, by the applications, the systems and services to be provided, and estimates as to when they might begin to attract private investment.

APPLICATIONS	SYSTEMS / SERVICES	DATE
• Transportation	• Expendable launchers	• now in service
	• Upper Stages	• now in service
	• 2nd generation Shuttle	• 2000
	• Orbital Transfer Vehicles	• 2000
	• Solar Sails	• 2010
• Communications	• 30/20 GHz System	• 1988
	• Large communications platforms	• after 1990
	• Remote servicing	• after 1995
	• 2nd/3rd generation 30/20 GHz Systems	• 2000

67 Mama, H.P., "Launch Vehicle Developments", SPACEFLIGHT, Volume 28, December 1986, page 433.

• Remote sensing (active and passive)	• General land remote sensing	• now in service
	• Special purpose platforms for minerals exploration, land use planning, crop assessment	• after 1985
	• Weather (special purpose warning systems)	• after 1990
	• Geostationary platforms	• 2000
• Materials processing/ manufacturing	• Furnaces, processing modules	• 1985
	• Large scale construction in space	• 2010
	• Lunar-based mining/processing	• 2020
• Structures	• Small multipurpose platforms for manufacturing, testing (LEO)	• currently
	• GEO platform (communications, remote sensing)	• after 1990
	• Large space structures	• 2010
• Space power	• Small photovoltaic systems	• currently
	• Large photovoltaic systems	• 1995
	• Thermal-electric systems	• 1995
	• Advanced photovoltaic systems	• 2000
	• Advanced thermal, nuclear systems	• 2010
• Navigation	• Small, special purpose system	• 1990

Table 4.2

Potential commercialization areas for private investment.[68]

The next significant area for commercialization is the space station. In his new national space policy released on 11 February 1988, President Reagan is

[68] Williamson, R., Office of Technology Assessment, "Commercialization of Space - the Investment Opportunities", SPACE POLICY, May 1985, pp. 210-211.

> proposing actions to encourage private-sector investment, including directing NASA to rely to the greatest extent feasible on private sector design, financing, construction and operation of future station requirements.[69]

An offshoot of the new space policy is the development of commercial space platforms in LEO which provide a manned presence to augment space station and shuttle operations. Two companies have been pursuing this type of development for the past few years.[70] Space Industries is developing an Industrial Space Facility (ISF) which is a free-flying platform, man-tended by the space shuttle. Space Industries is a partnership between Space Industries, Inc., and Wespace, a Westinghouse subsidiary. Boeing also plays a limited role in the partnership. Lockheed and Eagle Engineering are involved in the design of the ISF. Spacehab, Inc., is developing the spacehab module which is to be carried in the shuttle bay to provide increased manned habitation volume for either the space shuttle or the space station. Spacehab is associated with McDonnell Douglas, Aeritalia (Italian), and United Technologies.[71]

The new space policy lays a framework whereby these commercial facilities can be given guaranteed leasing agreements from the government. Although the policy is clear in not providing direct government subsidies, provisions for guaranteed leasing arrangements allow private financing ventures to attract investors. This approach is known as the

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69 A White House source, quoted in the following article:
Covault, Craig, "Space Policy Outlines Program To Regain U.S. Leadership", Aviation Week & Space Technology, 22 February 1988, page 21.

70 Maclennan, D., "Space for Rent", Spaceflight, Vol. 30, April 1988, pp. 138-140.

71 Foley, Theresa M., "U.S. Space Platform Firms Aim for 1991 Service Start", Aviation Week & Space Technology, 29 February 1988, pp. 36-41.

"anchor tenant" concept, and is being incorporated by NASA in a recent request by Marshall Space Flight Center for access to a leased space platform. Congress has provided $25 million to NASA in the 1988 budget to be placed in an escrow account and held for payment of lease obligations until service is delivered.[72]

4.6 INTERNATIONAL SPACE POLICY

The first words in the NAS Act of 1958 state that "The Congress hereby declares that it is in the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." The act goes on to state that the objectives of the new agency shall include

> The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof...
>
> Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results thereof...[73]

There is inherent in these two objectives a conflict between competition and cooperation that is manifest in U.S. international space policy. The space programs of the U.S. and the Soviet Union have been pitted against each other since the Soviets launched Sputnik in 1958. The space race was an individual sport and for a long time, only these

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72 "NASA Space Platform Specifications Resemble Industrial Space Facility's", Aviation Week & Space Technology, 29 February 1988, page 29.

73 United States Congress, National Aeronautics and Space Act of 1958, Public Law 85-568, 29 July 1958.

two superpowers were players. Competition was a motivating political factor behind the funding for U.S. civil space program. Nonetheless, these two competing superpowers cooperated to create the Apollo-Soyuz Test Project (ASTP) which took place in 1975.

The U.S. and the Soviet Union have concerns regarding multilateral cooperation and technology transfer in addition to their bilateral concerns. There has generally in the past been a strong willingness on the part of the superpowers to share their space programs with other nations. However, there is a limit to that sharing and the U.S. and the Soviet Union want to reserve their right to exploit the resources of space. The concept of space as being the "common heritage of mankind" is similar to the concept for the ocean resources. The two major space powers however, never ratified the UN space treaty, primarily over the issue of exploitation of lunar resources.[74] This unwillingness to sign the treaty is reflective of the concerns these two nations have over the potential for exploitation of space and the issue of competition for those resources, and in the space race.

It is important to realize that while several other nations besides the U.S. and the Soviet Union are entering space, the level of their expenditure on space in both real terms and percent of GNP fall far behind these two leaders. Figure 4.10 indicates the expenditures of the five nations which had the highest funding, as well as the European Space Agency (ESA).

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[74] Jasentuliyana, N., "The UN Space Treaties and the Common Heritage Principle", SPACE POLICY, November 1986, page 296.

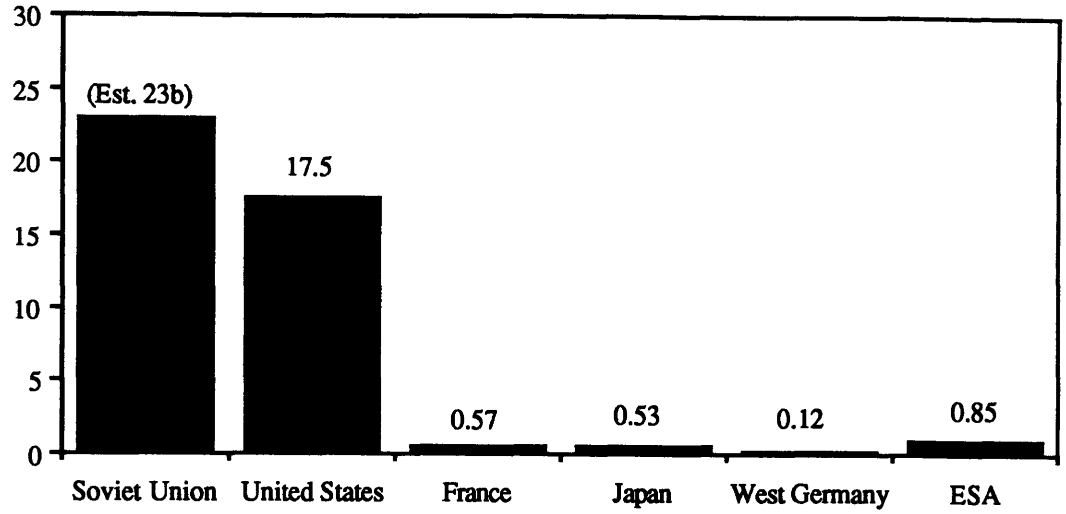

Figure 4.10
National Space Budgets Compared - 1984 (US Billion $FY84).[75]

The domination of the U.S. and the Soviet Union in space expenditures, hence space programs, is clear. This dominanation is not only in the real terms of actual dollars spent, but in relative terms as percent of GNP spent on space. This point is made by Figure 4.11. The percentage of GNP spent by the space superpowers on their space programs is roughly an order of magnitude more than any other nations.

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[75] United States and Soviet Union Budgets include military space budget, but exclude classified military and intelligence programs. Soviet budget is the estimated cost the United States would incur to duplicate the Soviet program. Source:

Office of Technology Assessment, International Cooperation and Competition in Civilian Space Activities, U.S. Government Printing Office, Washington, D.C., OTA-ISC-239, July 1985, page 65.

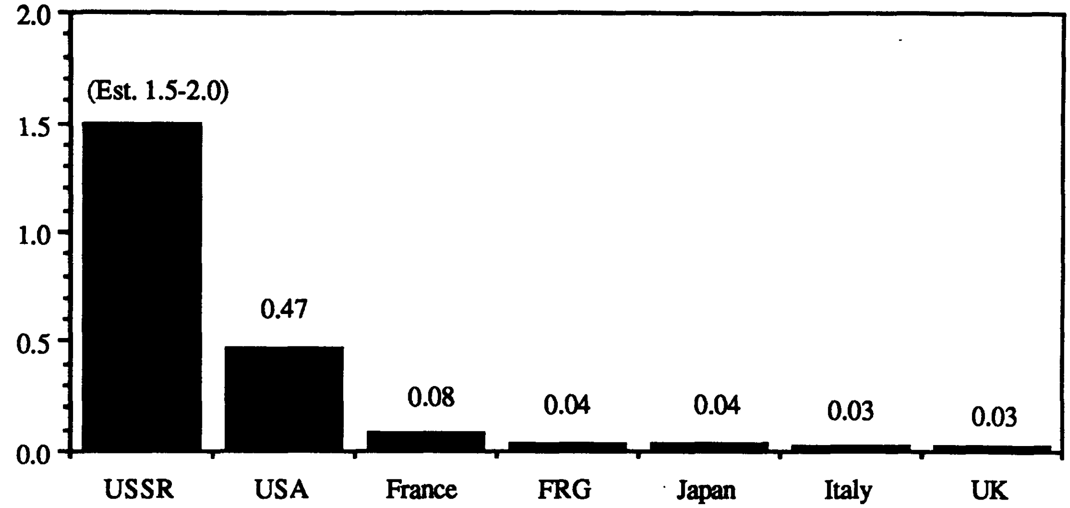

Figure 4.11
Expenditure on space programs as percent of GNP.[76]

4.6.1 COMPETITION

Competition in space to date has been almost exclusively between the United States and the Soviet Union, with the Europeans, Japanese, and Chinese entering the scene in the past decade. There are three primary facets to competition between national space programs: Political, Military, and Economic. Competition in the political arena was initiated by the launch of Sputnik in 1957 by the Soviet Union. For reasons of national prestige and political statements, the United States was compelled to match and exceed Soviet accomplishments. The ensuing space race saw enormous resources being devoted

[76] Soviet figure is OTA estimate. Other figures from SEST/Euroconsult 1984-85.

Office of Technology Assessment, International Cooperation and Competition in Civilian Space Activities, U.S. Government Printing Office, Washington, D.C., OTA-ISC-239, July 1985, page 66.

to the space programs of each country, as evidence of the tremendous force behind political motivation.

Military motivations were somewhat juxtaposed with political motives in the early days of the space program, as placing satellites in orbit was testimony of the ability to also place nuclear warheads between continents. However the two soon diverged, and this was reflected by the creation of NASA in 1958 to separate the civil space program which was highly politically motivated from the military space program. Military reasons for space development and utilization are many. Among them are:

- Strategic weapons
- Geodesy
- Navigation
- Weather forecasting
- Reconnaissance
- Missile launch warning
- Communications
- Strategic Defense

The space programs of the Soviet Union and the United States shared fairly similar goals until after the Apollo-Soyuz Test Project (ASTP) mission in 1975. They each were focusing on manned operations, with a considerable launch capacity for such operations. However, in the post ASTP period, the space programs of the two countries began to diverge. They each shared a similar destination, the exploration and exploitation of space highlighted with a manned mission to Mars, but they were in pursuit of that destination on different courses.

The ASTP mission was in fact the last manned mission for the U.S. space effort until the first launch of the space shuttle in 1981. The emphasis of the U.S. program had undergone a shift from the single use launch vehicles such as the Mercury, Gemini, and Apollo to the multi-use, multi-functional and purportedly more economic space shuttle.

Due to their budged constraints and political pressures, NASA tends to place all their eggs, so to speak, into one basket. For the time period after the Apollo program, of which the ASTP was the last mission, all of NASA's eggs were in the basket marked space shuttle.

The goal of the American space program was to utilize a very economic means of space transportation that would eventually make space transport routine. The vehicle would have many capabilities, would be able to provide manned presence in space when needed, would be able to deploy many satellites, and could be reused. The key to the economic promise of the space shuttle was its reusability.

The next large program on the U.S. agenda is the well publicized and somewhat controversial space station. The goal of the space station is to achieve a permanent manned presence in space. At the space station, research of various types will be conducted on various topics, from space manufacturing to human physiology and the way humans are adversely or positively affected by weightlessness. The space station is in the development phase, and optimistic estimates place its initial operational capability to be in the mid to late 1990s.

The Soviets meanwhile, in the post-ASTP space program, were continuing their manned operations in a big way. They continued to place men in space for extended periods of time, they were gathering data and conducting extensive studies on the effects of prolonged human weightlessness. They continued to build their presence in space and today they have the MIR space station which has nearly achieved the plateau of achieving a permanent manned presence in space.

The Soviet space program has currently taken an unquestioned lead over U.S. manned flight operations, and the USSR's rapid pace in unmanned launches and development threatens to overcome the West's technological lead in space. Launch failure of the space shuttle, Titan, Delta, Atlas, and Ariane vehicles have allowed the Soviet space program to gain a greater advantage over Western operations than at any other time since the launch of Sputnik 1 in 1957. The Soviet manned program represents the most visible challenge to Western space leadership.[77]

After achieving some of the goals they have set out for in manned space operation, the Soviets are beginning to look to the future, for development of inexpensive and reusable transport systems. They need cheap transportation to this space station they have in low earth orbit.

The paths of the U.S. and Soviet space programs, after their divergent courses of the post ASTP period, are beginning to converge. The U.S. is now in pursuit of a permanent manned presence in space, and the Soviets are in pursuit of economic, reusable space transportation. Each of these pursuits have already been mastered to some degree by the other. The potential for cooperation between these two great space powers is apparent, however with motives of military and political competition, each will continue in isolation to pursue the goals which the other has already achieved.

The differences in the U.S. and Soviet space programs can be represented graphically by comparing the satellite launch rates of the two countries. Figure 4.12 presents the satellite launch rates, dividing each nations satellites into military and civil categories. The annual launch rates for civil, military, and the total launch rate for each nation are indicated in the figure.

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[77] "Soviet Union Takes Lead in Manned Space Operations", Aviation Week & Space Technology, 9 March 1987, Page 129.

YEARLY SATELLITE LAUNCHES OF THE USA AND USSR

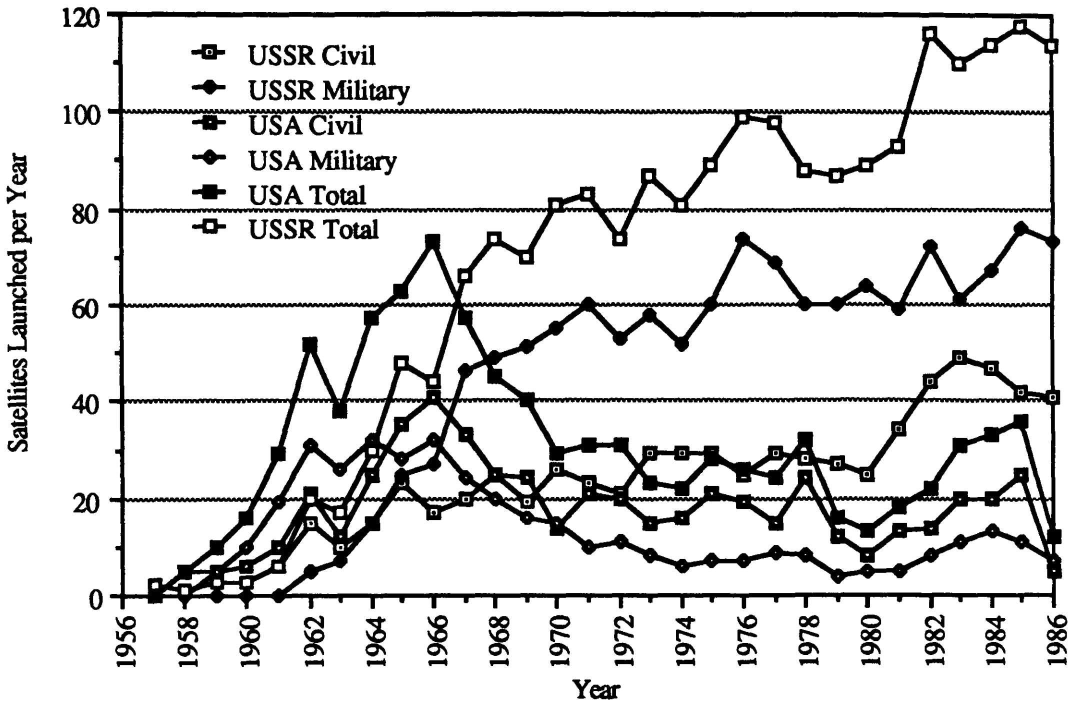

Figure 4.12

Annual Civil and Military satellite launch rates for the U.S. and the Soviet Union.[78]

Competition between nations in space is beginning to emerge from purely political and military areas into the economic realm. The potential for economic development of space activities is apparent in the communications, remote sensing, and space transportation areas. The economic motivations for national space programs as summarized in a recent OTA report, are many:

- Space research will contribute to the general advancement of national scientific development

[78] Sheldon, Charles S., and Smith, Marcia S., Space Activities of the United States, Soviet Union and other Launching Countries / Organizations, U.S. Library of Congress, Congressional Research Service (CRS), CRS Report no. 82-45, U.S. Government Printing Office, Washington, D.C., 26 February 1982.

Jane's Spaceflight Directory 1987, Jane's Publishing Inc., New York, 1987.

- Efforts in space technology will contribute to building and maintaining a strong national technology base
- Applications of space technology such as remote sensing or satellite communications will contribute to national economic growth
- Useful products will spin off from space technology
- Leadership in space technology will benefit other industries in international competition by promoting perceptions of the nation as being at the forefront of modern technology in general
- The space program will foster the development of space-related industries with competitively exportable products
- The export of space-related goods or services will help open up new markets for other high technology exports[79]

Private companies and governments are involved in the commercial space arena, and in some cases in direct competition with one another. An example is for launch services where the space programs in the Soviet Union, China, and the European Space Agency (ESA) are competing with private companies in the U.S. satellite launches. The foreign governments subsidize their launch costs and the insurance packages they are offering with their launch services. Private companies are crying foul, claiming that this type of competition is unfair. Arianespace recently initiated an insurance pool which will provide $73 million in insurance coverage for launch, greatly easing the pressure on its customers to find insurance. Ariane is charging an 11-13 percent premium for this service, although their demonstrated failure rate is about twice that. This is bringing outcries from insurers and launch firms in the U.S. Regarding this policy, James Barrett, President of International Technology Underwriter, has said:

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[79] Office of Technology Assessment, International Cooperation and Competition in Civilian Space Activities, U.S. Government Printing Office, Washington, D.C., OTA-ISC-239, July 1985, page 70.

> How can they possibly justify the rates they are charging? We believe that to be unfair use of a government's resource to compete with private industry.[80]

Barrett's view is widely shared. It is not a new complaint and it has no easy solution. A recent trade case illustrates the complexities of the problem. Transpace Carriers, the private U.S. firm which was marketing the Delta launch vehicle manufactured by McDonnell Douglas, filed a complaint under Sec. 301 of the Trade Act of 1974, asserting the Europeans used unfair methods of competition in the sale of commercial satellite launch services on Ariane. Following a year of government investigation, a Presidential Determination Memorandum of July 1985 found that, while Arianespace does not operate under purely commercial conditions, this is largely a result of the history of the launch services industry, which is marked by almost exclusive government involvement. It concluded that conditions did not require affirmative U.S. action at the time.[81]

4.5.2 COOPERATION

International cooperation in space has been successful in many areas in the past. There are many ways in which nations cooperate in space activities, and they have been organized in a sort of flow chart by the OTA as shown in Figure 4.13.

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80 "Satellite Owners Reenter Insurance Market", Aviation Week & Space Technology, 26 January 1987, page 79.

81 "Legal Aspects", Aerospace America, December 1986, Page 52.

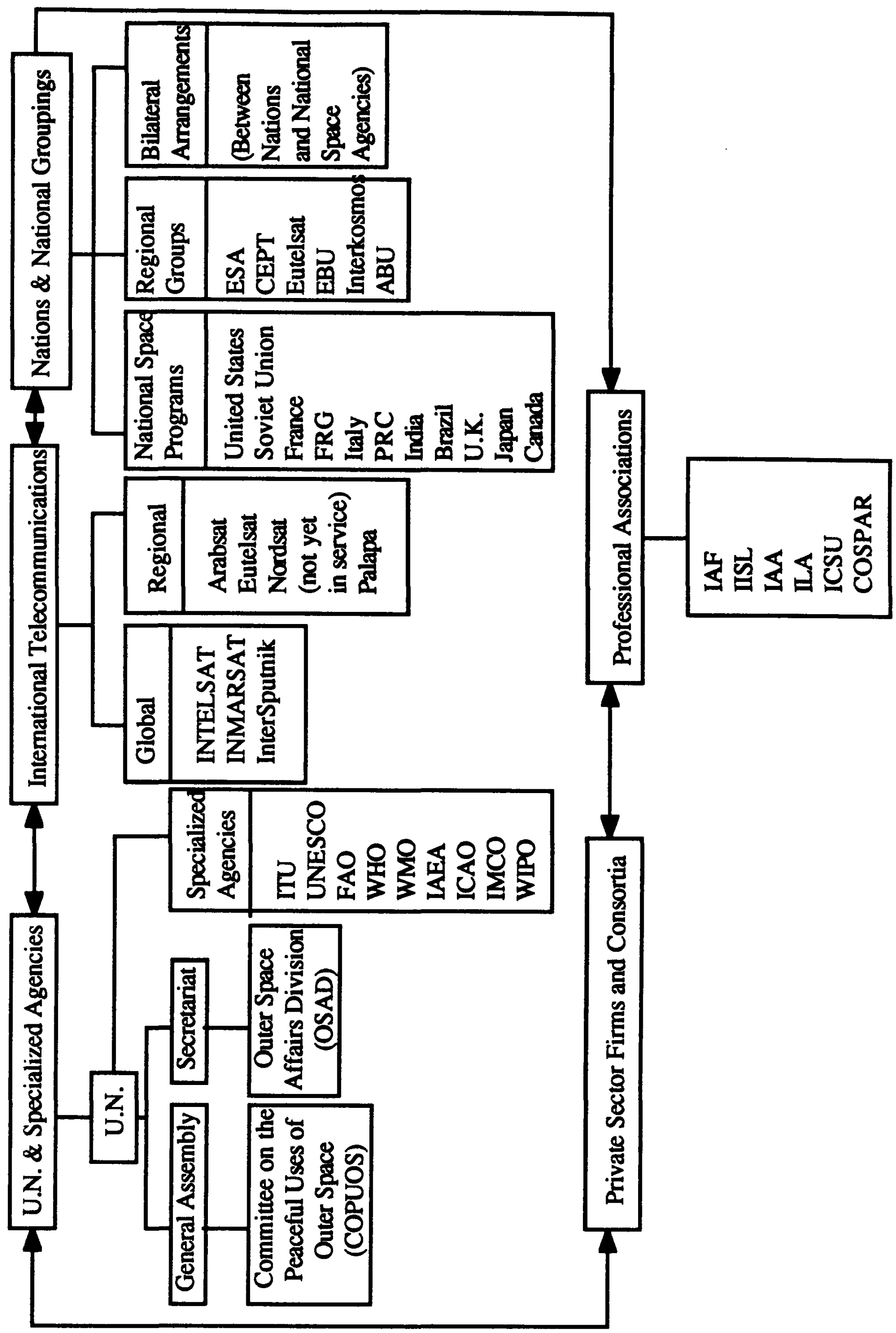

Figure 4.13

Patterns of Global Governmental Outer Space Activities.[82]

[82] Office of Technology Assessment, International Cooperation and Competition in Civilian Space Activities, U.S. Government Printing Office, Washington, D.C., OTA-ISC-239, July 1985, page 34.

Issues of international space law are growing in importance with the development of new multinational space projects. There are three components which must be considered when addressing space law. They are an international juridical framework, individual national legal policies and regulations, and the political climate of the administration in each of the respective nations.[83] A number of international agreements involving space have been negotiated.[84] Among them are:

- 1967 Outer Space Treaty: establishes that governments are responsible for all launches from their territory [85]
- 1968 Astronaut Assistance and Return Agreement: provides for assistance to astronauts, notification of accidents, and the rescue and return of spacecraft personnel and space objects [86]
- 1972 Convention on International Liability for Damage Caused by Space Objects: establishes the rule of absolute liability for a launching state for losses suffered by persons (other than its nationals) and property from reentering space objects [87]

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83 Dula, A., Space Law for Business Profits, Space Commerce '86, 16-20 June 1986, Montreux, Switzerland, Conference Proceedings, pp. 97-118.

84 Hazelrigg, G.A., Hymowitz, M.E., "Space Commercialization: Lessons from History", Space Policy, May 1985, pp. 187-201.

85 Treaty of Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 27 January 1967 [1967], 18 UST 2410, TIAS 6347.

86 Agreement on the Rescue of Astronauts, and the Return of Objects Launched into Outer Space, 22 April 1968 [1969], 19 UST 7570, TIAS 6599.

87 Policy and legal issues involved in the commercialization of space, Committee Print, Committee on Commerce, Science, and Transportation, U.S. Senate, 23 September 1983, page 10.

- 1975 Convention on the Registration of Objects Launched into Outer Space: requires a launching state to enter each launching in an appropriate registry [88]

The space station has long been touted by President Reagan as an opportunity for collaboration between western nations in space. However there are many snags that are prolonging negotiations between the European, Japanese, Canadian space agencies and NASA. Among the most significant concerns are technology transfer, intellectual property rights and management control.[89]

The International Telecommunications Satellite Organization (INTELSAT) has been a model example for space commercialization and international cooperation. INTELSAT is a global commercial telecommunications satellite system owned by at least 109 member nations. The United States played a big role in the development of INTELSAT. During its first six year of operation INTELSAT was operated by the Commercial Satellite Corporation (COMSAT), a U.S. firm. Since 1977 however, INTELSAT has been operated by an international secretariat. Under its operating agreement, INTELSAT states that each signatory shall have an investment share equal to its percentage of all utilization of the INTELSAT space segment by all signatories. The U.S. has a 23.1 percent share through COMSAT, and the U.K. holds the next highest share at 12.9 percent.[90]

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[88] Convention of the Registration of Objects Launched into Outer Space, 14 January 1975 [1976], 28 UST 695, TIAS 8480.

[89] Cox, A.R., "US Status in Space Eroded", Spaceflight, Volume 30, February 1988, pp. 83-85.

[90] Office of Technology Assessment, International Cooperation and Competition in Civilian Space Activities, U.S. Government Printing Office, Washington, D.C., OTA-ISC-239, July 1985, page 49.

The United Nations is sponsor to many initiatives aimed at promoting and developing international cooperation in outer space. The UN has formed a Committee on the Peaceful Uses of Outer Space (COPUOS) which is the focus of such activities.[91]

[91] United Nations Association of the United States of America (UNA-USA), The Next Giant Leap in Space: An Agenda for International Cooperation, UNA-USA Publications, 1986.

CHAPTER 5 PROPELLANT RECLAMATION TECHNOLOGY REQUIREMENTS

The task of transferring propellant between tanks in orbit is much more difficult than propellant transfer on earth. There are two primary reasons for this. First is the absence of gravity which necessitates an alternative force to provide propellant motion. The second is the vacuum of space which necessitates a sealed system with no allowance for leakage. Another significant problem is created with the use of high energy cryogenic propellants with the extremely low temperatures required to keep them in liquid state.

In recognition of the need to develop enabling technologies for cryogenic and storable propellant transfer in orbit, several research programs have been performed[1] and others are under way. Interest in this problem is widespread within NASA as well as with the DoD and the SDIO. A summary of ongoing programs is shown below in Table 5.1.

[1] General Dynamics Convair Division, Orbital Refill of Propulsion Vehicle Tankage, NASA-CR-159722, February 1980.

PROGRAM	AGENCY
• Orbital Spacecraft Consumables Resupply System (OSCRS)	JSC
• Superfluid Helium Tanker Resupply (SFHT)	JSC
• Cryogenic Fluid Management Flight Experiment (CFMFE)	LERC
• Long Term Cryogenic Storage Facility Systems Study	MSFC
• Superfluid Helium on Orbit Transfer (Shoot)	GSFC
• Space Assembly, Maintenance, and Servicing Study (SAMS)	DoD, NASA, SDIO
• Long Term Cryogenic Fluid Storage (LTCFS)	LERC
• Space Station Satellite Servicing (Package 3)	GSFC
• Satellite Servicing Project	GSFC

Table 5.1

Programs addressing orbital propellant transfer.[2]

There are several objectives which NASA has defined for the development of an orbital fluid resupply tanker. These objectives can be realized through incorporation of not only the right technologies, but the right combination of technologies and systems. NASA's overall programmatic objectives are:

- Safety
- Minimum Cost
- Reliability
- Minimum Turnaround Time and Manifesting Flexibility
- Minimize the Number of Different Tanker Designs
- Minimize Fluid Spills and Venting.[3]

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[2] Microgravity Fluid Management Symposium, NASA Conference Publication 2465, NASA Lewis Research Center, Cleveland, Ohio, 9-10 September, 1986.

[3] Griffin, J.W., NASA JSC, Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers, AIAA Paper 86-1601, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama, pp. 6-7.

NASA has had interest in orbital propellant supply and transfer for a number of years. Cryogenic fluid transfer experiments in orbit were planned over a decade ago, but have yet to fly.[4] In order to transfer propellant from a spent launch vehicle to an orbiting propellant depot there are several technologies involved, which are dictated by the process. There are basically two classes of transfer processes, the first being for storable propellants and the second for cryogenic propellants. There are several processes which may be employed to achieve propellant transfer for each.

5.1 STORABLE PROPELLANTS

The processes for transfer of storable propellants are best understood and are in routine use by the Soviet program and have been used in flight experiments in the U.S. There are basically four methods which can be employed for transfer of storable propellants and those are outlined below:

- Adiabatic Ullage Compression
- Ullage Exchange
- Vent / Fill / Repressurize
- Drain / Vent / Fill / Repressurize

Adiabatic ullage compression, also known as ullage recompression is a relatively simple method that can be used for resupply of spacecraft tankage using either diaphragm or simple surface tension propellant management devices (PMD) and blowdown expulsion. The process is basically to force propellant from the servicer tanks into the spacecraft

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[4] McDonnell Douglas Astronautics Company, Filling of Orbital Fluid Management Systems, NASA-CR-159405, August 1978.
General Dynamics Convair Division, Filling of Orbital Fluid Management Systems, NASA-CR-159404, July 1978.

receiver tanks. The major limitation to this resupply method is the compressive heating effect on the hydrazine as it is being transferred. Slow transfer rates must therefore be employed in order to avoid rapid decomposition of the hydrazine, or the possibility of adiabatic detonation. The primary advantages of adiabatic ullage compression are its mechanical and operational simplicity, and the fact that it does not need pressurant gas resupply. This resupply technique will be used on the Gamma Ray Observatory (GRO) for resupply missions.

Ullage exchange is used on spacecraft tankage which have surface tension devices utilizing regulated pressure. This process requires a closed circulation loop and is only feasible on bipropellant systems or non-diaphragm monopropellant systems. A constant pressure process is used in which the propellant is pumped from the servicer to the user spacecraft tanks. As the resupply propellant enters the user spacecraft tanks, it displaces ullage which is sent back to the servicer tanks. An assumption in this process which is as yet unproven is that no ullage bubbles become trapped within the user spacecraft tanks, which would leave them partially unfilled.

The Vent / Fill / Repressurize method can be used for spacecraft tankage using either diaphragm or surface tension devices. The initial step in the process is pressure reduction in the receiving tank by venting. Then propellant from the servicer tanks can be transferred at low pressure, eliminating the compressive heating problems associated with high pressure methods. There are several unproven aspects associated with this method. The first is that vapor / liquid separation is achievable which is simple with diaphragm tanks but as yet unproven for surface tension tanks. Another assumption is that venting of pressurants can occur without expulsion of any propellant. Another problem associated with this method is determination of the amount of propellant required for resupply, so that the proper ullage volume is left for repressurization.

The final method is the Drain / Vent / No-Vent Fill / Repressurize method which is used for tankage with compartmented surface tension devices for use in propellant management. These systems are complicated and must be drained prior to refilling in order to assure elimination of ullage voids. A benefit of starting with an empty tank for the filling process is knowing what the starting conditions are and thus how much propellant should be transferred. This process begins with the draining of propellants from the user spacecraft into the servicer tanks. Then user tanks are then vented of remaining pressurants and residual propellants to create a vacuum in the tanks. Then a no-vent fill can be done from the servicer tanks to the user spacecraft tanks, knowing how much propellant is required. After filled with the proper amount of propellants, the user spacecraft tanks are then repressurized to the appropriate level.[5,6]

Each of these techniques has drawbacks as well as advantages, which have been summarized in tabular form. In addition, the particular transfer methods have applicability for certain tankage configurations. The benefits associated with each of these four techniques can be seen in Figure 5.1.

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[5] Eberhardt, R.N., Tracey, T.R., and Bailey, W.J., Martin Marietta Denver Aerospace, Orbital Spacecraft Resupply Technology, AIAA Paper 86-1604, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama.

[6] Chandler, F.O., Rockwell International, Expendable Resupply Fluid System Design Issues, AIAA Paper 86-1758, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama.

	ADVANTAGES	RESUPPLY METHODS[†] 1	2	3	4
1	No Overboard Venting Required	√	√		
2	Small Quantities Transferred	√		√	
3	State of the Art Gaging Accuracy is Adequate	√		√	√
4	Only One Fluid Interface Required	√			
5	No Pressurant Resupply Required	√			
6	Empty Servicer Catch Tanks Not Required	√		√	
7	Vent Products Contained within Servicer for Ground Disposal		√		
8	Minimal Adverse Effect of Dissolved Gas		√		
9	Resupply Complicated Compartmented Tankage			√	√
10	Low Servicer Pressure		√		√
11	Quantity of Products to be Vented Overboard Less Than Vent/Fill				√
12	Does Not Require Active Elements, e.g., Pump, Liquid/Vapor Separators	√		√	√
13	State of the Art Approach for NTO				√
14	Not Limited by Spacecraft Tankage PMD Type				√

† Resupply Methods:
1 Ullage Compression
2 Ullage Exchange
3 Vent/Fill/Repressurize
4 Drain/Vent/Fill/Repressurize

Figure 5.1

Advantages of various methods of resupply for storable propellants.[7]

The disadvantages of each of the systems can then be seen in Figure 5.2.

[7] Eberhardt, R.N., Tracey, T.R., and Bailey, W.J., Martin Marietta Denver Aerospace, Orbital Spacecraft Resupply Technology, AIAA Paper 86-1604, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama.

DISADVANTAGES	RESUPPLY METHODS † 1	2	3	4
1 Compressive Heating Effects	Ø			
2 Hydrazine Decomposition Design Concern	Ø			
3 Propellant Transferred at High Pressure (350 psia)	Ø			
4 Limited to Blowdown Systems Only	Ø			
5 Pump Required for Fluid Circulation		Ø		
6 Required Excessive Electrical Power		Ø		
7 Drive Ullage into Servicer Tanks (Open Tech Issue)		Ø		
8 Requires Propellant Drain Back into the Servicer to Reestablish Ullage		Ø		
9 Pressurant/Ullage Requires Reservicing		Ø	Ø	Ø
10 Not Applicable to Diaphragm Tankage		Ø		
11 Two Propellant Interfaces Required		Ø	Ø	Ø
12 Ullage Venting Without Major Propellant Entrainment (Open Technology Issue)		Ø	Ø	Ø
13 Real-Time Overboard Disposal of Propellant-Contaminated Vent Products			Ø	Ø
14 Empty Catch Tank(s) Required on the Servicer				Ø
15 Tight Gaging Accuracy Required		Ø		

† Resupply Methods: 1 Ullage Compression
2 Ullage Exchange
3 Vent/Fill/Repressurize
4 Drain/Vent/Fill/Repressurize

Figure 5.2
Disadvantages of various methods of resupply for storable propellants.[8]

The Soviets initiated the task of refuelling in space on a regular basis with the refuelling of the Salyut 6 space station with the world's first space tanker. The tanker, Progress 1, was first launched on 20 January 1978 and was completely successful in refueling the space station. Orbital refueling of Soviet space stations with Progress tankers is now routine.

[8] Eberhardt, R.N., Tracey, T.R., and Bailey, W.J., Martin Marietta Denver Aerospace, Orbital Spacecraft Resupply Technology, AIAA Paper 86-1604, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama.

The process of refuelling the Salyut can be performed either by the crew or remotely by ground control. The Salyut uses a bipropellant system for its propulsion and attitude control system (known as ODU). This system uses nitrogen tetroxide (NTO) as the oxidizer and unsymmetrical dimethylhydrazine (UDMH) as the fuel. The connections between the fuel and oxidizer lines of the Progress tanker and the Salyut station are made during docking. The tanks used are pressurized internal bladder tanks with the pressure being provided by gaseous nitrogen. The basic process used for the refuelling is that the pressure in the Salyut tanks is decreased as the pressure in the Progress tanks are increased. This effectively forces propellant out of the Progress tanks into the Salyut tanks. The fuel and oxidizer are transferred at different times for safety reasons, with the fuel being transferred first.[9]

NASA has performed flight experiments aboard the shuttle on propellant transfer, but as yet has no operational propellant transfer system. The first experiment was the orbital refueling system (ORS) which began in late 1982 and culminated with a successful flight on STS-41G in October 1984. The experiment involved the connection of hydrazine lines between a simulated tanker and a simulated Landsat type propulsion system. Standard couplings used for ground transfers were also used for the experiment. The crew performed the connection with special tools in an extravehicular activity (EVA) in the shuttle bay. Hydrazine was transferred between the tanks 6 times to gather data on control of hydrazine heating in the adiabatic ullage compression process.[10]

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[9] Mills, P., REFUELLING SALYUT SPACE STATIONS BY PROGRESS TANKERS, Journal of the British Interplanetary Society, August 1985, pp. 381-384.

[10] Griffin, J.W., NASA JSC, Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers, AIAA Paper 86-1601, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Alabama.

The Storable Fluid Management Demonstration (SFMD) was launched aboard STS Mission 51-C on 24 January 1985. The experiment was mounted in the shuttle middeck, and used transparent tanks which permitted direct observation of the fluid phenomena by the astronaut operator. Tank refill, liquid expulsion, and static and dynamic low-g liquid behavior were demonstrated during 16 hours of testing. The SFMD was a joint venture between Martin Marietta who provided the hardware, and NASA and the Air Force who provided the integration and launch.[11]

5.2 CRYOGENIC PROPELLANTS

The transfer of cryogenic propellants is more complicated than the transfer of storable propellants because of the low temperatures involved and the concerns of limiting boiloff. Several techniques have been explored for cryogenic propellant transfer including capillary, positive expulsion, fluid vortexing, tank rotation, dielectrophoretic, and magnetic transfer (oxygen only). Of these techniques, the most favorable one is capillary action using screens as propellant acquisition devices. Its potential as a technique for cryogenic propellant acquisition and transfer was identified early, and its advantages are low weight and simplicity.[12] This technique has achieved a mature development status, and has been proven to be reliable.[13]

[11] Tegart, J., Kirklant, Z, Martin Marietta Aerospace, On-Orbit Propellant Resupply Demonstration - Flight Results, AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, 8-10 July 1985, Monterey, California, AIAA Paper 85-1233.

[12] Stark, J.A., General Dynamics Corporation, Low-G Fluid Transfer Technology Study, NASA-CR-135020, May 1976.

[13] Schuster, J.R., Bennett, F.O., Liggett, M.W., and Torre, C.N., General Dynamics Space Systems Division, and Brown, N., NASA MSFC, Evaluation of On-Orbit Cryogenic Propellant Depot Options for

NASA's lead center for microgravity fluid management is Lewis Research Center in Cleveland, Ohio. They are developing the Cryogenic Fluid Management Flight Experiment (CFMFE) which is an orbital test bed for demonstration of critical technologies and verification of analytical tools.[14] There are many experimental objectives to be met by the CFMFE, which will fly three missions in the shuttle. The first flight will be in 1991, followed by the second mission in 1993 and the third in 1995. These dates were set after the Challenger disaster, but may be affected by a new shuttle manifest plan.[15] Until the shuttle is operational again, development and testing of technologies for microgravity cryogenic fluid management will continue on the ground.[16] The CFMFE is run by the Cryogenic Fluid Management Project Office (CFMPO) at NASA Lewis, and is the primary focus of their efforts. NASA Lewis has been addressing the technologies associated with low gravity fluid management for the past 25 years, and have issued a number of contracts which have developed new technologies and analytical tools.

Technologies associated with low gravity cryogenic fluid management can be grouped into three categories: fluid storage, supply, and transfer. Fluid storage deals with thermal control and pressure regulation systems necessary for cryogenic storage. Cryogenic fluid supply deals with the acquisition of liquid and the necessary conditioning

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the Orbital Transfer Vehicle, Paper 88c, 6th Intersociety Cryogenics Symposium, 2-7 November 1986, Miami Beach, Florida.

14 Aydelott, J.C., NASA LeRC, Rudland, R.S., Martin Marietta Denver Aerospace, Technology Requirements to be Addressed by the NASA Lewis Research Center Cryogenic Fluid Management Facility Program, NASA-TM-87048, 1985.

15 DeFelice, D.M., NASA LeRC, Cryogenic Fluid Management Flight Experiment, Microgravity Fluid Management Symposium, NASA Lewis Research Center, Cleveland, Ohio, 9-10 September 1986, NASA Report N87-21150, Page 119-124.

16 Liggett, M.W., General Dynamics Space Systems Division, Longsworth, R.C., APC Cryogenics, Inc., Low-Earth LH_2 Propellant Storage Facility Ground Test Program, AIAA 22nd Thermophysics Conference, 8-10 June 1987, Honolulu, Hawaii, AIAA Paper 87-1560.

of that liquid prior to transfer. The objective of an acquisition system is to position the liquid contents of a storage tank at the tank outlet such that vapor free extraction can occur. Liquid acquisition devices (LADs), liquid settling, and pressurization systems are part of the supply technologies. Transfer technologies involve the transport of a single phase liquid from a supply tank to a receiver tank.[17]

For the CFMFE, liquid hydrogen is the base fluid for the experiments because it is one of the primary cryogenic fluids planned for orbital use in the future, and because it has more demanding properties than liquid oxygen which is the other primary propellant. It has a lower temperature, density, and more challenging surface tension characteristics than liquid oxygen. With the development of systems for storage, supply and transfer of liquid hydrogen, the technologies incorporated will be readily transferred to other cryogenic systems with less demanding requirements.[18]

No-vent fill is the preferred method of transfer for cryogenic propellants in low-gravity conditions. The process involved is composed of three phases. Initial conditions assume that the receiver tank is in vacuum condition, with a certain pre-fill temperature which can be somewhat above the required temperature of the cryogenic fluid. The cryogenic fluid is in a sub-cooled condition prior to the transfer process. As the cryogenic fluid begins to enter the receiver tank, it initially flashes to a vapor state because the tank pressure is below the vapor pressure of the liquid. It continues to flash to vapor until the pressure in the tank matches the vapor pressure of the liquid, but continues to vaporize until

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[17] Meserole, J.S., Boeing Aerospace Company, Fluid Acquisition and Transfer Overview, Microgravity Fluid Management Symposium, NASA Lewis Research Center, Cleveland, Ohio, 9-10 September 1986, NASA Report N87-21146, Page 57-65.

[18] DeFelice, D.M., and Aydelott, J.C., NASA Lewis, Thermodynamic Analysis and Subscale Modeling of Space-Based Orbit Transfer Vehicle Cryogenic Propellant Resupply, AIAA Paper 87-1764, AIAA / SAE / ASME / ASEE 23rd Joint Propulsion Conference, 29 June - 2 July 1987, San Diego, CA.

the tank wall temperature is reduced to the liquid temperature and the excess thermal energy in the tank walls have been removed.

After these conditions have been met fluid begins to accumulate in the tank, marking the beginning of phase two. As fluid continues to enter the tank, the vapor is displaced and begins to compress. The pressure of the vapor in the tank continues to rise to the point where the tank pressure equals the vapor pressure at the liquid-vapor interface. At this point, the vapor begins to condense back into liquid form. This condition marks the third phase of the no-vent fill. Fluid transfer continues to the point where the tank pressure reaches its maximum operational value, at which point transfer can only continue as vapor condenses thereby reducing the vapor pressure.

There are many technologies which will be required for orbital management of cryogenic propellants. Table 5.2 outlines many of the technology requirements for the components of the propellant supply infrastructure, and indicates which future experiments will address those technologies. The resupply tanker referred to in the table could be either the separate tanks carried to orbit by the shuttle (infrastructure A), or by an ELV (infrastructure B), or the integral tanks of the ELV (infrastructure C). The resupply tanker must deliver the propellant and transfer it to the orbital propellant depot. The orbital propellant depot must receive the propellants from the resupply tanker, store them until they are needed, then transfer them to the user spacecraft (OTV). The OTV must receive propellant from the propellant depot and then use the propellant to perform its mission.

	Future Requirements			Future Experiments	
	Resupply Tanker	OTV	Propellant	CFMFE	LTCFS
Passive Thermal Technologies					
Dual Stage Support			X		X
Para-Ortho Conversion			X		X
Thick MLI		X	X	X	X
TVS	X	X	X	X	X
Thermal Coatings		X	X		X
Soft Outer Shell		X	X	X	X
Hard Outer Shell	X			X	X
Fluid Transfer					
Capillary Acquisition	X	X	X	X	X
Low-G Quantity Gaging	X		X	X	X
Mass Flow Meters	X		X	X	X
Low Heat Leak Values	X		X		X
Low Heat Leak Transfer Lines	X		X		X
Cryogenic Disconnects	X	X	X		X
External Pressurization	X	X	X		X
HPG Pressurization				X	X
Metal Hydride Comperssor					X
Active Refrigerator					
Long Lifetime Refrigerator			X		X
Reliquefaction			X		X
Cryogenic Heat Exchanger			X		X
Refrigerator to S.S. Thermal Bus HEX			X		X

Table 5.2

Definition of technology hardware requirements for orbital cryogenic fluid management.[19]

Table 5.3 is similar to Table 5.2 but outlines the technology issues associated with development of long term cryogenic fluid storage and transfer for orbital operations. Included among these issues are fluid management, logistics, and phenomena which occur in the orbital environment.

[19] Riemer, David H., Space Station Experiment Definition: Long Term Cryogenic Fluid Storage, Microgravity Fluid Management Symposium, NASA Lewis Research Center, Cleveland, Ohio, 9-10 September 1986, NASA Report N87-21144, Page 40.

	Future Requirements			Future Experiments	
	Resupply Tanker	OTV	Propellant	CFMFE	LTCFS
Investigated Phenomena					
Long-Term Stratification Effects			X		X
Sofr OS Performance Degradation		X	X		X
Thermal Coating Degradation		X	X		X
Micro-Meteoroid Protection		X	X		X
Fluid Management					
LAD Refill		X	X	X	X
Transfer Line Cooldown	X	X	X	X	X
ET Scavenging	X				Possible
Receiver Tank Cooldown	X	X	X	X	X
Receiver No-Vent Fill		X	X	X	X
Refill of Partially Full Tank			X	X	X
Propellant Settling		X		X	
Boiloff Collection			X		X
Slosh Suppression	X	X	X		
On-Orbit Logistics					
System Safing	X	X	X	X	X
Space Station Interfacing	X	X	X		X
Space Station Operations	X	X	X		X
On-Orbit Leak Detection	X	X	X		Possible

Table 5.3

Definition of technology issues for orbital cryogenic storage and transfer.[20]

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20 Riemer, David H., Space Station Experiment Definition: Long Term Cryogenic Fluid Storage, Microgravity Fluid Management Symposium, NASA Lewis Research Center, Cleveland, Ohio, 9-10 September 1986, NASA Report N87-21144, Page 41.

CHAPTER 6 PROPELLANT RECLAMATION SIMULATION - OPSIS

In order to address the impact that propellant reclamation might have on the supply of propellants and their cost in the future space infrastructure, a computer model was developed. Called the Orbital Propellant Supply Infrastructure Simulation (OPSIS), the simulation provides information on the cost and propellant supply effects of various scenarios which can be provided as input. The simulation can be broken down into three primary parts: input, execution, and output. The basic relationship between these elements of the simulation can be seen in Figure 6.1 on the following page.

The simulation was developed and run on the Academic Micro-VAX in the Department of Aeronautics and Astronautics at MIT. The programming language used is Fortran 77[1], and a copy of the code is included in Appendix B. Outputs were taken from the VAX and transferred to a Macintosh Plus. Cricketgraph was used with the Macintosh to tabulate the data and generate the graphs. The system used for the simulation is shown in Figure 6.2.

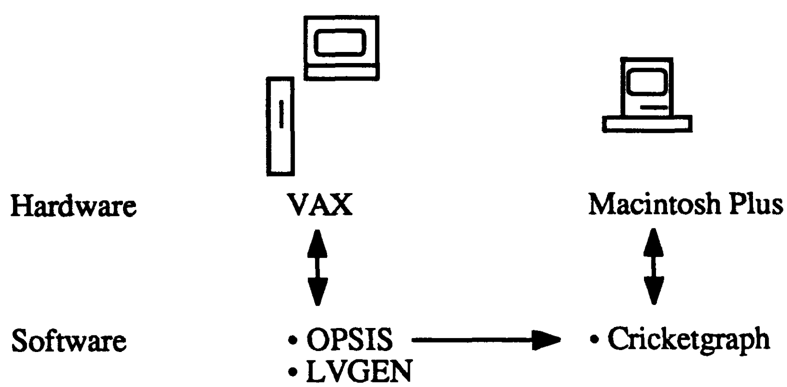

Figure 6.2
Hardware and software used for simulation and presentation.

[1] Etter, D.M., Structured Fortran 77 For Engineers and Scientists, second edition, The Benjamin / Cummings Publishing Company, 1987.

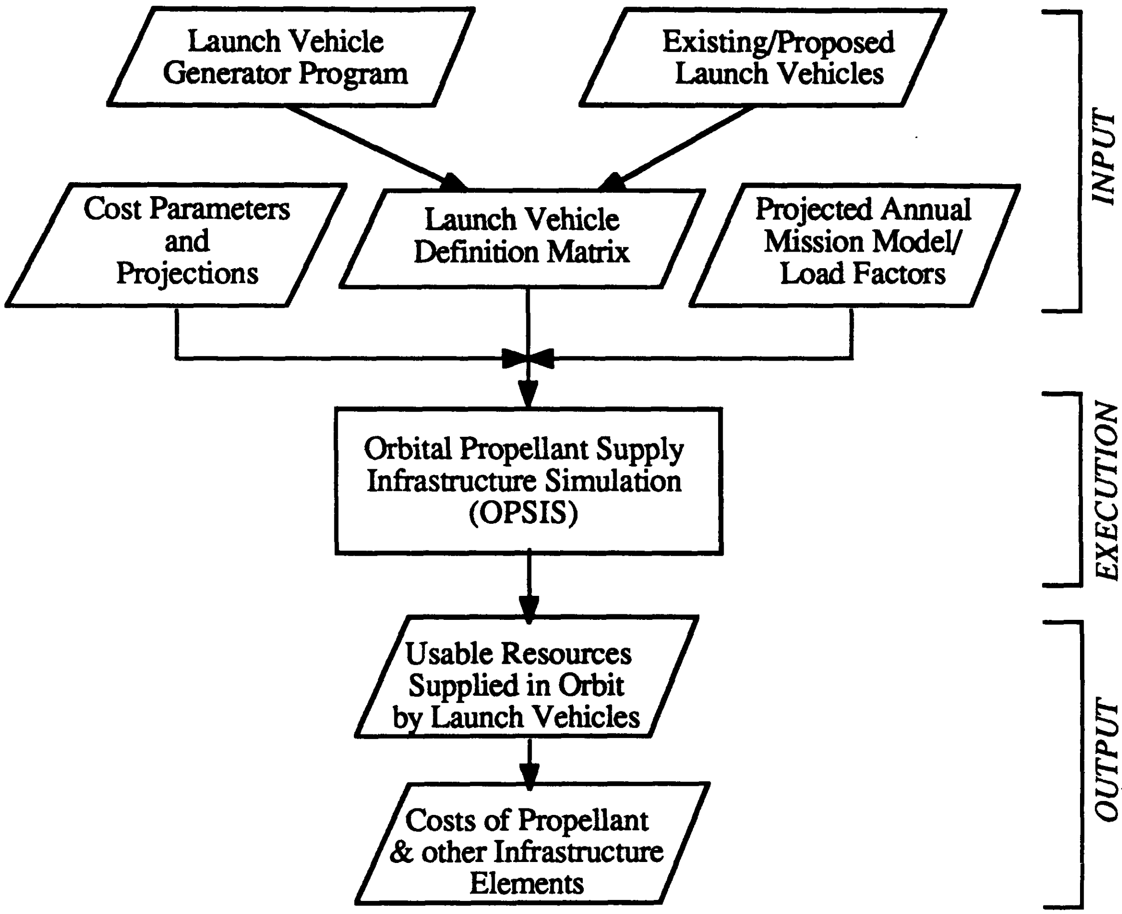

Figure 6.1
OPSIS input and output relationship.

6.1 INPUT

The input to OPSIS is required to provide the data for three basic elements of the simulation. The first part is the characterization of the launch vehicle, the second the definition of the mission model, and the third involves the cost parameters associated with the various elements of the infrastructure. The input files are generated with the use of software besides OPSIS such as the LVGEN program, and from outside sources and entered. When running OPSIS the user is asked the name of the input file to be used. The simulation then accesses that input file for the information needed to run the program. The OPSIS executable code and the input files must be in the same directory in the VAX system in order to be accessed.

6.1.1 LAUNCH VEHICLE

Inputs which describe the launch vehicle are generated by the launch vehicle generator program (LVGEN) which was developed along with OPSIS as an analytical tool for the assessment of propellant reclamation. This program can size new launch vehicles when basic performance parameters are given, or take data from existing launch vehicles or designs and convert it to the proper format for use as input to OPSIS. The launch vehicle is defined within OPSIS in matrix form and is provided as input in that form. It is a two dimensional matrix, with N+1 columns representing the N stages of the launch vehicle and the N+1 column representing the overall launch vehicle. There are thirteen rows which represent the mass properties and performance characteristics of the launch vehicle and they are indicated in Table 6.1.

ROW	Definition	Dimensions
1	Total Launch Vehicle weight from this stage up	[lb]
2	Mass ratio of vehicle for this stage up	
3	Delta Velocity of this stage	[feet/second]
4	Propellant used by this stage	[lb]
5	Unused nominal ascent propellant for this stage	[lb]
6	Total weight of this stage only	[lb]
7	Total propellant weight of this stage only	[lb]
8	Residual propellant weight of this stage only	[lb]
9	Reserve propellant weight of this stage only	[lb]
10	Payload weight of this stage	[lb]
11	Vacuum specific impulse of this stage	[sec]
12	Mass fraction of this stage	
13	weight of required propellant transfer hardware	[lb]

Table 6.1

Row identification for launch vehicle definition matrix.

An example of an input for the baseline vehicle being used in the simulation is shown in Table 6.2. The vehicle is an Advanced Launch System (ALS) type of vehicle with a nominal payload capability of 100,000 lb, a single stage of cryogenic liquid oxygen (LOX) and liquid hydrogen (LH2) propellants, some solid rocket motors for thrust augmentation at lift-off, and an integral orbital maneuvering system (OMS) for orbital rendezvous maneuvers and satellite deployment.

Rows	Column 1 (Stage 1) (Solids)	Column 2 (Stage 2) (Liquid Core)	Column 3 (Total Vehicle)
1	2492291.00	1065191.00	2492291.00
2	2.15	4.77	
3	6487.29	22552.13	29039.42
4	1331099.5	841839.63	2172939.25
5	13445.45	17180.40	30625.85
6	1427100.00	965191.00	2392291.00
7	1344545.00	859020.00	2203565.00
8	13445.45	8590.20	22035.65
9	0.00	8590.20	8590.20
10	1065191.00	100000.00	100000.00
11	264.00	448.70	
12	0.93	0.87	0.91
13	0.00	1562.00	1562.00

Table 6.2
Launch Vehicle Definition Matrix baseline input values.

6.1.2 MISSION MODEL

The next primary set of input data for OPSIS is the characterization of the mission model. The mission model is particular to the launch vehicle that is being used for the simulation. It defines for each year the launch vehicle is in operation the number of missions that are flown and the average load factor of the launch vehicle. The Mission Model is characterized in the form of a two dimensional matrix as was the launch vehicle. The matrix has three columns, the first representing the year of operation, the second provides the number of missions which are flown for that year, and the third defines the average load factor of missions for that year. The number of rows in the matrix is simply the number of years in which the launch vehicle is operational.

The values used as input for the mission model matrix are based on projections of launch rates over the next thirty to forty years for the particular type of launch vehicle which is being used for the simulation. These data vary significantly as do any data on projections of future events. The baseline values which are used are a generally conservative consensus of what is expected as the usage rate for a new ELV. The number of years being used as the baseline value for program life is twenty years, from 1995 to 2014. The number of missions actually flown per year will vary between year to year, but for purposes of comparison in the sensitivity studies an average value of ten missions per year will be used as the baseline. The load factor has been estimated to be on the order of 60 to 80 percent on the average for a vehicle of this type. To be on the conservative side a baseline value of .80 for the load factor will be used.

Different values will be used in sensitivity studies, and any combination of these parameters can be input into OPSIS for evaluation. An example of the basic input matrix for the mission model is shown in Table 6.3.

YEAR	NUMBER OF FLIGHTS	AVERAGE LOAD FACTOR
1995	10	.8
1996	10	.8
.	.	.
.	.	.
2013	10	.8
2014	10	.8

Table 6.3
Mission Model Definition Matrix baseline input values.

6.1.3 INFRASTRUCTURE ELEMENTS AND COSTS

The third area of input for the simulation involves the costs parameters associated with each of the elements required of the infrastructure for propellant reclamation and supply in orbit. The infrastructure elements required are as previously defined in Section 3.1.1. They are broken down further to separate the costs of the SRBs of the ELV from the liquid portion. The costs of the infrastructure will be separated into five elements, which are:

- Solid Rocket Booster
- Liquid Rocket
- Transportation Tank
- Storage Depot Facility
- Additional ELV Hardware

Costs for the various systems being modeled will be derived using parametric cost estimating relationships (CERs). The relationships are derived from correlation of hardware mass with cost, and are typically straight line curve fits on a semi-logarithmic graph. The CERs that will be used here are mathematically represented as:

$$\text{COST} = (\text{Constant}) \times ((\text{Weight})^{\text{raised to an exponent}})$$

All costs are in fiscal year (FY) 1988 dollars unless otherwise indicated. Costs from other sources in other than FY 88 dollars have been converted to FY 88 dollars with the composite deflator index used in the Federal Budget.[2] The costs are divided into two primary categories, the first being recurring and the second non-recurring. Recurring costs

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[2] Historical Tables, Budget of the United States Government, Fiscal Year 1989, Executive Office of the President, Office of Management and Budget, U.S. Government Printing Office, 1988.

are essentially those which arise for each flight. These include costs such as production of hardware for non-reusable systems, refurbishment of reusable systems, propellant cost, mission control manpower requirements, etc.

Non-recurring costs are those which do not arise for each flight, but rather only once or occasionally. Included in non-recurring costs are such things as Design, Development, Test, and Evaluation (DDT&E), ground support equipment (GSE), and production of reusable hardware. The total Life Cycle Cost (LCC) is a summation of recurring costs for all flights, and all non-recurring costs. Both recurring and non-recurring costs are represented parametrically in exponential form as indicated above.[3] Non-recurring costs are distributed evenly over the number of systems being produced on a per-flight basis, and the average recurring cost is the summation of each unit recurring cost divided by the number of units.

There is a large difference between the actual recurring costs of the first and the last flights due to the effect of learning on labor reduction. The learning curve is used to represent this and the slope of the learning cure, r, is the factor used in the calculations. From the effect of learning, the cost of production for unit 2n is r times the production cost of unit n. The definitions of the variables associated with the parametric CERs are shown below.

C_o = Non-recurring costs for DDT&E
C_1 = First vehicle production cost
C_{cum} = Cumulative recurring cost of producing N vehicles
C_{ave} = Average recurring cost per vehicle
C_{dis} = Distributed non-recurring cost per vehicle
C_{totave} = Total average cost per vehicle

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[3] Miller, R.H., Stuart, D.G., and Azarbayejani, A., FACTORS INFLUENCING SELECTION OF SPACE TRANSPORTATION OPTIONS, IAF Paper 86-108, 37th Congress of the International Astronautical Federation, Innsbruck, Austria, October 4-11, 1986, Permagon Press, 1986.

q_o = Exponent in non-recurring parametric relationship
q_1 = Exponent in recurring parametric relationship
WE = Weight empty of hardware element
F_o = Constant in non-recurring parametric relationship
F_1 = Constant in recurring parametric relationship
N = Total number of elements produced
r = Slope of learning curve
p = Napierian form for r

The non-recurring costs are represented parametrically by equations 6.1-6.3 indicated below.

$$C_o \approx (WE)^{q_o} \tag{6.1}$$

$$C_o = F_o\,(WE)^{q_o} \tag{6.2}$$

Distributed non-recurring cost for each of N vehicles:

$$C_{dis} = C_o / N \tag{6.3}$$

Recurring costs are indicated by equations 6.4 - 6.8 which are very similar to the equations for non-recurring cost with the exception of the learning effect. The learning curve reflects the relative improvement in labor efficiency with time. The effect of learning on recurring costs is represented by the equation for C_{cum}. This relationship gives an accurate representation of the integration of the cost reduction due to learning over the life of the program.[4]

$$C_1 \approx (WE)^{q_1} \tag{6.4}$$

$$C_1 = F_1\,(WE)^{q_1} \tag{6.5}$$

Average recurring cost for each of N vehicles:

$$C_{ave} = C_{cum} / N \tag{6.6}$$

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[4] Woodcock, Gordon R., SPACE STATIONS & PLATFORMS: Cost & Cost Estimating, Orbit Book Company, Inc., 1986.

$$C_{cum} = C_1 \left[\frac{(N+0.5)^{(p+1)} - 1.5^{(p+1)} + 1}{(p+1)} \right] \qquad (6.7)$$

$$p = [\ \ln(r) / \ln(2)\ ] \qquad (6.8)$$

Through summation of the total recurring and non-recurring costs and division by the number of flights, the total average cost per flight can be determined as shown in equation 6.9.

$$C_{totave} = [\ F_o\ (WE)^{q_o}\ ] / N + \frac{\{F_1\ (WE)^{q_1}\ [\ (N+0.5)^{(p+1)} - 1.5^{(p+1)} + 1\ ]\}}{N\ (p+1)} \qquad (6.9)$$

Variables for the CERs of each of the hardware elements required for the space infrastructure have been determined on the basis of estimates found in literature, historical figures, and correspondence. The definition of these CER variables is an uncertain task as the future is inherently uncertain. Nonetheless they serve to represent the expected costs of the systems elements which are being addressed. Certain basic variables vary slightly between sources. However, they have been assigned values which are held constant throughout the simulation to provide consistency. These assigned variable values are representative of values which are employed in CERs for aerospace systems.[5] The variables which will be held constant are the exponent of non-recurring costs, the exponent of recurring costs, the slope of the learning curve, and its Napierian form. The values for these variables which are used in the simulation are as shown below.

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[5] Miller, R.H., EFFECT OF DEMAND ON OPTIMUM LAUNCH VEHICLE SIZE, Journal of Spacecraft and Rockets, Volume 16, Number 4, July-August 1979, Page 287.

$$q_o = 0.5$$
$$q_1 = 0.8$$
$$r = 0.9$$
$$p = -0.152$$

The variables which remain to be identified for each of the hardware systems being costed are the constants for the recurring and non-recurring CERs, and the number of elements being produced. The number of elements being produced is a function of the mission model and will be derived from the annual utilization rate and the duration of use. The constants F_o and F_1 are derived from available data on cost estimates for similar systems from NASA and various aerospace contractors.

The generic form of input for each of the infrastructure element cost parameters consists of a row of seven elements. The first two are number of hardware items produced and the dry weight of the hardware. In most cases this data is calculated internally within OPSIS but for some it is provided as input. The third and fourth elements of the row are constants used in the CERs, F_o and F_1, respectively. The fifth, sixth, and seventh elements are the exponents in the CERs and the slope of the learning curve. They are q_o, q_1, and r, respectively. These constants will be addressed and defined for each of the elements going into the model, in the following sections.

6.1.3.1 SOLID ROCKET BOOSTER (SRB)

The costs of SRBs are significantly different from the costs of the liquid rocket. The cost parameters use the empty weight of the system as the figure of merit for cost estimation, and the cost of a solid rocket motor casing is substantially less per unit weight than the cost of a liquid rocket. For this reason, the SRB costs have been broken out as a separate item from the liquid rocket costs. The established cost of the SRBs used on the space shuttle is 16.2 million per booster.[6] The relationship between production life cycle costs and costs for DDT&E for solid rockets has been established as approximately eight percent.[7] Using the 16.2 million per booster as the cost of the theoretical first unit (TFU) for recurring costs, the values determined for use in the CERs are as shown below.

$$C_0 = 360{,}000 \times WE^{.5}$$

$$C_1 = 1{,}100 \times WE^{.8}$$

The input for SRBs to OPSIS is in the form:

N	WE	F_0	F_1	q_0	q_1	r
calc.	calc.	360,000	1,100	.50	.80	.90

6.1.3.2 LIQUID ROCKET

The liquid rocket is a very complicated machine with many components of varying complexity and cost. For this case however, the cost of the rocket will be taken to be related to the aggregate weight of the system hardware. This includes the tankage, avionics, propulsion system, and support structure. Cost figures taken from several sources including NASA[8], Martin Marietta Corporation[5], and General Dynamics

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[6] Martin Marietta Corporation, Denver Aerospace, Michoud Division, Shuttle Derived Vehicles (SDV) Technology Requirements Study, Phase II Final Report, Volume III, Program Cost and Work Breakdown Structure/Dictionary, NASA-CR-170701, May 1982.

[7] Gaunt, David C., Hercules Incorporated, Understanding Costs of Solid Rocket Motors, AIAA Paper 86-1638, AIAA / ASME / SAE / ASEE 22nd Joint Propulsion Conference, 16-18 June 1986, Huntsville, Al.

[8] NASA Space Launch System Studies, NASA Cargo Vehicle Studies, Briefing of 8 April 1987.

Corporation[9] have been used to derive the constants in the CERs. The values derived for the recurring and non-recurring CERs are seen below.

$$C_o = 5{,}000{,}000 \times WE^{.5}$$

$$C_1 = 5{,}000 \times WE^{.8}$$

The input for the Liquid Rocket to OPSIS is in the form:

N	WE	F_o	F_1	q_o	q_1	r
calc.	calc.	5,000,000	5,000	.50	.80	.90

6.1.3.3 TRANSPORTATION TANK

If the propellant supply is transported to orbit as part of a payload, whether it be dedicated or simply as filler payload, a transportation tank will be required to hold the propellant. The transportation tank will then transfer its propellant to the storage tank in orbit. Studies have been done which address this type of scenario and cost figures have been estimated.[10] Transportation tanks can be either reused or disposed of in the simulation. However, if the tanks are disposed the costs are very high. When reusable tanks are used, the number of tanks to be built must be established. This is done by estimating the turnaround time of the tanks in terms of flights per year for each tank. Dividing the total number of flights per year by this number will give the number of tanks required, if rounded up. Refurbishment costs are added to this at a percentage of

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[9] General Dynamics Space Systems Division, Space Transportation Architecture Study, First Special Report, NASA Contract NAS8-36615, 9 May 1986.

[10] Rockwell International Corporation, Space Platform Expendables Resupply Concept Definition Study, Volume II, Technical Report, NASA-CR-178821, December 1984.

production costs for each flight. The baseline value that is used in the simulation is ten percent of production cost for refurbishment. The basic CERs for the costs associated with a transportation tank for propellant storage during ascent are seen below.

$$C_o = 870{,}000 \times WE^{.5}$$

$$C_1 = 16{,}500 \times WE^{.8}$$

The input for Transportation Tank to OPSIS is in the form:

N	WE	F_o	F_1	q_o	q_1	r
calc.	calc.	870,000	16,500	.50	.80	.90

6.1.3.4 STORAGE FACILITY

The storage facility for propellants in orbit will receive propellants from earth to orbit transportation vehicles, store them for a period of time, then transfer the stored propellants to orbital transfer vehicles. The facility will likely be co-orbital with the space station, to facilitate OTV use of space station as a base. Storage facilities are under design and cost estimates have been made. Based on these cost estimates, the factors used in the cost equations are as follows.

$$C_o = 1{,}465{,}000 \times WE^{.5}$$

$$C_1 = 4{,}500 \times WE^{.8}$$

The number of storage facilities required is a function of their capacity, the annual propellant being supplied, and the turnover rate which is expected. To get the number of storage facilities required, the following relationship is used.

Number = (Truncation of ((Annual Supply)/(Capacity x 2))) + 1

The capacity of the facility is doubled to signify that it has an annual turnover rate of two. This relationship provides the number of storage facilities which must be built for use. The expected life of an orbital storage facility such as this is expected to be 30 years, so that replacement is not an issue over the time period being considered here.[11]

The input for the propellant storage facility to OPSIS is in the form:

N	WE	F_o	F_1	q_o	q_1	r
calc.	calc.	1,465,000	4,500	.50	.80	.90

6.1.3.5 ADDITIONAL HARDWARE

Additional hardware will be required on a launch vehicle to enable it to transfer propellant from its tanks to an orbital storage facility. The hardware will consist of propellant acquisition devices which consist of wire mesh screens, additional plumbing including tubing, interfaces, and pumps. These items are similar in nature to the items which compose the storage facility, in that they are required to perform the same functions of propellant acquisition and transfer. Therefore the costs associated with the propellant storage facility will also be used for the additional ELV hardware as shown below.

$$C_o = 1{,}465{,}000 \times WE^{.5}$$

$$C_1 = 4{,}500 \times WE^{.8}$$

[11] Schuster, J.R., Bennett, F.O., Liggett, M.W., and Torre, C.N., General Dynamics Space Systems Division, and Brown, N., NASA MSFC, Evaluation of On-Orbit Cryogenic Propellant Depot Options for the Orbital Transfer Vehicle, Paper 88c, 6th Intersociety Cryogenics Symposium, 2-7 November 1986, Miami Beach, Florida.

The mass of the hardware necessary for propellant acquisition and transfer will increase with the size of the vehicle, but there are certain fixed items as well. Therefore the mass estimating relation for the additional hardware elements required will be of the form:

Mass = Fixed Value + (Constant x Booster Empty Weight)

Based on data from studies for development of cryogenic propellant transfer, the baseline values for these are indicated below, which results in the final equation as shown.[12]

Fixed Mass = 500 [lb]

Constant = 0.01

Additional Mass = 500 + 0.01(Empty Mass)

The input for additional ELV equipment to OPSIS is in the form:

N	WE	F_o	F_1	q_o	q_1	r
calc.	calc.	1,465,000	4,500	.50	.80	.90

The data are input in a form which allows for sequential reading of the data for each of the infrastructure elements. They are used internally in the program to provide the basic inputs needed in generation of the cost matrix for the simulation which defines the cost parameters for each of the infrastructure elements as well as the calculated costs for each of them based on the particular scenario being used. The characteristics of the cost matrix will be discussed in the output section.

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[12] Rockwell International Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume I, Technical Report, NASA -CR-171848, January 1985.

A summary of the primary input variables is seen in Table 6.4.

VARIABLE NAME	IDENTIFICATION
M_{lv}	Launch Vehicle Definition Matrix
N_s	Number of Stages
W_{lv}	Launch Vehicle Weight
MR	Mass Ratio
ΔV	Delta Velocity
W_{pu}	Useable Propellant Weight
W_{pn}	Non-Useable Propellant Weight
W_s	Total Stage Weight
W_{pt}	Total Propellant Weight
W_{pr}	Residual Propellant Weight
W_{pv}	Reserve Propellant Weight
$W_{p/l}$	Payload Weight
I_{sp}	Specific Impulse
MF	Mass Fraction
W_x	Weight of extra Propellant Transfer Hardware
M_{mm}	Mission Model Definition Matrix
Y	Years of Program Duration
L	Load Factor
R	Annual Launch Rate
M_c	Cost Definition Matrix
F_o	Fixed Cost Constant
F_1	Recurring Cost Constant
q_o	Fixed Cost Exponent
q_1	Recurring Cost Exponent
r	Slope of Learning Curve

Table 6.4

Summary and Definition of Primary Input Variables.

An example input file is seen in Table 6.5.

```
      ALS100K
      12        2
2492291.00  1065191.00  2492291.00
      2.15        4.77        0.00
   6487.29    22552.13    29039.42
1331099.50   841839.63  2172939.25
  13445.45    17180.40    30625.85
1427100.00   965191.00  2392291.00
1344545.00   859020.00  2203565.00
  13445.45     8590.20    22035.65
      0.00     8590.20     8590.20
1065191.00   100000.00   100000.00
    264.00      448.70        0.00
      0.93        0.87        0.91
      500       0.01      0.90
      ALS20
      20        3
      1995      10        .8
      1996      10        .8
      1997      10        .8
      1998      10        .8
      1999      10        .8
      2000      10        .8
      2001      10        .8
      2002      10        .8
      2003      10        .8
      2004      10        .8
      2005      10        .8
      2006      10        .8
      2007      10        .8
      2008      10        .8
      2009      10        .8
      2010      10        .8
      2011      10        .8
      2012      10        .8
      2013      10        .8
      2014      10        .8
      6         7
      ALSSOLID
      0.        0.        250E3     750.      0.5       0.8       0.9
      ALSLIQUID
      0.        0.        5E6       5000.     0.5       0.8       0.9
      ALSEXTRA
      0.        0.        1.465E6 4.5E3     0.5       0.8       0.9
      0.0
      TANK
      0.        2000.     0.        0.        0.5       0.8       0.9
      STORAGE
      0.        27770.    1.465E6 4.5E3     0.5       0.8       0.9
      100000.
      OTV
      5         10000.    23E6      2E4       0.5       0.8       0.9
      LOTV
      2         20000.    23E6      2E4       0.5       0.8       0.9

      THIS FILE IS CALLED ALS2010.DAT
```

Table 6.5

An example input file for OPSIS.

6.2 EXECUTION

The calculations involved in the simulation are performed by OPSIS and four subroutines. OPSIS is the main program which drives the subroutines. There are two level 1 subroutine and two level 2 subroutines. The basic relationship between OPSIS and the subroutines is seen in Figure 6.7.

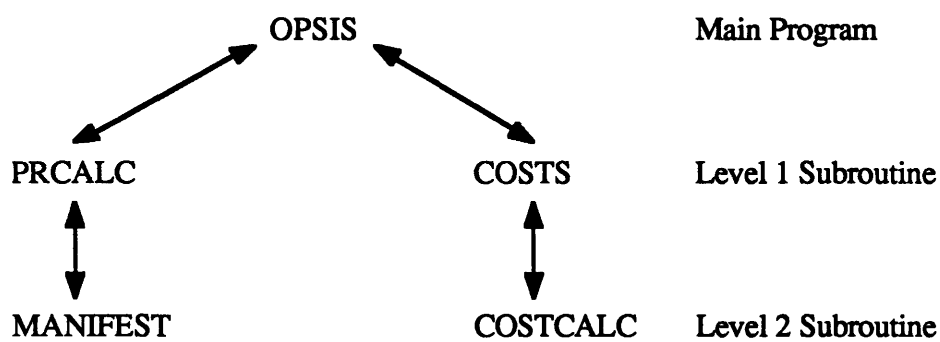


Figure 6.3
Overall program architecture for OPSIS.

Each of the elements of the program architecture will be addressed in the following sections. The basic purpose of each element will be outlined and a simple flow diagram will indicate the contents and processes involved.

6.2.1 OPSIS

OPSIS is the main program involved in the simulation. It interfaces with the user, reads in data from input files and is the driver for the level 1 subroutines. There is an option to make multiple runs with the simulation rather than having to run the simulation several times individually. The flow diagram for OPSIS is seen in Figure 6.4.

6.2.2 PRCALC

PRCALC is a level 1 subroutine which is called from OPSIS to calculate the propellant quantities available from reclamation. It generates a Propellant Reclamation Matrix (PRM) which contains the data on propellant quantities available, calls the level 2 subroutine MANIFEST to perform the actual calculations, and prints out the contents of the PRM. A flow diagram for PRCALC is shown in Figure 6.5.

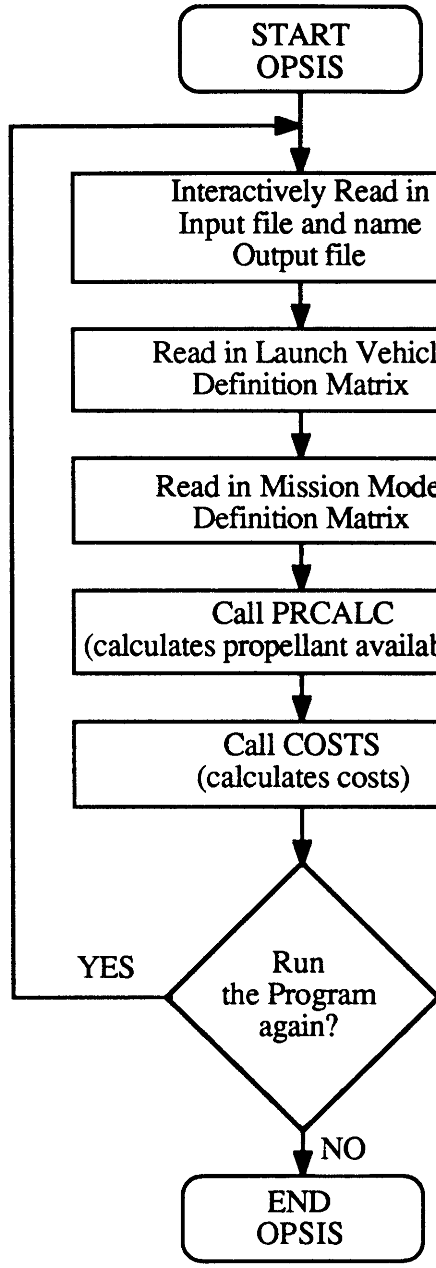


Figure 6.4
Flow diagram for OPSIS.

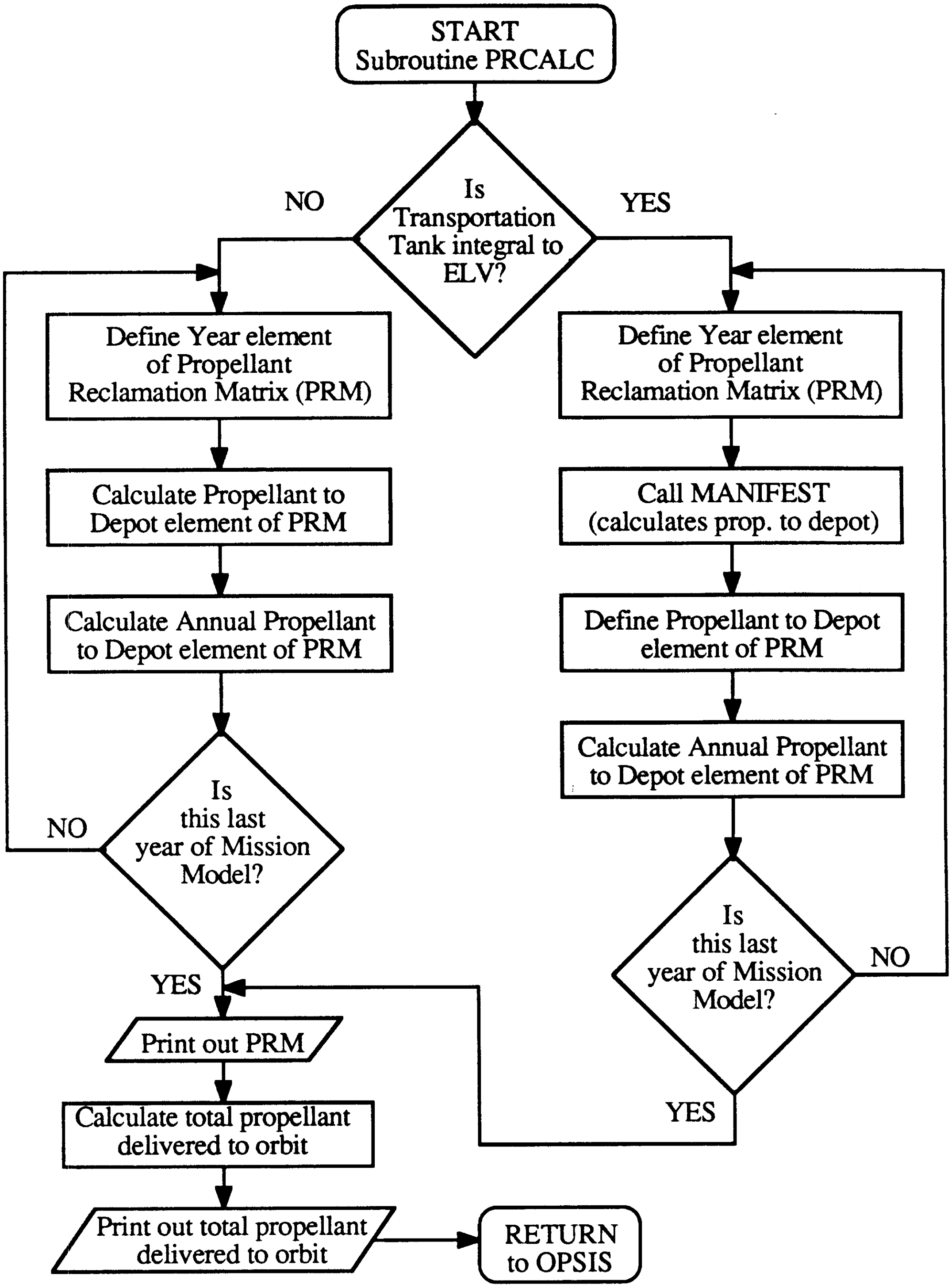


Figure 6.5
Flow diagram for PRCALC.

6.2.3 MANIFEST

MANIFEST is a level 2 subroutine that is called from PRCALC for calculation of the propellant transferred to a storage depot from an ELV. The process involves calculation of the ΔV for the various stages of the launch vehicle on the basis of flying with a less than nominal GLOW when the load factor is less than one hundred percent. The launch vehicle has a higher mass ratio therefore is capable of higher ΔV generation.

It is assumed that the total ΔV for the vehicle is the same as for the nominal mission. This is a conservative assumption because with a lower GLOW the thrust to weight will be higher, reducing gravity losses, thereby reducing the total ΔV requirement. When the ΔV of the lower stages is known, the ΔV requirement of the upper stage can be calculated along with the amount of propellant required to generate that ΔV. The propellant unused in the ascent of the upper stage is the nominal propellant requirement less the calculated propellant requirement. This propellant is then added to the reserves and residuals to constitute the total propellant available, then transferred to the storage depot.

There is a factor which is multiplied with the total propellant available to account for propellants left in the tanks which are not extractable, and for losses incurred in the transfer process. The baseline value used in the simulation for this factor is 0.9 which says that ninety percent of the propellant available in the ELV tanks makes it into the tanks of the storage depot. A flow diagram of the basic calculations involved in operation of the MANIFEST subroutine is shown in Figure 6.6.

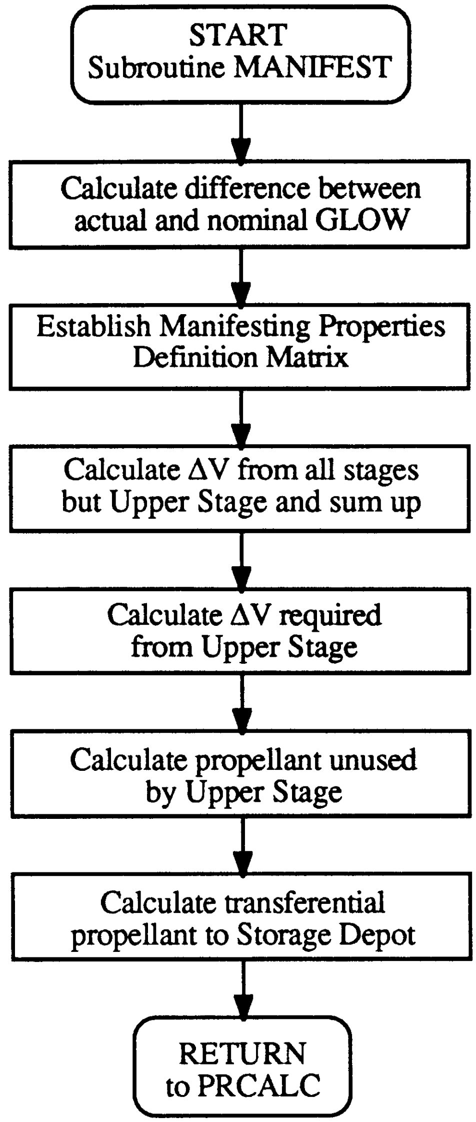
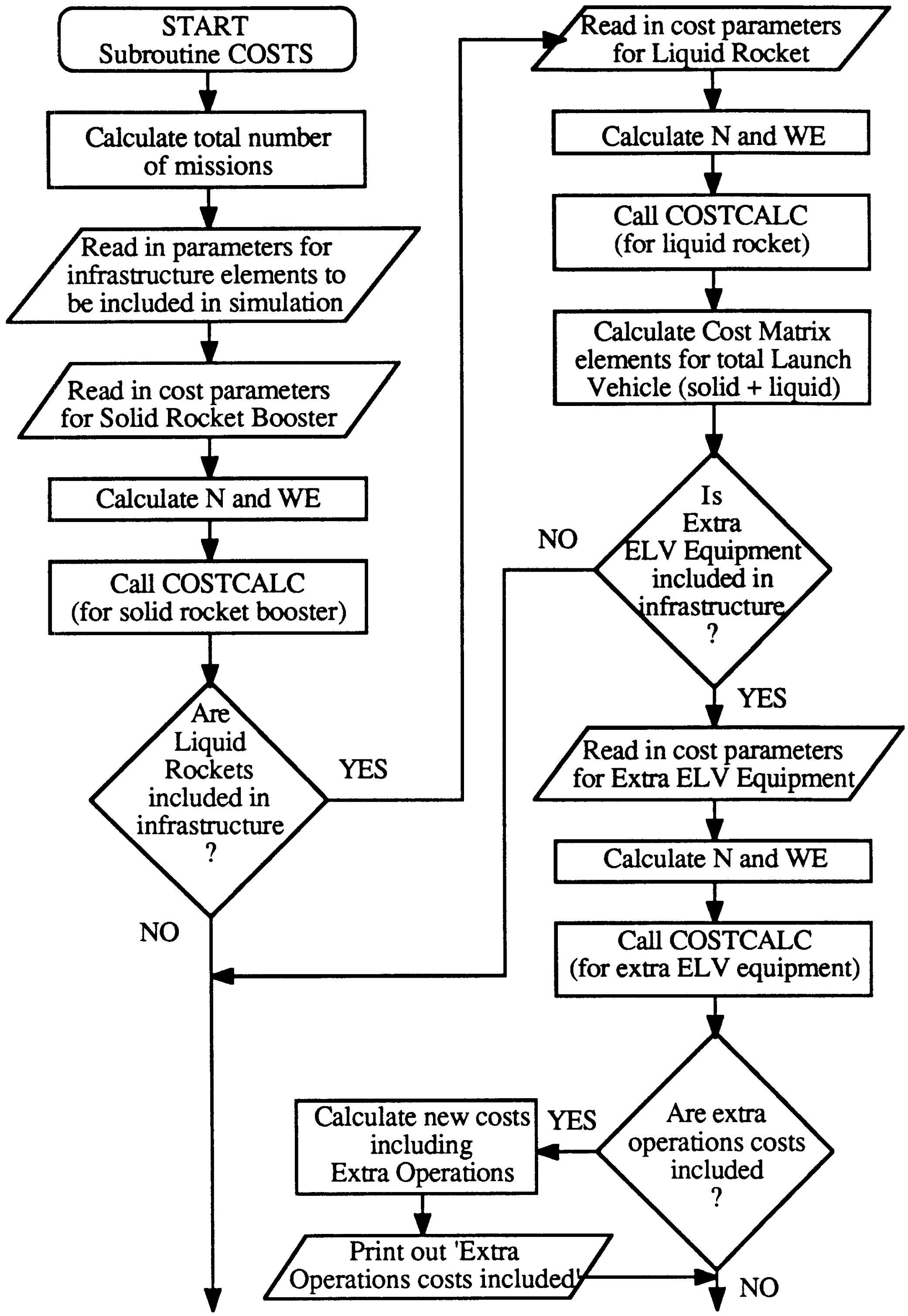
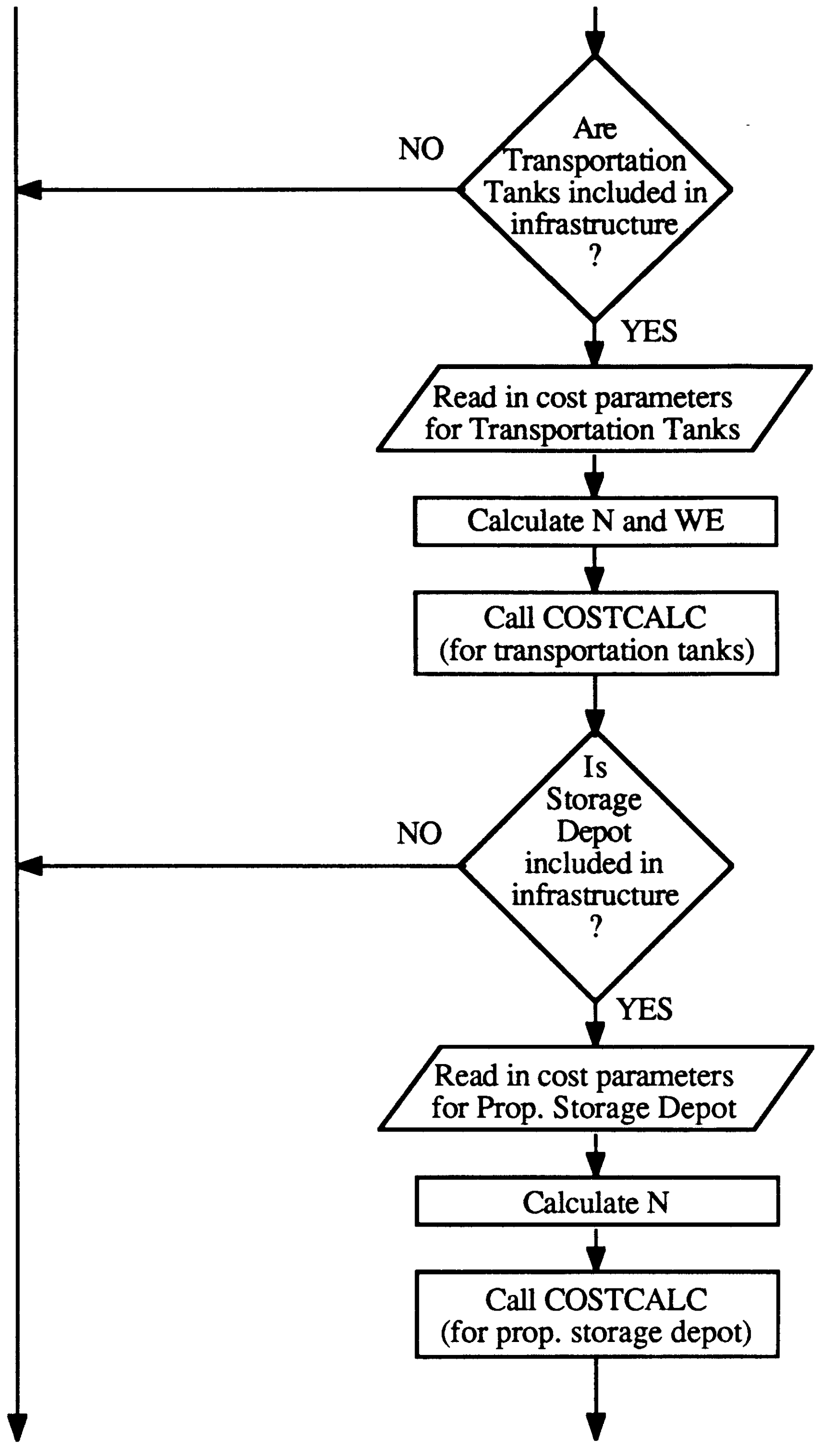


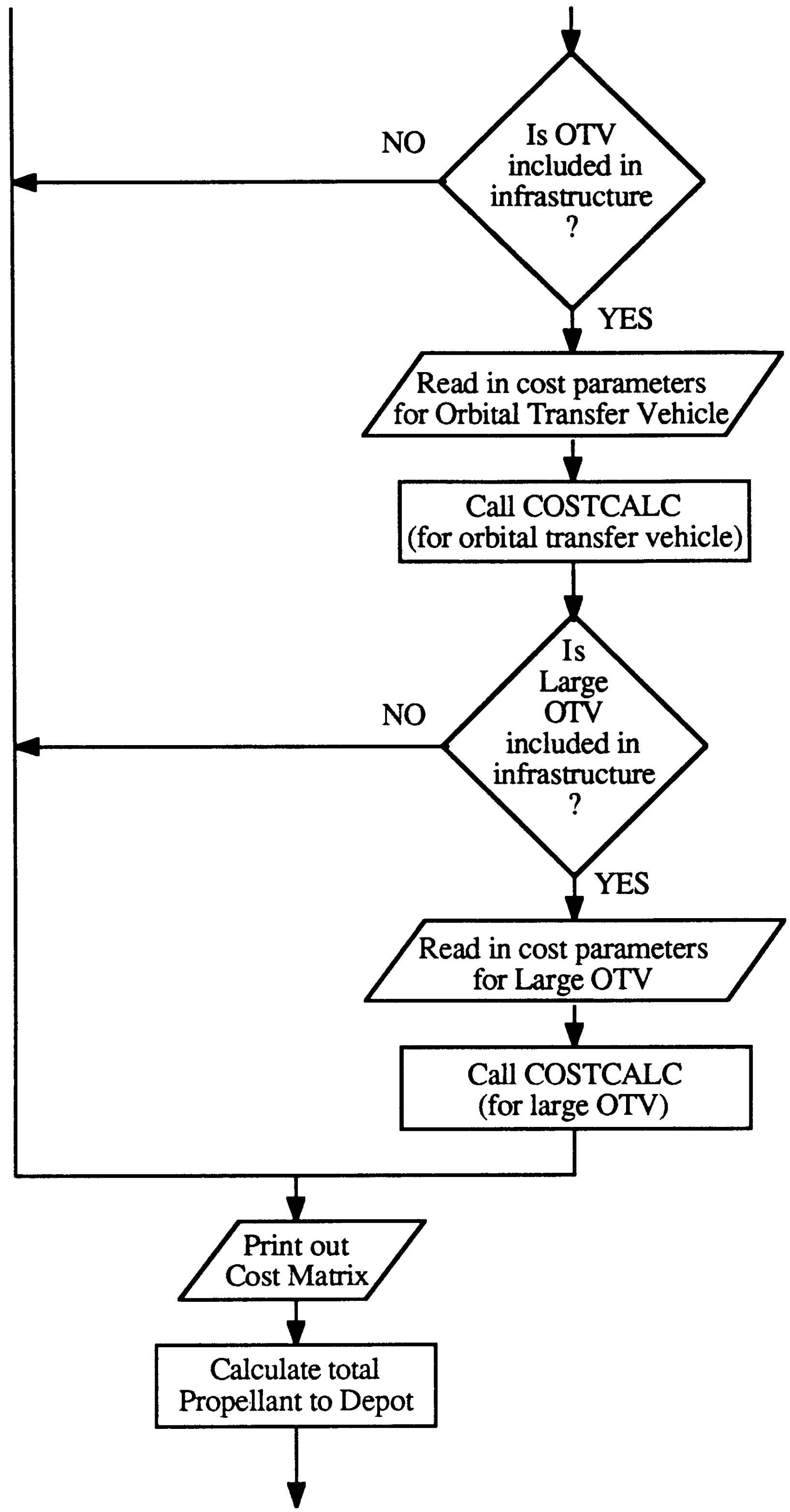
Figure 6.6
Flow diagram for MANIFEST.

6.2.4 COSTS

COSTS is a level 1 subroutine which is called from OPSIS to calculate the costs of the various components of the propellant reclamation infrastructure. The subroutine reads in data on cost parameters for each of the infrastructure elements, calls the level 2 subroutine COSTCALC to perform the actual calculations, generates the Cost Matrix which contains data on costs for each of the elements, and prints out the Cost Matrix. This subroutine is the longest of the simulation, and its flow diagram is seen in Figure 6.7.


START
Subroutine COSTS
Calculate total number of missions
Read in parameters for infrastructure elements to be included in simulation
Read in cost parameters for Solid Rocket Booster
Calculate N and WE
Call COSTCALC (for solid rocket booster)
Are Liquid Rockets included in infrastructure ?
YES
NO
Read in cost parameters for Liquid Rocket
Calculate N and WE
Call COSTCALC (for liquid rocket)
Calculate Cost Matrix elements for total Launch Vehicle (solid + liquid)
Is Extra ELV Equipment included in infrastructure ?
NO
YES
Read in cost parameters for Extra ELV Equipment
Calculate N and WE
Call COSTCALC (for extra ELV equipment)
Are extra operations costs included ?
YES
Calculate new costs including Extra Operations
Print out 'Extra Operations costs included'
NO


Are Transportation Tanks included in infrastructure ?
NO
YES
Read in cost parameters for Transportation Tanks
Calculate N and WE
Call COSTCALC (for transportation tanks)
Is Storage Depot included in infrastructure ?
NO
YES
Read in cost parameters for Prop. Storage Depot
Calculate N
Call COSTCALC (for prop. storage depot)


Is OTV included in infrastructure ?
NO
YES
Read in cost parameters for Orbital Transfer Vehicle
Call COSTCALC (for orbital transfer vehicle)
Is Large OTV included in infrastructure ?
NO
YES
Read in cost parameters for Large OTV
Call COSTCALC (for large OTV)
Print out Cost Matrix
Calculate total Propellant to Depot

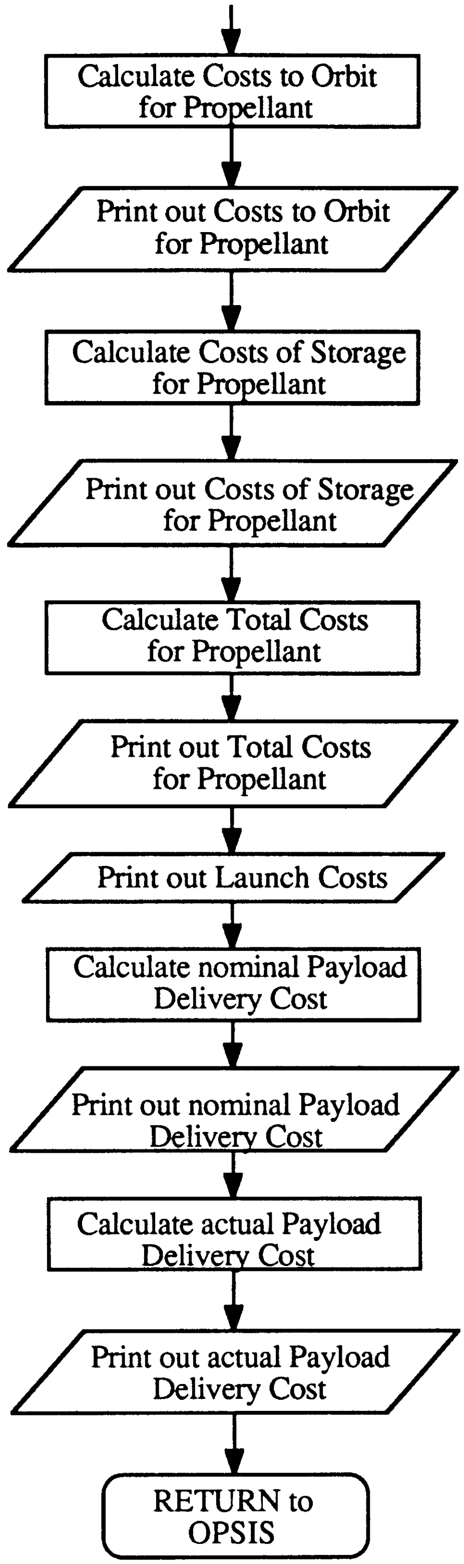


Figure 6.7
Flow diagram for COSTS.

6.2.5 COSTCALC

COSTCALC is a level 2 subroutine which is called from the level 1 subroutine COSTS to perform the actual cost calculations. The equations used for calculation of the various infrastructure element costs are those which were presented in the section 6.1.3. A flow diagram of the COSTCALC subroutine is shown in Figure 6.8.

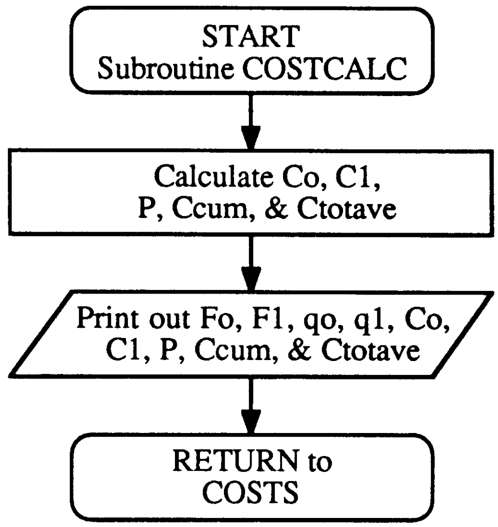


Figure 6.8
Flow diagram for COSTCALC.

6.3 OUTPUT

The output from OPSIS consists primarily of four matrices, with some additional calculations made from manipulation of particular matrix elements and presented separately for convenience. The first two matrices are simply the Launch Vehicle and Mission Model matrices which were read in as input. They are included in the output to verify the values which were used internally in the program, and to identify the input values so as to avoid potential confusion as to the input for a particular run. The other two output matrices are Propellant Reclamation and Cost, which are essentially outputs of the subroutines PRCALC and COSTS, respectively. An example of OPSIS output is seen in Table 6.7.

The output variables of primary interest resulting from the simulation are indicated in Table 6.6. These are the variables whose values will be presented in Chapter 7.

VARIABLE NAME	IDENTIFICATION
C_{pt}	Total Propellant Cost
C_{ps}	Propellant Storage Cost
C_{po}	Propellant To Orbit Cost
P_a	Annual Propellant Delivered
P_t	Total Propellant Delivered
C_l	Launch Costs
C_{p/l_n}	Nominal Payload Transportation Cost
C_{p/l_a}	Actual Payload Transportation Cost

Table 6.6
Summary and Definition of Primary Output Variables.

The output sheets of the various runs are saved and used to supply the results data which is input into Cricketgraph software on the Macintosh Plus. From the data files in Cricketgraph, plots of results from the simulation runs are generated and these are included in Chapter 7 which presents the results of the analysis.

THIS IS THE OUTPUT FILE OP2010

THIS IS LAUNCH VEHICLE ALS100K
WHICH HAS 2 STAGES.

2492291.0000	1065191.0000	2492291.0000
2.1500	4.7700	0.0000
6487.2900	22552.1309	29039.4199
1331099.5000	841839.6250	2172939.2500
13445.4502	17180.4004	30625.8496
1427100.0000	965191.0000	2392291.0000
1344545.0000	859020.0000	2203565.0000
13445.4502	8590.2002	22035.6504
0.0000	8590.2002	8590.2002
1065191.0000	100000.0000	100000.0000
264.0000	448.7000	0.0000
0.9300	0.8700	0.9100
0.0000	1561.7100	1561.7100

THIS IS MISSION MODEL ALS20
FOR LAUNCH VEHICLE ALS100K

YEAR	FLIGHT RATE	LOAD FACTOR
1995.0000	10.0000	0.8000
1996.0000	10.0000	0.8000
1997.0000	10.0000	0.8000
1998.0000	10.0000	0.8000
1999.0000	10.0000	0.8000
2000.0000	10.0000	0.8000
2001.0000	10.0000	0.8000
2002.0000	10.0000	0.8000
2003.0000	10.0000	0.8000
2004.0000	10.0000	0.8000
2005.0000	10.0000	0.8000
2006.0000	10.0000	0.8000
2007.0000	10.0000	0.8000
2008.0000	10.0000	0.8000
2009.0000	10.0000	0.8000
2010.0000	10.0000	0.8000
2011.0000	10.0000	0.8000
2012.0000	10.0000	0.8000
2013.0000	10.0000	0.8000
2014.0000	10.0000	0.8000

THIS IS THE AMOUNT OF PROPELLANT AVAILABLE ON
EACH FLIGHT AND FOR EACH YEAR OF OPERATION.

1995.00	29577.04	295770.38
1996.00	29577.04	295770.38
1997.00	29577.04	295770.38
1998.00	29577.04	295770.38
1999.00	29577.04	295770.38
2000.00	29577.04	295770.38
2001.00	29577.04	295770.38

2002.00	29577.04	295770.38
2003.00	29577.04	295770.38
2004.00	29577.04	295770.38
2005.00	29577.04	295770.38
2006.00	29577.04	295770.38
2007.00	29577.04	295770.38
2008.00	29577.04	295770.38
2009.00	29577.04	295770.38
2010.00	29577.04	295770.38
2011.00	29577.04	295770.38
2012.00	29577.04	295770.38
2013.00	29577.04	295770.38
2014.00	29577.04	295770.38

THE TOTAL PROPELLANT DELIVERED OVER THE
LIFE OF THE PROGRAM IS 5915409.00 [LB]

TOTAL NUMBER OF VEHICLES IS 200

THESE ARE THE COST CALCULATIONS FOR ALSSOLID

F0	F1	Q0	Q1
250000.0000	750.0000	0.5000	0.8000
C0	C1	P	CCUM
71830960.0000	6433629.0000	-0.1520	675324288.0000
CTOTAVE			
3735776.2500			

THESE ARE THE COST CALCULATIONS FOR ALSLIQUID

F0	F1	Q0	Q1
5000000.0000	5000.0000	0.5000	0.8000
C0	C1	P	CCUM
1629194624.0000	52453540.0000	-0.1520	5505935872.0000
CTOTAVE			
35675652.0000			

THESE ARE THE COST CALCULATIONS FOR ALSEXTRA

F0	F1	Q0	Q1
1465000.0000	4500.0000	0.5000	0.8000
C0	C1	P	CCUM
57894564.0000	1614703.7500	-0.1520	169492000.0000
CTOTAVE			
1136932.7500			

THESE ARE THE COST CALCULATIONS FOR TANK

F0	F1	Q0	Q1
0.0000	0.0000	0.5000	0.8000
C0	C1	P	CCUM
0.0000	0.0000	-0.1520	0.0000
CTOTAVE			
0.0000			

THESE ARE THE COST CALCULATIONS FOR STORAGE

F0	F1	Q0	Q1
1465000.0000	4500.0000	0.5000	0.8000
C0	C1	P	CCUM
244132480.0000	16146310.0000	-0.1520	30705076.0000
CTOTAVE			
137418784.0000			

THIS IS THE COST MATRIX FOR THE SIMULATION

NVEH	WE	F0	F1
200.0000	82555.0000	250000.0000	750.0000
200.0000	106171.0000	5000000.0000	5000.0000
200.0000	188726.0000	0.0000	0.0000
200.0000	1561.7100	1465000.0000	4500.0000
200.0000	2000.0000	0.0000	0.0000
2.0000	27770.0000	1465000.0000	4500.0000

Q0	Q1	R	C0
0.5000	0.8000	0.9000	71830960.0000
0.5000	0.8000	0.9000	1629194624.0000
0.0000	0.0000	0.0000	1701025536.0000
0.5000	0.8000	0.9000	57894564.0000
0.5000	0.8000	0.9000	0.0000
0.5000	0.8000	0.9000	244132480.0000

C1	P	CCUM	CTOTAVE
6433629.0000	-0.1520	675324288.0000	3735776.2500
52453540.0000	-0.1520	5505935872.0000	35675652.0000
58887168.0000	0.0000	6181260288.0000	39411428.0000
1614703.7500	-0.1520	169492000.0000	1136932.7500
0.0000	-0.1520	0.0000	0.0000
16146310.0000	-0.1520	30705076.0000	137418784.0000

THE COSTS TO ORBIT ARE AS FOLLOWS

EXNONREC	EXREC	PSUM	PROPCOST[$/LB]
57894564.0000	169492000.0000	5915409.0000	38.4397

THE COSTS OF STORAGE ARE AS FOLLOWS

EXNONREC	EXREC	PSUM	PROPCOST[$/LB]
244132480.0000	30705076.0000	5915409.0000	46.4613

THE TOTAL COSTS ARE AS FOLLOWS

EXNONREC	EXREC	PSUM	PROPCOST[$/LB]
302027040.0000	200197072.0000	5915409.0000	84.9010

AVERAGE LAUNCH COSTS	39411428.00 [$/LAUNCH]
NOMINAL P/L DELIVERY COST	394.11 [$/LB]
ACTUAL P/L DELIVERY COST	492.64 [$/LB]

Table 6.7

Output file from OPSIS.

CHAPTER 7 RESULTS

Cost calculations were made for the B and C infrastructures for propellant costs to an OTV or other user spacecraft. The costs components are separated into cost to orbit and storage costs. Cost to orbit is the additional cost of transporting the propellant, beyond what is required of a nominal launch. Included are DDT&E and production costs of additional hardware that is required. Cost of storage is the cost of the propellant depot facility that is in orbit. This facility acts as a receptacle of propellant from the source, as a storage tank, then as a dispenser to the users, primarily the OTV.

A diagram of the various elements of the infrastructures being considered is shown in Figure 7.1. This is a simplified version of the infrastructures previously shown in Figure 3.1. Descriptions of the infrastructures can be found in Chapter 3. Only the earth to orbit transportation, propellant storage tank, and depot facility are included in this figure, to represent the elements used in the simulation and cost analysis. In essence, only the supply side of the infrastructure is shown in this figure.

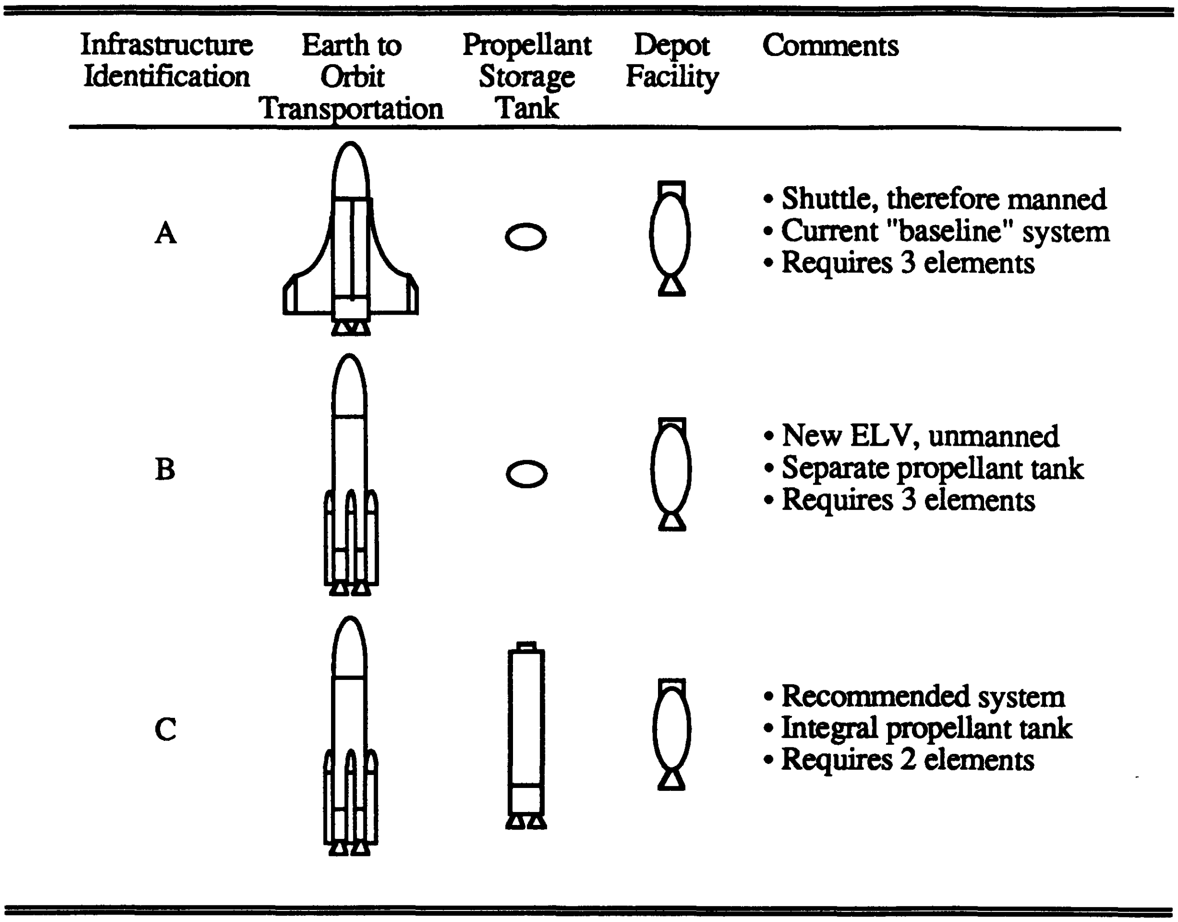


Figure 7.1
Elements of three infrastructures for orbital propellant supply.

The output variables are functions of a number of input variables. The basic functional relationships of the primary output variables to input variables are indicated in equations 7.1-8.

$$C_{pt} = f(W_{pr}, W_{pv}, W_x, Y, L, R, F_o, F_1, q_o, q_1, r) \tag{7.1}$$

$$C_{ps} = f(W_{pr}, W_{pv}, W_x, Y, L, R, F_o, F_1, q_o, q_1, r) \tag{7.2}$$

$$C_{po} = f(W_{pr}, W_{pv}, W_x, Y, L, R, F_o, F_1, q_o, q_1, r) \tag{7.3}$$

$$P_a = f(W_{pr}, W_{pv}, W_x, Y, L, R) \tag{7.4}$$

$$P_t = f(W_{pr}, W_{pv}, W_x, Y, L, R) \tag{7.5}$$

$$C_l = f(Y, R, F_o, F_1, q_o, q_1, r) \tag{7.6}$$

$$C_{p/l_n} = f(Y, R, F_o, F_1, q_o, q_1, r) \tag{7.7}$$

$$C_{p/l_a} = f(Y, L, R, F_o, F_1, q_o, q_1, r) \quad (7.8)$$

Each of these output variables has been calculated using different values for their primary input variables while holding all other inputs constant, in order to determine their sensitivities. The plots of the results from the sensitivity runs are included in section 7.2, along with calculation of partial derivatives of the output variables with respect to their input variables.

7.1 Infrastructure Comparisons

There are several different infrastructures which can be considered for the role of providing propellants to orbit. The one that is generally considered given current thinking in the industry is infrastructure A. This thesis has introduced several alternative infrastructures for providing propellants through enhanced orbital utilization of ELVs. These are infrastructures B, B-1 and C. The cost of propellant is the primary figure of merit for comparison of these architectures. Another is the amount of propellant supplied annually. All but the scenario for infrastructure A (Dedicated) take advantage of the unused lift capability of the launch vehicles due to load factors less than one. However only infrastructure C provides enough propellant using this lift capability alone to meet the expected demand. A demand of 250,000 pounds per year is used as a representative demand, as discussed in Chapter 3. When an infrastructure cannot meet demand through utilization of excess lift capability, dedicated flights must be provided for propellant supply. This raises the cost of propellant delivery by the nominal payload delivery rate of the launch services for each pound of propellant delivered. Figure 7.2 compares costs for six scenarios using the three basic infrastructures.

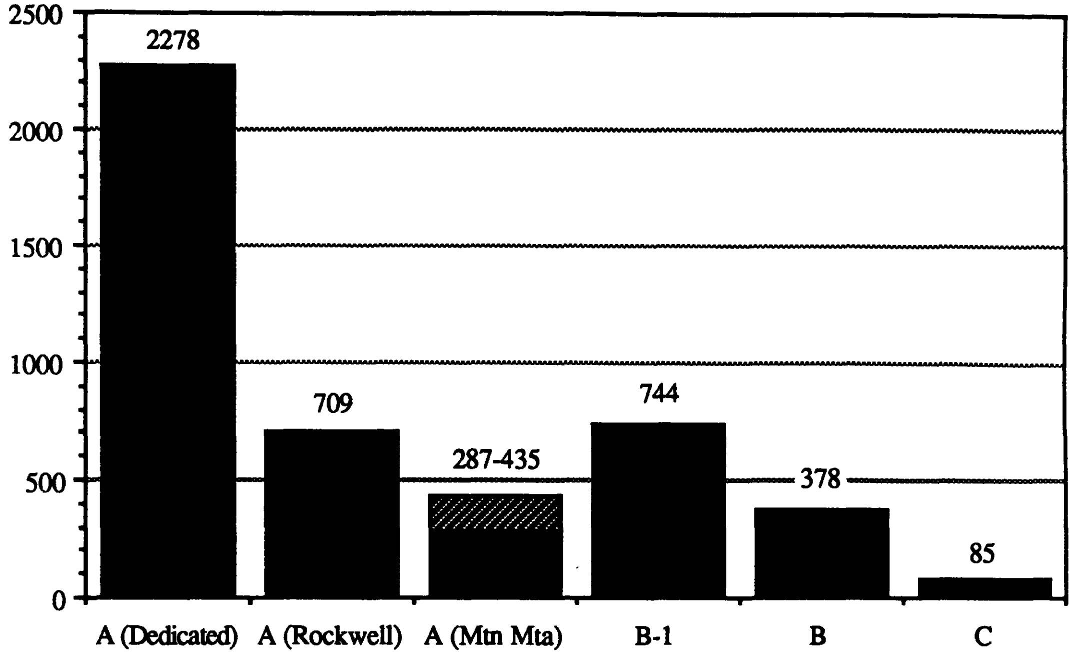


Figure 7.2
Comparisons of propellant delivery costs in FY88$/pound between infrastructures for at least 250,000 pounds to orbit per year.

Comparisons between infrastructures serve to indicate which can provide the most cost effective supply of propellants to orbit. The infrastructures under comparison here are A, B and C. Infrastructure A is the generally accepted infrastructure for propellant supply. Cost figures for infrastructure A are taken from various industry sources as indicated. Operationally for infrastructure A, the space shuttle is the transportation vehicle, and a separate reusable tank is used for transportation of the propellant to orbit. The tank is stored either in the payload bay or the aft cargo carrier (ACC). The A (Dedicated) column is for purely dedicated propellant supply missions in which the propellant is the primary payload of the shuttle, therefore paying the shuttle launch costs.[1] The A (Rockwell) is from a Rockwell study which used propellant scavenging to take advantage of the shuttles low load factor. By doing this, the cost is reduced significantly by not having to pay for the transportation directly and in effect hitching a ride aboard the launch vehicle. The scavenging of propellants provides 92,600 lb of propellant annually, with the balance being provided as dedicated payload.[2] The A (Mtn Mta) value is from a Martin Marietta study which uses a transportation scenario similar to the Rockwell study. The cost range for the Martin Marietta study were from 287 to 435 dollars per pound. This study also used a mix of scavenging flights and dedicated flights to provide the required propellants.[3]

Infrastructure B incorporates the future ELV rather than the space shuttle, using a reusable propellant storage tank for the earth to orbit transportation phase, and an orbital propellant storage depot which is a separate system from the ELV. The ELV in this scenario is being used only as a transport vehicle for the propellant. The propellant is not paying for the transportation service however, because the amount being transferred to orbit takes advantage of the excess payload capability of the ELV due to a load factor of less than one hundred percent. However, only 128,000 pounds annually can be supplied through this approach. The amounts in excess of this must be provided as dedicated payloads. Infrastructure B incorporates a reusable tank for the earth to orbit transportation

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[1] Rockwell International Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume I, Technical Report, NASA -CR-171848, January 1985.

[2] Rockwell International Space Transportation Systems Division, Space Transportation System (STS) Propellant Scavenging System Study Final Report, Volume 3: Cost and Work Breakdown Structure, NASA -CR-171850, January 1985.

[3] Fester, D., Martin Marietta Denver Aerospace, Earth-to-Orbit Propellant Transportation Overview, NASA Report N85-17002, 1985.

Also, SPACEFLIGHT, Volume 28, February 1986, page 80.

of the propellant which is returned to earth and refurbished for its next mission. Infrastructure B-1 uses an expendable tank which is disposed of after each mission, along with the rest of the ELV.

Infrastructure C builds on B, and replaces the separate tank for earth to orbit transportation of the propellant with the existing tanks of the ELV. This infrastructure has the capability of delivering up to 295,000 pounds to orbit annually before having to use dedicated payloads. Additional hardware is added to the ELV tanks to incorporate the technology necessary for propellant transfer in orbit. This infrastructure is significantly less costly than the others, at 85 dollars per pound of propellant delivered.

The costs of delivering propellant to orbit can be broken into two basic components. The first is the earth to orbit cost and the second is the storage cost. Earth to orbit cost involves the additional hardware that is required for propellant transportation beyond the standard ELV configuration. For infrastructure B this involves the transportation storage tank and for infrastructure C it involves the additional hardware required by the ELV tanks to allow for propellant transfer to the depot.

Storage costs are the costs required for propellant storage facilities in orbit, which receive propellant from the ELV and store it until it is transferred to a user spacecraft. For each of the scenarios considered here, the storage facility is the same. Figure 7.3 shows the overall comparison between infrastructures B and C for cost of propellant in orbit to the user spacecraft, based on a range of ELV annual flight rates.

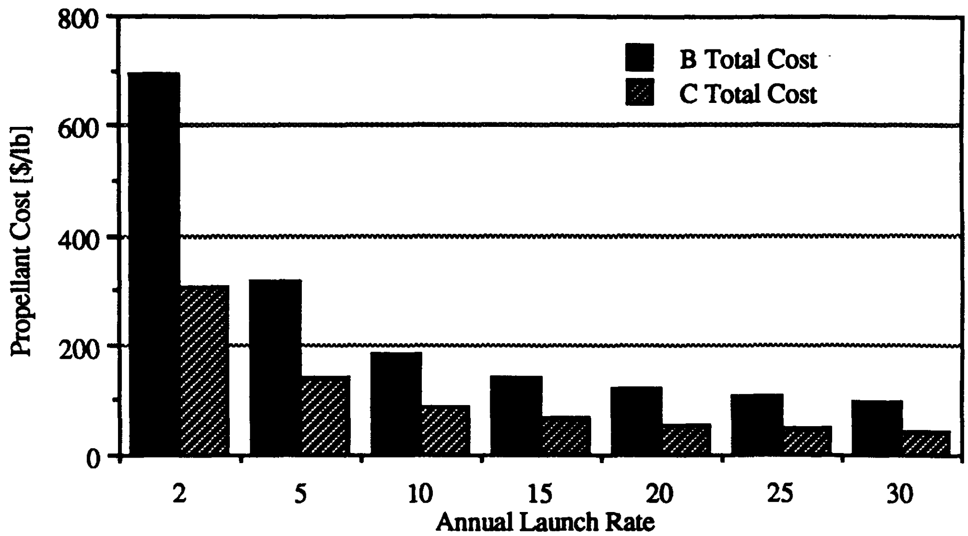

Figure 7.3
Effect of Annual Launch Rate on Propellant Costs
for Infrastructures B and C.

It is seen from Figure 7.3 that the costs of propellant for infrastructure B are roughly twice those of infrastructure C independent of launch rate. The distribution of costs within each of the infrastructures along with the total costs are shown in Figure 7.4, to illustrate the primary differences in cost between the two scenarios.

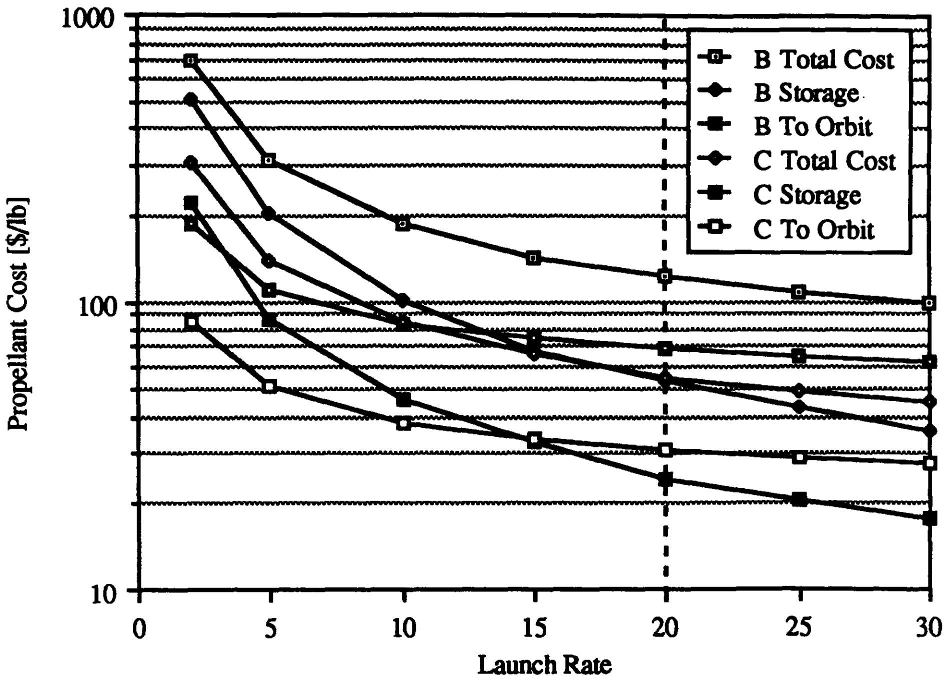

Figure 7.4
Effect of Launch Rate on Storage, To Orbit, and
Total Propellant Costs for Infrastructures B and C.

The costs for infrastructure B are higher for storage, to orbit, and total regardless of launch rate. The reason that storage costs for B are higher than C is that B is providing less propellant in orbit, therefore the costs of storage are distributed over less propellant. It is assumed that the propellant storage depot is of the same design for both, and is sized based on current sizing estimates at 100,000 capacity.[4,5] Multiple depots are used if one cannot accommodate the supply, as was discussed in section 6.1.3.4. To orbit costs are higher

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[4] Fester, D., Martin Marietta Denver Aerospace, Earth-to-Orbit Propellant Transportation Overview, NASA Report N85-17002, 1985, page 149.

[5] Schuster, J.R., Bennett, F.O., Liggett, M.W., and Torre, C.N., General Dynamics Space Systems Division, and Brown, N., NASA MSFC, EVALUATION OF ON-ORBIT CRYOGENIC PROPELLANT DEPOT OPTIONS FOR THE ORBITAL TRANSFER VEHICLE, Paper 88c, 6th Intersociety Cryogenics Symposium, 2-7 November 1986, Miami Beach, Florida, pp. 1-4.

for B because a separate tank is required, as opposed to the addition of transfer equipment to existing tanks.

The differences between infrastructures B and C regarding amount of propellant delivered to orbit annually can be seen in Figure 7.5. These annual propellant amounts reflect only the amount of propellant that is delivered by taking advantage of 'free transportation'. This is the lift capability that is left unused by a load factor of less than one hundred percent, which can be utilized for propellant reclamation and delivery. Propellant deliveries can be increased for either scenario by setting aside dedicated payload capability for propellant transportation, but is not included here. In using dedicated payload capability for propellant delivery, the costs of the transportation must be included in the propellant costs. This is done in proportion to the percentage of dedicated payload the delivered propellant displaces.

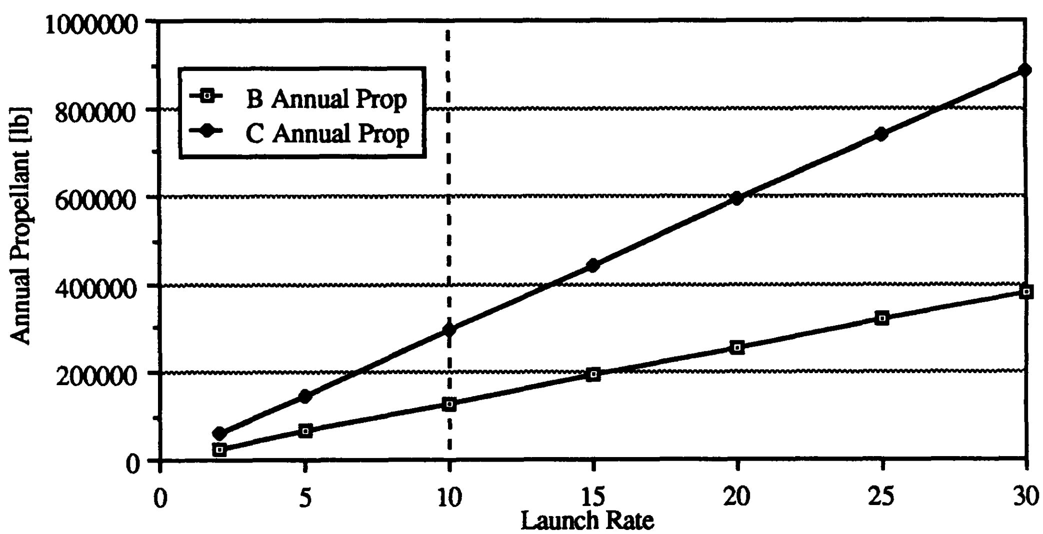


Figure 7.5
Effect of Launch Rate on Annual Propellant
Delivered to Orbit for Infrastructures B and C

7.2 Sensitivity Analysis

The sensitivity analysis is intended to determine the effect of variation of certain input parameters on the output parameters for the system of propellant reclamation. Isolated relationships between input and output variables have been established by running the simulation varying only the input variable in question. The results of these runs are shown in the figures that follow. In some cases the relationships are linear, and in some cases they are non-linear. The equation relating the two variables (with all others held constant) can be determined from the graphs, and is given for each sensitivity following the appropriate figure. Sensitivity functions are calculated from the equations relating the isolated variables by taking the derivative of the isolated equation. The sensitivity function is the partial derivative of the output variable with respect to the input variable.[6] The following example should help to illustrate this point. Take equation 7.1 which is the relationship for total propellant costs:

$$C_{pt} = f(W_{pr}, W_{pv}, W_x, Y, L, R, F_o, F_1, q_o, q_1, r)$$

When the simulation is run for various values of R holding all other input values constant, the relationship between C_{pt} and R can be isolated in the following equation:

$$C_{pt} = f(R)$$

The sensitivity of the output variable C_{pt} with respect to the input variable R can then be determined as follows:

---

[6] Frank, P.M., Introduction to System Sensitivity Theory, Academic Press, 1978, pp.6-13.

$$\frac{\partial C_{pt}}{\partial R} = \frac{d f(R)}{d R}$$

This is the method that is used to determine the relationships between input and output variables, and to calculate the sensitivities of those relationships. Once the sensitivity functions are known, it is easy to calculate changes in system behavior from parameter deviations, or different parameter assumptions.[7,8]

7.2.1 Infrastructure C

Sensitivities for Infrastructure C are determined in the following section. The sensitivities will be grouped by output variable, determining the relationship between each primary output variable of concern with certain input variables.

7.2.1.1 Propellant Cost Sensitivities

The relationships between launch rate R and propellant costs are represented in figure 7.5. Based on the relationships indicated in that figure, the following equations have been determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for propellant cost to launch rate R holding all other input variables constant.

---

[7] de Neufville, R., Stafford, J., Systems Analysis for Engineers and Managers, McGraw-Hill Book Company, 1971, pp. 70-86.

[8] Sensitivity Analysis in Engineering, Proceedings of a symposium held at Langley Research Center, Hampton, Virginia, 25-26 September 1986, pp. 90-91.

$$C_{pt} = 459.18\ R^{-.7028} \tag{7.9}$$

$$C_{ps} = 406.35\ R^{-.9319} \tag{7.10}$$

$$C_{po} = 105.48\ R^{-.4112} \tag{7.11}$$

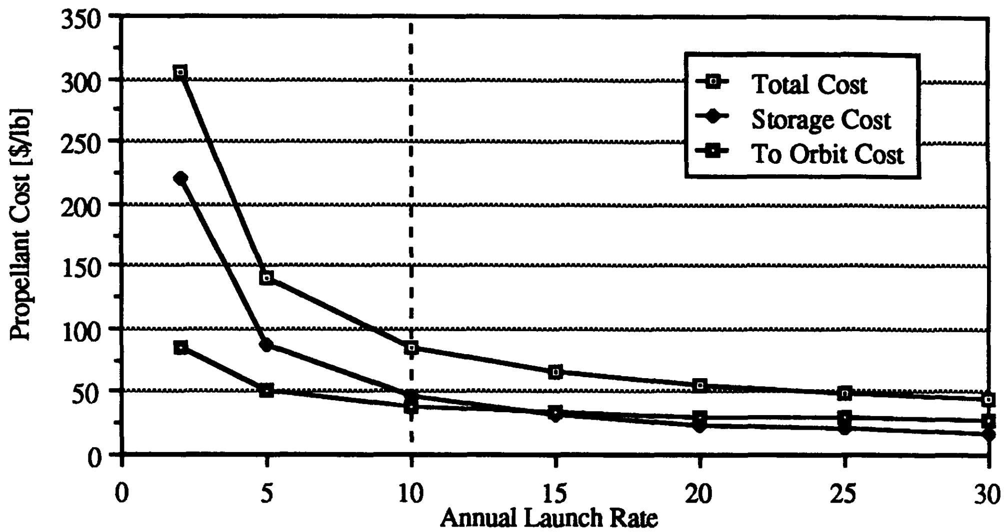


Figure 7.6
Effect of Launch Rate on Propellant Cost
for Infrastructure C

The following sensitivity functions represent the effect of a change in launch rate on propellant costs. They are derivatives of equations 7.9-11, which were generated from the data in Figure 7.6.

$$\frac{\partial C_{pt}}{\partial R} = -322.71\ R^{-1.7028} \tag{7.12}$$

$$\frac{\partial C_{ps}}{\partial R} = -378.68\ R^{-1.9319} \tag{7.13}$$

$$\frac{\partial C_{po}}{\partial R} = -43.37\ R^{-1.4112} \qquad (7.14)$$

The relationships between load factor L and propellant costs are represented in figure 7.7. Based on the relationships indicated in that figure, the following equations have been determined through a second order polynomial curve fit of the curves in the graph. These are the equations which relate the output variables for propellant cost to load factor L holding all other input variables constant.

$$C_{pt} = 156.15 - 413.12\ L + 408.30\ L^2 \qquad (7.15)$$

$$C_{ps} = 81.39 - 210.01\ L + 209.69\ L^2 \qquad (7.16)$$

$$C_{po} = 74.76 - 203.12\ L + 198.61\ L^2 \qquad (7.17)$$

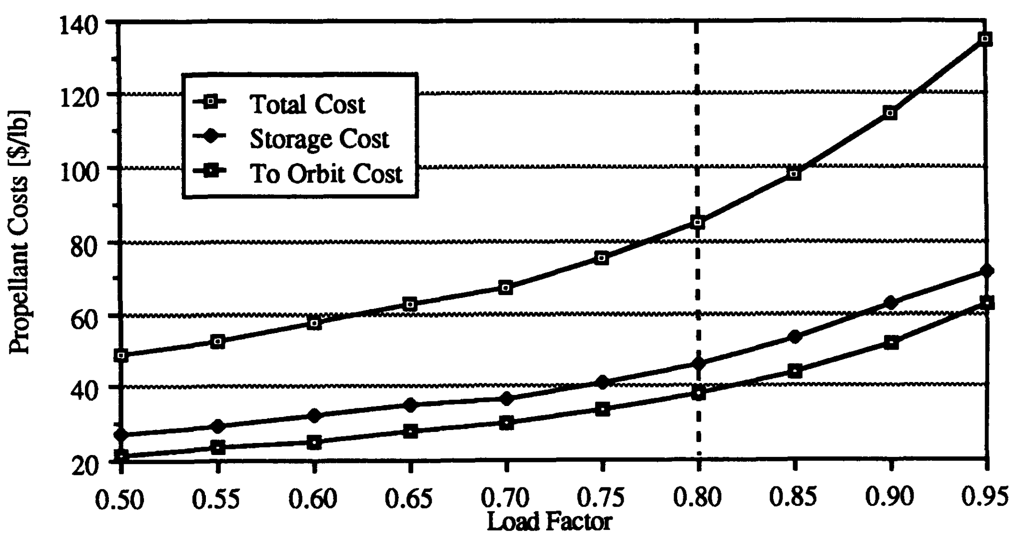


Figure 7.7
Effect of Load Factor on Propellant Cost
for Infrastructure C

The following sensitivity functions represent the effect of a change in load factor on propellant costs. They are derivatives of equations 7.15-17, which were generated from the data in Figure 7.7.

$$\frac{\partial C_{pt}}{\partial L} = -413.12 + 816.60\,L \tag{7.18}$$

$$\frac{\partial C_{ps}}{\partial L} = -210.01 + 419.38\,L \tag{7.19}$$

$$\frac{\partial C_{po}}{\partial L} = -203.12 + 397.22\,L \tag{7.20}$$

The relationships between program duration Y and propellant costs are represented in Figure 7.8. Based on the relationships indicated in that figure, the following equations have been determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for propellant cost to program duration Y holding all other input variables constant.

$$C_{pt} = 773.73\,Y^{-.7341} \tag{7.21}$$

$$C_{ps} = 929.23\,Y^{-1} \tag{7.22}$$

$$C_{po} = 123.34\,Y^{-.3887} \tag{7.23}$$

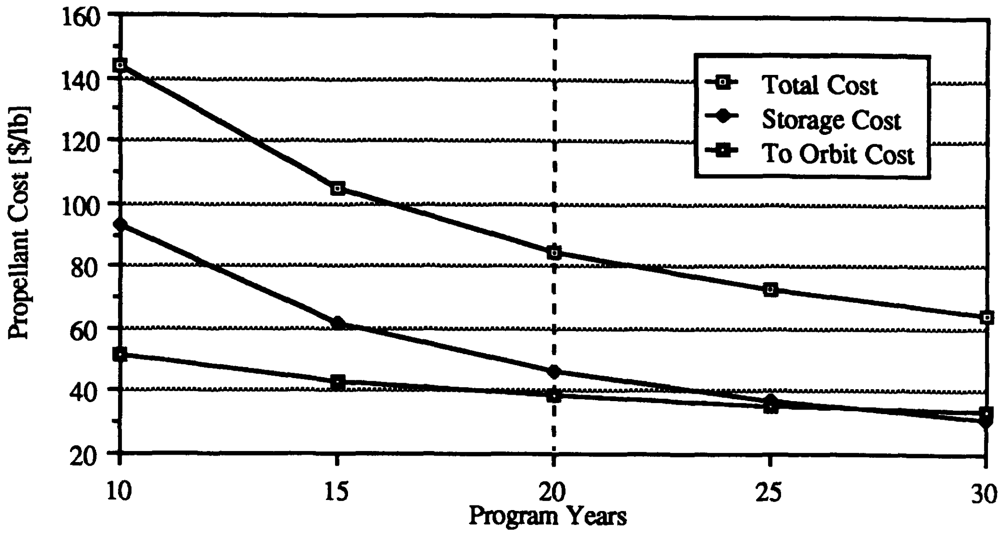


Figure 7.8
Effect of Program Duration on Propellant Cost
for Infrastructure C

The following sensitivity functions represent the effect of a change in program duration on propellant costs. They are derivatives of equations 7.21-23, which were generated from the data in Figure 7.8.

$$\frac{\partial C_{pt}}{\partial Y} = -568.00\, Y^{-1.7341} \tag{7.24}$$

$$\frac{\partial C_{ps}}{\partial Y} = -929.23\, Y^{-2} \tag{7.25}$$

$$\frac{\partial C_{po}}{\partial Y} = -47.90\, Y^{-1.3887} \tag{7.26}$$

7.2.1.2 Propellant Delivered Sensitivities

The relationship between launch rate R and annual propellant delivered P_a are represented in Figure 7.9. Based on the relationships indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of annual propellant delivered to launch rate holding all other input variables constant.

$$P_a = 29{,}580\ R \tag{7.27}$$

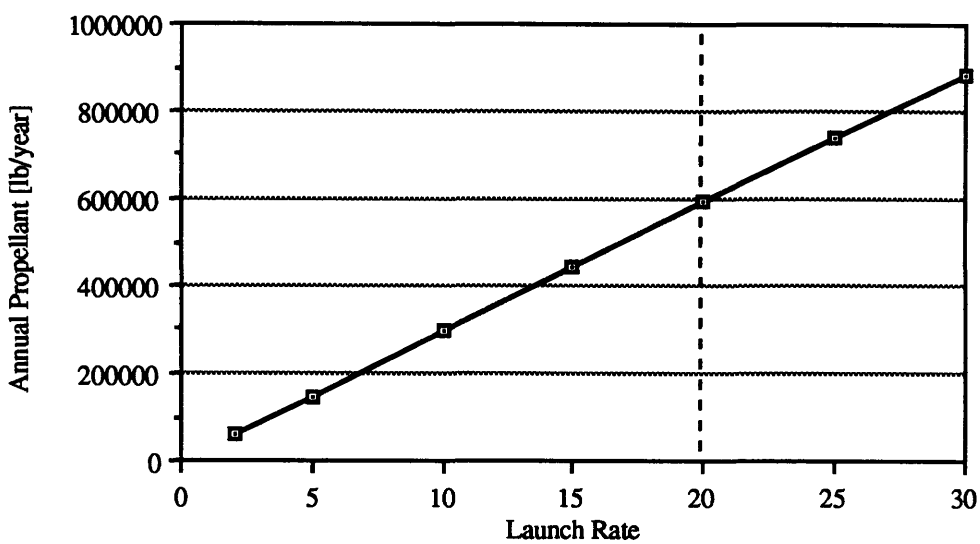


Figure 7.9
Effect of Launch Rate on Annual Propellant Delivered
for Infrastructure C

The following sensitivity function represents the effect of a change in annual launch rate on annual propellant delivered to orbit. It is a derivative of equation 7.27, which was generated from the data in Figure 7.9.

$$\frac{\partial P_a}{\partial R} = 29{,}580 \qquad (7.28)$$

The relationships between load factor L and annual propellant delivered P_a are represented in Figure 7.10. Based on the relationship indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of annual propellant delivered to load factor holding all other input variables constant.

$$P_a = 907{,}900 - 765{,}200\ L \qquad (7.29)$$

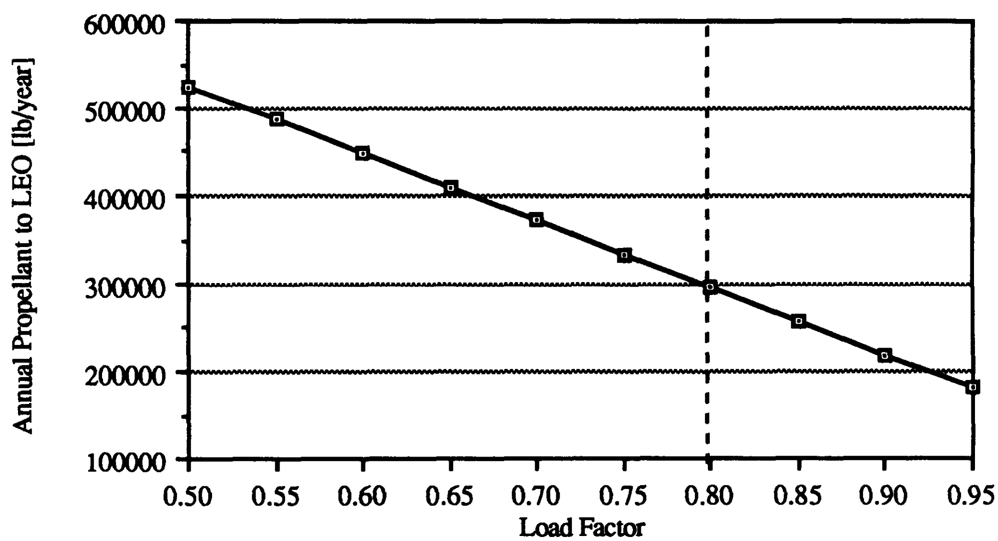


Figure 7.10
Effect of Load Factor on Annual Propellant Delivered
for Infrastructure C

The following sensitivity function represents the effect of a change in load factor on annual propellant delivered to orbit. It is a derivative of equation 7.29, which was generated from the data in Figure 7.10.

$$\frac{\partial P_a}{\partial L} = -765{,}200 \qquad (7.30)$$

The relationships between program duration Y and total propellant delivered P_t are represented in Figure 7.11. Based on the relationship indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of total propellant delivered to program duration holding all other input variables constant.

$$P_t = 295{,}700\ Y \qquad (7.31)$$

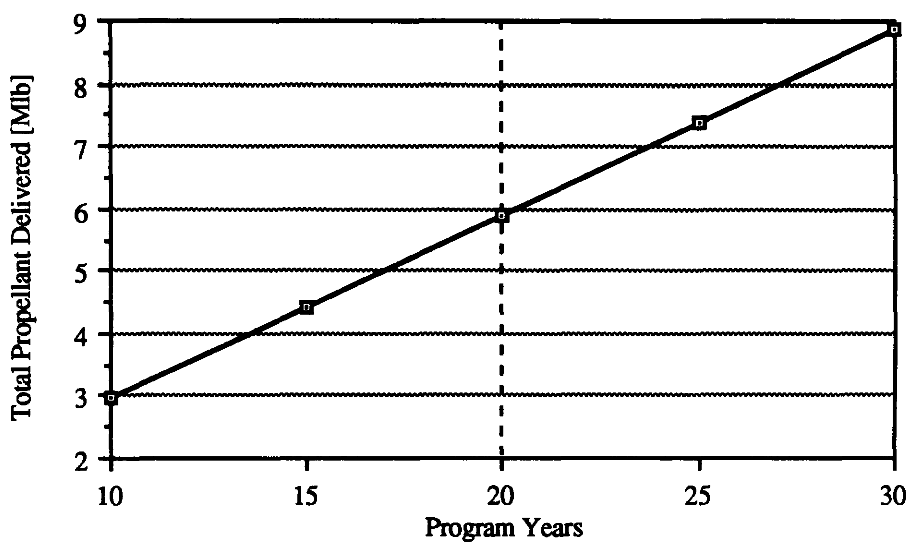


Figure 7.11
Effect of Program Duration on Total Propellant Delivered
for Infrastructure C

The following sensitivity function represents the effect of a change in program duration on total propellant delivered to orbit. It is a derivative of equation 7.31, which was generated from the data in Figure 7.11.

$$\frac{\partial P_t}{\partial Y} = 295{,}700 \tag{7.32}$$

The relationships between annual launch rate R and total propellant delivered P_t are represented in Figure 7.12. Based on the relationship indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of total propellant delivered to annual launch rate holding all other input variables constant.

$$P_t = 591{,}600\ R \tag{7.33}$$

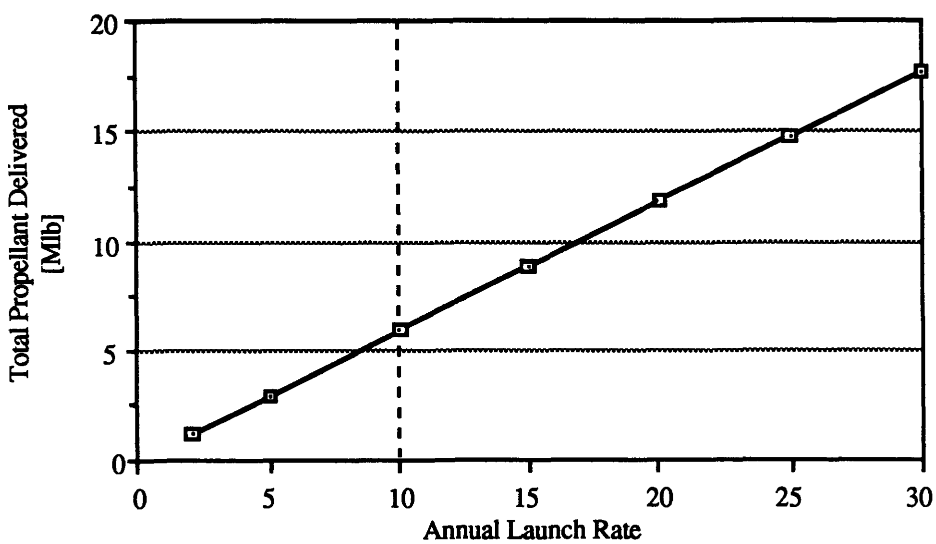


Figure 7.12
Effect of Annual Launch Rate on Total Propellant Delivered
for Infrastructure C

The following sensitivity function represents the effect of a change in annual launch rate on total propellant delivered to orbit. It is a derivative of equation 7.33, which was generated from the data in Figure 7.12.

$$\frac{\partial P_t}{\partial R} = 591{,}600 \qquad (7.34)$$

7.2.1.3 Launch Cost Sensitivities

The relationships between annual launch rate R and launch cost C_L are represented in Figure 7.13. Based on the relationship indicated in that figure, the following equation has been determined through a logarithmic curve fit of the curve in the graph. This is the equation which relates the output variable of launch cost to annual launch rate holding all other input variables constant.

$$C_L = 99.2\,(10^6)\,R^{-.3761} \qquad (7.35)$$

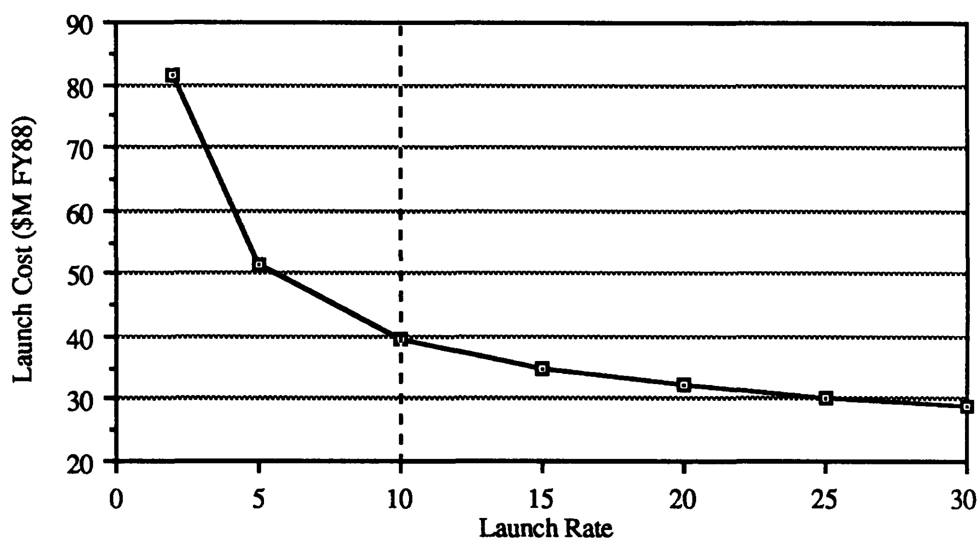


Figure 7.13
Effect of Launch Rate on Launch Costs
for Infrastructure C

The following sensitivity function represents the effect of a change in annual launch rate on launch cost. It is a derivative of equation 7.35, which was generated from the data in Figure 7.13.

$$\frac{\partial C_L}{\partial R} = -37.3\,(10^6)\,R^{-1.3761} \qquad (7.36)$$

The relationships between program duration Y and launch cost C_L are represented in Figure 7.14. Based on the relationship indicated in that figure, the following equation has been determined through a logarithmic curve fit of the curve in the graph. This is the equation which relates the output variable of launch cost to program duration holding all other input variables constant.

$$C_L = 114.6\,(10^6)\,Y^{-.3536} \qquad (7.37)$$

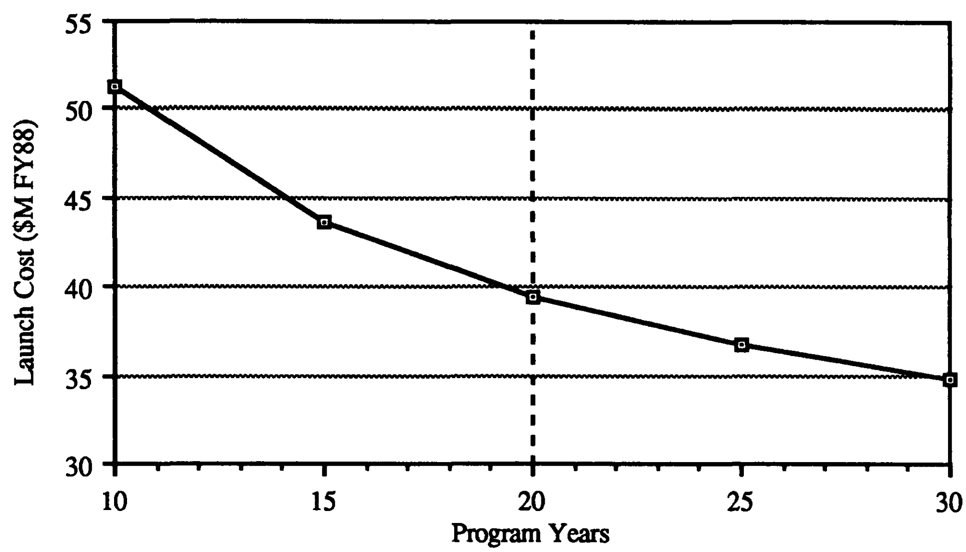


Figure 7.14
Effect of Program Duration on Launch Costs
for Infrastructure C

The following sensitivity function represents the effect of a change in program duration on launch cost. It is a derivative of equation 7.37, which was generated from the data in Figure 7.14.

$$\frac{\partial C_L}{\partial Y} = -40.52\,(10^6)\,Y^{-1.3536} \qquad (7.38)$$

7.2.1.4 Payload Delivery Cost Sensitivities

The relationships between launch rate R and payload delivery costs are represented in Figure 7.15. Based on the relationships indicated in that figure, the following equations have been determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for payload delivery cost to launch rate R holding all other input variables constant.

$$C_{P/L_n} = 991.87\,R^{-.3761} \qquad (7.39)$$

$$C_{P/L_a} = 1{,}239.84\,R^{-.3761} \qquad (7.40)$$

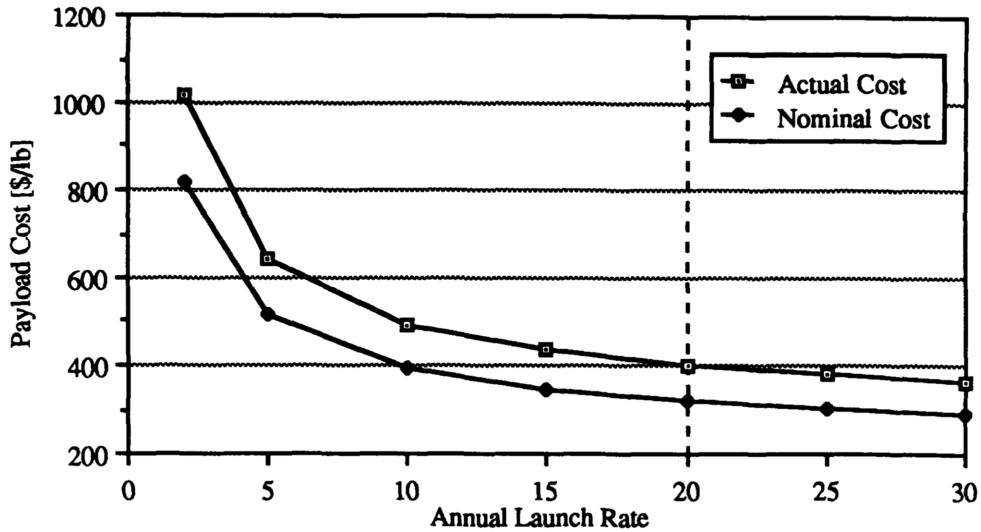


Figure 7.15
Effect of Launch Rate on Payload Costs
for Infrastructure C

The following sensitivity functions represent the effect of a change in annual launch rate on payload delivery costs. They are derivatives of equations 7.39-40, which were generated from the data in Figure 7.15.

$$\frac{\partial C_{P/L_n}}{\partial R} = -373.04\ R^{-1.3761} \tag{7.41}$$

$$\frac{\partial C_{P/L_a}}{\partial R} = -466.30\ R^{-1.3761} \tag{7.42}$$

The relationships between program duration Y and payload delivery costs are represented in figure 7.16. Based on the relationships indicated in that figure, the following equations have determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for payload delivery cost to program duration holding all other input variables constant.

$$C_{P/L_n} = 1{,}146.47\ Y^{-.3536} \tag{7.43}$$

$$C_{P/L_a} = 1{,}433.19\ Y^{-.3536} \tag{7.44}$$

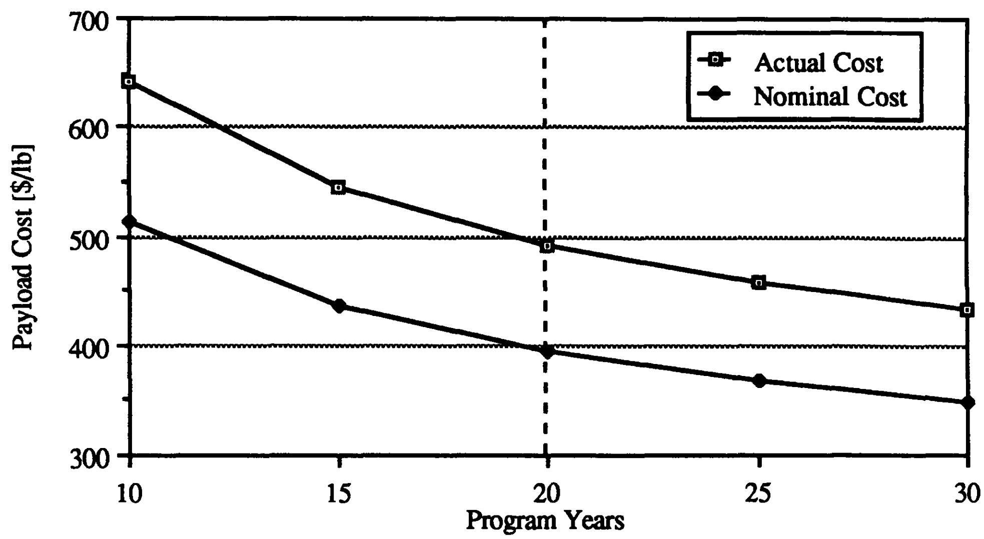


Figure 7.16
Effect of Program Duration on Payload Costs
for Infrastructure C

The following sensitivity functions represent the effect of a change in program duration on payload delivery costs. They are derivatives of equations 7.43-44, which were generated from the data in Figure 7.16.

$$\frac{\partial C_{P/L_n}}{\partial Y} = -405.39\ Y^{-1.3536} \tag{7.45}$$

$$\frac{\partial C_{P/L_a}}{\partial Y} = -506.74\ Y^{-1.3536} \tag{7.46}$$

The relationships between load factor L and payload delivery costs are represented in figure 7.17. Based on the relationships indicated in that figure, the following equations have determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for payload delivery cost to load factor holding all other input variables constant.

$$C_{P/L_n} = 394.11 \tag{7.47}$$

$$C_{P/L_a} = 394.11\ L^{-1} \tag{7.48}$$

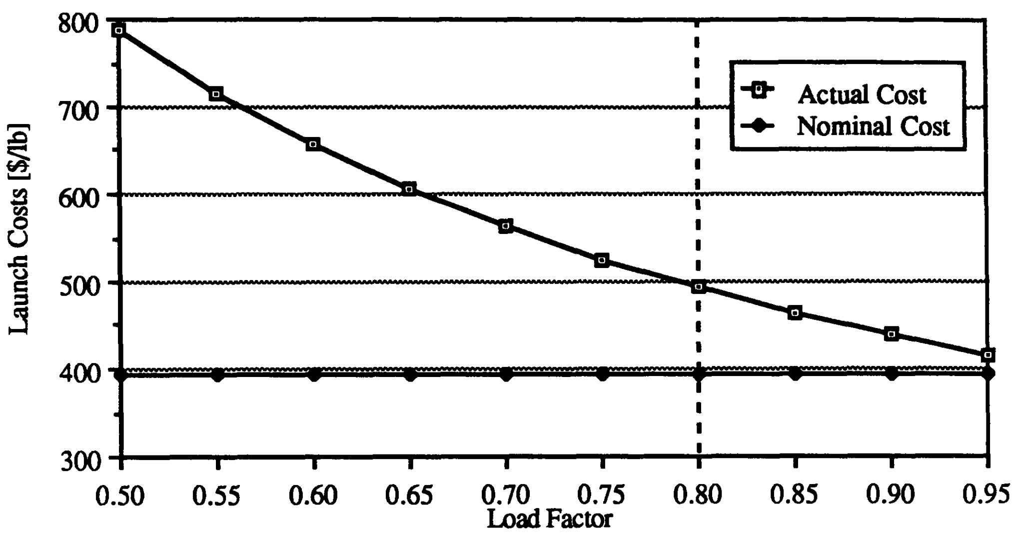


Figure 7.17
Effect of Load Factor on Payload Costs
for Infrastructure C

The following sensitivity functions represent the effect of a change in load factor on payload delivery costs. They are derivatives of equations 7.47-48, which were generated from the data in Figure 7.17.

$$\frac{\partial C_{P/L_n}}{\partial L} = 0 \qquad (7.49)$$

$$\frac{\partial C_{P/L_a}}{\partial L} = -394.11\, L^{-2} \qquad (7.50)$$

7.2.2 Infrastructure B

The relationship between launch rate R and annual propellant delivered P_a for infrastructure B are represented in Figure 7.18. Based on the relationships indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of annual propellant delivered to launch rate holding all other input variables constant.

$$P_a = 12{,}800\, R \qquad (7.51)$$

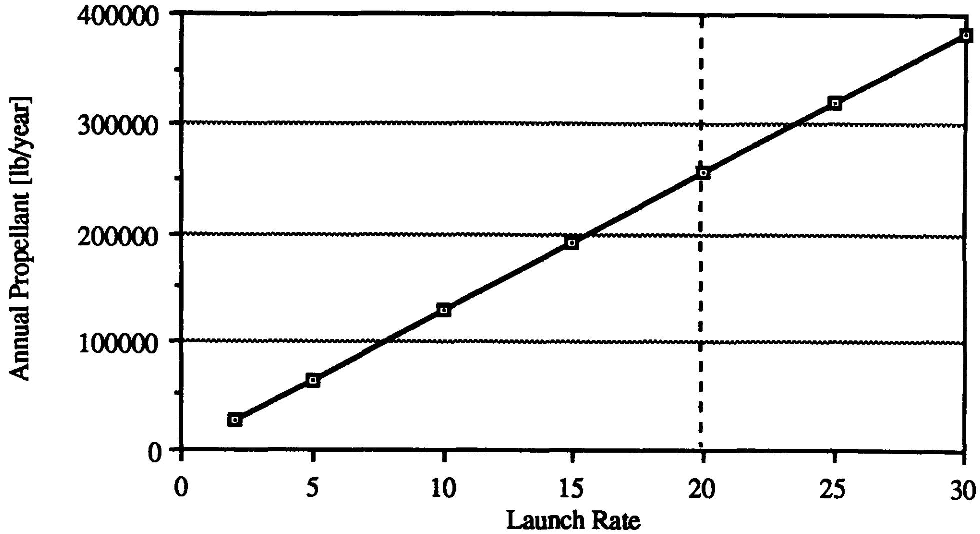


Figure 7.18
Effect of Launch Rate on Annual Propellant Delivered
for Infrastructure B

The following sensitivity function represents the effect of a change in annual launch rate on annual propellant delivered to orbit. It is a derivative of equation 7.51, which was generated from the data in Figure 7.18.

$$\frac{\partial P_a}{\partial R} = 12{,}800 \qquad (7.52)$$

The relationship between launch rate R and total propellant delivered P_t are represented in Figure 7.19. Based on the relationships indicated in that figure, the following equation has been determined through a linear curve fit of the curve in the graph. This is the equation which relates the output variable of total propellant delivered to launch rate holding all other input variables constant.

$$P_a = 256{,}000\ R \qquad (7.53)$$

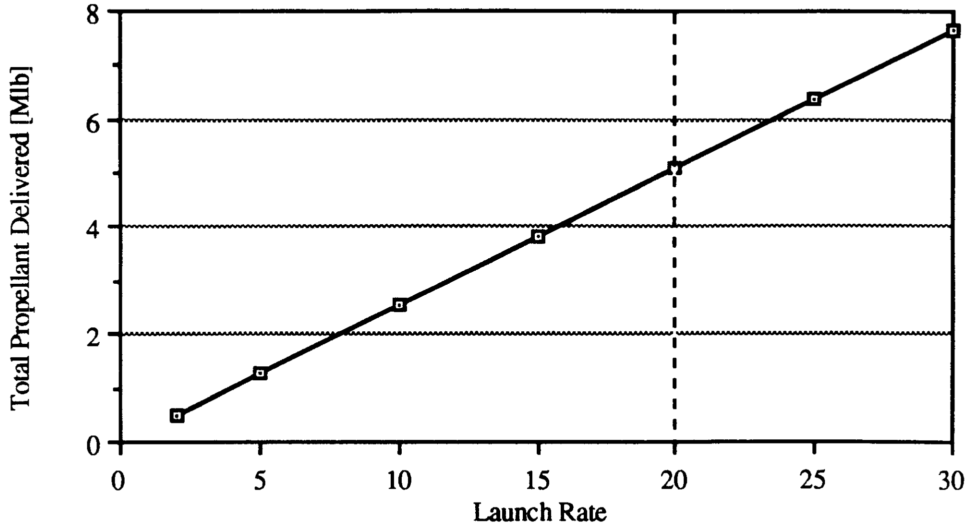


Figure 7.19
Effect of Launch Rate on Total Propellant Delivered
for Infrastructure B

The following sensitivity function represents the effect of a change in annual launch rate on annual propellant delivered to orbit. It is a derivative of equation 7.53, which was generated from the data in Figure 7.19.

$$\frac{\partial P_t}{\partial R} = 256{,}000 \qquad (7.54)$$

The relationships between launch rate R and propellant costs for infrastructure B are represented in figure 7.20. Based on the relationships indicated in that figure, the following equations have determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for propellant cost to launch rate R holding all other input variables constant.

$$C_{pt} = 1{,}054.00\, R^{-.7193} \qquad (7.55)$$

$$C_{ps} = 985.18\, R^{-.9770} \qquad (7.56)$$

$$C_{po} = 223.67\,R^{-.3941} \qquad (7.57)$$

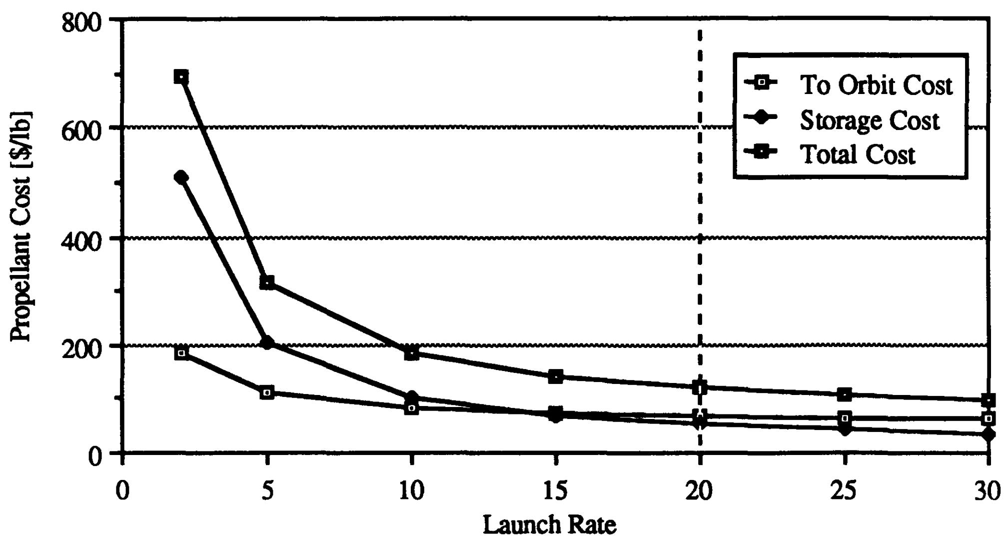


Figure 7.20
Effect of Launch Rate on Propellant Costs
for Infrastructure B

The following sensitivity functions represent the effect of a change in launch rate on propellant costs. They are derivatives of equations 7.55-57, which were generated from the data in Figure 7.20.

$$\frac{\partial C_{pt}}{\partial R} = -758.14\,R^{-1.7193} \qquad (7.58)$$

$$\frac{\partial C_{ps}}{\partial R} = -962.52\,R^{-1.9770} \qquad (7.59)$$

$$\frac{\partial C_{po}}{\partial R} = -88.15\,R^{-1.3941} \qquad (7.60)$$

7.2.3 Infrastructure B-1

The relationships between launch rate R and propellant costs are represented for infrastructure B-1 in figure 7.21. Based on the relationships indicated in that figure, the following equations have determined through a logarithmic curve fit of the curves in the graph. These are the equations which relate the output variables for propellant cost to launch rate R holding all other input variables constant.

$$C_{pt} = 1{,}395.00\ R^{-.3769} \tag{7.61}$$

$$C_{ps} = 985.17\ R^{-.9773} \tag{7.62}$$

$$C_{po} = 722.54\ R^{-.1990} \tag{7.63}$$

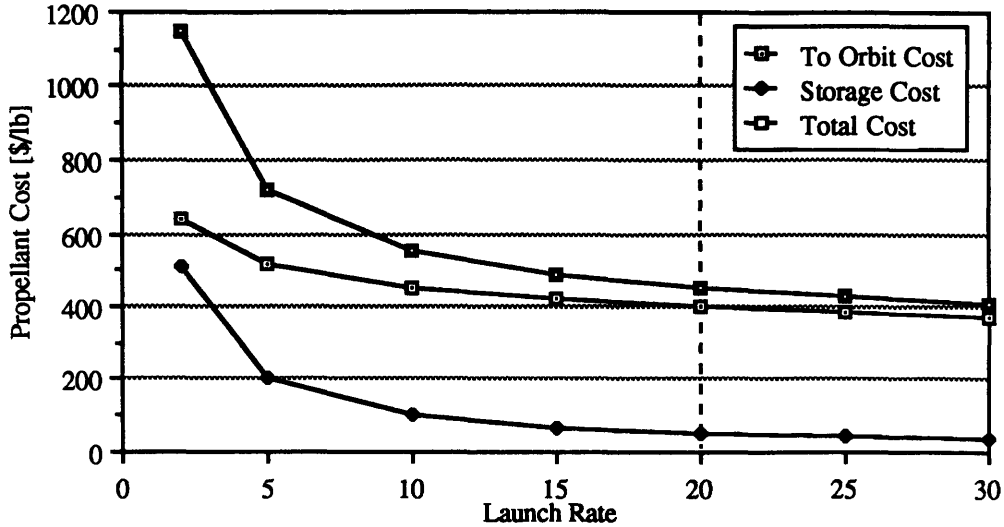


Figure 7.21
Effect of Launch Rate on Propellant Costs
for Infrastructure B-1

The following sensitivity functions represent the effect of a change in load factor on propellant costs. They are derivatives of equations 7.61-63, which were generated from the data in Figure 7.21.

$$\frac{\partial C_{pt}}{\partial R} = -525.78\, R^{-1.3769} \tag{7.64}$$

$$\frac{\partial C_{ps}}{\partial R} = -962.81\, R^{-1.9773} \tag{7.65}$$

$$\frac{\partial C_{po}}{\partial R} = -143.79\, R^{-1.1990} \tag{7.66}$$

CHAPTER 8 CONCLUSIONS & POLICY RECOMMENDATIONS

It is essential for the United States space program that a new space infrastructure be established. The realities of political, technical, and economic competition in the world community are significant factors beyond the basic human motivation for exploration and discovery. The primary political reason is to maintain parity in space development with the Soviet Union. To be a second-tier space power would be politically unsettling, from the view of national prestige as well as from the military reality that space is an integral portion of the nations military strength.

The technical achievements which made the U.S. a space power have provided a solid backdrop for science in general. Scientific experiments and observations made in space cannot be matched in many respects by those done on the Earth. The loss of a strong foundation in space science and exploration would have a profound effect on the scientific community and the technical level of achievement of the U.S. vis a vis the rest of the world.

As space becomes more developed, its commercial applications will grow evermore rapidly. Space operations will one day have a significant effect on global economics. The U.S. must proceed with the development of a new space infrastructure to maintain a competitive posture. The Soviet Union is not the only concern in this regard. The Chinese have developed a launch capability and are proceeding with an independent space program. The European Space Agency (ESA) has a strong and ambitious program, as does the National Space Development Agency (NASDA) of Japan. All of these space programs have recognized the profitability of commercial space launches and entered the market, in direct global competition with U.S. firms. This is a trend that will surely be followed by many more applications in the future.

Expendable launch vehicles (ELVs) will play a significant role in the future space infrastructure. There are roles beyond earth-to-orbit transportation which ELVs can fulfill in a very cost effective manner, beginning with propellant reclamation. Enhancing the orbital utilization of ELVs in this manner will add a degree of efficacy to the infrastructure by reducing the resources required for orbital propellant supply. This will strengthen the infrastructure by allowing finite resources to be used for other applications.

This final chapter will present conclusions drawn from the research and analyses that have been presented on enhancing the orbital utilization of expendable launch vehicles. Using the conclusions as a premise, recommendations will be made for development of an orbital propellant supply infrastructure which utilizes ELV resources. A framework will be established for this utilization, and a roadmap presented for its implementation. The policy precedents which enable certain aspects of the implementation will be referred to, and the technology development requirements will be addressed.

8.1 CONCLUSIONS

The conclusions of this section are based on the results of the OPSIS simulation and the contents of the previous chapters. Answers will be provided for many of the questions which have been raised regarding the enhanced utilization of ELVs. The conclusions will be made in a sequential order which allow each conclusion to build on the previous ones. The rationale behind each of the conclusions will be summarized in a brief discussion following each.

(1) A NEW INFRASTRUCTURE SHOULD BE DEVELOPED FOR SPACE OPERATIONS OVER THE NEXT 10 TO 15 YEARS

The U.S. should proceed with a new infrastructure for space operations. The infrastructure should be composed of several elements, including a space station, orbital maneuvering vehicles, orbital transfer vehicles, earth to orbit transportation vehicles, and a supply infrastructure for replenishment of consumables including propellant. The motives for development of a new infrastructure are many. Political, military, and economic competition with the other spacefaring nations are significant factors, as are the human aspirations for scientific exploration and discovery.

(2) A NEW EXPENDABLE LAUNCH VEHICLE SHOULD BE DEVELOPED FOR USE IN THE NEW INFRASTRUCTURE.

There is a need for development of a new vehicle to augment the current space transportation system (STS) in the new infrastructure. Existing ELVs do not have the capability for lifting the payloads required, and they are more costly than is desired. A new launch vehicle will provide the required lift capability, and do so for less cost than current systems. Development of a new vehicle will also allow U.S. industry to compete more effectively in the international marketplace for space launch services. The new vehicle will be likely be a product of either the Shuttle-C or the ALS program. Which one will be developed is dependent on the political climate in the coming years, but indications are that the ALS has the best chance of being developed.

(3) THERE WILL BE A SIGNIFICANT DEMAND FOR CRYOGENIC PROPELLANTS IN LOW EARTH ORBIT

A space based reusable orbital transfer is being planned for use in the new infrastructure for a variety of high energy missions. This vehicle will have significant economic advantages over expendable OTVs or ground based OTVs. The propellants used will be liquid oxygen and liquid hydrogen, for which the annual demand will be from a few to several hundred thousand pounds.

(4) THE TECHNOLOGICAL CAPABILITY FOR TRANSFER AND LONG TERM STORAGE OF CRYOGENIC PROPELLANTS IN ORBIT SHOULD BE ESTABLISHED

There has been considerable research to date on the topics of transfer and long term storage of cryogenics in orbit. Many NASA centers are participating and actively funding research in this area, as is the DoD, in particular for SDI. Flight experiments are planned, but further delays in launch schedule could block the timely development of this technological capability.

(5) THE PROPELLANT RECLAMATION SCENARIO FOR ELVS PROPOSED BY INFRASTRUCTURE C IS THE BEST APPROACH TO ORBITAL PROPELLANT SUPPLY FOR THE FUTURE SPACE INFRASTRUCTURE.

The infrastructures under consideration can be seen in Figure 3.1. The scenario for propellant reclamation proposed in infrastructure C is the best approach for a variety of reasons. There are essentially eight reasons that point to this infrastructure as being the best, and they are as follows.

- *COST EFFECTIVENESS:* Infrastructure C reduces costs by at least a factor of three over propellant supply options which are currently under consideration (i.e. shuttle), and also costs less than other infrastructures which are proposed in this thesis. This can be seen in Figure 7.2.

- *LOWER TECHNICAL RISK:* Development of an ELV propellant reclamation capability for the new infrastructure will reduce the technology requirements on other systems. In particular, the OTV will not need to be developed with aerobraking technology. The primary reason for development of aerobraking is to reduce propellant consumption of reusable OTVs, and the primary reason for reduction is the high cost of propellants in orbit. If propellant costs decrease significantly, the high technology aerobraking requirements placed on an OTV will be eliminated.

- *IMPROVED SAFETY:* Utilization of ELVs can be done in an unmanned manner eliminating the heightened safety concerns when manned systems such as the shuttle are involved.

- *SUFFICIENT PROPELLANT SUPPLY:* Propellant reclamation using ELVs will provide the capability to put as much propellant in orbit as is desired, simply by building and launching dedicated ELVs. The shuttle is limited to flight rates of less than 15 per year as indicated in Chapter 4, and dedicated propellant delivery missions would have stiff competition for manifesting. The construction cost of another orbiter to raise launch rates for propellant delivery is significant.

- *REDUCED COMPLEXITY:* Enhancing the orbital utilization of ELVs reduces the number of components required in the infrastructure, creating a simpler system.

- *INCREASED FLEXIBILITY:* Through ELV propellant reclamation, the propellant supply infrastructure can be made more flexible than if separate transportation tanks are required. Separate transportation tanks are fixed in size therefore fixed in propellant delivery quantities. By using the propellant tanks inherent in an ELV, the quantity of propellant delivered is readily variable creating flexibility for the delivery system.

- *SCHEDULING:* ELVs which may incorporate propellant reclamation technology are currently in the design phase. There is no retro-fitting required to provide propellant delivery as there is with the shuttle. An integrated design can be made which will incorporate not only the earth to orbit transporation capability into the ELV, but the propellant reclamation capability as well.

- *INTERNATIONAL PARTICIPATION AND COOPERATION:* Developing an ELV utilization capability for propellant reclamation can allow other nations to participate directly in a propellant supply infrastructure. By making their launch vehicles capable of propellant transfer, they can provide a portion of orbital propellants for their own use. International partners entering now can participate in the design phase of the propellant supply infrastructure.

These reasons favoring infrastructure C are consistent with NASA's programmatic objectives for orbital fluid supply as shown in Chapter 5, particularly for cost, safety, flexibility, and reduced complexity. General conclusions regarding each of the scenarios will be discussed below in relation to the points made in favor of infrastructure C.

INFRASTRUCTURE A: Due to the policy which NASA began by cancelling the Shuttle/Centaur high energy upper stage, the availability of the space shuttle to carry cryogens to orbit is questionable. The primary reason for this policy is concern over safety. If the shuttle were to provide cryogenic propellants to orbit, the cost of doing so would be at least three times higher than the costs with use of expendables in infrastructure C as indicated in Chapter 7.

INFRASTRUCTURE B: The use of infrastructure B would provide propellant on orbit that is comparable in cost to that which could be provided with the shuttle. Infrastructure B-1 in which the transportation tank for propellants is expendable is much more costly than B which reuses the tank. The costs of this scenario are significantly higher than those for infrastructure C, in part because the amount of propellant that can be supplied annually without dedicated transportation is fifty percent less than C.

INFRASTRUCTURE C: This scenario is the best alternative for propellant supply to orbit. The cost of propellant delivery at 85 dollars per pound is significantly less than the costs of other infrastructures by at least a factor of three. This is in part because the amount of propellant that can be supplied annually by infrastructure C without requiring dedicated transportation is significantly higher than for the other infrastructures.

INFRASTRUCTURE D: The use of an ELV for the propellant storage depot has many problems given the projected demand. This makes this utilization scenario unfeasible as discussed in Chapter 3.

INFRASTRUCTURE E: This scenario has the same problems as D for utilization of the ELV as a propellant depot. However, there may be benefits to using the ELV as a high energy upper stage for large payload missions. This utilization method should be developed following propellant reclamation as discussed in Chapter 3.

(6) ENHANCED ORBITAL UTILIZATION OF ELVS WILL STRENGTHEN THE NEW SPACE INFRASTRUCTURE

By utilizing ELVs for propellant reclamation, they are exceeding their traditional role of earth-to-orbit transportation. The cost for enhanced utilization of ELVs is much less than the cost for development and implementation of alternate systems to accomplish the same tasks. Therefore the cost of overall infrastructure operations is decreased. This strengthens the infrastructure by providing more opportunity for growth, and diverting into other areas, resources which would have gone into propellant delivery.

8.2 RECOMMENDATIONS

Orbital utilization of ELVs through propellant reclamation should be implemented in the future space infrastructure. The general functional relationships between primary elements of such an infrastructure are indicated in Figure 8.1.

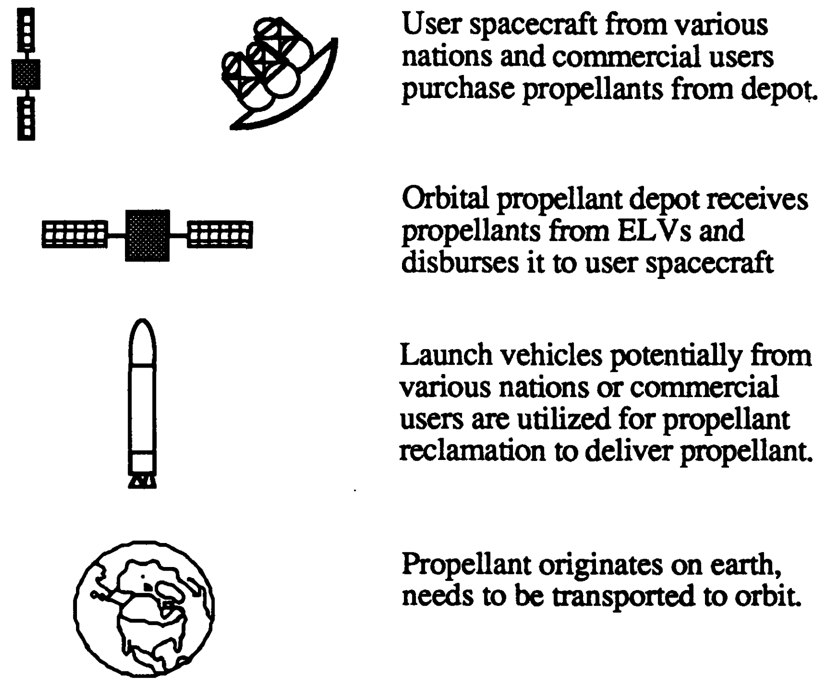


Figure 8.1
Basic functional relationships of infrastructural elements.

NASA and the DoD are each interested in obtaining an infrastructure for propellant supply and transfer in space. The presence of a propellant supply infrastructure will reduce transportation costs significantly for high energy missions. This will allow greater participation in the utilization of space for civil, military, and commercial ventures. The risk associated with development of a high technology program very high. Government has traditionally funded developments of this nature. When the benefits of a venture such as development of space are shared by many, the risks of undertaking the development are also shared by many through government funding. Government should bear the financial burden for funding of the development of a new space infrastructure and the associated developments for propellant reclamation. The civil and military space programs will be the prime beneficiaries of such a development, at least initially, which aids in justification of this recommendation.

In aerospace, large programs have historically been government funded, with the actual work being performed by the contractors. These roles are recommended for the development of an infrastructure for propellant supply and transfer. Through the research, development and test phase, the work should be primarily funded by the government, split between the civil and military space programs in some efficacious manner. There should be some international involvement as well. Foreign programs will be interested in obtaining or having access to a propellant supply capability. In order to facilitate international cooperation and transfer of technology from work being done on this subject by other spacefaring nations, it should be a multinational effort. The proportion of the funding and work to be done by foreign governments and contractors is difficult to estimate, but will likely be less than that spent by the U.S.

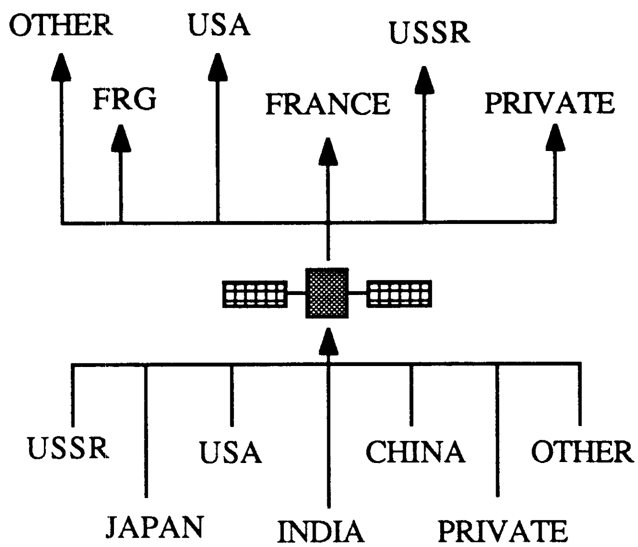
The development and test phase of the program should be set up in a manner similar to the research phase. Because of the level of risk involved and the national interest in the program, the majority of the funding should be covered by the government, with some private and some international funding. This phase will verify the technology required for development of the program, and establish its feasibility. This scenario for development has precedent in the communications, remote sensing, and launch vehicle industries. In these examples, the government provided the developmental funding and when the technologies were mature, turned them over to private industry for commercialization as seen in section 4.5.

With feasibility established and interest in the program from government and/or private users, private industry can proceed with production and deployment of the system under private funding. The "anchor tenant" concept can be employed for the funding, as was discussed in section 4.5.2. This method of funding is currently being initiated for low earth space facilities. Such a precedent will provide a basis for moving forward with more privately funded space program developments, of which a propellant supply infrastructure should be one. The government can provide the developer with a guaranteed leasing agreement which will reduce the risk to investors, allowing private financing of the program. The private sector should work with foreign contributors to set up an organization which may follow the Intelsat model. Such an organization would create a framework for participation, and an authority to run the operation.

Military users of orbital propellants will likely desire a separate facility from one used for international civil and private spacecraft. This stems from security concerns, level of control, and resource availability particularly in the event of conflict. The military should use technology which had been developed in the integrated program previously, and develop a separate orbital facility for their dedicated use. They may use the same contractor as the privately funded program, but should directly manage their own facility in contrast to the commercial facility which would be governed by private industry in an international consortia.

Users of the facilities should be from various nations. A policy decision should be made early in the program as to whether Soviet bloc nations would be allowed to participate in the program if they wished to. The Soviet Union may be hoping to develop such a facility for their own use, primarily out of military motives. Their military would surely have the same concerns as that of the U.S. over sharing a facility.

Membership in an international consortia for supply of orbital propellants should be in the spirit of the Intelsat model. A schematic of how the facility should work is shown in figure 8.2.



User spacecraft from various nations and commercial users purchase propellants from depot.

Orbital propellant depot receives propellants from ELVs and acts as middleman for distribution of propellants to user spacecraft.

Propellant can be supplied from ELVs of various nations as well as provate industry.

Figure 8.2
Orbital depot as middleman for international supply and demand.

An orbital depot should be the center of the propellant supply infrastructure. Use of ELVs to supply propellants should be done by several nations as well as private users, if they incorporate the necessary transfer technologies into their launch vehicles. Propellants will be reclaimed from the launch vehicles and stored in the depot facility which will then act as an orbital gas station to provide propellants to spacecraft for a number of users. The user spacecraft should also be from a number of nations or private ventures. An accounting system should be established for purchase of propellants from ELV suppliers and selling of propellants to spacecraft users with the depot acting as middleman.

The development scenario which has been outlined in the previous discussion is summarized in Table 8.1. The numbers used in this table regarding level of involvement are estimates by the author. These estimates should allow favorable participation by the various parties, which will strengthen the potential for development of this utilization capability.

Program Task	Groups and % of functional involvement or responsibility NASA	DoD	Foreign	Private Sector
Technology Development Funding	40	25	25	10
Technology Development Work	10	10	25	55
Hardware Dev. & Test Funding	40	40	25	10
Hardware Dev. & Test Work	10	10	25	55
Production	Oversight	Oversight	25	75
Deployment	Oversight	25	25	50
Operational Responsibility	Oversight	25	25	50
Operational Utilization	25	25	25	25

Table 8.1
Development scenario for ELV propellant reclamation.

In order to accomplish this recommended scenario for incorporation of propellant reclamation into the new space infrastructure, several things should occur. The following recommendations will outline the necessary steps.

- ADVANCED SPACE OPERATIONS INFRASTRUCTURE STUDIES SHOULD INCORPORATE ELV UTILIZATION SCENARIOS

The ongoing studies for development and definition of the advanced space infrastructure should consider the various scenarios presented here for enhanced orbital utilization of ELVs. These scenarios offer the potential for reduced cost of the overall infrastructure through reduction of separate system element development programs. ELVs will be an important element of the new infrastructure and their potential for utilization should be thoroughly investigated so that full advantage can be made of their capabilities.

• ORBITAL PROPELLANT SUPPLY STUDIES SHOULD INVESTIGATE ELVS AS A RESOURCE

The orbital utilization of ELVs through propellant reclamation has been identified here as having the potential for substantially reducing the cost of orbital propellant supply. Studies which are investigating scenarios for orbital propellant supply should seriously consider ELV propellant reclamation.

• ORBITAL PROPELLANT TRANSFER TECHNOLOGY DEVELOPMENT SHOULD BE ACCELERATED

The need for propellants in orbit is currently in existence and will grow tremendously in the next ten years. Technology requirements for transfer and storage of storable propellants have been demonstrated and are well established. However there is much work to be done on developing the technological capability for transfer and long term storage of cryogenic propellants. These technologies are critical many of the proposed elements of the new infrastructure, particularly the OTV. Their development schedules should be seriously addressed and accelerated to assure the maturity of the necessary technologies for cryogenic propellant operations in orbit.

• ADVANCED LAUNCH SYSTEM (ALS) AND SHUTTLE-C STUDIES SHOULD INCORPORATE DESIGN OPTIONS WHICH PROVIDE PROPELLANT RECLAMATION TECHNOLOGY

The utilization of ELVs for propellant reclamation is dependent on the incorporation of the necessary technologies for propellant transfer into their designs. Studies for advanced transportation vehicles should interface with studies for cryogenic transfer and storage to collect data on performance and design for propellant transfer. The incorporation of these technologies into advanced launch vehicles should be verified, and propellant transfer and storage studies should develop strong lines of communication, if not merge with the programs for vehicle development.

- INTERNATIONAL INVOLVEMENT SHOULD BE ENCOURAGED AND PARTICIPATION IN DESIGN STUDIES INITIATED

Development of an infrastructure for orbital propellant supply and distribution is of interest to all spacefaring nations. Participation by other nations will reduce the development burden and foster technology transfer and international cooperation. Early involvement will allow farsighted planning, thus reducing the potential for problems and enhancing communication.

This is an opportune time for evaluation of systems which can make the new space infrastructure more economically and operationally attractive. Space programs require a large amount of resources, and during times of fiscal restraint such programs are not readily approved. International participation will reduce the burden of development on any single space program. The benefits should be made available to be used by all, and reciprocally so should the costs and risks be shared. Additionally, international cooperation in space has had strong support and participation in the past. New areas of development that foster such cooperation can only help in reiterating the point that from space there are no boundaries.

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```
      PROGRAM OPSIS
C
C
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C     MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C     SPRING 1988
C
C     THIS PROGRAM IS THE ORBITAL PROPELLANT SUPPLY
C     INFRASTRUCTURE SIMULATION (OPSIS)
C
C     THIS IS THE EXECUTIVE PROGRAM WHICH RUNS THE
C     SIMULATION  FOR PROPELLANT RECLAMATION FROM EXPENDABLE
C     LAUNCH VEHICLES IN ORBIT
C
C
      REAL PMFST,MANM,MASS
C
      CHARACTER VEHICLE*15,MMNAME*15,SIMDAT*15,DATAIN*15
C
      COMMON MASS(13,5),MANM(5,5),VMM(30,4),RECP(30,10),COST(8,12)
C
C     VARIABLE DEFINITION
C
C     M       = COUNTER
C     MANM    = MANIFESTING CALCULATION MATRIX
C     MASS    = VEHICLE DEFINITION MATRIX
C     PMFST   = MANIFESTING RATIO
C     N       = COUNTER
C     NSTAGE  = NUMBER OF STAGES FOR VEHICLE
C     TOTDV   = TOTAL DELTA VELOCITY UP TO NSTAGE
C
C
C     TO ENTER DATA
C
1002  CONTINUE
C
      WRITE (6,*) ' ENTER NAME FOR THE OUTPUT DATA FILE WHICH'
      WRITE (6,*) ' YOU WISH TO CREATE FROM THIS SIMULATION'
      READ (5,'(A)') SIMDAT
C
      OPEN (UNIT=7,FILE=SIMDAT,STATUS='NEW')
C
      WRITE (7,50) SIMDAT
      NCYC=1
C
C     TO OPEN DATA FILE FOR VEHICLE
C
      WRITE (6,*) ' ENTER NAME OF INPUT DATA FILE'
      WRITE (6,*) ' WHICH YOU WISH TO USE FOR SIMULATION'
      READ (5,'(A)') DATAIN
C
      OPEN (UNIT=10,FILE=DATAIN,STATUS='OLD')
      REWIND (UNIT=10)
      READ (10,'(A)') VEHICLE
      READ (10,*) NROW,NSTAGE
C
C     TO DESCRIBE MASS PROPERTIES DEFINITION MATRIX
```

```
C
C       THIS IS AN N X M MATRIX, WITH M COLUMNS REPRESENTING
C       THE M-1 STAGES OF THE LAUNCH VEHICLE, AND M REPRESENTING
C       THE OVERALL MASS PROPERTIES OF THE LAUNCH VEHICLE.
C
C       THE ROWS ALL REPRESENT DIFFERENT COMPONENTS OF THE
C       LAUNCH VEHICLE MASS, AND ARE BRIEFLY DEFINED BELOW
C       BY ROW NUMBER.
C
C       1       TOTAL VEHICLE MASS INCLUDING THIS STAGE
C       2       MASS RATIO OF VEHICLE TO THIS STAGE
C       3       DELTA VELOCITY OF THIS STAGE
C       4       PROPELLANT USED BY THIS STAGE
C       5       RECLAIMABLE PROPELLANT FROM THIS STAGE
C       6       TOTAL WEIGHT OF ONLY THIS STAGE
C       7       TOTAL PROPELLANT WEIGHT OF ONLY THIS STAGE
C       8       RESIDUAL PROPELLANT WEIGHT OF ONLY THIS STAGE
C       9       RESERVE PROPELLANT WEIGHT OF ONLY THIS STAGE
C       10      PAYLOAD WEIGHT OF THIS STAGE
C       11      VACUUM SPECIFIC IMPULSE OF THIS STAGE
C       12      MASS FRACTION OF THIS STAGE
C       13      MASS OF ADDITIONAL PROP TRANSFER HARDWARE
C
        READ (10,*) ((MASS(I,J),J=1,NSTAGE+1),I=1,NROW)
C
        READ (10,*) X,Y,TREFF
C
        MASS(13,NSTAGE) = X + Y * (MASS(6,NSTAGE)-MASS(7.NSTAGE))
        MASS(13,NSTAGE+1) = MASS(13,NSTAGE)
C
        WRITE (6,65) VEHICLE,NSTAGE
        IF (NSTAGE .EQ. 1) THEN
                WRITE (6,60) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 2) THEN
                WRITE (6,70) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 3) THEN
                WRITE (6,80) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 4) THEN
                WRITE (6,90) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        END IF
C
        WRITE (7,65) VEHICLE,NSTAGE
        IF (NSTAGE .EQ. 1) THEN
                WRITE (7,60) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 2) THEN
                WRITE (7,70) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 3) THEN
                WRITE (7,80) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        ELSEIF (NSTAGE .EQ. 4) THEN
                WRITE (7,90) ((MASS(I,J),J=1,NSTAGE+1),I=1,13)
        END IF
C
C       TO OPEN DATA FILE FOR MISSION MODEL
C
        READ (10,'(A)') MMNAME
        READ (10,*) NYEARS,NCOL
C
```

```
      READ (10,*) ((VMM(I,J),J=1,NCOL),I=1,NYEARS)
C
      WRITE (6,66) MMNAME,VEHICLE
      WRITE (7,66) MMNAME,VEHICLE
C
      WRITE (6,70) ((VMM(K,J),J=1,NCOL),K=1,NYEARS)
      WRITE (7,70) ((VMM(K,J),J=1,NCOL),K=1,NYEARS)
      WRITE (6,30)
      WRITE (7,30)
C
      CALL PRCALC (NSTAGE,NCYC,NYEARS,X,Y,TREFF)
C
      CALL COSTS (NSTAGE,NCYC,NYEARS)
C
      ENDFILE (UNIT=7)
      CLOSE (UNIT=10)
      CLOSE (UNIT=7)
C
      WRITE (6,30)
      WRITE (6,*) ' DO YOU WISH TO RUN A NEW SIMULATION ?'
      WRITE (6,*) ' IF YES ENTER '1'   IF NO ENTER '0''
      READ (5,*) NAGAIN
      WRITE (6,30)
      IF (NAGAIN .EQ. 1) GO TO 1002
C
C
100   FORMAT (2F20.5)
200   FORMAT (//)
30    FORMAT (/)
50    FORMAT (/,2X,'THIS IS THE OUTPUT FILE ',A,/)
55    FORMAT (2X,F14.4)
60    FORMAT (2X,2F14.4)
65    FORMAT (/,2X,'THIS IS LAUNCH VEHICLE ',A,/,
     1 2X,'WHICH HAS ',I2,' STAGES.',/)
66    FORMAT (/,2X,'THIS IS MISSION MODEL ',A,/,
     1 2X,'FOR LAUNCH VEHICLE ',A,//,2X,10X,'YEAR',
     2 3X,'FLIGHT RATE',3X,'LOAD FACTOR',/)
70    FORMAT (2X,3F14.4)
80    FORMAT (2X,4F14.4)
90    FORMAT (2X,5F14.4)
C
      STOP
      END
```

```
      SUBROUTINE MANIFEST (NSTAGE,PMFST,PREC,X,Y,TREFF)
C
C     THIS SUBROUTINE CALCULATES THE EFFECT OF NON-OPTIMAL
C     PAYLOAD MANIFESTING ON AMOUNT OF PROPELLANT AVAILABLE
C     FOR RECLAMATION
C
C
      REAL PMFST,MANM,MASS
C
      COMMON MASS(13,5),MANM(5,5),VMM(30,4),RECP(30,10),COST(2,12)
C
C
C     VARIABLE DEFINITION
C
C     M        = COUNTER
C     MANM     = MANIFESTING CALCULATION MATRIX
C     MASS     = VEHICLE DEFINITION MATRIX
C     PMFST    = MANIFESTING RATIO
C     N        = COUNTER
C     NSTAGE   = NUMBER OF STAGES FOR VEHICLE
C     PREC     = PROPELLANT AVAILABLE FOR RECLAMATION [LB]
C     TOTDV    = TOTAL DELTA VELOCITY UP TO NSTAGE
C
C
C     TO DESCRIBE MANIFESTING PROPERTIES DEFINITION MATRIX
C
C     THIS IS AN N X M MATRIX, WITH M COLUMNS REPRESENTING
C     THE M-1 STAGES OF THE LAUNCH VEHICLE, AND M REPRESENTING
C     THE OVERALL MANIFESTING PROPERTIES OF THE LAUNCH VEHICLE.
C
C     THE ROWS ALL REPRESENT DIFFERENT COMPONENTS OF THE
C     LAUNCH VEHICLE MASS, AND ARE BRIEFLY DEFINED BELOW
C     BY ROW NUMBER.
C
C     1        TOTAL VEHICLE MASS INCLUDING THIS STAGE
C     2        MASS RATIO OF VEHICLE TO THIS STAGE
C     3        DELTA VELOCITY OF THIS STAGE
C     4        PROPELLANT USED BY THIS STAGE
C     5        RECLAIMABLE PROPELLANT FROM THIS STAGE
C
C
      SUBT=MASS(10,NSTAGE)*(1.0-PMFST)-MASS(13,NSTAGE)
      DO 10 N=1,NSTAGE
              DO 15 M=1,5
                      MANM(M,N)=MASS(M,N)
15            CONTINUE
      MANM(1,N)=MANM(1,N)-(SUBT)
10    CONTINUE
C
      TOTDV=0.0
      IF (NSTAGE .EQ. 1) GO TO 1000
C
      DO 20 N=1,NSTAGE-1
              MANM(2,N)=MANM(1,N)/(MANM(1,N)-MASS(4,N))
              MANM(3,N)=32.174*MASS(11,N)*LOG(MANM(2,N))
              TOTDV=TOTDV+MANM(3,N)
20    CONTINUE
```

```
C
C       TO CALCULATE NECESSARY DELTA V FROM UPPER STAGE
C
        MANM(3,NSTAGE)=MASS(3,NSTAGE+1)-TOTDV
C
C       TO CALCULATE MASS RATIO OF UPPER STAGE
C
        MANM(2,NSTAGE)=EXP(MANM(3,NSTAGE)/(32.174*MASS(11,NSTAGE)))
C
1000    CONTINUE
C
C       TO CALCULATE USED PROPELLANT IN UPPER STAGE
C
        MANM(4,NSTAGE)=MANM(1,NSTAGE)-(MANM(1,NSTAGE)/MANM(2,NSTAGE))
C
C       TO CALCULATE TOTAL PROPELLANT AVAILABLE FOR RECLAMATION
C
        MANM(5,NSTAGE)=MASS(5,NSTAGE)+MASS(4,NSTAGE)-MANM(4,NSTAGE)
        PREC=MANM(5,NSTAGE)*TREFF
C
C
C       TO PRINT OUT VARIABLES
C
C       WRITE (6,100) PMEST,TOTDV
C       WRITE (7,100) PMEST,TOTDV
C       WRITE (6,200)
C       WRITE (7,200)
C       DO 50 N=1,5
C               WRITE (6,100) MANM(N,NSTAGE),MASS(N,NSTAGE)
C               WRITE (7,100) MANM(N,NSTAGE),MASS(N,NSTAGE)
C50     CONTINUE
C       TO PRINT OUT THE LAUNCH VEHICLE MANIFESTING MATRIX
C
C       WRITE (6,200)
C       WRITE (7,200)
C       DO 400 M=1,5
C               IF (NSTAGE .EQ. 1) THEN
C                       WRITE (7,55) MANM(M,1)
C                       WRITE (6,55) MANM(M,1)
C               ELSEIF (NSTAGE .EQ. 2) THEN
C                       WRITE (7,60) MANM(M,1),MANM(M,2)
C                       WRITE (6,60) MANM(M,1),MANM(M,2)
C               ELSEIF (NSTAGE .EQ. 3) THEN
C                       WRITE (7,70) MANM(M,1),MANM(M,2),
C    1                  MANM(M,3)
C                       WRITE (6,70) MANM(M,1),MANM(M,2),
C    1                  MANM(M,3)
C               ELSEIF (NSTAGE .EQ. 4) THEN
C                       WRITE (7,80) MANM(M,1),MANM(M,2),
C    1                  MANM(M,3),MANM(M,4)
C                       WRITE (6,80) MANM(M,1),MANM(M,2),
C    1                  MANM(M,3),MANM(M,4)
C               END IF
C400    CONTINUE
C
C       WRITE (6,250)
C       WRITE (7,250)


100     FORMAT (2F18.4)
200     FORMAT (/)
250     FORMAT (//)
55      FORMAT (2X,2F12.2)
60      FORMAT (2X,3F12.2)
70      FORMAT (2X,4F12.2)
80      FORMAT (2X,5F12.2)
C
C
        RETURN
        END
```

```
      SUBROUTINE PRCALC (NSTAGE,NCYC,NYEARS,X,Y,TREFF)
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF PROPELLANT
C     AVAILABLE FOR RECLAMATION FOR THE PARTICULAR LAUNCH
C     VEHICLE GIVEN THE LOAD FACTOR AND THE FLIGHT RATE
C
C
      REAL PMFST,MANM,MASS
C
      CHARACTER VEHICLE*15
C
      COMMON MASS(13,5),MANM(5,5),VMM(30,4),RECP(30,10),COST(8,20)
C
C     VARIABLE DEFINITION
C
C     M       = COUNTER
C     MANM    = MANIFESTING CALCULATION MATRIX
C     MASS    = VEHICLE DEFINITION MATRIX
C     PMFST   = MANIFESTING RATIO
C     N       = COUNTER
C     NSTAGE  = NUMBER OF STAGES FOR VEHICLE
C
C
      PREC=0.0
C
      DO 100 I=1,NYEARS
              RECP(I,1)=VMM(I,1)
              CALL MANIFEST (NSTAGE,VMM(I,3),PREC,X,Y,TREFF)
              RECP(I,2)=PREC
              RECP(I,3)=RECP(I,2)*VMM(I,2)
100   CONTINUE
C
      WRITE (6,*) ' THIS IS THE AMOUNT OF PROPELLANT AVAILABLE ON'
      WRITE (6,*) ' EACH FLIGHT AND FOR EACH YEAR OF OPERATION.'
      WRITE (6,30)
      WRITE (7,*) ' THIS IS THE AMOUNT OF PROPELLANT AVAILABLE ON'
      WRITE (7,*) ' EACH FLIGHT AND FOR EACH YEAR OF OPERATION.'
      WRITE (7,30)
C
      WRITE (6,*) '          YEAR       PER FLIGHT          TOTAL
      DO 120 I=1,NYEARS
              WRITE (6,90) (RECP(I,K),K=1,3)
              WRITE (7,90) (RECP(I,K),K=1,3)
120   CONTINUE
C
      WRITE (6,30)
      WRITE (7,30)
C
      SUM=0
      DO 300 I=1,NYEARS
              SUM=SUM+RECP(I,3)
300   CONTINUE
      WRITE (6,50) SUM
      WRITE (7,50) SUM
C
30    FORMAT (/)
50    FORMAT (2X,'THE TOTAL PROPELLANT DELIVERED OVER THE',/,


     1 2X,'LIFE OF THE PROGRAM IS',F14.2,' [LB]',/)
90    FORMAT (2X,3F15.2)
C
      RETURN
      END
```

```
      SUBROUTINE COSTS (NSTAGE,NCYC,NYEARS)
C
C     THIS SUBROUTINE CALCULATES THE COST OF PROPELLANT
C     AVAILABLE FOR RECLAMATION FOR THE PARTICULAR LAUNCH
C     VEHICLE GIVEN THE LOAD FACTOR AND THE FLIGHT RATE
C
C
      REAL PMFST,MANM,MASS
C
      CHARACTER COST1*15,COST2*15,COST3*15,COST4*15,COST5*15,
     1 COST6*15,COST7*15,COST8*15
C
      COMMON MASS(13,5),MANM(5,5),VMM(30,4),RECP(30,10),COST(8,12)
C
C     VARIABLE DEFINITION
C
C     M       = COUNTER
C     MANM    = MANIFESTING CALCULATION MATRIX
C     MASS    = VEHICLE DEFINITION MATRIX
C     PMFST   = MANIFESTING RATIO
C     N       = COUNTER
C     NSTAGE  = NUMBER OF STAGES FOR VEHICLE
C
C     COST DEFINITION MATRIX
C
C     THIS MATRIX PROVIDES A DEFINITION OF COSTS OF THE
C     PROPELLANT RESUPPLY SYSTEM.  IT CONSISTS OF 12 COLUMNS
C     AND 8 ROWS, WHICH ARE DESCRIBED BELOW.
C
C     COLUMNS:
C     1)      NVEH    = NUMBER OF ITEMS PRODUCED OVER LIFE OF PROGRAM
C     2)      WE      = WEIGHT EMPTY OF HARDWARE
C     3)      F0      = CONSTANT FACTOR IN NON-RECURRING COST EQUATION
C     4)      F1      = CONSTANT FACTOR IN RECURRING COST EQUATIONS
C     5)      Q0      = EXPONENTIAL FACTOR IN NON-RECURRING COST EQNS
C     6)      Q1      = EXPONENTIAL FACTOR IN RECURRING COST EQUATIONS
C     7)      R       = FACTOR FOR LEARNING CURVE IN RECURRING COST EQ
C     8)      C0      = TOTAL NON-RECURRING COST FOR SYSTEM ELEMENT
C     9)      C1      = FIRST UNIT COST FOR SYSTEM ELEMENT
C     10)     P       = FACTOR DERIVED FROM R USED IN COST EQUATIONS
C     11)     CCUM    = TOTAL RECURRING COST FOR SYSTEM ELEMENT
C     12)     CTOTAVE = TOTAL AVERAGE COST FOR SYSTEM ELEMENT
C
C     THE EIGHT ROWS ARE DESCRIBED BELOW
C     1)      SOLID STAGE TRANSPORTATION COSTS
C     2)      LIQUID STAGE TRANSPORTATION COSTS
C     3)      TOTAL TRANSPORTATION COSTS
C     4)      DELTA TRANSPORTATION COSTS (RECLAMATION EQUIP)
C     5)      TRANSPORTATION TANK COSTS
C     6)      STORAGE FACILITY COSTS
C     7)      OTV COSTS
C     8)      LARGE UPPER STAGE COSTS
C
      NVEH=0.0
C
      DO 300 I=1,NYEARS
              NVEH = NVEH + VMM(I,2)
```

```
300     CONTINUE
C
        WRITE (6,54) NVEH
        WRITE (7,54) NVEH
C
        READ (10,*) NROW,NCOL
        READ (10,'(A)') COST1
        READ (10,*) (COST(1,J),J=1,NCOL)
        COST(1,1)=NVEH
        WRITE (6,65) COST1
        WRITE (7,65) COST1
        COST(1,2)=MASS(6,1)-MASS(7,1)
        ROW=1
        CALL COSTCALC(ROW)
C
        IF (NROW .GE. 2) THEN
                READ (10,'(A)') COST2
                READ (10,*) (COST(2,J),J=1,NCOL)
                COST(2,1)=NVEH
                WRITE (6,65) COST2
                WRITE (7,65) COST2
                COST(2,2)=MASS(6,2)-MASS(7,2)
                ROW=2
                CALL COSTCALC(ROW)
C
C               TO CALCULATE VARIABLES FOR TOTAL VEHICLE
C
                COST(3,1)=COST(1,1)
                COST(3,2)=COST(1,2)+COST(2,2)
                COST(3,8)=COST(1,8)+COST(2,8)
                COST(3,9)=COST(1,9)+COST(2,9)
                COST(3,11)=COST(1,11)+COST(2,11)
                COST(3,12)=COST(1,12)+COST(2,12)
        END IF
C
        IF (NROW .GE. 4) THEN
                READ (10,'(A)') COST4
                READ (10,*) (COST(4,J),J=1,NCOL)
                READ (10,*) OPFACT
                COST(4,1)=NVEH
                COST(4,2)=MASS(13,NSTAGE)
                WRITE (6,65) COST4
                WRITE (7,65) COST4
                ROW=4
                CALL COSTCALC(ROW)
                OPCOST=OPFACT*COST(3,11)
                COST(4,11)=COST(4,11)+OPCOST
                COST(4,12)=(COST(4,12)*NVEH+OPCOST)/NVEH
                IF (OPFACT .NE. 0) THEN
                        WRITE (6,*) ' OPERATIONS COSTS ARE INCLUDED'
                        WRITE (7,*) ' OPERATIONS COSTS ARE INCLUDED'
                END IF
        END IF
C
        IF (NROW .GE. 5) THEN
                READ (10,'(A)') COST5
                READ (10,*) (COST(5,J),J=1,NCOL)
```

```
               COST(5,1)=NVEH
               WRITE (6,65) COST5
               WRITE (7,65) COST5
               ROW=5
               CALL COSTCALC(ROW)
        END IF
C
        IF (NROW .GE. 6) THEN
               READ (10,'(A)') COST6
               READ (10,*) (COST(6,J),J=1,NCOL)
               READ (10,*) STCAP
               COST(6,1) = RECP(1,3)/(STCAP*2)
               COST(6,1) = AINT(COST(6,1)) + 1
               WRITE (6,65) COST6
               WRITE (7,65) COST6
               ROW=6
               CALL COSTCALC(ROW)
        END IF
C
        IF (NROW .GE. 7) THEN
               READ (10,'(A)') COST7
               READ (10,*) (COST(7,J),J=1,NCOL)
               WRITE (6,65) COST7
               WRITE (7,65) COST7
               ROW=7
               CALL COSTCALC(ROW)
        END IF
C
        IF (NROW .GE. 8) THEN
               READ (10,'(A)') COST8
               READ (10,*) (COST(8,J),J=1,NCOL)
               WRITE (6,65) COST8
               WRITE (7,65) COST8
               ROW=8
               CALL COSTCALC(ROW)
        END IF
C
C       TO PRINT OUT THE COST MATRIX
C
        WRITE (6,30)
        WRITE (7,30)
        WRITE (6,*) '  THIS IS THE COST MATRIX FOR THE SIMULATION'
        WRITE (7,*) '  THIS IS THE COST MATRIX FOR THE SIMULATION'
        WRITE (6,30)
        WRITE (7,30)
        WRITE (6,200)
        WRITE (7,200)
        DO 150 I=1,NROW
               WRITE (6,100) (COST(I,J),J=1,4)
               WRITE (7,100) (COST(I,J),J=1,4)
150     CONTINUE
        WRITE (6,30)
        WRITE (7,30)
C
        WRITE (6,210)
        WRITE (7,210)
        DO 160 I=1,NROW
```

```
              WRITE (6,100) (COST(I,J),J=5,8)
              WRITE (7,100) (COST(I,J),J=5,8)
160       CONTINUE
          WRITE (6,30)
          WRITE (7,30)
C
          WRITE (6,220)
          WRITE (7,220)
          DO 170 I=1,NROW
              WRITE (6,100) (COST(I,J),J=9,12)
              WRITE (7,100) (COST(I,J),J=9,12)
170       CONTINUE
          WRITE (6,30)
          WRITE (7,30)
C
          PSUM=0.0
          DO 502 I=1,NYEARS
              PSUM=PSUM+RECP(I,3)
502       CONTINUE
C
C         COSTS TO ORBIT
C
          PROPCOST=(COST(4,8)+COST(4,11)+COST(5,8)+COST(5,11))/PSUM
          WRITE (6,30)
          WRITE (7,30)
          WRITE (6,*) '  THE COSTS TO ORBIT ARE AS FOLLOWS'
          WRITE (7,*) '  THE COSTS TO ORBIT ARE AS FOLLOWS'
          WRITE (6,230) COST(4,8)+COST(5,8),
      1   COST(4,11)+COST(5,11),PSUM,PROPCOST
          WRITE (7,230) COST(4,8)+COST(5,8),
      1   COST(4,11)+COST(5,11),PSUM,PROPCOST
C
C         COSTS OF STORAGE
C
          PROPCOST=(COST(6,8)+COST(6,11))/PSUM
          WRITE (6,30)
          WRITE (7,30)
          WRITE (6,*) '  THE COSTS OF STORAGE ARE AS FOLLOWS'
          WRITE (7,*) '  THE COSTS OF STORAGE ARE AS FOLLOWS'
          WRITE (6,230) COST(6,8),COST(6,11),PSUM,PROPCOST
          WRITE (7,230) COST(6,8),COST(6,11),PSUM,PROPCOST
C
C         TOTAL COSTS
C
          PROPCOST=(COST(4,8)+COST(4,11)+COST(5,8)+COST(5,11)
      1   +COST(6,8)+COST(6,11))/PSUM
          WRITE (6,30)
          WRITE (7,30)
          WRITE (6,*) '  THE TOTAL COSTS ARE AS FOLLOWS'
          WRITE (7,*) '  THE TOTAL COSTS ARE AS FOLLOWS'
          WRITE (6,230) COST(4,8)+COST(5,8)+COST(6,8),
      1   COST(4,11)+COST(5,11)+COST(6,11),PSUM,PROPCOST
          WRITE (7,230) COST(4,8)+COST(5,8)+COST(6,8),
      1   COST(4,11)+COST(5,11)+COST(6,11),PSUM,PROPCOST
C
C         ADDITIONAL COST OUTPUT
C
```

```
      WRITE (6,30)
      WRITE (6,240) COST(3,12)
      WRITE (6,244) COST(3,12)/MASS(10,NSTAGE)
      WRITE (6,248) COST(3,12)/(MASS(10,NSTAGE)*VMM(1,3))
      WRITE (7,30)
      WRITE (7,240) COST(3,12)
      WRITE (7,244) COST(3,12)/MASS(10,NSTAGE)
      WRITE (7,248) COST(3,12)/(MASS(10,NSTAGE)*VMM(1,3))
C
C
30    FORMAT (/)
54    FORMAT (2X,'TOTAL NUMBER OF VEHICLES IS ',I3,/)
60    FORMAT (2X,2F14.4)
65    FORMAT (/,2X,'THESE ARE THE COST CALCULATIONS FOR ',A,/)
80    FORMAT (2X,4F18.4)
200   FORMAT(14X,'NVEH',16X,'WE',16X,'F0',16X,'F1')
210   FORMAT(16X,'Q0',16X,'Q1',17X,'R',16X,'C0')
220   FORMAT(16X,'C1',17X,'P',14X,'CCUM',11X,'CTOTAVE')
100   FORMAT(4F18.4)
230   FORMAT(10X,'EXNONREC',13X,'EXREC',14X,'PSUM',4X,
     1 'PROPCOST[$/LB]',/,4F18.4)
240   FORMAT(10X,'AVERAGE LAUNCH COSTS',10X,F15.2,' [$/LAUNCH] )
244   FORMAT(10X,'NOMINAL P/L DELIVERY COST',5X,F15.2,' [$/LB]')
248   FORMAT(10X,'ACTUAL P/L DELIVERY COST',6X,F15.2,' [$/LB]')
C
      RETURN
      END
```

```
      SUBROUTINE COSTCALC (ROW)
C
      COMMON MASS(13,5),MANM(5,5),VMM(30,4),RECP(30,10),COST(8,12)
C
C     THIS SUBROUTINE PERFORMS THE CALCULATION FOR THE COST
C     OF SYSTEM ELEMENTS IN THE PROPELLANT RESUPPLY SCENARIO
C
C     VARIABLE DEFINITION
C
      NVEH    = COST(ROW,1)
      WE      = COST(ROW,2)
      F0      = COST(ROW,3)
      F1      = COST(ROW,4)
      Q0      = COST(ROW,5)
      Q1      = COST(ROW,6)
      R       = COST(ROW,7)
C
      VARLN=0.693147
C
      C0=F0*(WE**Q0)
      C1=F1*(WE**Q1)
      P=LOG(R)/VARLN
      CCUM=C1*(((((NVEH+0.5)**(P+1))-1.5**(P+1))/(P+1))+1)
      CTOTAVE=(C0+CCUM)/NVEH
C
      COST(ROW,8)      = C0
      COST(ROW,9)      = C1
      COST(ROW,10)     = P
      COST(ROW,11)     = CCUM
      COST(ROW,12)     = CTOTAVE
C
      WRITE (7,80) F0,F1,Q0,Q1
      WRITE (7,90) C0,C1,P,CCUM
      WRITE (7,100) CTOTAVE
      WRITE (6,80) F0,F1,Q0,Q1
      WRITE (6,90) C0.C1,P.CCUM
      WRITE (6,100) CTOTAVE
C
80    FORMAT (18X,'F0',16X,'F1',16X,'Q0',16X,'Q1',/,2X,4F18.4)
90    FORMAT (18X,'C0',16X,'C1',17X,'P',14X,'CCUM',/,2X,4F18.4)
100   FORMAT (13X,'CTOTAVE',/,2X,F18.4)
      RETURN
      END
```