THE IMPACT OF LAUNCH VEHICLE CONSTRAINTS ON SPACE SYSTEM DESIGN

by

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The Impact of Launch Vehicle Constraints on Space System Design

by
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Submitted to the Department of Aeronautics and Astronautics and the Engineering Systems Division on May 25, 2001 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.

Abstract

While there are many factors that contribute to the high cost of developing spacecraft systems, one of the most often cited culprits is the launch vehicle. The explicit, first order impact of lowering space transportation costs is obvious. The cost of the launch vehicle system can consume anywhere from 10 to 75 percent of the space program budget depending on mission type. What is less understood are the implicit, second order impacts that launch capabilities have on the design of space systems. Limitations in launch capability, or constraints, can drive spacecraft design decisions and significantly alter subsystem and architectural choices. In many cases, the resulting decisions can lead to unnecessary hardware and software, increased system complexity, longer development and deployment times, continuous subsystem optimization, and multiple redesigns to comply with launch vehicle restrictions. The possibility that many of these design decisions be might be radically different under relaxed launch vehicle constraints is highly probable.

This research presents an analysis of the complex launch vehicle-spacecraft relationship focusing on how launch vehicle constraints influence the design and development of space systems. A myriad of launch constraints spanning across technical, operational, budgetary, and policy themes were identified and explained. The impact of each constraint on space system design and development, both by itself and coupled with other constraints, was substantiated and supported by historical examples from military, commercial, and civil space missions. Both architecture and subsystem level design changes were explored as well as prevailing design philosophies that have created a high cost of failure mentality and limited the ability to make inter-enterprise design trades. Finally, a simple model considers the potential changes to spacecraft system design and development in the wake of launch system improvements.

Thesis Advisor: Dr. Joyce Warmkessel
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"Success is based on planning and implementation: planning without implementation leads to stagnation, implementation without planning leads to chaos..."

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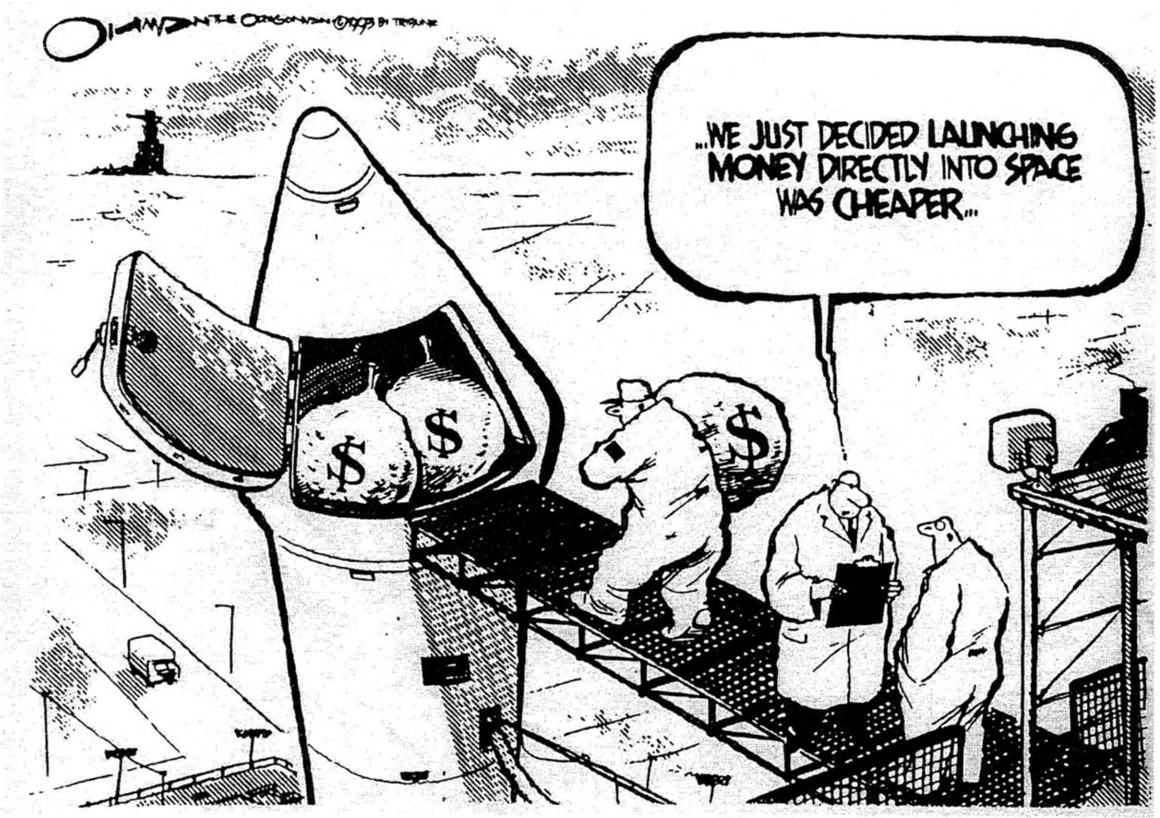

The Stanford Daily, November 18, 1994

"The principal deterrent to the expanded use of space, both for NASA and industry, is high cost." US National Research Council [1]

CHAPTER 1 INTRODUCTION

In the last four decades, space has become an integral part of the world's scientific, military, and commercial endeavors. In the defense industry, space represents the ultimate high ground, providing irreplaceable reconnaissance, communications, tracking, navigation, and potentially ultra-rapid weapons deployment. Similarly, space delivers key products for the commercial world including mobile and fixed communications, direct broadcast, multi-spectral imaging, and resource mapping. For science, space offers the opportunity to look outward to answer questions about the nature of the universe and look inward to monitor the Earth's fragile biosphere. While the value of these tasks is unquestionable, the cost of performing them is excessive.

1.1 Overview of the Research

The development of space systems is extremely expensive. This is a fact that is as true today as it was at the birth of the space industry in the late 1950's. Since the launch of the first artificial satellite in 1957 through the present, commercial aerospace and government organizations have successfully ventured into space by overcoming many technological challenges. Yet, realizing the true potential of space remains out of reach. Whether it is launch vehicles or spacecraft, the last barrier to the successful exploitation of space continues to be the high cost of designing, producing, deploying, and operating space systems. The end of the Cold War has eliminated the national security-based justification for enormous space expenditures. In the current environment of budget cuts and bottom-line performance pressures, it is crucial to drive down costs to sustain current missions and enable new projects to be initiated.

While there are many factors that contribute to the high cost of developing spacecraft systems, one of the most often cited culprits is the launch vehicle. The explicit, first order impact of lowering space transportation costs is obvious. The cost of the launch system can consume anywhere from 15 to 70 percent of a space program's budget depending on mission type and objectives. What is less understood are the implicit, second order impacts that launch capabilities have on the design of spacecraft systems. Many times limitations in launch capabilities, or constraints, can drive spacecraft design decisions and significantly alter subsystem and architectural choices. Any factor that drives the design and program decisions will ultimately have a significant impact on life-cycle costs. In many cases, the resulting launch-constraint-based decisions can lead to unnecessary hardware and software, increased system complexity, longer development and deployment times, and multiple subsystem redesigns to comply with launch vehicle restrictions. The possibility that many of these design decisions might be radically different under relaxed launch vehicle restrictions is highly probable.

This research presents an analysis of the complex launch vehicle – spacecraft relationship focusing on how launch vehicle constraints influence the design and development of spacecraft systems. Launch system constraints can be divided into four categories depicted in Figure 1-1.

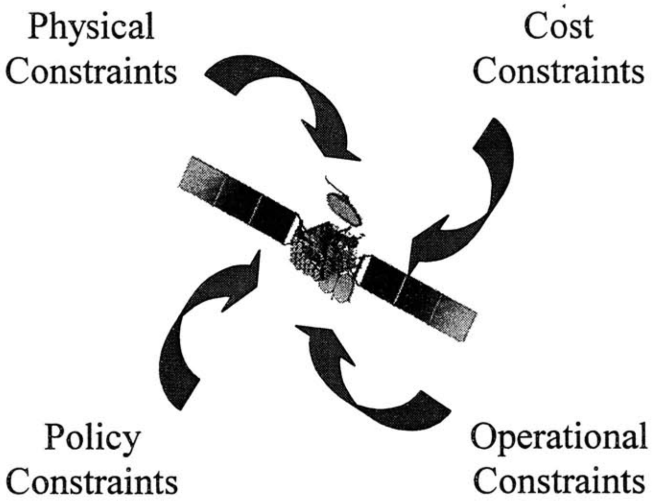

FIGURE 1-1 LAUNCH SYSTEM CONSTRAINTS

Physical constraints deal primarily with limitations based on physics and the laws of nature. Physical constraints include lift capabilities (mass), volume boundaries, dynamic and static loads, environmental conditions, and system-to-system interfaces. Operational constraints consider the functionality of the launch vehicle performing its primary task of delivering payloads to orbit. Operational constraints consist of vehicle reliability, availability, schedule dependability, and contract timelines. Cost constraints involve all fiscal matters including standard vehicle procurement, insurance, range fees, and vehicle mission-specific modifications. Finally, policy constraints entail the role and influence of government and commercial decision-makers. Policy constraints cover government enacted space transportation regulations, management practices and procedures, politics and international relations, and future launch vehicle development strategies. The focus of this research is to understand how these constraints affect current spacecraft systems as well as how changes to these constraints might affect the development of future spacecraft systems.

1.2 Motivation

Improved launch vehicle capabilities and more affordable access to space have become high priorities in the United States. In the last decade, nine government sponsored programs have been initiated to reduce space-access costs and develop launch systems with "aircraft-like" operations. Aircraft-like operations encompass quick vehicle turn-around times, ability to function in adverse weather conditions, and multi-order of magnitude improvements in safety, reliability, and flight rates. Demand for such capabilities has been forecasted by numerous commercial companies and government agency studies. Recent publications enumerate a myriad of new market opportunities that will flourish with improved space access from microgravity materials and pharmaceuticals processing, to space solar power and transport of cargo and passengers. However, very few studies discuss the complex, technical relationship between spacecraft systems and launch capabilities. Few consider how radical changes in the launch system will not only open up new markets but also alter spacecraft design, development, and deployment philosophies. To understand how spacecraft systems might change in this new "liberated-state," it is vital to understand how they exist in the current "constrained-state."

The complex relationship between launch vehicles and spacecraft is a result of their symbiotic link and is characteristics of products considered to be 'complimentary.' According to economic theory, the connection between complimentary products produces a positive coupling effect whereby the success, or failure, of one system determines the outcome of the other, and vice versa. Such a coupling can lead to explosive market growth when improvements in both products reinforce each other such as the introduction of the IBM PC and the Windows operating system. However, the reverse is also true. Stagnation of one product can hamper the growth of the other. Unfortunately, this negative feedback loop has plagued the space industry for several decades. High launch costs limit the number and the scope of spacecraft missions. However, the vehicle flight rate, or the number of missions launched in a specified period of time, is a major driver for launch costs. Thus, the space industry is caught in a vicious cycle scenario where spacecraft missions need low transportation costs in order to be viable and more numerous, yet launch systems need more missions (higher flight rates) to reduce per flight costs. A better understanding of the complex interfaces and relationship between spacecraft and launch vehicles is necessary to break this cycle.

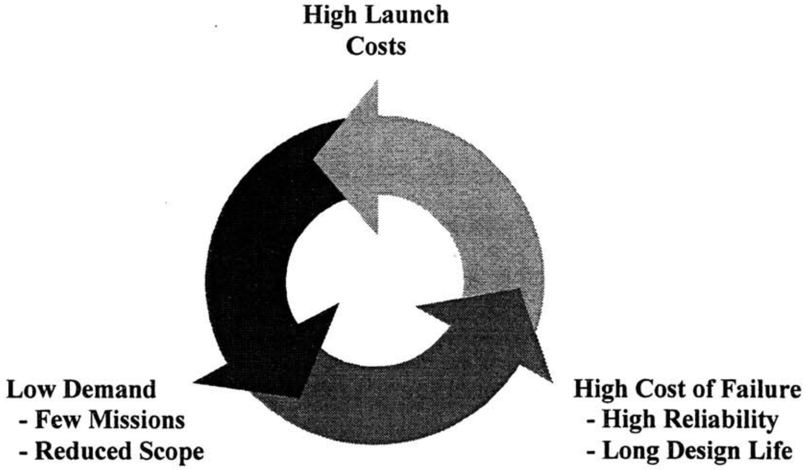

FIGURE 1-2 THE SPACECRAFT – LAUNCH VEHICLE VICIOUS CIRCLE [2]

An added feature of this vicious cycle or "symbiotic paradox," shown in Figure 1-2, is the creation of a "high cost of failure" mentality. In a typical commercial application, ensuring that customers have reliable service is driven by the corporate profit motive. Likewise, in military operations assurance of reliable information and communication is crucial to the warfighter's success in the field. Mission requirements drive spacecraft engineers to pursue high reliability strategies and design systems with excessive redundancy to ensure that failure does not occur.

Launch constraints such as high costs and lengthy procurement timelines typically exceeding 30 months also play a significant role in driving high spacecraft system reliability.[3] The loss of a spacecraft is financially difficult to replace. Launch vehicle procurement timelines averaging 30 months combined with the lack of "launch-on-demand" capability indicates that even if the funds and a replacement spacecraft are available, there is still a high probability of a two and a half year delay before the spacecraft could be delivered to orbit. High space access costs and other technical barriers also make maintenance or fixing spacecraft on-orbit prohibitive. All of these factors further reinforce the mindset that the spacecraft must not fail and that it also should last as long as possible to produce revenue or other value metrics to cover its development and deployment costs. Thus, mission requirements combined with launch constraints contribute to the "high cost of failure" mentality, driving reliability and long system lifetimes.

While many studies have looked at the explicit impacts of launch systems or focused on how to reduce the cost of either the launch vehicle or the spacecraft in isolation, relatively little work has looked across architecture segments to evaluate the coupled relationship and how changes in one segment might impact another. The primary motivation for the research focuses on trying to fill a portion of this gap and to gain a better understanding of the role that transportation systems play in the design and development of in-orbit space systems.

1.3 Key Questions

Based on the motivation outlined above, this thesis research was framed around answering two critical questions:

- How do launch vehicle system constraints impact the design and development of spacecraft systems?
- What aspects of spacecraft design and space system architecting might change with relaxed launch vehicle constraints?

Figure 1-3 illustrates the connection between the two central questions showing how the first question defines the present state while the second question seeks to explore the potential ramifications of altering the present state.

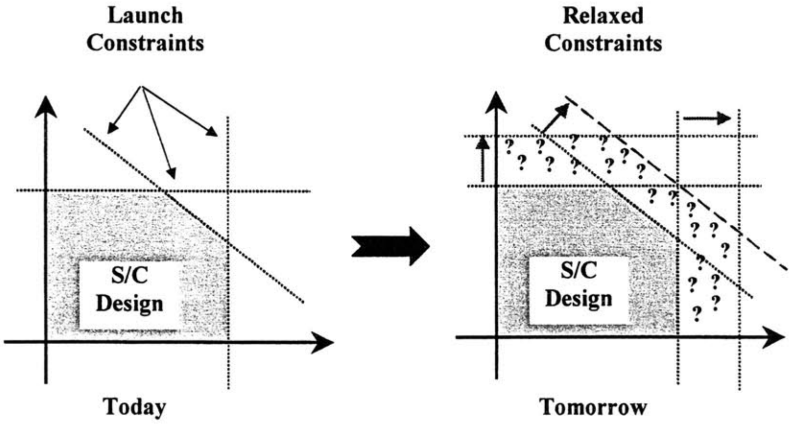

FIGURE 1-3 RELATIONSHIP OF RESEARCH QUESTIONS

1.4 Objectives and Contributions

The relationship between launch vehicles and spacecraft is both complex and dynamic. Changes in spacecraft design strategies in the early 1990's from large, individual geostationary communications spacecraft to distributed, small, multi-satellite constellations in Low Earth Orbit (LEO) had a dramatic impact on the launch community. The sudden surge in new commercial launch companies attempting to build both expendable and reusable vehicles in the mid 1990's in response to increased demand and the change in space system architecture provides direct evidence.

The development of a low cost, reliable, and flexible launch system will represent a disruptive technology in the space arena. Firms that understand how to best adapt and utilize the new capabilities will thrive while those that do not will loose market share and their competitive advantage. The development of affordable air transport in the 1930's had an incredible impact on the affairs of the world. Prior to 1935, aircraft primarily carried out military purposes and mail transport, both essentially subsidized by the US government. However, the advent of the Douglas DC-3 in 1936 changed everything. "The DC-3 freed the airlines from complete dependence on mail pay. It was the first aircraft that could make money just by hauling passengers."[4] Air transportation and the aviation industry quickly converted from a government subsidy program to a $200 billion market; aviation products and services are now the US's top export.

Whether the space transportation industry will witness a similar "DC-3-like" event and what its ultimate impact will be is unknown. Clearly the emergent benefits of improved launch capabilities cannot be completely fathomed. However, there are significant benefits to identifying and characterizing current constraints and how they effect spacecraft systems. Identification of the most detrimental constraints and quantitative assessment of their cost and schedule impacts provides the rationale and substantiation for approaching launch providers to request system improvements. It provides a listing of which changes will have the most significant benefits and what magnitude of change is required. Additionally, familiarization with the mode that constraints influence system design is the first step in formulating a strategy for mitigating these impacts and making more informed design decisions. Looking forward, knowledge of constraint impacts forms the basis of technology roadmaps that outline which capabilities are required to effectively utilize new launch systems quickly. Finally, focusing on the interface between the launch vehicle and spacecraft stimulates a system-level view of the design process. Approaching the design and development of complex systems from a system-of-systems framework is necessary to avoid the pitfall of local, subsystem optimization and enables a focus on creating the best life-cycle value for the end user.

Objectives and contributions of this work include:

1) Identification and characterization of thirteen launch vehicle constraints that influence the design of current spacecraft systems
2) Industry examples across military, civil, and commercial sectors providing scope and quantitative data
3) An analysis of the influence current space transportation policy has on spacecraft systems and the potential impact of policy decisions related to the development of the next generation of launch systems
4) An example quantitative model demonstrating the sensitivity of spacecraft design parameters to relaxed launch constraints

1.5 *Research Design*

The methodology employed to answer the research questions and meet the research objectives focused on the collection and analysis of both qualitative and quantitative data. A multiple-method approach was selected to collect a wider range of evidence to substantiate the possible impacts and their magnitudes and to strengthen the validity of the quantitative modeling results. The multi-method approach combines qualitative data gathered from expert industry interviews with quantitative analysis based on mathematical modeling. Research activities can be separated into four distinct phases: 1) background investigation and data collection, 2) expert interviews, 3) model formulation, and 4) analysis and discussion.[5]

The goals of the background investigation included familiarization with the design of spacecraft and launch systems, surveying the current literature for previous or related studies, and determining the suitable companies, programs, engineers, and managers to consult. The background investigation formed the basis for the interview questionnaire and the appropriate parameters for the mathematical model.

To better understand the nature of spacecraft design decisions, an interview questionnaire was developed to obtain relevant opinions and data from design engineers and managers at multiple levels of the design spectrum. Individuals from both the spacecraft and launch sectors across military, civil, and commercial programs were surveyed in order to:

- Investigate and document the rationale and motivation behind historical design decisions
- Obtain relevant design guidelines currently used by industry
- Gain an understanding how the spacecraft industry might react to significant improvements in space transportation capabilities
- Identify what sub-system and system elements might change with improved launch capabilities and by how much

The interview process concentrated on companies involved with the Lean Aerospace Initiative at MIT (See Appendix A: Lean Thinking). Site visits were conducted at 10 different organizations across military, civil, commercial, and academia sectors. Approximately 43 individuals were interviewed during a three months period from January through March 2001. The majority of the interviews were conducted on site at the host organization facilities and usually lasted between 1 to 2 hours per interview. The interview questionnaire is included in Appendix C. All data and examples form resulting from these interviews is presented in a general and non-attributable manner in order to protect company proprietary information.

The goal of the quantitative analysis was to support the qualitative assessment with hard numbers indicating the magnitude of potential impacts and the required change in launch capabilities. The primary goal was not to establish the exact levels of change, but to generate first order approximations. The quantitative model developed and presented in Chapter 8 considers the impact of lower launch costs on the replenishment rate (design lifetime) of spacecraft for geostationary communication missions. Additional architecture options enabled by improved launch capabilities are also presented.

1.6 Thesis Outline

The general layout of the thesis is cast around addressing the two primary research questions. To answer these questions, the thesis is composed of four themes. The first theme (Chapters 1 through 3) provides perspective and background information. After initially summarizing the thesis topic, key questions, and research methodology, Chapters 2 and 3 provide the fundamentals of spacecraft systems, launch systems, and the involvement of constraints in the spacecraft systems engineering design process. The second theme (Chapters 4 through 7) covers an in-depth discussion of the major launch vehicle constraints and how they impact spacecraft design. Each chapter first introduces and defines the launch constraints, discusses how they impact spacecraft design, provides examples from industry, and concludes with a summary of impacts. The third theme (Chapter 8) explores the implications of relaxing several of these launch constraints on spacecraft design. A simple mathematical model is presented demonstrating how current spacecraft design philosophies might change in an environment of improved launch capability. The final theme (Chapter 9) serves to pull everything together summarizes key findings, conclusions, and future work. Figure 1-4 displays a "map" illustrating the flow of the thesis.

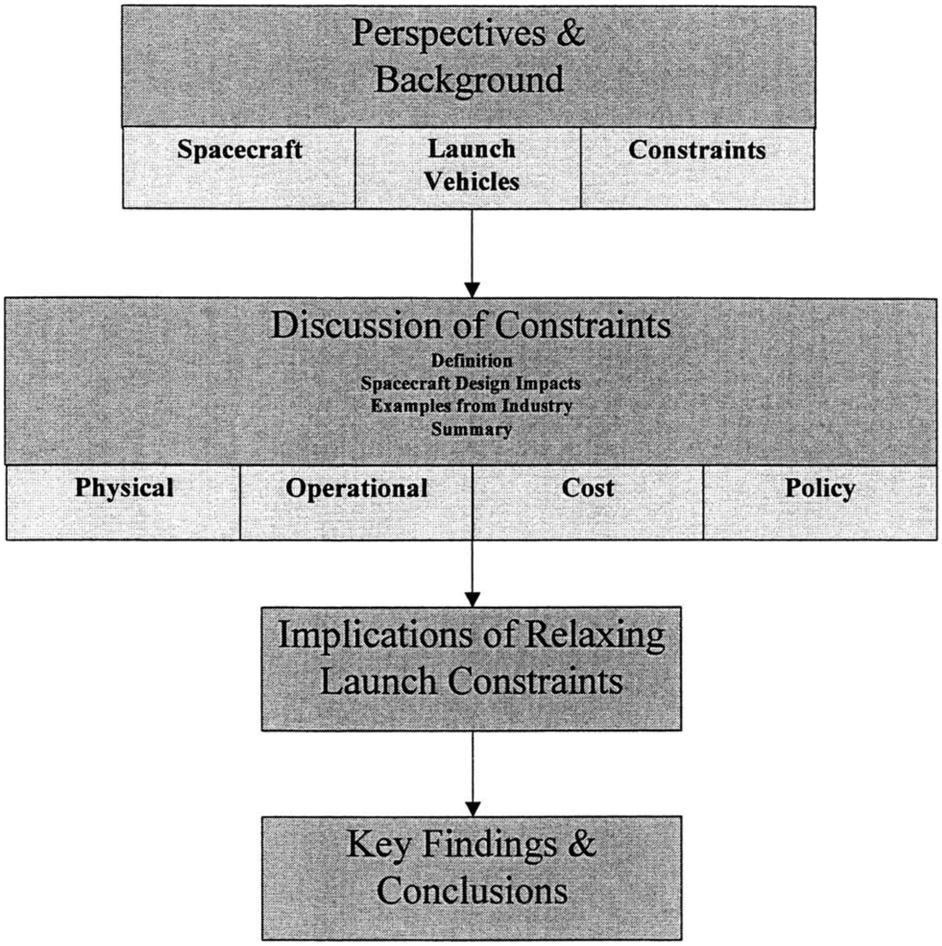

FIGURE 1-4 MAP OF THE THESIS

CHAPTER 2 SPACE SYSTEM DEVELOPMENT

2.1 History of Spacecraft Development

Prior to the early 1900's, the unknowns of spaceflight were unknown. While mankind demonstrated an fascination for studying the meaning and significance of the stars and other celestial bodies for thousands of years, the thought of physically venturing out into the heavens existed in the realm of dreamers and was captured in the writings of Jules Verne. A Russian teacher, Konstantin Tsiolkovsky, was the first to accurately describe the physics of rockets and spaceflight in a 1903 journal article that derived the now famous rocket equation. However, while Tsiolkovsky's work provided the engineering analysis, the technology and hardware was not developed until Robert Goddard from the United States and Werner von Braun from Germany attempted the first rocket launches in the early 1930's.

The launch of Sputnik I, the first artificial satellite, by the Russians on October 4, 1957 commenced the space era. This feat was quickly followed by the United States' first successful launch of Explorer I on January 31, 1958. The pace of progress from 1903 through 1957 quickly ramped up in the 1960's, fueled by the Cold War space race between the US and the USSR, which culminated in landing a man on the Moon in 1969. Space missions evolved from simple, single channel radio transmitters weighing only a few kilograms to gigantic 5,000 kilogram spacecraft offering sophisticated communications and data collection capabilities.[6] The next 30 years witnessed remarkable achievements in space including landing robotic craft on two planets, constructing several inhabited orbital space stations, and sending spacecraft to explore many other planets, moons, asteroids, and comets. After the 1960's, the pace of progress slowed considerably as one to two-year projects became 10 to 20-year programs.

In the past, space was the realm of scientific research and government activities. In fact, most activities in space were limited to three large governments: the USSR, the EU, and the US. Over the years, commercial activities started to flourish and governments encouraged the private sector to develop space capabilities. Up through the mid 1980's, private companies mainly produced space hardware as suppliers to national governments.[7] In 1997, commercial spending on space exceeded government space spending for the first time, a trend that will most likely never reverse course. In contrast to the three major players in the 1960's and 1970's, today's space industry is much more diversified with government and commercial organizations in more than ten countries capable of developing and launching spacecraft. Spacecraft systems have become a vital part of the military, commercial, and scientific sectors. The growth in capability combined with the diffusion of spacecraft technology have firmly entrenched space systems in today's society.

2.2 Space Enterprise: Space System

Space systems are complex entities composed of diverse, specialized units each with unique functionality that work in tandem to perform a particular task. A more formal definition specifies that a system is "a collection of interrelated elements with functionality greater than the sum of the independent element functions."[8] This definition clarifies the purpose of a system, to perform functions that individual entities, or subsystems, cannot. While the sub-unit performs a particular task, it also contributes to the much larger mission. Figure 2-1 shows the hierarchy of systems that can exist where one system can be both a supersystem (composed of many systems) and a subsystem of another larger system simultaneously. This hierarchy has been labeled "system-of-systems." The highest level supersystem is labeled the enterprise. The enterprise represents the summation of the all relevant systems and subsystems.

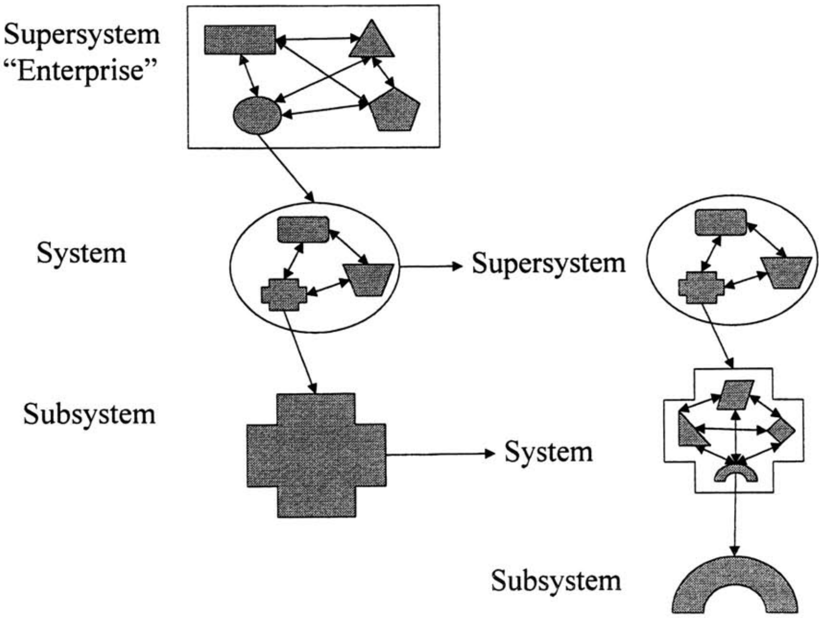

FIGURE 2-1 SYSTEM-OF-SYSTEMS DIAGRAM[8]

In order to carry out its mission, a spacecraft must also be integrated with other complex systems. In this manner, the spacecraft itself is only a single element or subsystem of the larger space enterprise. The space enterprise includes all spacecraft, launch vehicles, launch ranges, ground stations, radar stations, control centers, and land-, air-, and sea-based receivers (end users). Figure 2-2 shows the space enterprise and the relationships between the complex systems.

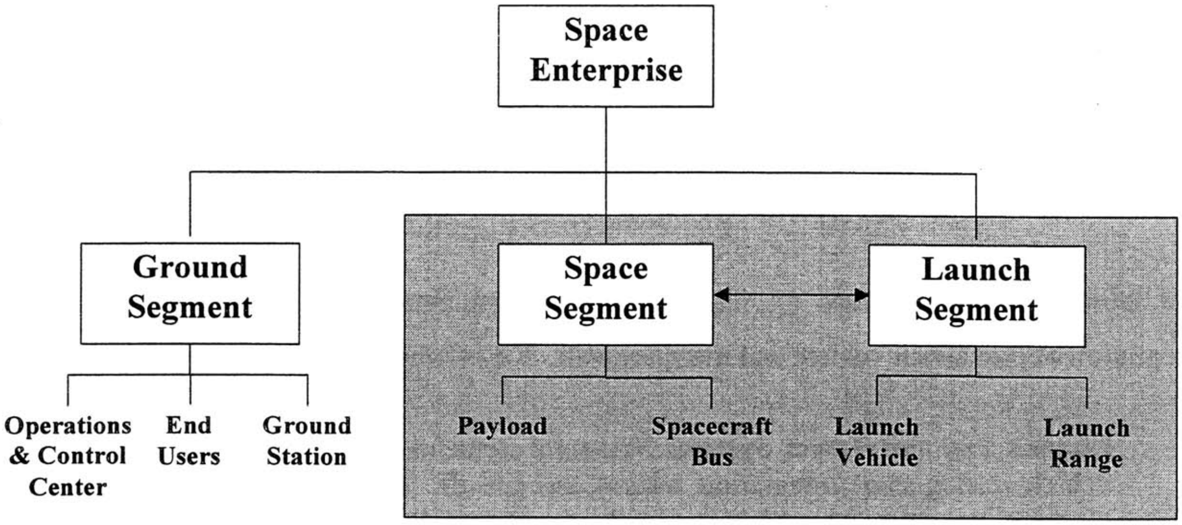

FIGURE 2-2 SPACE ENTERPRISE

A complete characterization of the entire space enterprise would also include all elements that design, supply components, manufacture parts, and provide financing and sales. All of these elements are necessary to complete the primary mission objectives. While there are many elements in the space enterprise, the focus of the thesis is on the interactions between the space and the launch segments highlighted in the shaded box in Figure 2-2. The following two sections will briefly outline the fundamental elements of the launch and space segments.

2.3 Launch Fundamentals

2.3.1 Elements of the Launch Segment

Following the system-of-system paradigm, the launch segment is itself a compilation of smaller systems. The launch segment is composed of two major systems, the launch vehicle and the launch range. Each of these systems can be further broken down into their subsystems and their subsystems' subsystems. Figure 2-3 displays a breakdown of the launch segment.

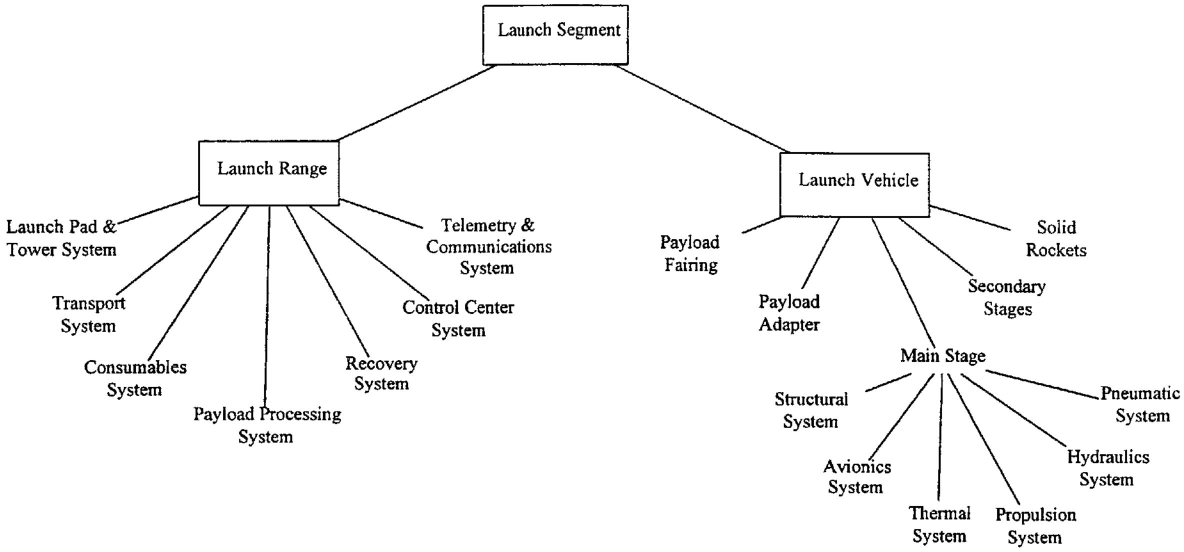

FIGURE 2-3 ELEMENTS OF THE LAUNCH SEGMENT

The launch range comprises all facilities and infrastructure to support the processing and integration of the launch vehicle and the spacecraft. Key elements include the:

Launch Pad and Tower System: Structural elements that physically support the launch vehicle during stage integration, testing, and lift-off. Umbilicals from the tower provide electrical power to the vehicle and payload and propellant loading shortly before lift-off.

Control Center System: Facilities, computers, and communications equipment that manage launch procedures from arrival at the pad through countdown, lift-off, and orbital insertion of the payload

Transport System: Equipment used in the movement of vehicle stages, spacecraft, propellant, and other vehicle consumables

Consumables System: Storage facilities for vehicle propellant and fluids for the vehicle hydraulic and pneumatic systems

Payload Processing System: Facilities and equipment used to store and prepare the spacecraft for integration with the launch vehicle upper stage

Communications System: Ground, air, and sea-based facilities and equipment that communicate with and track the launch vehicle from lift-off through ascent and orbital insertion [9]

Recovery System: Structural elements such as landing strips and equipment utilized in the ground and sea recovery of vehicles, vehicle components, spacecraft, or debris

The launch vehicle typically consists of multiple stages that are utilized at various points in the launch ascent cycle. Key elements include:

Payload Fairing: Structural element providing protection for the spacecraft during ascent. Also regulates the environmental conditions for the spacecraft during pad integration, ascent, and prior to orbital deployment.

Payload Adapter: Structural element providing electrical and physical connections between the spacecraft and the final launch vehicle stage. Also provides damping of launch vehicle loads.

Main Stage: Provides initial thrust for lift-off and initial ascent in the atmosphere. Includes the main engine, fuel tanks, and oxidizer tanks as well as structural elements and avionics.

Secondary Stages: Provide vehicle thrust following main stage/main engine cut-off. Responsible for delivering the spacecraft to the appropriate orbital altitude and inclination.

Solid Rockets: Provide additional thrust to the main stage at lift-off

Figure 2-4 shows the major elements of and expendable launch vehicle.

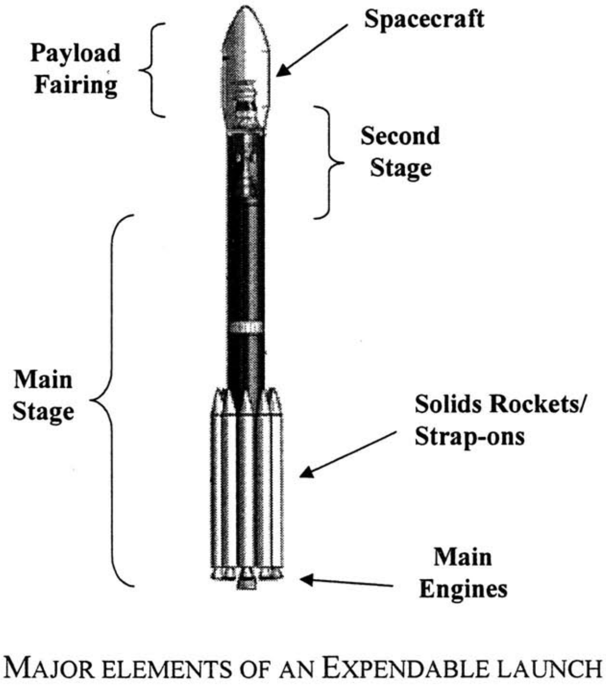

FIGURE 2-4 MAJOR ELEMENTS OF AN EXPENDABLE LAUNCH VEHICLE [17]

2.3.2 The Cost of Launch Vehicles

Compared to any other mode of transportation, launching objects into space is by far the most expensive. The costs associated with space access and payload delivery varies significantly depending primarily on the payload size and the orbital destination. It is also important to note that the exact launch costs for a particular vehicle will vary slightly from launch to launch depending on mission-specific equipment. These costs, also known as "drive-away" costs, include add-ons and extra features that are not included in the base vehicle price and cover equipment and operations such as special payload adapters, thrust augmentation, unique separation mechanisms, or telemetry equipment.

Launch costs are typically measured by two methods, vehicle procurement price and price per unit mass. The vehicle procurement price is the absolute cost of purchasing the launch vehicle for a single payload. For current vehicles, costs are roughly a function of the lift capacity of the launch vehicle with cost increasing at a fairly linear rate. Launch vehicle costs range from the least expensive Orbital Sciences Pegasus' vehicle at $15 million per flight up to the most expensive Lockheed Martin Titan IV vehicle at $400 million. Another cost measurement that is often quoted is the price per kilogram. For low Earth orbit launches, the average price is $9,800 per kilogram while the average price to geostationary orbit is $26,500 per kilogram.[16] Typically, the launch segment will consume roughly 30 to 40 percent of the program costs but can range anywhere from 15 to 70 percent in extreme cases. On average, when launch insurance is included, the launch segment consumes 50 percent of the total program budget. A more thorough discussion of launch costs and drivers is included in Chapter 6: Cost Constraints.

2.4 Spacecraft Fundamentals

2.4.1 Elements of the Space Segment

The spacecraft system is composed of two major subsystems, the payload and the spacecraft bus. The payload usually consists of various instruments, sensors, or antennas which are responsible for carrying out the primary mission objectives. The spacecraft bus consists of multiple subsystems that support the payload in carrying out its mission by providing power generation and storage, structural support, heat dissipation, data processing, and signal transmission. Each of the subsystems illustrated in Figure 2-5 are also collections of smaller and more focused subsystems and components.

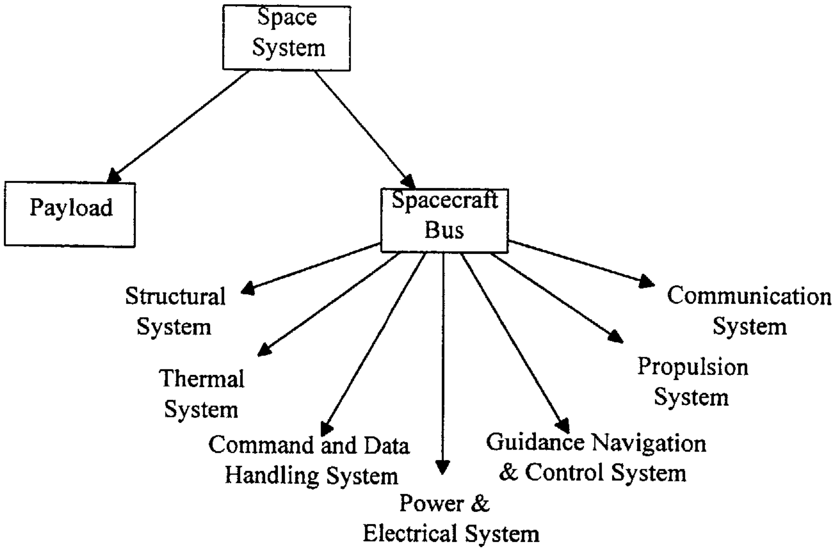

FIGURE 2-5 SPACECRAFT SUBSYSTEMS

Functions and typical components of spacecraft bus elements:

Structural System
Function: To physically support the payload and all spacecraft subsystems during ground integration, launch, and on-orbit operation in addition to providing an attachment fixture for securing the spacecraft to the launch vehicle. *Typical Components*: launch adapters, shielding, skin panels, fixtures, tanks, plates, trusses, frames, pressure vessels, brackets, and equipment boxes.

Thermal System
Function: To insure that the spacecraft and its subsystems remain within the desired temperature range through heat generation and heat dissipation. *Typical Components:* electrical heaters, temperature controllers, heat exchangers and heat pipes, sensors, cryogenic systems, solar reflectors, insulation, and coatings.

Command and Data Handling System
Function: To receive, validate, decode, process, and distribute mission data between spacecraft subsystems. *Typical Components*: central computer, data storage mechanism, software, database, command decoder, and A/D converters.

Power and Electrical System
Function: To generate, store, and distribute power between all spacecraft subsystems. *Typical Components:* solar arrays, primary battery, secondary battery, distribution system, regulators, converters, cabling, and switches.
Guidance, Navigation, and Control System

Function: To determine and control the spacecraft's position and velocity as well as maintain an appropriate orbital altitude and orientation. *Typical Components:* star sensors, actuators, ephemeris data, software, and GPS receivers.

Propulsion System
Function: To deliver the spacecraft to higher orbital altitudes and different inclinations following separation from the launch vehicle, to adjust the spacecraft's attitude and altitude during normal mission operations, and to de-orbit the spacecraft following end-of-life. *Typical Components:* fuel tanks, nozzle, ignition system, combustion chamber, filters, regulators, valves, pumps, propellant, and meters.

Communication System
Function: To provide an interface between the spacecraft and ground systems or other spacecraft through receiving and transmitting data. *Typical Components:* antenna, transmitters, receivers, filters, and switch diplexers.

2.4.2 The Cost of Spacecraft

The life-cycle cost of most space systems is normally measured in hundreds of millions to billions of dollars. The space segment life-cycle cost spans all aspects of the space program from conception to destruction and typically includes research and development, production, transportation, operations, management, and overhead costs. On a per unit basis, space system costs dwarf most other industries ranging from \$50,000 per kilogram to well over \$500,000 per kilogram. [2]

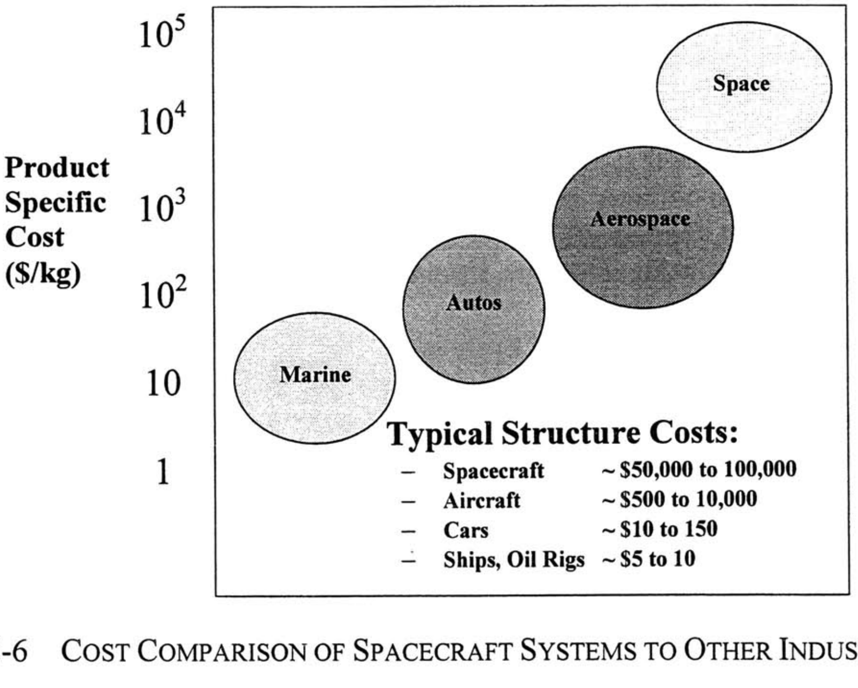

FIGURE 2-6 COST COMPARISON OF SPACECRAFT SYSTEMS TO OTHER INDUSTRIES [2]

The cost of space systems is typically broken down by three methods. One method involves separating costs as a function of time and phase in the mission life-cycle. In this scenario, costs are spread across the three main phases of: 1) research and development, 2) production and acquisition, and 3) operations and support. The percentage of life-cycle costs is roughly equal to 10%, 30%, and 60%, respectively. [10] A second method of breaking down costs is by architecture segment. Architecture segments include the space segment, the launch segment, the ground segment, and the human segment. Percentages for this breakdown vary considerably depending on the mission. Finally, spacecraft system cost can be broken down by subsystem. The payload typically consumes the largest portion of the budget averaging roughly 35 percent of the total spacecraft segment cost. [2] The spacecraft bus subsystems make up the remaining 65 percent with power, attitude determination and control (AD&C), communications, and structures comprising 20, 15, 10, and 10 percent, respectively. The computer, thermal, and propulsion consume the remaining 20 percent. It should be noted that these are average values and that each spacecraft system is very unique. Percentages can possibly vary by more than 10 percent depending on the mission. [11]

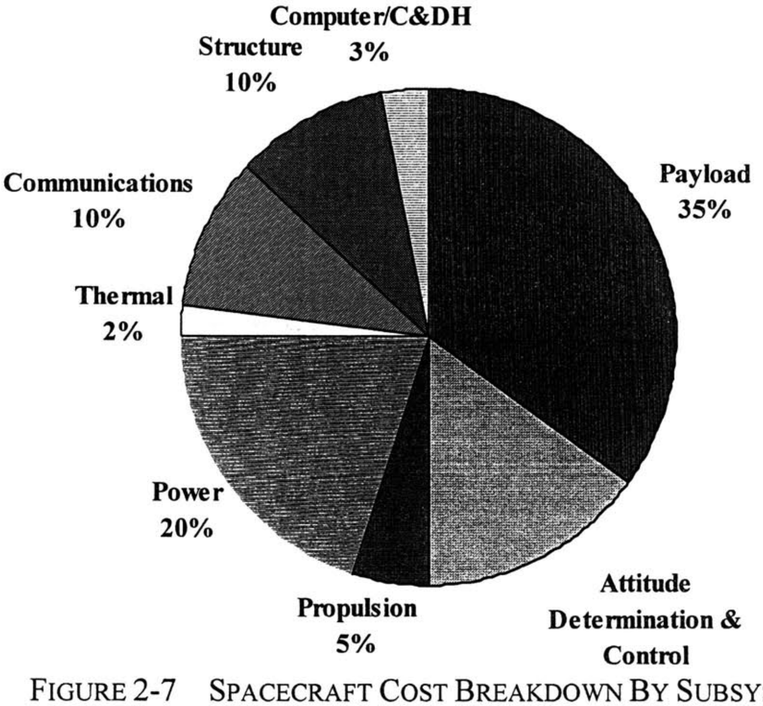

FIGURE 2-7 SPACECRAFT COST BREAKDOWN BY SUBSYSTEM

2.4.3 Spacecraft Design Drivers

Many factors influence the design and development of the spacecraft systems. Mission requirements, program type (military, civil, or commercial), orbital mechanics, the space environment, payload instruments, ground systems, and launch systems have the greatest influence on the final space system architecture and spacecraft design. These factors not only impact the architecture and design, but also determine the program costs and reinforce the high cost of failure described in Chapter 1. It is important to recognize that while launch systems can be a significant design and cost driver, they also represent one of many drivers. Figure 2-8 shows the primary factors that influence spacecraft design.

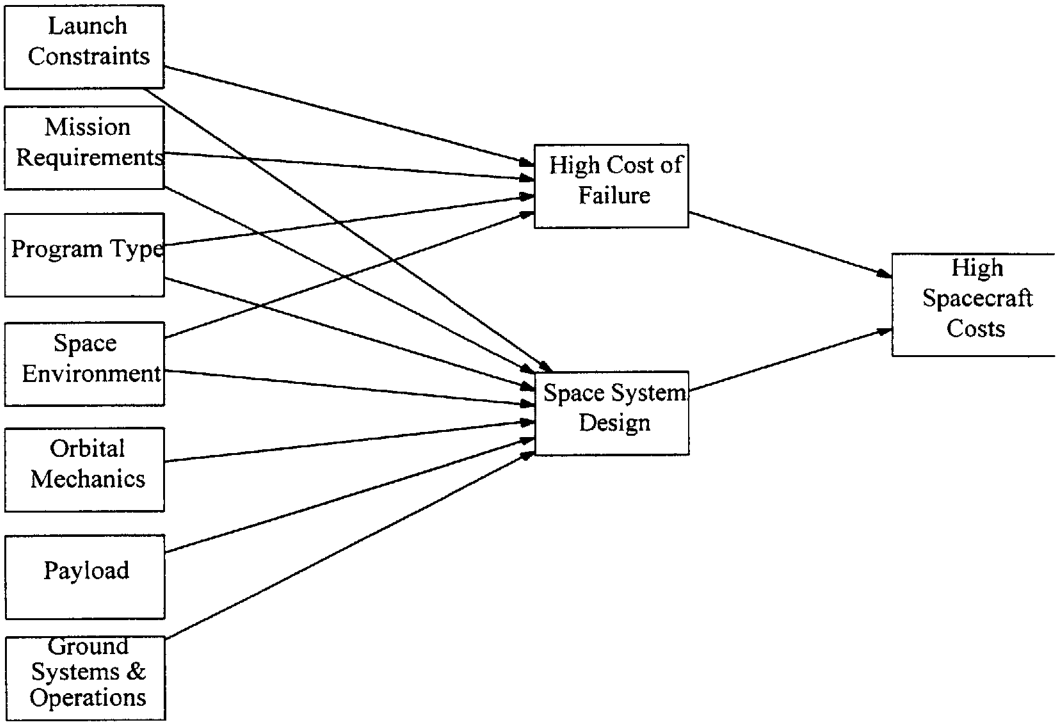

FIGURE 2-8 SPACECRAFT DESIGN DRIVERS

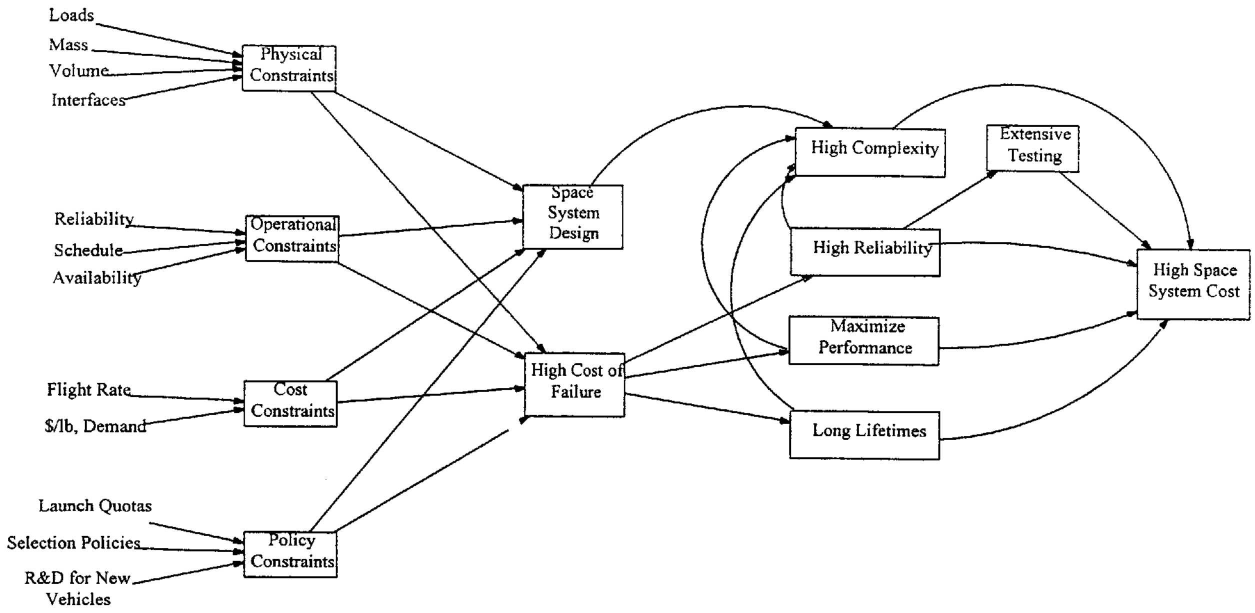

FIGURE 2-9 IMPACT OF LAUNCH ON SPACE SYSTEMS DESIGN

Figure 2-9 focuses in on the launch constraints box from the previous figure. As mentioned previously, launch constraints can be divided into four areas: physical, operational, cost, and policy. These four areas are further broken down and discussed in Chapters 4 through 7.

CHAPTER 3 FUNDAMENTALS OF CONSTRAINTS

According to Webster's Dictionary, the word constraint is defined as "a limitation, restriction, or something that constrains." The verb "to constrain" takes on the following meanings: 1) to force, compel, pressure, or oblige, 2) to confine forcibly, as by bonds, and 3) to repress or restrain. The most common antonym is "to be free."[12] Based on these definitions, constraints hold a very negative connotation. While there are instances where this is not the case, (i.e. a constraint or limitation on the amount of money one could lose by using a put option in finance), the majority of constraints evoke negative sentiments. Applying these definitions to spacecraft design yields:

Constraint: Anything that limits the trade space for a design (eliminates design choices)

In the realm of product development, designing under constraints is the norm. Throughout history, engineers and scientists have been challenged by constraints such as budgets, time, and the laws of physics. Moving from the design of simple machines (systems, devices) to the design of complex systems has made it increasingly more difficult to manage constraints arising from the complicated interaction between multiple systems. Moving forward, it will be necessary to renovate traditional engineering solutions and develop innovative methods for understanding how to design complex systems under complex constraints. One novel methodology, systems analysis, integrates economic resource utilization theory into traditional engineering environment that enables designing complex systems under constraints.

The purpose of this section is to present some fundamental background information on constraints and their interaction with the spacecraft design environment. This information sets the stage for a more technical discussion of how constraints impact spacecraft design covered in Chapters 4 through 8.

3.1 *Types of Constraints*

3.1.1 Constraint Ranges

There are several approaches to characterizing constraints. The most common way to classify constraints is according to their physical nature. At one extreme exist the technical constraints which are associated with physics and the laws of nature. Physical limitations based on masses, volumes, and forces fall at the far left of the spectrum under technical constraints. Policy-based constraints such as government regulations, business practices, and international agreements fall at the opposite side of the spectrum. In between these two extremes exist the "fuzzy" constraints which blend technical with political characteristics. These include such things as schedules and availability. For example, a schedule constraint could exist because it is physically impossible to process a launch vehicle in a given time period versus political obstacles that force the schedule to be extended.

Technical ------------------- Fuzzy ------------------- Political

FIGURE 3-1 RANGE OF CONSTRAINT TYPES

3.1.2 Constraint Rigidity

Another means for classifying constraints is according to constraint rigidity. Constraint rigidity deals with how easy it is to stretch or push-back on the constraint. While some constraints represent definitive physical barriers, such as the speed of light, others are artificially set and can be altered. This is very common in sensitivity analysis when one tries to determine what benefits would be gained for each increment that a constraint is relaxed. The degree of constraint rigidity is the primary determinant of how a constraint is handled in a design. The more flexible a constraint is, the easier it is to make trades between the individual constraint and other design factors. While all design environments will have constraints, design problems with high degrees of constraint flexibility and a large fraction of flexible constraints expand the design trade space that can be evaluated and increases the probability of achieving a better, more optimum design.

Flexible ------------------- Fuzzy ------------------- Fixed

FIGURE 3-2 RANGE OF CONSTRAINT RIGIDITY

3.1.3 Constraint Relevancy

An alternative approach for viewing constraints considers constraint relevancy. In many cases, even though a constraint exists, its limit may be so far removed from the design problem that it is either labeled as irrelevant or instead considered an enabling capability. For example, a launch vehicle that can lift 1,000 kilograms into low Earth orbit places definite weight constraints on a spacecraft whose weight starts to approach 1,000 kilograms or more. However, for a smaller spacecraft that only requires 200 kilograms of hardware, the 1,000 kilogram limit is irrelevant. In fact, to this spacecraft designer, the 1,000 kilogram limit appears as an enabling capability. The large margin allows the designer to consider adding features or using components that would otherwise be prohibited if the launcher could only lift 200 kilograms. (Note: other constraints such as cost, volume, etc. must also be considered)

Constraint -------------------- Irrelevant -------------------- Capability

FIGURE 3-3 RANGE OF CONSTRAINT RELEVANCY

Clearly whether a spacecraft designer considers a launch characteristic a constraint or an enabling capability depends entirely on the mission and the designer's frame-of-reference. Since launch characteristics can be either capabilities or constraints, it is interesting to examine the threshold at which a constraint becomes a capability or vice versa. It is unlikely that a single point or number can define where this change takes place. It is more likely that a constraint gradually becomes irrelevant (and eventually an enabling capability) when it is no longer considered one of the top design drivers. At this point, the characteristic has such a minor impact that the designer does not even consider trades between the characteristic and others parameters. For example, if the launch vehicle consumes 50 percent of the total program costs, it is definitely a design driver. However, as this percentage slides, there is a point where other factors, such as material costs, testing, or operations begin to drive and constrain the design.

> An example from the computer industry: The first personal computer file storage devices (5 ¼ floppy disks) introduced in the early 1980's had storage capacity of 360K and eventually reached the standard of 1.4 MB in 1988. While files during this period were often quite small and composed of mostly text, people where careful about the size of their files because they knew that the only way to physically transfer files was using a floppy disk with a 1.4 MB capacity. In this situation, even though floppy disks allowed

> people to store and transport information, they were also viewed as severely constraining the potential storage and transport file size. The introduction of zip disks with capacities in the 100 to 200 MB range greatly alleviated this constraint while high capacity CD's and DVD's continued the trend. People became less concerned with file size and limitations on storage capacity became irrelevant for many applications. Additionally, as a physical entity, floppy disks, zip disks, CD's and DVD's had the potential for damage or misplacement, leading to complete loss of data. However, the development of the internet, e-mail, and file-transfer protocol (FTP) exchanges made transferring even the largest files not only possible, but also limited the potential for loss of data through damage or misplacement. While the internet also has capacity and data loss limitations, rather than being viewed as constraint, the internet is viewed as an enabling capability mainly because for individuals, data storage and transport are no longer primary drivers.

In today's space system environment, spacecraft designers tend to highlight launch system limitations instead of their amazing capabilities. Typical comments from the spacecraft community include "launch systems...

...cost too much"
...have excessive cycle times"
...have poor reliabilities"
...never lift-off on time"
...require too many people to operate"
...cannot lift enough weight"

These limitations or constraints restrict the design trade space and force designers to make sub-optimal design choices.

3.2 Constraints in Spacecraft Design

The ability to effectively deal with constraints in a complex system design environment depends to a large extent on properly identifying and tracking constraints as well as the methodology employed to manage them. The following two sections briefly address the theory behind managing constraints and where constraints enter the design process.

3.2.1 Managing Constraints: Resource Allocation Theory

While the existence of complex systems such as spacecraft and launch vehicles only date back to the 1950's, applicable theory dealing with managing constraints has been around for over a hundred years. This theory, outlined in the field of economics forms the basis for how spacecraft designs now deal with complex constraints. Microeconomics is the quintessential science of decision making under scarcity. In theory, microeconomics focuses on how individuals make choices involving the efficient utilization of limited resources. How individuals choose to allocate these resources, whether the resources are money, time, material, energy or space, has a direct impact on the individuals' lives. For example, given a set annual income, should a person choose to spend all of his money on buying a house, taking a trip, paying off debt, or contributing it to savings? Or should the individual spend a fraction of the total income on each? And what fraction is appropriate for each? The choice depends on both the short and long-term objectives of the individual and the results of the decision can either lead to a positive or negative future. The basic message behind the example is that money, as well as time, energy, space and material, are limited quantities and the decision of how to allocate these quantities among a range of options can have a strong influence on future events and situations.[13]

The decision making process in the design of a complex space systems shares many similarities to the individual microeconomics decision making process described above. The notion of making difficult choices on allocation, trade-offs, and dealing with limitations and constraints is very consistent with the task of the spacecraft designers. Designing a complex spacecraft system requires a series of decisions about how limited resources should be transformed to achieve some objective. In many situations launch characteristics become limited resources available to spacecraft designers (lift capability, available volume, etc.). Integrating economic theory into engineering design, while difficult, has many advantages including the large body of theory and analysis methods already developed. Concepts such as mathematical programming optimization and sensitivity analysis are examples of some of the economic theory and tools used by spacecraft system designers that have been incorporated into engineering systems analysis.

3.2.2 Identifying and Tracking Constraints

One of the most difficult aspects to managing constraints is properly identifying and tracking them. Because spacecraft system design is an iterative process, as the design changes, the type and magnitude of launch vehicle constraints also changes. This is further complicated by the fact that launch vehicle constraints impact spacecraft throughout the design, development, and deployment phases. Figure 3-4 shows a map illustrating how different launch constraints impact spacecraft systems at various points along the development process.

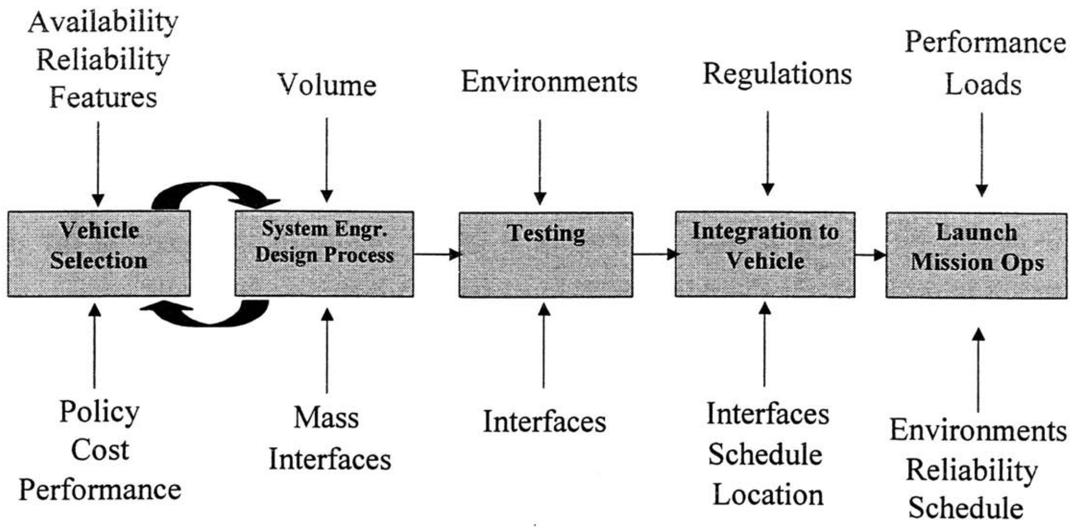

FIGURE 3-4 CONSTRAINTS MAP

3.3 Discussion of Launch Vehicle Constraints

In the process of performing 43 interviews across 10 organizations, several common themes emerged dealing with the complex interaction of launch and spacecraft systems.

3.3.1 Constraint Priority Differences

All of the spacecraft designers interviewed agreed that launch constraints played a role in spacecraft design. Besides cost and weight, most differed on what they believed were the most important constraints from adapters, access panel locations, and integration software to propellant slosh during ascent, fairing shape complaints, and separation mechanisms. Not surprising is the fact that constraint priorities mirrored spacecraft designer functionality. Structural engineers cited loads as the most significant constraint while electrical engineers cited communications and adapter interfaces. Many designers also discussed a disconnect between the top attributes for selection of the launch vehicle and the most significant design drivers. In many cases, the fact that these were not the same constraints led to a situation where management's views of launch constraints differed significantly from the design engineer's. This observation was one the driving forces behind trying to devise a strategy for dividing launch constraints.

3.3.2 Tier Structure of Launch Constraints

Many designers spoke of an "inequality" of launch constraints, with some holding much more weight than others. This led to the notion of a tiered structure for identifying launch constraints.

Launch constraints can be loosely separated into three tiers depending on their degree of influence on launch vehicle selection and level of rigidity. First tier constraints, such as political restrictions or physical limitations such as lift capacity or volume, have substantial design impacts and are either impossible or extremely difficult to trade-off. Second tier constraints also have significant design impacts, usually can be traded, and are the most influential in making the final choice from the suitable vehicles. The third tier factors usually do not have a large influence in the selection decision but can be traded and do impact the spacecraft design following selection.

These two observations, along with several additional observations outlined in Appendix B, helped create the framework used in the thesis for discussing launch vehicle constraints. Each of the following four chapters discusses one of four launch constraint themes: physical, operational, cost, and policy. Each chapter looks at several individual launch constraints under a specific theme and provides a constraint definition, an analysis of how the constraint impacts spacecraft design, several actual examples of the impact from industry, and a summary of these impacts.

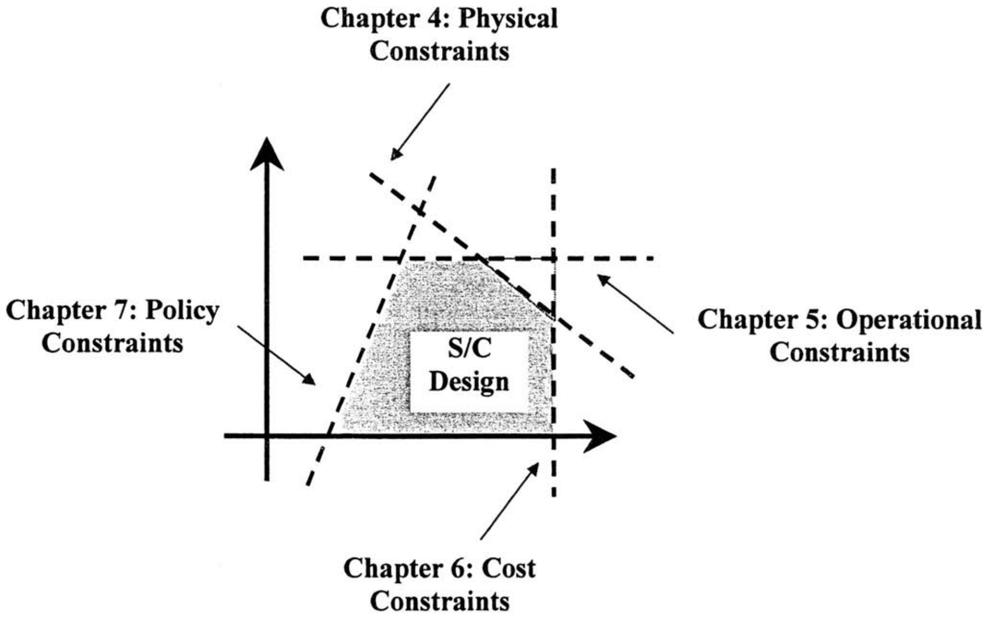

FIGURE 3-5 OUTLINE OF CONSTRAINT THEMES

CHAPTER 4 DISCUSSION OF PHYSICAL CONSTRAINTS

4.1 Overview of Physical Constraints

Physical constraints deal primarily with limitations based on physics and the laws of nature. The following technical constraints were identified to have a major impact on spacecraft design:

Lift Capacity: A limit on the maximum available spacecraft mass that can be placed into the desired orbit

Fairing Volume: A limit on the maximum available spacecraft size based on height and Diameter measurements

System Interfaces: Characteristics of the umbilicals and structures that connect the spacecraft and the launch vehicle to handle communication and stabilization of the two systems

Launch Loads & Environments: Characteristics of the physical forces and environments experienced by the spacecraft during lift-off, ascent, and orbital insertion

The following sections introduce each of the four major physical constraints that must be considered in the design of spacecraft systems. It is important to note that while they are discussed on an individual basis, many of the constraints are highly coupled, further complicating the design process. This coupling forces more complex trade analysis and is further evidence of the need to fully understand how launch constraints impact the spacecraft system.

4.2 Lift Capacity

4.2.1 Constraint Definition

Each launch vehicle system has a specific limit to the amount of mass it can deliver to a particular orbit. This limit, or the lift capacity of a launch vehicle, is linked to the desired orbital destination and the amount of thrust that the launch vehicle propulsion system can create. In the simplest terms, the launch vehicle must provide the payload a particular velocity to reach its desired orbit. The *rocket equation* defines this velocity change as:

$$\Delta V = gI_{sp} \ln\left(\frac{m_o}{m_o - m_p}\right) = gI_{sp} \ln\left(\frac{m_o}{m_f}\right) \qquad [3\text{-}1]$$

where m_o is the initial mass of the system (launch vehicle plus payload), m_p is the mass of propellant consumed to reach the desired orbital altitude and inclination, m_f is the final system mass at burnout, g is the force of gravity, and I_{sp} the specific impulse. The specific impulse, I_{sp}, essentially measures the energy content of the propellants used. In this instance, $\dot{m}$ is the mass flow rate of the propellants out of the exhaust nozzle and I_{sp} is defined by:

$$I_{sp} = \frac{Thrust}{\dot{m} g} = \frac{F}{\dot{m} g} \qquad [3\text{-}2]$$

Integrating these two equations reveals that, the final mass that can be delivered to the specified orbit (based on ΔV) and for a given thrust **F** is determined by:

$$m_f = \frac{m_o}{e^{\frac{\Delta V}{g I_{sp}}}} = \frac{m_o}{e^{\frac{\dot{m} \Delta V}{F}}} \qquad [3\text{-}3]$$

In a typical launch vehicle system, the largest fraction of the initial mass, roughly 85 percent, is consumed by the propellant. The remainder is divided between the launch vehicle structure and supporting systems (~ 13 %) and the payload (~2 %).[14]

Spacecraft systems can be divided into five weight classes shown in Table 4-1.

TABLE 4-1 SPACECRAFT WEIGHT CLASSES [15]

Weight Class	Range
Nano	< 20 kg
Micro	20 - 100 kg
Small	100 - 500 kg
Medium	500 – 3,500 kg
Heavy	3,500 + kg

Accordingly, the launch industry has developed a range of launch vehicles to service each of the major satellite weight class markets. Lift capabilities vary depending on the orbital altitude that the payload must be delivered to. For Low Earth Orbits (LEO) with altitudes between 180 and 250 kilometers and inclinations between 0° and 28.5°, lift capacities range from 443 kilograms

(Orbital Sciences' Pegasus Booster) to 25,800 kilograms (Boeing's Delta IV Heavy).[16] Other common orbits such as Polar LEO and the elliptical Sun Synchronous have ranges of 332 to 20,800 kilograms and 203 to 14,300 kilograms, respectively.[16] The most sought after orbit, geostationary, exists at roughly 35,786 kilometers above the Earth surface, where spacecraft have velocities equal to the Earth's rotational speed and thus are able to stay fixed over one unique spot above the equator. Most launch vehicles do not deliver spacecraft directly to geostationary orbit. Instead, they place the spacecraft in Geo-Transfer Orbits (GTO) with the spacecraft providing the final stage to propel the satellite to its final destination. Figure 4-1, shows the lift capacities for the world's major launch vehicles to geostationary transfer orbit which range from 448 kilograms to 12,018 kilograms.

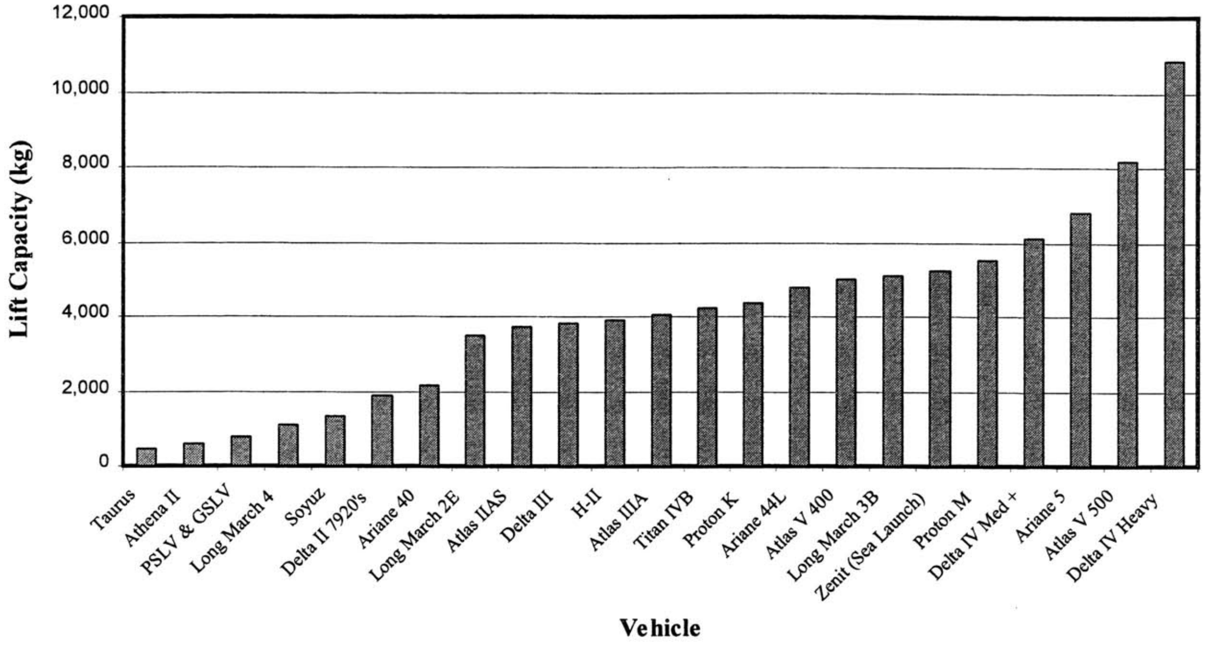

FIGURE 4-1 LIFT CAPACITIES TO GTO [16]

Over the past 40 years, the launch-spacecraft relationship has been defined by a continuous game of catch-up. Figure 4-2 shows the time-based increases in lift capacity for Boeing's Delta launch vehicle family. While the percentage growth in lift capacity on an annual basis has remained quite steady, the last 10 years have witnessed fairly substantial absolute gains.

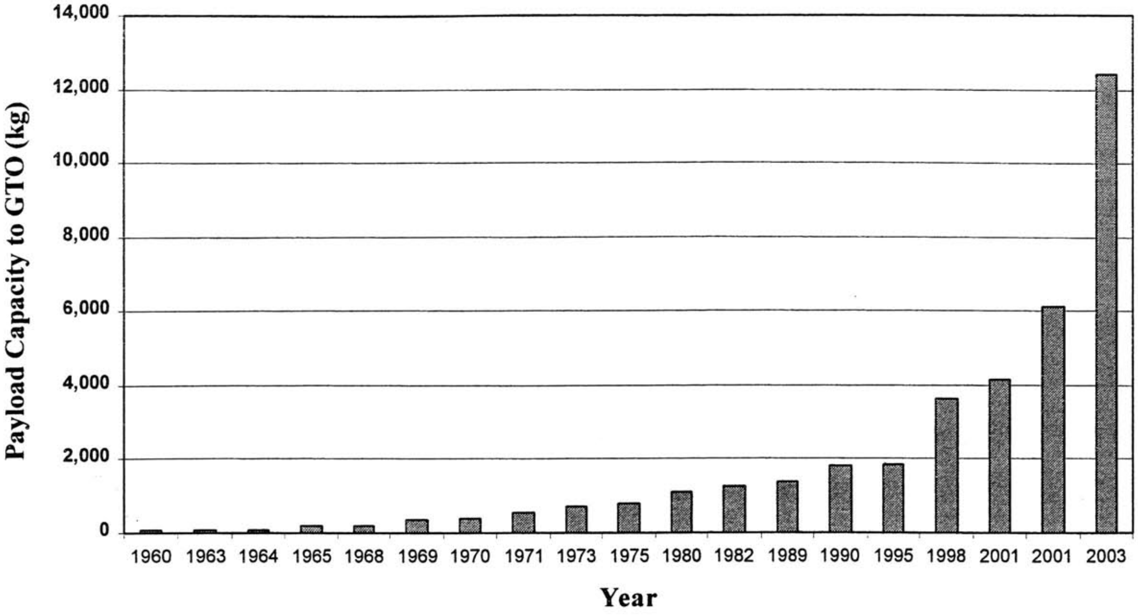

FIGURE 4-2 TIME-BASED LIFT CAPACITY INCREASES FOR THE DELTA FAMILY [16]

In comparison, Figure 4-3 shows the increase in weight of commercial geostationary communications spacecraft over the last 25 years. The growth in spacecraft weight mirrors the growth in lift capacity and it is difficult to determine which is driving which. Do spacecraft developers push for heavier spacecraft when faced with increased lift capability available? Or do the spacecraft developers drive the launch industry larger and larger vehicles to satisfy the spacecraft world's hunger for more lift capability? It is most likely the latter.

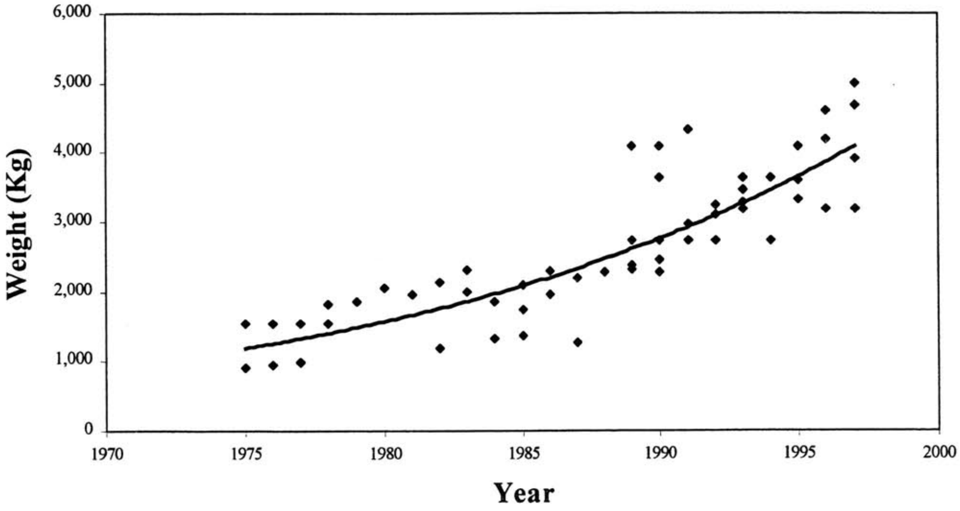

FIGURE 4-3 WEIGHT GROWTH OF GEO COMMUNICATIONS SPACECRAFT [31]

4.2.2 Impact of Lift Capacity on Spacecraft Design

One of the most fundamental effects of lift capacity on spacecraft design is the strong drive to reduce or minimize spacecraft weight. This process of weight-based optimization has been practiced since the first satellites were launched in the late 1950's. As demonstrated in the previous section, substantial increases in the lift capacity of launch vehicles, has occurred steadily over the last 40 years. The substantial cost of space access pushes satellite developers to maximize spacecraft capabilities. Given a specific weight restriction, they will attempt to use all available mass up to and, in many instances, exceeding the limit. Available lift capacity combined with high launch costs induces spacecraft weight optimization.

What compounds the weight optimization problem is the fact that while the spacecraft can easily grow or shrink by a kilogram or 10, the launch vehicle cannot. Lift capacity follows a standard step-function characteristic with each rung separated by hundreds if not thousands of kilograms. Similar to the weight classes of spacecraft shown in Table 4-1, launch vehicles also can be divided into particular weight divisions that mirror the spacecraft divides. Figure 4-4 shows the lift capacities for all active and soon to be active launch vehicles in the United States' two primary expendable launch vehicle families. The average difference between each step is 2,548 kilograms, with the largest being a difference of 6,450 kilograms. Unlike spacecraft, launch vehicles do not have the ability to easily grow capacity on the scale of less than 100 kilograms. The possibility does exist to boost weight ceilings with the addition of solid, strap-on motors. However, the addition of solid rockets to a mainly liquid rocket system brings increased complexity, cost, and risk. Unlike liquid rocket engines, solids cannot be shut-down once ignited even if serious problems arise. Thus, the step-function nature of launch vehicles lift capability further entrenches the push for weight optimization.

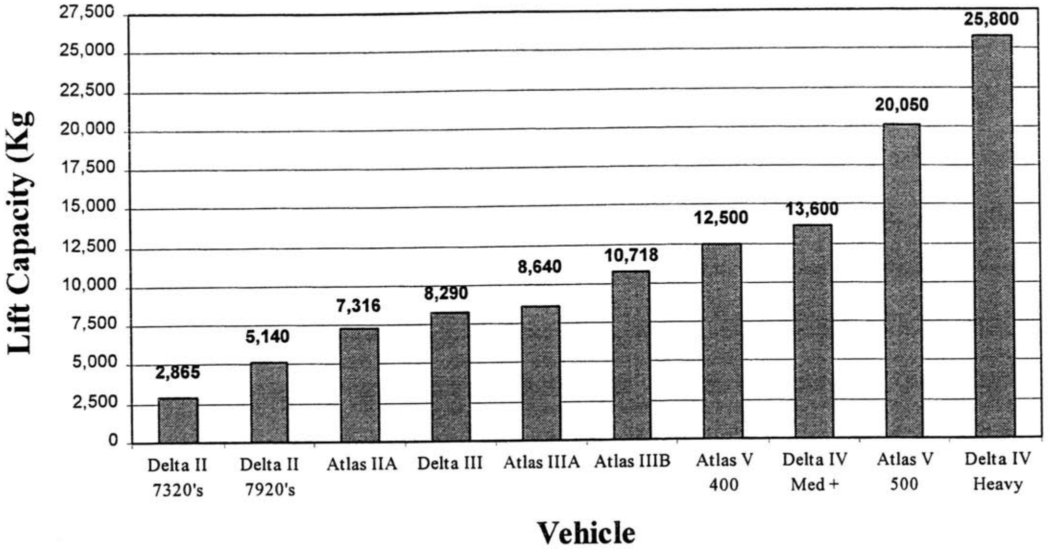

FIGURE 4-4 LIFT CAPACITY FOR PRIMARY US EXPENDABLE VEHICLES [17,18]

Spacecraft designers face the very difficult dilemma of either jumping to a larger launch vehicle or staying within the lift capacity of the selected vehicle. The consequences of either action are costly. If the designer decides to upgrade to a larger vehicle, the spacecraft will most likely face substantial excess capacity. The spacecraft might end up only 50 kilograms overweight, but the next launch vehicle size up will offer 500 to 1000 kilograms of additional capacity. Thus, the spacecraft developer must pay for the extra 500 kilogram even if only 50 kilograms are needed. Continuing along this path, the designer will realize that to be cost effective it is necessary to utilize all available capacity (weight optimization) and the spacecraft will grow in turn to fill-up the excess capacity, or an extra 450 kg. As the spacecraft grows in size, its cost can also inflate leaving the design with a more expensive spacecraft and a more expensive launch vehicle. Ironically, as the additional capacity is utilized, there is always the inherent risk that the redesigned, larger spacecraft might actually overrun the lift capacity of the larger vehicle triggering the problem to start all over.

In most cases, the designer does not make the choice above, but instead elects to try to remove weight from the spacecraft. However, this choice does not come without penalties. Trying to downscale an overweight satellite entails design changes and initiating a "witch hunt" for where mass can be removed or expendable components or mechanisms can be abandoned. This requires that either lighter components must substituted and integrated into the current design or that the current components must be redesigned. Both cases result in additional costs and increases in program schedule. One example from a military communications satellite program, when faced with a 20 kilogram overrun, elected to replace every stainless screw on the spacecraft with a lighter, yet more expensive titanium screw. In total, over 400 screws were replaced to maintain the weight budget. The redesign route does not offer a much better option. In general, industry estimates that re-designing and re-qualifying a component for a small, simple change normally increases the cost of that component by a factor of two. One manager in a commercial program cited an example where it was calculated that the cost to remove each kilogram of additional weight from a spacecraft late in the design phase reached an estimated $250,000 per kilogram.[19] In comparison to launch costs at a rate of $10,000 per kilogram, it seems impractical to spend $250,000 to save $10,000 per kilogram. However, it is important to keep in mind the step-function problem discussed previously. While it might only cost $10,000 per kilogram to deliver to orbit, it is not possible to buy lift capacity in 1 kilogram units making this trade more complicated than it might seem to be.

The weight optimization problem also influences the use of commercial off-the-shelf parts or COTS. COTS include components that are sold to more traditional, terrestrial-based applications and components that have been designed and used on previous space missions. Components used on previous missions carry the advantage of already being space qualified. Space qualification means involves a series of tests demonstrating that they will work as expected in the harsh space environment. Qualifying parts for space is an expensive task. Parts that already have this designation or have been shown to work in space on a previous mission are coveted for cost and performance reasons. Additionally, COTS parts are already designed and can cut time off the program design schedule. While using COTS can bring significant cost and time savings, these benefits come at a price. COTS components tend to be larger than the state-of-the-art systems since their designs are typically several years old. Likewise, commercial components, ones used for terrestrial applications, also must be space qualified and because weight constraints are not as important on Earth, they too tend to be larger than space available. In one example, a hardware element off the shelf with full traceability and space qualification cost roughly $100,000. For weight and volume related issues, a decision was made to design a completely new component where the final cost fell in the $1-2 million range. Because spacecraft are so weight optimized, COTS systems present designers with difficult choices – pick a cheaper, qualified, but heavier component versus a lighter, more compact, more expensive, newly designed component.

To cope with these problems, spacecraft developers initially set a rough estimate for the weight of their vehicle and then add in margin, or unused weight, to compensate for weight growth during design. Most programs start with weight margins in the 10-20% range and quickly consume all of it. One science mission in the NASA Discovery-class program experimented with even larger initial margins (>25%) only to have overrun these two to three times as quickly as previous programs. Two weeks into the design the margin went from over 25 percent to zero. The primary science instrument alone grew by 30 percent in weight. The loss in margin and weight growth forced a major re-design that led to substantial changes to the spacecraft structure. Instead of using the rebuild of a previously used aluminum structure from another Discovery-class mission, the team moved to a more expensive, yet lighter graphite composite structure substantially reducing the structural weight. Engineers cited the knowledge of more available weight led designers to make assumptions and decisions based on the knowledge of additional capacity. When a single designer does this, there are few problems. When every subsystem designer makes this assumption and over-designs, the spacecraft grows very rapidly. Thus, starting off with too much margin can lead to a dangerous situation where it is difficult to stop adding extras beyond what is needed.

Lift capacity constraints also affect system redundancy issues. Because of the high costs of failure discussed earlier for space systems, there is always a drive for high reliability. This high reliability can be achieved by two methods. One method involves designing-in component reliability through robust designs and high levels of testing to ensure against failure. Several designers expressed their concern over the high cost and extensive timescales associated with this method. The other option for high reliability is through the use of redundancy. Redundancy involves including one or more back-up systems that assume responsibilities when the primary component or system fails. This option can save significant amounts of time and money, however, not without a price. Several commercial satellite programs acknowledged that in many of their spacecraft, greater than 50 percent of active payload weight is redundant systems and never actually used. This is the weight price of reliability. Adding redundant systems adds significant weight to the spacecraft, opposing the weight minimization and optimization philosophy. In limiting the availability of redundant systems, weight restrictions coupled with cost and time constraints can curtail system reliability and in some cases force single string systems with no back-up for critical systems. The extremely successful Lunar Prospector mission to the Moon in 1998 was designed without redundancy for the majority of its critical subsystems because of launch vehicle-related weight and budget constraints.

Another result of mass minimization is the uneven burden placed on the spacecraft payload. In general, the mass fraction of most payload systems varies from 30 to 60 percent of the total spacecraft mass. The remainder is consumed by the spacecraft bus systems and propellant. However, mass minimization does not equally affect each of these systems. In most commercial missions, the payload is sized to fit a pre-designed, generic bus. A generic bus saves design time and reduces the bus cost by taking advantage of larger production lot sizes and amortizing the initial development costs over multiple spacecraft. The consequence of using a generic bus is that there is substantial resistance to making any alterations to the bus that would lead to re-designing or re-qualifying all or part of the spacecraft bus. Industries' motto is "fit the payload on the smallest bus possible and make it work." Moving to a generic bus has led to a factor of four to five times improvement in cost effectiveness in one commercial companies spacecraft line. While cost and schedules decrease for generic buses, payload performance suffers. With the spacecraft bus labeled "untouchable," all mass trades and mass reductions to stay within the lift capacity of the selected launch vehicle usually falls on the payload.

In contrast to the generic spacecraft buses used in the commercial world, military and scientific missions tend to favor more customized buses and payloads. But this is the engineering trade-off between cost and performance. From a life-cycle value standpoint, more data is required to determine which design philosophy leads to higher value-per-cost incurred.

Weight restrictions also have a significant effect on component selection. In many cases, the drive to reduce satellite weight and the desire to minimize the launch costs leads to utilizing expensive, lightweight materials with high packaging densities.[20] The end result is a spacecraft that is smaller and lighter, but usually more complex and more expensive. These choices affect all subsystems at all levels of the spacecraft design. Table 4-2 shows example subsystems and the heavier versus lighter trades available.

TABLE 4-2 WEIGHT IMPACTED DESIGN OPTIONS

Subsystem	**Choices** **Heavier**	**versus Lighter**
Structures	Aluminum Alloys	Graphite composites
Solar Arrays	Silicon cells	GaAr cells
Power Storage	Nickel-Cadmium	Nickel-Hydrogen

By driving component selection, weight restrictions directly affect component sizes and consequently spacecraft performance parameters. For communications satellites, performance depends to a large degree on power available to the spacecraft's communications subsystem, with higher power levels enabling greater throughput capacity and signal strength. Substantial power is also necessary to run all of the other subsystems that support the payload. However, power generation and storage systems such as solar arrays, batteries, distribution cables, switches, and converters consume an average of 30 percent of the spacecraft's total dry weight. The weight versus power trade-off is fundamental to spacecraft design and realistically translates into a weight versus capability/performance trade-off.

Another significant trade-off exists between spacecraft weight and spacecraft lifetime, another key spacecraft performance parameter. Mass constraints dictate the amount of propellant available to maintain correct attitude and orbital positioning. One commercial communications program surveyed cited that its geostationary satellites consumed approximately 27 kilograms of fuel per year for a total of 410 kilograms over its 15-year lifetime. This was the equivalent to 15 percent of its final in-orbit operational weight. Thus, the weight versus propellant trade-off translates into a weight versus lifetime or capability trade-off. It should also be noted that component failures, system degradation from the space environment and debris impacts, and operator errors also contribute to limiting spacecraft lifetimes. Lifetime factors will be discussed in greater detail in Chapter 8.

4.2.3 *Summary of Lift Capability Impacts*

Lift capacity affects spacecraft design and development in various ways ultimately impacting program cost, schedule, and system performance. Mass boundaries induce weight minimization philosophies which, in the iterative spacecraft design process, can lead to expensive late-design phase weight reduction practices. Weight restrictions also influence component and materials selection, sub-system redundancy and reliability strategies, and propellant levels that ultimately drove spacecraft lifetime. The increased use of generic, 'untouchable' spacecraft buses has significant influences on payload capabilities as weight reduction practices generally affect the payload. Figure 4-5 provides a summary of the major design influence of launch vehicle weight restrictions on space system design:

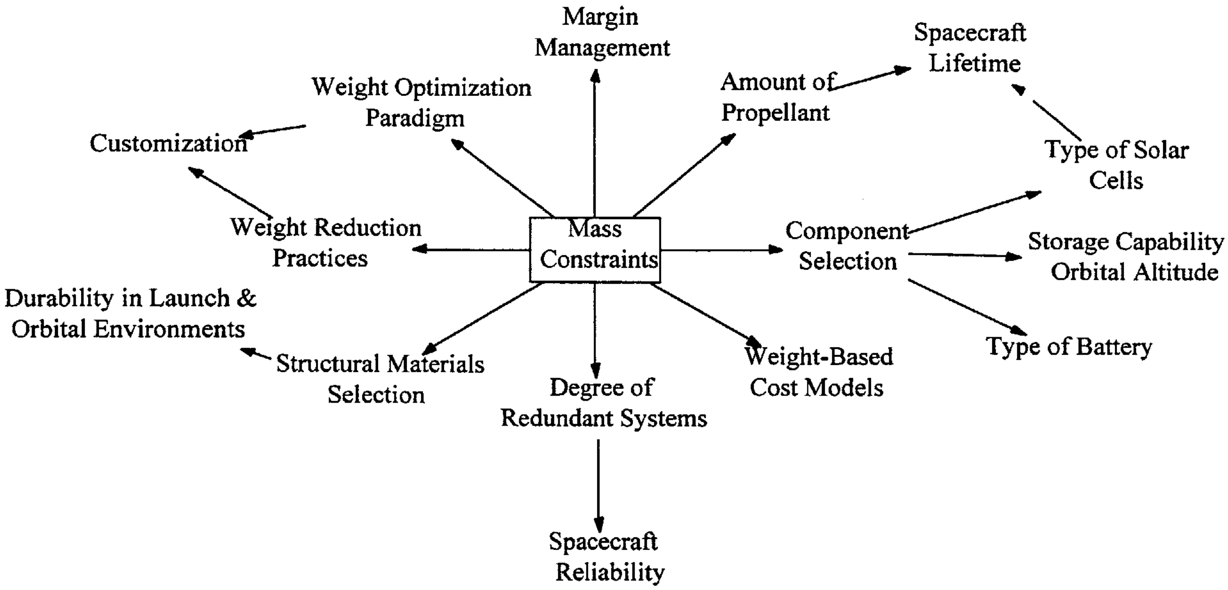

FIGURE 4-5 IMPACT OF MASS-BASED DESIGN CHOICES

4.3 *Fairing Volume*

4.3.1 *Constraint Definition*

Chapter 2 presented a brief overview of the primary launch vehicle systems and components. The payload sits atop the final stage of the launch vehicle protected from the harsh ascent environment by the launch fairing. The fairing is designed to absorb both the extreme heating from atmospheric friction as well as the aerodynamic loads created during ascent at speeds in excess of 30,000 kilometers per hour. For its own protection, the spacecraft is encapsulated inside the launch vehicle fairing which is composed of two halves called shrouds that are separated in orbit by explosive event that frees the spacecraft and sends the shrouds out away from the spacecraft. This separation normally occurs before the spacecraft reaches it final destination as a secondary engine on the spacecraft called the apogee assist motor propels the spacecraft into its appropriate orbit.

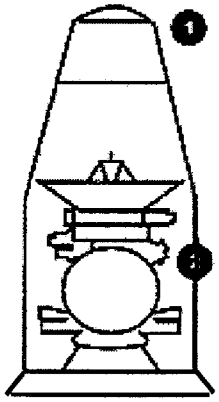

FIGURE 4-6 SPACECRAFT ENCAPSULATED INSIDE THE LAUNCH FAIRING [21]

The most important aspects of the launch fairing are its diameter, its total height, and its maximum cylindrical height. Most launch vehicles offer a selection of launch fairings allowing some flexibility in design. Traditionally, fairing diameters have been offered in 3, 4, and 5 meters. It is important to note that while the fairing might have a 4-meter diameter, not all of this space is usable. In order to protect the spacecraft from heat and loads, the fairing is lined with acoustic blankets and thermal insulation which consume space. When designing a spacecraft, the dimension that should be considered is the usable geometric dimensions also labeled as the envelope. Additionally, the top of the launch vehicle, or the nose cone, is shaped toward a point to optimize aerodynamic performance. The uniqueness of each vehicle leads to a situation where nose cones vary significantly in heights and nose cone curvature angles. Trying to accurately determine the exact useable space is a complicated task. Figure 4-7 shows a launch vehicle fairing setup for Boeing's Delta IV launch vehicle family with the envelope, nose cone, and insulation/support labeled. Top measurements are in millimeters and bottom measurements are in inches.

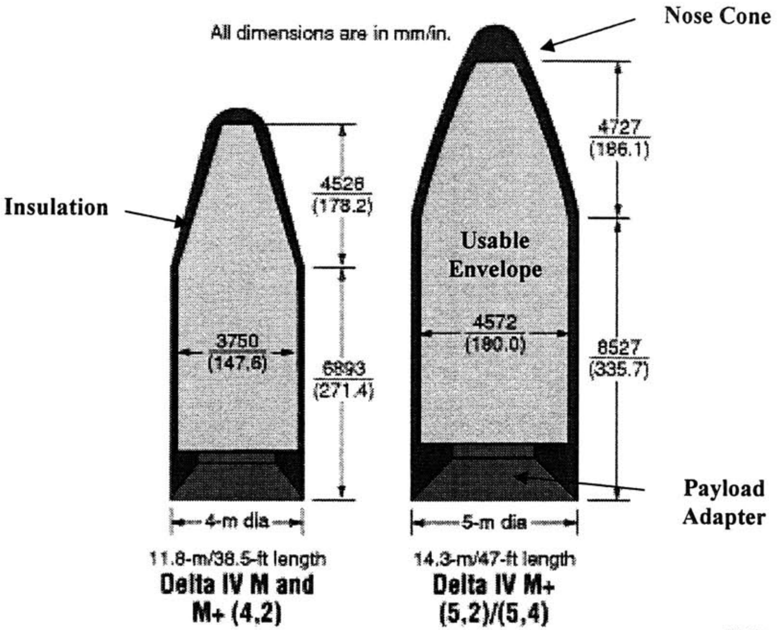

FIGURE 4-7 EXAMPLE EXPENDABLE VEHICLE FAIRING [22]

In the 5-meter diameter case, the difference between the launch fairing diameter and the envelope diameter is close to one-half a meter. This is an important aspect. While the outside diameter of most launch vehicles conforms to the standard 3, 4 or-5 meter length, the critical measurement is actually the outside diameter of the envelope. Since each vehicle adds different amount of insulation, structural support, and acoustic blankets, the actual diameter that satellites design for is not as standard as one might assume. Additionally, while the 3, 4, and 5 meters are standard, some vehicles design with these standards as the outside diameter (mostly US) and some design with the standards as the inside diameter (mostly Russian). For example, the Russian made Zenit rocket has an outside fairing diameter of 4.15 meters and an inside diameter of 3.9 meters whereas the US Delta III has an outside diameter of exactly 4 meters and an inside diameter of 3.75 meters. Table 4-3 shows the range of available launch fairings geometric dimensions for several foreign and domestic launch vehicles.

TABLE 4-3 RANGE OF AVAILABLE FAIRING DIAMETERS (IN MILLIMETERS) [16]

Vehicle	**Volume** Maximum Payload Diameter	Maximum Cylinder Length
Ariane 40	3650	6460
Ariane 5	4570	9822
Athena II	2057	2294
Atlas IIAS	2921	4100
Atlas IIIB	3650	5015
Atlas V 400	3650	5015
Atlas V 500	4572	7631
Delta II 7320's	2540	2004
Delta II 7920's	2743	2004
Delta III	3750	4365
Delta IV Med +	3750	5281
Delta IV Heavy	4572	7246
H-II	4600	5800
Kosmos	2200	1809
Long March 2E	3800	3105
Long March 3B	3650	4610
Pegasus	1168	1110
Proton K	4100	9047
Proton M	3800	6010
PSLV & GSLV	2900	3000
Soyuz	3000	3018
Molniya	3435	2364
Space Shuttle	4570	18300
Taurus	2048	3310
Titan IVB	4570	18850
Zenit (Sea Launch)	3750	4937

4.3.2 Impact of Volume Restrictions on Spacecraft Design

While the launch fairing does provide necessary protection for the payload (the payload would have to be much larger and heavier if it had to protect itself), it also "defines the usable volume" of the spacecraft and sets limits on the geometry of the payload. In determining the maximum height and diameter of the satellite, the rigid walls of the fairing also influence design choices for the spacecraft. Because of the complex geometries, especially those related to the cone section, the volume constraint is more difficult to address than mass constraints. While the spacecraft can be weighed to determine if it exceeds or is below the mass limit, many times it is necessary to do fit check rehearsals with dummy payloads to be certain that the spacecraft and any appendages actually fit into the launch vehicle envelope.

One of the most significant impacts of volume constraints on a spacecraft system is to the size of the spacecraft antenna. The majority of spacecraft missions focus on the collection and transmission of information. The need to collect and distribute data is the primary goal of the spacecraft and drives most of the design. The ability to collect and distribute data depends on several subsystems. These subsystems are generally involved with two sets of functions: keeping the spacecraft in good health and helping it perform its mission, collection and transmission. The second function, collection and transmission of data, is carried out mainly by the interaction of three major subsystems. The attitude control subsystem adjusts the pointing direction of the spacecraft, the power and electrical subsystem provides power to receive, amplify, and transmit the signal, and the communications subsystem actually carries out the receiving and transmitting functions. The spacecraft antenna is one of the key components of the satellite communications system. The spacecraft retransmits signals it receives by way of a transponder, a receiver-transmitter combination.

Volume restrictions place limitations on the size of the antenna, ultimately affecting the performance of the spacecraft in its receiving and transmitting duties. Smaller volumes necessitate smaller antennas (and batteries for power) leading to reduced performance. The performance of the communications subsystem is generally determined according to the link budget equation which defines the signal-to-noise ratio. This ratio is essentially a measure of the strength of the signal and is determined by the power of the signal and the amount of noise or distortion to this signal. The governing link budget equation.

$$\frac{E_b}{N_o} = \frac{P L_l G_t L_s L_a G_r}{k T_s R} \qquad [3\text{-}4]$$

The signal-to-noise ratio is a function of the transmitter power P, the data rate R, the system noise temperature T_s, the Boltzmann constant k, the transmitter gain G_t, the receiver gain G_r, and the line, space and path loses L_l, L_s, and L_a respectively. Both the transmitter and receiver gains are significant drivers of the signal-to-noise ration and are functions of antenna diameters. Trades between large power in space and large power required on the ground effects coverage, frequencies, and the size of the required ground-based receiver.

One trade recently explored on a new military communications program looked at using a phased array versus a gimbled dish. The phased array required more power, had similar performance characteristics, and was a less mature technology yet was ultimately selected because it was substantially smaller and more dense.

Not only does the volume of the fairing restrict the size of the antenna, but also the number of antennas that can be included. In the last few years, the market has changed from satellite service providers wanting to serve one or two large markets with a few wide spot beams, to the "direct-to-home market" requiring a greater number of smaller spot beams. In the past, two to four antenna horns were sufficient. Now, the market is moving towards 25 to 50. More spot beams allow frequency reuse but also require more antenna aperatures meaning more antennas and volume. Thus, volume restrictions place a limit on the number of antennas and the competitive performance of the spacecraft. Recent market dynamics have led to an increased attention to antenna packaging schemes and a push for moving from 4 to 5 meter fairings.

The fairing volume limits the size of the power producing and power storage devices. To produce power, spacecraft use solar arrays. Solar cells on solar arrays typically have efficiencies in the 15 to 25 percent range. The amount of power generated by the solar arrays is function of their efficiency and their collection area. Holding efficiency constant, to generate more power requires more solar cells, hence larger surface area. To store this power requires high capacity primary and secondary batteries, where the battery capacity is a function technology and size, usually in terms of both weight and volume. Similar to mass constraints, volume constraints also force technology and component trades between the desire for as much power generation and storage capability as possible and the available volume. Demand for small, low cost terminals on the ground requires high power, high gain systems to be placed in space. The result is a push for more power in orbit and thus larger spacecraft.

Another effect of limited volume is the drive to deployable mechanisms that allow components to be collapsed and compacted during launch to fit inside the vehicle envelope and then unfurled once released from the fairing in orbit. The move to deployable structures, while enabling larger antennas and solar arrays, also adds a great deal of complexity to the system design. Systems that have to be deployed or unfurled require mechanisms to mechanically deploy them. The possibility that one of these mechanisms does not work could render the spacecraft partially or completely useless should the power generating array or antenna not unfurl or unfurl in the wrong way. The potential for vibrational loads and oscillations during deployment also presents potential dangers for the spacecraft. Volume restrictions force the spacecraft designer to utilize folding, furling, and telescoping appendages for various systems such as solar arrays, communications antennas, and scientific instruments adding to the complexity and vulnerability of the payload.

To save on launch costs and take advantage of economies of scale, spacecraft developers have started to put more than one spacecraft on each launch vehicle. This is mainly due to the fact that the larger launch vehicles have historically been able to offer much lower prices than the small launchers (Pegasus' 443 kg at $30,474/kg versus Ariane V's 18,000 kg at $9,167/kg). For example, developers of the large LEO constellation Iridium were faced with the challenge of launching more than 70 spacecraft into orbit. Instead of purchasing 70 launch vehicles, the Iridium program looked to multiple manifesting launches to deploy its constellation using a minimum number of launches. However, not wanting to launch all on the same launch vehicle, the Iridium program instituted a design policy whereby one of the main requirements for the spacecraft design was that the seven spacecraft could fit on a Proton, five on a Delta III, and three on the Long March. This decision was also driven by political motivations since the Iridium system was trying to compete on the global marketplace and by giving launches (local work/money) to multiple countries these countries would be more friendly and open to purchasing the communications service. The desire to fit more than one spacecraft on a launch vehicle is constrained by volume limits and forces innovative stacking or bundling designs. Additionally, changing from one fairing to another for stacking purposes has an impact on the spacecraft by affecting dimensions as well as potential design changes to move the center of gravity. Figure 4-8 shows an example of a dual manifest with multiple spacecraft inside the fairing.

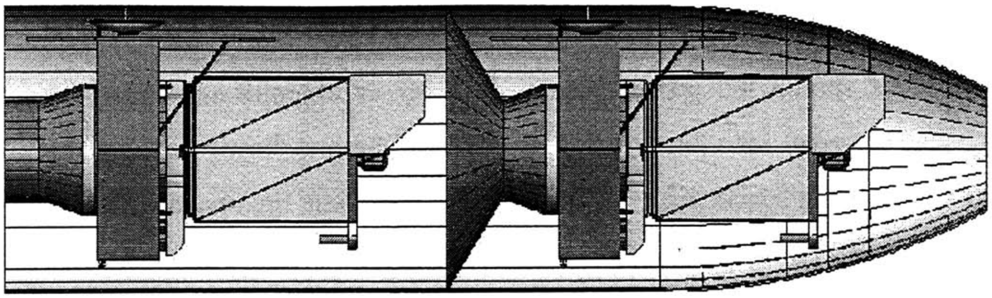

FIGURE 4-8 CONFIGURATION FOR MULTIPLE PAYLOADS [23]

4.3.3 *Summary of Fairing Volume Impacts*

The vehicle fairing places a volume limit on the maximum available spacecraft size based on height and diameter. Volume restrictions affect the geometry of key spacecraft sub-systems such as the size and number of antennas and available power based on the sizing of solar arrays and batteries. Limited volume also encourage complicated stacking designs for multi-manifest launches and complex deployable mechanisms allowing components to be compressed during ascent and unfurled once in orbit.

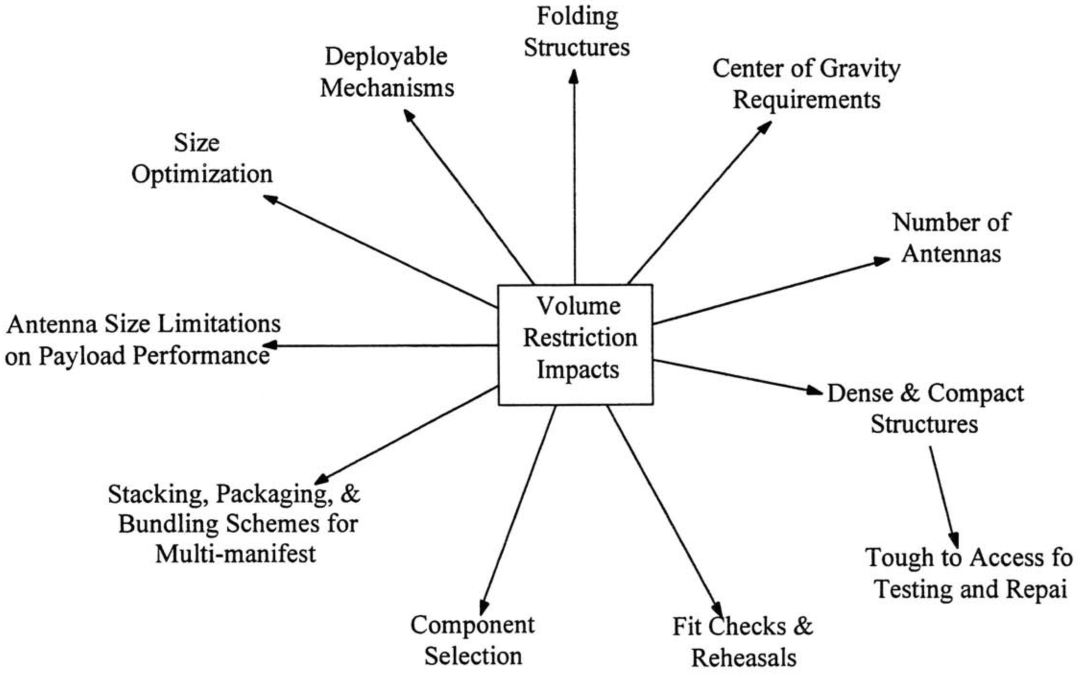

FIGURE 4-9 VOLUME IMPACTS

4.4 Launch Loads and Environments

4.4.1 Constraint Definition

The essential task of the launch system is to change the energy state of the spacecraft. The spacecraft starts off with essentially zero potential energy (height) and no kinetic energy (speed) from the inertial reference point of the Earth's surface. Through the combustion of volatile materials, the launch vehicle transmits potential and kinetic energy to the spacecraft in order to deliver the spacecraft to a height of over 300 kilometers and a speed of greater than 30,000 kilometers per hour. However, this great energy transfer does not come without a price and the spacecraft is exposed to harsh physical forces and environments.

The best way to understand the influence of launch loads is to become familiar with the different phases of the launch cycle. The launch cycle can be broken down into eight major phases according to when load events occur. These are during:

- Ground Transport
- Integration and Testing
- Main Engine Ignition
- Lift-off
- Main Engine Cut-off
- Stage Separations
- Stage Ignitions
- Deployment and Orbital Insertion

During each phases the launch vehicle exerts unique forces on the spacecraft that belong to one of three classes:

- **Vibration (Structural and Acoustical) Loads**
- **Acceleration (Steady-State) Loads**
- **Shock Loads**

Vibration loads are due to forces created by the launch vehicles rocket engines and aerodynamic forces against the launch fairing. Random vibrations are generated by mechanical parts moving in turbo pumps, combustion phenomena, or structural elements excited by the acoustic environment.[24] Acoustic vibrations are generated by engine noise and aerodynamic noise causing serious problems for thin structures.[24] Additional loads occur during pre-flight testing and during handling and stacking of the spacecraft onto the launch vehicle.

There are two maximums levels of vibration loads that occur at lift-off and during transonic flight. When the main launch engines are initially ignited, forces from the combustion coupled with forces from the exhaust products reflecting off the ground create a maximum vibration load that peaks at the point of release, once the vehicle officially leaves the pad. Vibration loads then taper-off during normal ascent but do not go to zero. Forces from the engine combined with aerodynamic forces excite the launch shroud generating an additional source of vibrational loads.

A second spike in vibration loads occurs when the launch vehicle transitions from sub-sonic to supersonic flight crossing over the Mach 1 level. While the spacecraft experiences two main peaks in vibration intensity, it is also important to note that vibration loads occur across a broad spectrum. Table 4-4 shows the maximum acoustical levels for several vehicles while Figure 4-10 shows the vibration loads over the range of frequencies in the applicable spectrum.

TABLE 4-4 COMPARISON OF ACOUSTICAL LOADS FOR VARIOUS VEHICLES [16]

	Acoustical Loads	
Vehicle	Max Acoustic Level	Sound Pressure
Ariane 40	139 dB at 2000-4000Hz	142 dB
Athena II	133.2 dB	140.5 dB
Atlas IIAS	131 dB at 200 Hz	140.5 dB
Atlas IIIB	132 dB at 200 Hz	140.8 dB
Atlas V 400	131 dB at 200 Hz	140.5 dB
Atlas V 500	126 dB at 125 Hz	136.3 dB
Delta II 7320's	140.5 dB	139.8 dB
Delta II 7920's	140.5 dB	139.8 dB
Delta III	130 dB	140 dB
Delta IV Med +	130 dB at 125 Hz	140 dB
Delta IV Heavy	133 dB at 125 Hz	142. 7 dB
H-II	133 dB at 250 Hz	137.5 dB
Kosmos	128 dB at 100 Hz	137.5 dB
Long March 3B	136 dB at 500 Hz	141 dB
Pegasus	119 dB at 800 Hz	124.8 dB
Proton K	132.4 dB at 100 Hz	141.4 dB
Proton M	132.4 dB at 100 Hz	141.4 dB
PSLV & GSLV	137 dB at 500 Hz	143 dB
Soyuz	140 dB at 90 Hz	144 dB
Molniya	140 dB at 90 Hz	144 dB
Zenit (Sea Launch)	134 dB at 250 Hz	142 dB

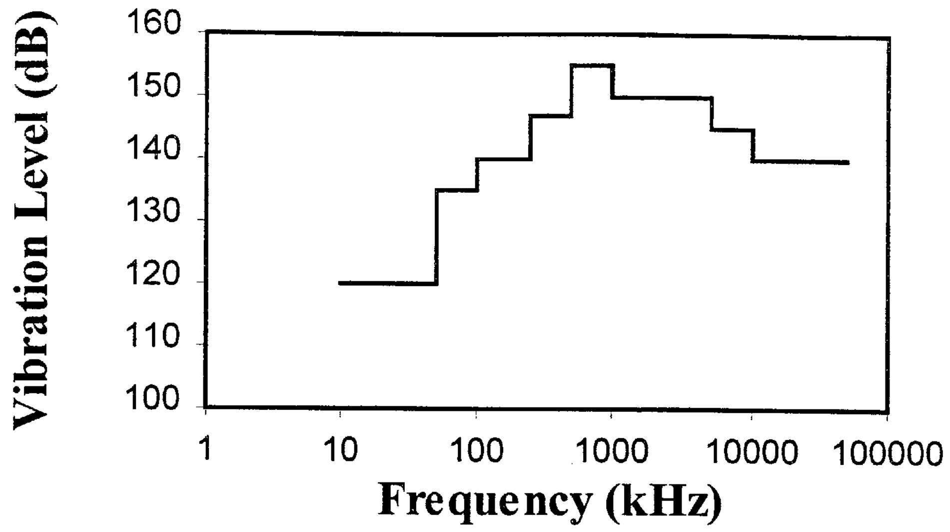

FIGURE 4-10 ACOUSTICAL SPECTRUM FOR DELTA II VEHICLE [17]

In order to achieve final orbital velocity, which can be anywhere from 6 to 10 kilometers per second (21,000 to 36,000 kilometers per hour), the vehicle must accelerate from zero to the final velocity. During this acceleration, the payload is exposed to high steady-state loads. These can range anywhere from 4 to 14 g's depending on the type of vehicle. These loads are applied along two geometric dimensions, both axially (along the flight path of the vehicle) and laterally (radiating out from the centerline of the vehicle). Typically the axial loads are substantially higher than the lateral loads. Generally, low-mass vehicles, sounding rockets, and ballistic missiles have much higher peak g-levels while large payload and manned vehicles have lower peak g-levels to protect the payload or crew. Table 4-5 below shows the range of values for the acceleration loads in both the axial and lateral directions.

TABLE 4-5 ACCELERATION LOADS IN LATERAL AND AXIAL DIRECTIONS [16]

Vehicle	Acceleration Loads	
	Maximum Axial (g)	Maximum Lateral (+/-g)
Ariane 40	4.5	0.2
Ariane 5	4.25	0.25
Athena I	8.1	1.8
Athena II	8	1.8
Atlas IIA	6	2
Atlas IIIB	6	2
Atlas V 500	6	2
Delta II 7320's	6.65	2
Delta II 7920's	6	2
Delta III	3.75	2
Delta IV Med +	6.5	2
Delta IV Heavy	6	2.5
H-II	4	1.8
Kosmos	6.9	1.4
Long March 2C	7.9	1
Long March 3B	6.1	1.5
Pegasus	11	4.7
Proton K	4.3	2.3
Proton M	4.3	1.35
PSLV & GSLV	6.4	1.1
Soyuz	4.8	1
Molniya	4.8	1
Space Shuttle	3.2	2.5
Taurus	8	2.5
Titan IVB	5	1.5
Zenit (Sea Launch)	4.5	2

Acceleration loads are time-based and increase and decrease according to vehicle staging. Acceleration peaks as each stage maximizes the energy it transfers to the spacecraft. These peaks coincide with the end of the each stages' burn and separation. The number of peaks is therefore determined by the number of stages, engines, and changes over the flight history of the vehicle.

Shock Loads are instantaneous events that impart extremely high accelerations for extremely short periods of time often only fractions of a second. These are experienced during ignition, staging, fairing-jettison, and payload separation due to ordinance detonation and engine start. Shock load magnitudes can vary from 500 to well over 8,000 g.

From lift-off through orbital injection, the surrounding environment of the spacecraft differs dramatically from the production and on-orbit environments. The environmental changes fall under one of the following three categories:

> **Thermal Gradients:** If not protected by the launch shroud, the payload would experience significant temperatures extremes during lift-off. Frictional forces during ascent through the atmosphere at high speeds causes high temperatures on the launch shroud. The payload is somewhat protected inside the fairing, but still experiences temperature gradients as some heat is transferred inside through conduction and radiation. The gradient experienced by the payload depends on the insulation material, the fairing shape, and the ascent angel of the vehicle.
>
> **Pressure gradients:** Ambient atmospheric pressure declines as the launch vehicle ascends. The rate of depressurization is dependent on the venting system installed in the launch vehicle shroud and the location of venting ports. During ascent, vehicles provide conditioned air and minimize any effects of rapid depressurization. Maximum pressure gradients faced by spacecraft during ascent can vary between 1.5 to 7 kilopascals per second.
>
> **Cleanliness:** Cleanliness refers to the degree of contamination within the launch shroud. Each vehicle has a rated clean room factor determined by the number of foreign particles per cubic meter. Vehicles typically rank from 5,000 to 100,000 parts per million.

4.4.2 Impact of Loads and Environments on Spacecraft Design

The most significant impact of launch loads and environments falls on the spacecraft structure. Spacecraft structures serve three primary purposes: to absorb dynamic and static loads, to protect the payload from launch and on-orbit environmental factors such as debris, radiation, and temperature gradients, and to serve as an attachment interface for mounting the bus and payload subsystems and connecting to the launch vehicle upper stage. Spacecraft typically have two sets of structures that divide these tasks. The primary structure carries the majority of the dynamic and static loads, connects to the launch vehicle, and has some environmental responsibilities. The secondary structure serves mostly the on-orbit mission of protection and support.[10]

While the maximum launch loads and environments were specified above, in most cases the structural design includes additional margins of safety to ensure that the spacecraft will survive in the event of abnormal loads. Factors of safety typically range form 25 to 40 percent above expected loads. Launch vehicle loads are also responsible for a large part of the expensive and extensive testing that spacecraft must go endure to ensure that they survive ascent and orbital injection. Launch loads necessitate the "shake" environment tests: shock, acoustic, and vibration.

4.4.3 Summary of Loads and Environments Impacts

Loads impact spacecraft structural designs, requiring high margins of safety and driving structures to consume a high fraction of the spacecraft's dry weight (15 to 25%). Excessive loads are also the primary driver for expensive spacecraft "shake" testing environments including vibration, acoustic, and shock analysis. The forces experienced during launch are so severe, that calibration of spacecraft instruments and systems must be done in-orbit versus on the ground. To compensate for these forces and environments, special damping and insulation systems must be developed consuming already limited mass and volume resources. The spacecraft designer must also perform complex coupled loads analyses and be keenly aware of avoiding launch vehicle natural vibration frequencies and modes.

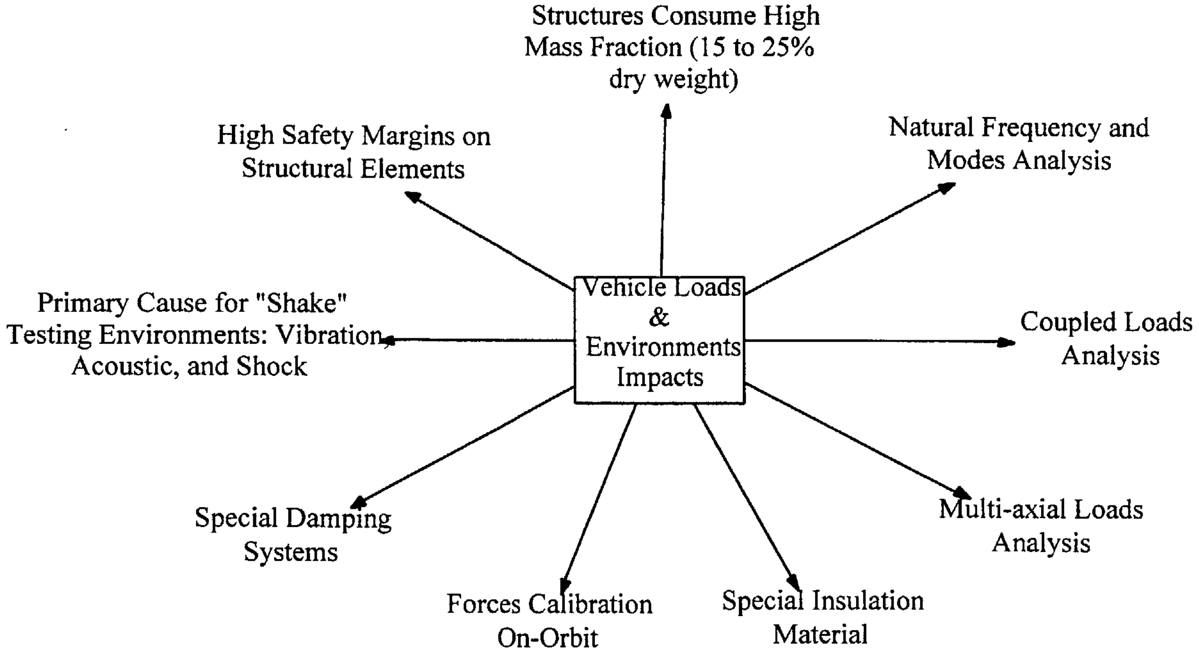

FIGURE 4-11 LOADS AND ENVIRONMENTS IMPACTS

4.5 System Interfaces

4.5.1 Constraint Definition

System interfaces refer to the structural and electrical connections between the spacecraft and the launch vehicle. System interfaces are important to consider for keeping the spacecraft and launch vehicle properly connected as well an insuring successful separation following ascent.

The main structural connections are through the payload adapter. The payload adaptor serve as the physical connection between the spacecraft and the launcher and as a conduit for electrical connections. While most vehicles come with a standard adapter, many spacecraft require either design changes to this adapter or additional support structures beyond that of the main adapter. Beyond connections to the spacecraft bus and payload, launch adapters also serve as attachment points for orbital transfer motors that enable the payload to move to higher altitudes following separation and house separation systems responsible for detaching the payload from the launch vehicle once in orbit.

While there is some thread of standardization in interface sizes there is still a wide array of adapter dimensions that spacecraft must consider. Newer vehicles have moved to more standard dimensions, especially among vehicles from the same country. Table 4-6 shows the range of adapter dimensions, measured in millimeters. Each vehicle typically has several standard interfaces and will produce customized interfaces if the customer is willing to spend more on the vehicle.

TABLE 4-6 ADAPTER DIMENSIONS

Vehicle	Adapter Payload Adapter Interface Diameters
Ariane 40	937, 1194, 1497, 1666
Ariane 5	937, 1194, 1666, 2624
Athena I	591, 944, 986, 1215, 1676
Athena II	591, 944, 986, 1215, 1676
Atlas IIAS	937, 1147, 1666
Atlas IIIA	937, 1147, 1666
Atlas IIIB	937, 1147, 1666
Atlas V 500	1215, 1666
Delta II 7320's	940, 1524
Delta II 7920's	940, 1524
Delta III	1194, 1666
Delta IV Med +	1194, 1666
Delta IV Heavy	1194, 1666
H-II	937, 1194, 1666, 2360
Kosmos	1060
Long March 2C	937, 1194
Long March 2E	1627, 1728, 3114
Long March 3B	937, 1194, 1666
Pegasus	985.8
Proton K	937, 1194, 1666
Proton M	937, 1194, 1666
PSLV & GSLV	937
Soyuz	Mission Specific
Molniya	Mission Specific
Space Shuttle	Mission Unique
Taurus	986, 944
Titan IVB	1426
Zenit 2	3620
Zenit (Sea Launch)	937, 1194, 1663

Launch vehicle firms provide all the necessary specifications dealing with vehicle connections in the launch user manual. This guide explains the physical, electrical, radio frequency, and optical access to the spacecraft during and after integration. The launch vehicle provides electrical and RF interfaces for the spacecraft to supply power to spacecraft while on the ground and when in-flight. The RF window provides communication access to payload while on ground and in-flight to help monitor the payload's condition.

4.5.2 Impact of System Interfaces on Spacecraft Design

Perhaps the most important impact of the system interfaces (especially structural) is that they take away mass and volume that could otherwise be available for the payload. As previous sections discussed, available mass and volume are already design drivers. The size and weight of structural interfaces depend primarily on the vehicle selected and must be factored into the spacecraft weight budget. In one military program, the decision to fly a medium-sized spacecraft on one of the heavy-lift Evolved Expendable Launch Vehicles (EELV) led designers to develop a fairly sizable and heavy payload adapter weighing approximately 2,000 pounds. Following a program restructuring, the payload was switched to one of the medium EELV's with substantially less lift capability. Based on the weight of the spacecraft, the designers ultimately only had 500 pounds to allocate to the adaptor and ended up not only re-designing the adaptor but also parts of the spacecraft triggering a substantial performance cut.

The lack of standardization among many launch vehicles, especially between foreign countries, forces the spacecraft designer to make a choice between designing the payload to be compatible with multiple launch vehicle interfaces or spending more time and money on the adapter system from the launch side. Allocating weight to the adapter directly consumes weight resources that could be available to the spacecraft. However, designing a more generic and multi-vehicle compatible spacecraft requires design trades which limit spacecraft design and consume cost and time.

The characteristics of both the launch vehicle fairing and the launch interface adapter have a impact spacecraft accessibility following integration. After the spacecraft and the launch vehicle have been structurally mated, various tests are run on all connections to ensure that the spacecraft can communicate with the launch system and to make sure that the spacecraft is functioning properly following the substantial handling involved with the integration activities. Ensuring compatibility with the launch vehicle, both physically and electrically, is a significant design impact on the payload.

The decision to launch with additional spacecraft, or multi-manifest, adds complexity to the integration process and interface requirements. Connectivity for each spacecraft to the launch vehicle as well as connectivity between the spacecraft must be considered. This equates to extra wire harnesses and bundles that must run along the side of lower spacecraft in the stacking order and extra structures to separate each spacecraft. These extra attachments can consume 10-15 percent of the vehicle's lift capability. The potential also exists for each spacecraft to exert additional loads on each along with those from the launch vehicle.

The final task of the launch vehicle interface is payload separation. Orienting and deploying the spacecraft in the correct direction is imperative to ensuring that it will reach its desired orbital location. In some cases, special tip-off or separation mechanisms can add an additional 5 to 20 percent cost increase depending on the complexity of the required maneuver. In the case of dual manifested spacecraft, the possibility that the top spacecraft of a multiple spacecraft stack does not deploy correctly is a contingency that must be planned and designed for.

Other interface issues involve special precautions taken for a crewed (human-rated) launch vehicle such as the space shuttle or the Pegasus vehicle. The Pegasus vehicle is considered to semi-man-rated because it is initially lifted to an altitude of 40,000 feet by a piloted L1011 aircraft. For these vehicles, extra safety measures are employed to make sure that the crew is not put in danger. In one NASA program, solid block hydrogen was going to be included on the payload to cool the science instruments for an astronomy mission. The potential dangers of the hydrogen in this form to the crew required additional equipment and safety procedures that added extensive costs to the mission.

Other Industry Examples of Interface Issues

Interface Compatibility: Choice between using all optical communications system desired by spacecraft versus RF which is common in launch vehicles

Coordination of Communications Architectures: Potential jamming of a military payload initially using same the telemetry/communications frequency as launcher

Data Transmission Conflicts: Disagreement over using copper wires and not fiber optics for data transmission in a new launch system

Software Compatibility: ETA versus standard C++.

Special Equipment: Desire to monitor a spacecraft throughout the launch phase using a Pegasus vehicle required special racks to be installed on the L1011 to handle the spacecraft-aircraft interface in addition to the normal launch vehicle-aircraft communications.

4.5.3 Summary of System Interface Impacts

System interfaces deal with physical and electrical connections between the spacecraft and the launch vehicle to handle communication and stabilization of the two systems. Systems interfaces require special coordination between the spacecraft designer and the launch firm to make sure communications are secure. Locations of access ports determine what areas of the spacecraft will be available following encapsulation and where integration testing connections must be located. Lack of standards across many vehicles leads to mission-unique support and connection structures that consume valuable mass and volume. Multi-manifested launches also require design coordination between associated spacecraft.

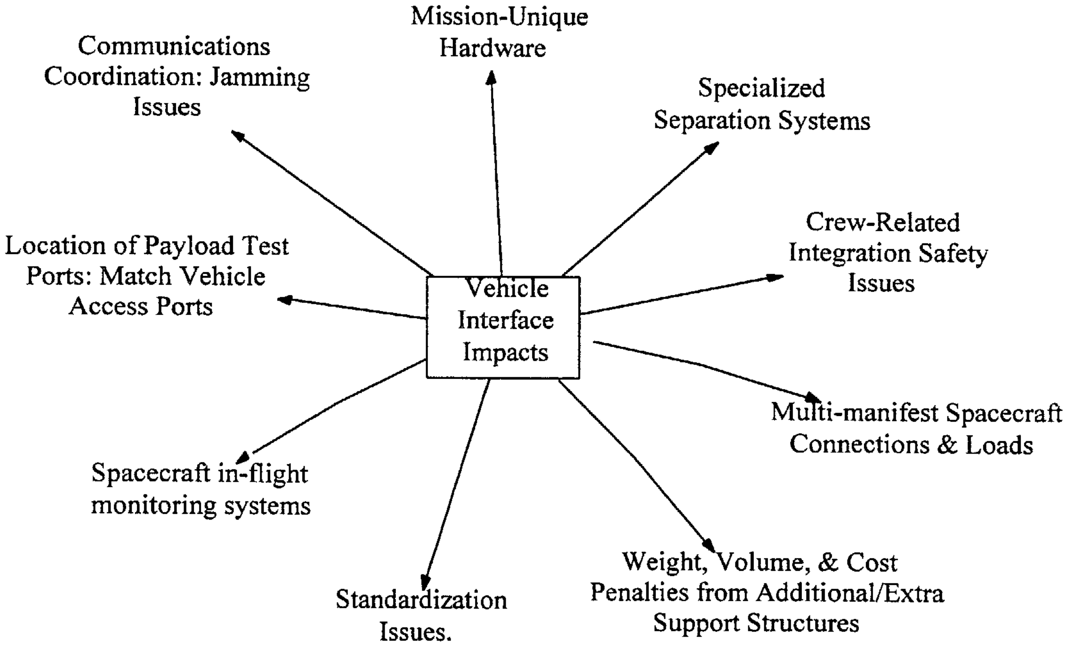

FIGURE 4-12 INTERFACES IMPACTS

CHAPTER 5 DISCUSSION OF OPERATIONAL CONSTRAINTS

5.1 Overview of Operational Constraints

Operational launch constraints impact not only the design of spacecraft systems, but also the deployment and operation of spacecraft systems. The following operational constraints were identified to have a major impact on space system design:

> **Schedules**: Timetable limits for finalizing launch vehicle procurement, arranging launch dates, and securing range equipment. Also includes schedule dependability or the probability of launching on the scheduled date.
>
> **Availability:** Refers to adequate supply of vehicle hardware to meet demand and operational status of vehicle program (online versus offline).
>
> **Reliability:** Probability of successfully completing the mission with failures defined as in-flight explosions and delivering a payload to the incorrect orbital altitude and inclination.

The following sections will introduce the each of the three major operational constraints that must be considered in the design and development of spacecraft systems. It is important to note that while they are discussed on an individual basis, many of the constraints are highly coupled further complicating the design process. This coupling forces more complex trade analysis and is evidence of the need to fully understand how launch constraints impact the spacecraft system.

5.2 Launch Schedules

5.2.1 Constraint Definition

Launch vehicle scheduling constraints impose temporal restrictions on the design and deployment of spacecraft systems. The process of procuring a launch vehicle requires drafting extensive contractual documents and reserving launch range equipment and personnel time. Vehicle procurement contracts can take months to negotiate and are typically initiated anywhere from 10 to 60 months in advance of the necessary launch date. The current Evolved Expendable Launch Vehicle program sponsored by the Air Force requires ordering the largest lift capacity vehicles 24 months in advance. Lengthy contract timelines are driven by vehicle processing cycles and the necessity to reserve limited range resources. Current vehicle processing schedules (time to integrate and launch) are measured in weeks with the fastest spanning 4 to 5 weeks and the longest well over 20 weeks.

Complex processes give rise to complex problems. The probability of actually launching at the scheduled time and date specified in the initial contract is defined by the vehicle schedule dependability. Delays in launching on schedule are a normal occurrence which must be planned for. Launch delays can be caused be a range of factors including weather, technical problems with the launcher or the payload following integration, shortages of vehicle hardware, failure of previous missions requiring investigation, and damage to the launch range.

5.2.2 Impact of Launch Schedules on Spacecraft Design

By forcing firms to procure launch vehicles so far in advance, the spacecraft developers are driven to select and contract a vehicle prior to completing the final spacecraft design. With a vehicle already purchased, the launch constraints explained in Chapter 4 are put into place and must be designed around. Long contract timelines pressure quick vehicle selection and reduce the potential for design trades between the vehicle and the spacecraft.

Schedule delays caused by weather, technical problems, vehicle failures, production shortages, or range-related problems can have a significant impact on the success of a spacecraft systems. When a launch vehicle does not lift-off on time, it directly delays the start of spacecraft operations. In the case of a commercial satellite that is deriving revenues from its operations, every day that the spacecraft spends on the ground is another day that it is not functioning and not generating revenue. With annual transponder lease rates hovering between $1 million to $2.5 million per year, every day spent on the launch pad equates to hundreds of thousands of lost revenue dollars. For military spacecraft, delays can affect national security mission success and increase defense vulnerability.

In the realm of new commercial applications, time to market can be crucial. Usually, new markets start off small but have high growth rates. The first firm to offer access has a competitive, first-mover advantage and the potential of capturing the burgeoning market and gaining momentum as the market expands. Many of the smaller space markets are only able to support one, perhaps two firms. If the first firm captures enough market share, it can build an effective barrier to newcomers. One example of a new space market that might be in this category is the competition for the satellite radio market. Two firms, XM Radio and Sirius, are vying for positions in the nationwide, direct-to-car radio service market. A delayed launch of one of XM Radio's two service satellites jeopardizes its chance of gaining market share. In the event of a significant time delay, by the time the new service is up and running, the competitor (Sirius) may have already seized the majority of the market leaving the delayed company with few new customers to pay off start-up costs.

The capability to schedule and launch quickly has been labeled Launch-on-Demand or LOD. While the capability to launch under extreme time pressures has some commercial and scientific importance, it's primary benefit is for military purposes. LOD provides assured access to space and space assets deemed crucial for national security. A military capabilities review which declared that "the ability to provide information and communication in fast, flexible manner is currently deficient" led to a study by the Department of Defense Space Architect and the National Reconnaissance Office to asses the impact of LOD capabilities on the management of satellite constellations [25] The report concluded that "extended timetables and system operational inflexibility were major limiting factors for potentially basing other defense systems in space." [26] Faced with lengthy schedule times, spacecraft developers are either forced to design spacecraft with excess capabilities to handle both routine mission functions and sporadic, possibly unnecessary mission functions or to design spacecraft for only routine mission functions and remain vulnerable to potential capability deficiencies. In the future, launching spacecraft to perform a specific duty on short notice will be crucial to replacing spacecraft that have malfunctioned or have been destroyed (by accident or on purpose) and to quickly augment existing systems in the event of unforeseen crises.

Launch delays can also completely ruin a science mission. Due to the complex motion of the planets around the sun, there are times when the alignment is such that launching during a particular "window" is essential to successful complete the mission. Missing a crucial launch window, such as the one that opens up for Mars missions every 26 months means either a complete spacecraft re-design or waiting another 26 months.

5.2.3 Summary of Launch Schedule Impacts

Schedule constraints place timetable limits for finalizing launch vehicle procurement, arranging launch dates, and securing range equipment. Additionally, schedule dependability is a vital factor affecting the probability of launching at the scheduled time and date. Schedule delays can result in lost revenue and potential market share to competitors, national security vulnerability for quickly replacing damaged or destroyed spacecraft, and missing narrow launch windows for interplanetary science missions. Lengthy contracting schedules force early vehicle selection and procurement to reserve spots on vehicle and range manifests. This reduces the amount of design trades that can be made between the spacecraft and launch vehicle. Finally, lack of "launch-on-demand" capabilities leads to designs with excess capabilities to handle both routine mission functions and sporadic, possibly unnecessary mission functions versus designs for routine mission functions only producing vulnerability and potential capability deficiencies.

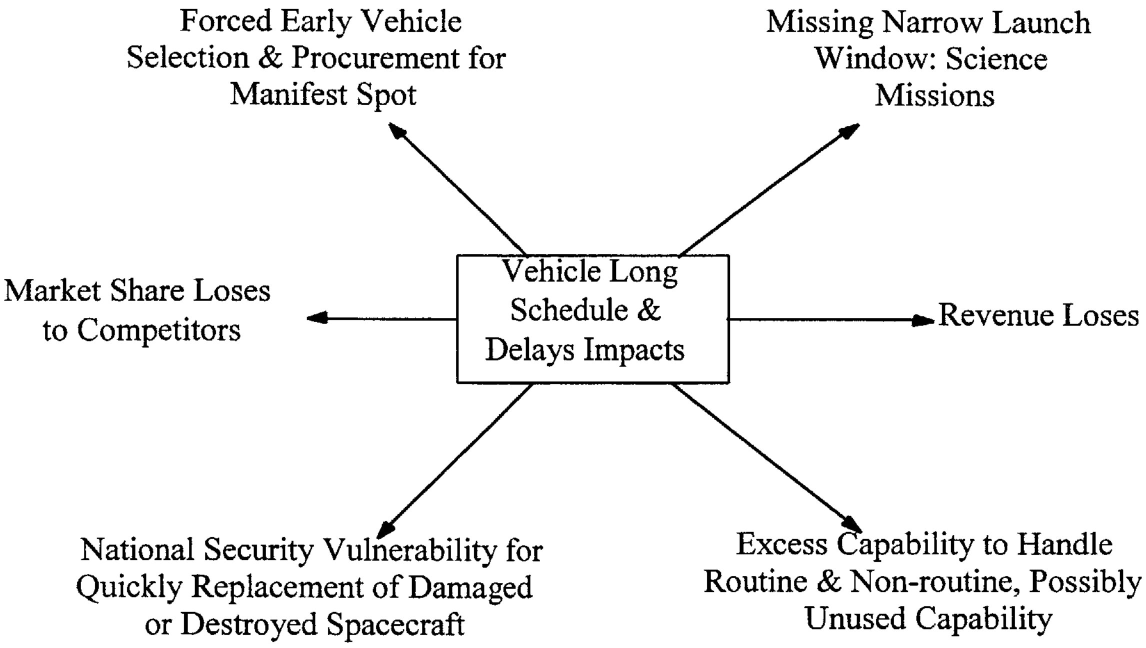

FIGURE 5-1 LAUNCH VEHICLE SCHEDULE IMPACTS

5.3 Vehicle Availability

5.3.1 Constraint Definition

The concept of launch vehicle availability deals not only with the issue of adequate supply of vehicle hardware to meet demand but more importantly with the functioning status of the vehicle. Following a full or partial launch failure, launch vehicles are said to be "offline." During this stand-down time, the cause of the failure is investigated and appropriate steps are then taken to bring the vehicle back "online." The length of time that a vehicle is "offline" varies depending on the type and severity of the failure as well as the type of vehicle. Increased downtimes are usually associated with successive failures, inability to detect the root cause, or design flaws to critical systems which require extensive re-design, testing and re-qualification. Table 5-1 shows the downtime resulting from several vehicles latest failures as well as the average downtime these vehicles have experienced over the life of the program. Primary availability drivers include operational status (online:offline), supply of launch vehicles (flight rate/processing timeline), and government regulation.

TABLE 5-1 LAUNCH SYSTEMS AVAILABILITIES [10]

Launch Vehicle	Downtime After Last Failure (Months)	Average Downtime (Months)
Space Shuttle	32	32
Titan IV	6	6
Atlas	8	10
Delta	4	4
Ariane 4	5	9
Ariane 5	17	17
Proton	4	3
Long March	1	12
Zenit	14	14
Pegasus	9	9
Tsyklon	5	6

While problem severity plays a significant role in the length of the downtime, the vehicle type also has a significant effect. Man-rated systems like the space shuttle are prone to extremely long timelines because of the fact that human lives are at stake.

The second part of launch availability relates to the ability of vehicle supply to meet demand. There are two critical numbers associated with the vehicle supply, the flight rate and the surge capacity. The flight rate is the average number of launches that can be performed in a given time period, usually a year. The majority of launch vehicles have flight rates in the 5 to 10 range. Performing a larger number of launches beyond the established flight rate deals with the surge capacity of the vehicle, or under heavy demand conditions, how many more flights above average can be performed. Surge rates can vary anywhere from 10 to 50 percent of the expected flight rate meaning that a vehicle that normally performs 10 missions a year might be able to perform 1 to 5 additional missions under special circumstances.

Limitations on the flight rate are related to several key factors. One of the most important and often over-looked is the availability of ground infrastructure. In the United States, the majority of launches occur at one of two locations the Eastern Range at Cape Canaveral in Florida and the Western Range at Vandenburg Air Force Base north of Los Angeles. Each of these facilities has a limited set of equipment to support launches such as the number of launch pads, the tracking and communications equipment, and skilled personnel. The Eastern Range in Florida can only handle a single active mission at a time and must dedicate its equipment and communications network to a single mission with a minimum change-over time of 45 hours. [27] Each range has a several launch pads meaning that multiple launch vehicles can be processed at the same time both on-site and off-site, however, only a single mission can be active at a time.

Other limiting factors for the flight rate deal with the processing of the launch vehicle, the processing of the payload, and the integration of the two vehicles. In the past, many vehicles were actually built stage by stage out on the launch pad, consuming this valuable, scarce resource. Processing timelines of two to four months was the norm. The new trend, following the example of the Russian launch processing method, is to process the vehicle horizontally off the pad and then erect the vehicle and integrate the payload on the pad only several days before launch. Processing timelines have been decreasing over time, coming down from a standard 60 to 70 plus days to less than 20 for the new generation of launch systems. Decreases in launch processing timelines as well as increased capacity to process multiple vehicles off-site (off the pad) have led to the capability of higher flight rates and greater vehicle availability. However, range equipment constraints will eventually limit these rates until the ranges can be updated.

Finally, the speed at which the payload can be integrated with vehicle also plays a role in determining how fast the launch can be processed and thus the vehicles flight rate.

A final aspect of vehicle availability is due to regulation and government policy. The potential for governments to deem certain vehicles from other countries "off limits" or to limit the number of satellites that can be launched on them is a serious factor. Chapter 7 will discuss the role of government regulations impact on space systems and this type of vehicle availability limits.

5.3.2 Impact of Launch Vehicle Availability on Spacecraft Design

In January 1986, tragedy struck NASA's space shuttle program with the loss of the Challenger STS-51 mission. The policy decision to have all US payloads fly on the shuttle had enormous consequences for the spacecraft community when the shuttle went offline in 1986. As a man-rated system, failures claimed more than just the payload and the vehicle. The death of seven astronauts was a crushing blow to the US space program, one that it would not let happen again. The failure investigation, generation of recommendations for safing the rest of the shuttle fleet, and implementation of the "back to flight" plan consumed 32 months. After ramping up from two flights in 1981 to nine in 1985, the shuttle program was brought back online in September 1988 with a flight rate cap of seven mission per year. With the prospect of reaching the initial program goals of 10 day turn-around times and 60 flights per year deemed impossible, the shuttle no longer could serve its intended role as the sole space transport vehicle. Prior to the Challenger accident, the shuttle system had been making strides toward its objective of carrying all commercial, military, and civil missions. In the process, NASA was cornering the US launch market and essentially driving commercial players out of the market. The US learned a costly, but valuable lesson about relying on a single machine for access to a crucial space property. Following the accident, vehicles that had been on the path to retirement had to be rapidly brought back into service. The revival process required a great deal of time and money and former expendable vehicles were not completely back online and able to handle the industry demand until the early 1990's, more than five years after the shuttle disaster.

The occurrence of a Challenger-like incident illustrates the severe impacts that launch vehicle availability has on the design and development of spacecraft systems. When the shuttle went offline, the schedule for every spacecraft that was slated to not only fly on the Challenger, but also the rest of the shuttle fleet was instantly delayed by at least a year. As mentioned in section 4.2, the impact of schedule delays can be enormous in terms of operations loses: loss of revenue, loss of market share, and loss of essential capabilities such as communications or defense functionality. The national security impacts of impaired or non-existent access to space were enormous in the late 1980's with the US and the USSR still engaged in the Cold War. The military, as well as commercial companies, vowed to not let this happen again. The most significant impact of vehicle availability on space system design is psychological.

Spacecraft designed in the 1990's were approached with a much different design philosophy than in the 1980's. The notion of designing for a single vehicle was eliminated from developers minds. The new design philosophy focused on multiple vehicle compatibility. While a primary launch vehicle was selected and optimized for, a secondary vehicle was also identified for the event of the primary vehicle going offline. Designing spacecraft to be compatible with multiple vehicles led to additional, sometimes unnecessary, equipment to enable the spacecraft to conform to multiple vehicle specifications such as loads, temperatures and pressures, adapter sizes, and communication frequencies among others. Compatibility consumed already limited mass and volume resources in addition to time and money.

Another impact of availability is the spacecraft communities' acceptance of using new vehicles. Offering improved capabilities does not equate to spacecraft developers utilizing such capabilities. Risk aversion leads designers to hold-off on developing spacecraft for new vehicles without a potential back-up with similar capabilities. One example of this involves the initial introduction of the Ariane 5 vehicle. The Ariane 5 offered substantially greater lift capability (over 6,800 kilograms to GTO) than any other vehicle, however, it is the only vehicle currently able to lift such large payloads (besides the Shuttle which is off limits to commercial payloads). Designers have shied away from using the Ariane 5 until another option in the 6,800 kilogram plus category is online. Fear of a vehicle going offline will stop spacecraft designers from utilizing new capabilities until secondary options are available.

In the event that a vehicle does go offline, the consequences for the spacecraft can be severe. Short delays simply result in a schedule push-back with the impacts summarized in the preceding schedules section. However, as Table 8 illustrates, some programs can be offline for significant periods of time exceeding 12 months. In these situations, time pressures and uncertainty about the future of the vehicle may lead developers to select another vehicle. In most cases, moving to another vehicle means costly design changes to ensure compatibility with the new vehicle. One program that definitely felt the effects of this was the US Air Forces' Milstar program. When the shuttle went offline, the Milstar program decided to abandon the shuttle in favor of the Titan IV vehicle. In doing so, the billion dollar program went through a several hundred million dollar redesign to comply with Titan IV characteristics.

5.3.3 Summary of Vehicle Availability Impacts

Concerns over vehicle availability drive spacecraft designs to multiple vehicle compatibility, lead to expensive re-designs following a vehicle going "offline," and create a conservative spacecraft community where developers resist designing for new vehicles with superior capabilities until a potential replacement vehicle is also available.

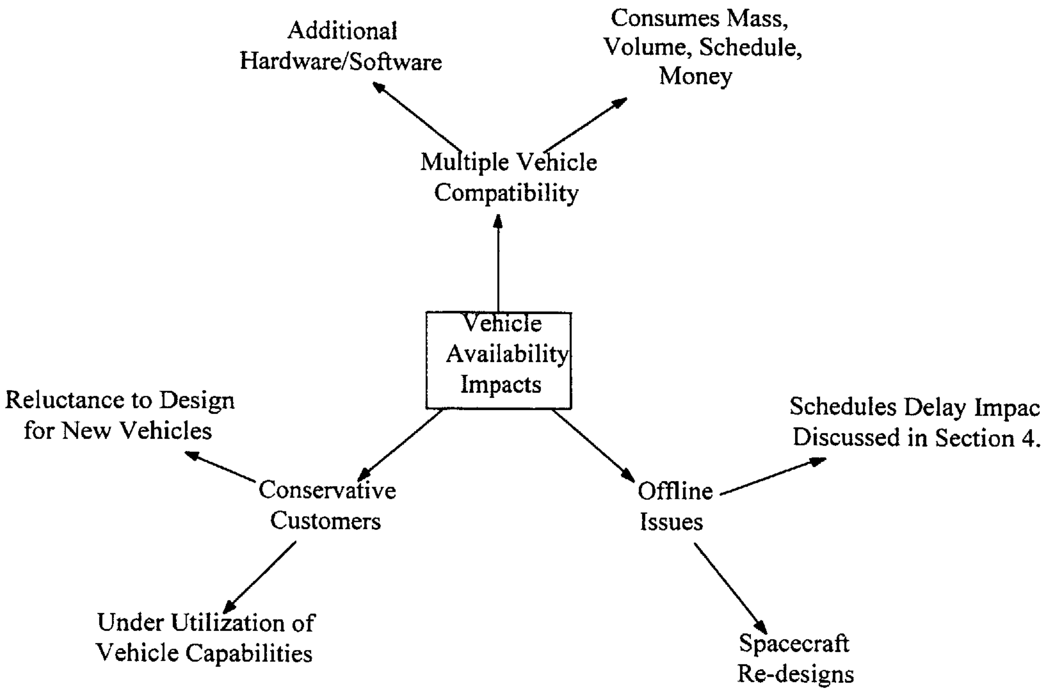

FIGURE 5-2 AVAILABILITY IMPACTS

5.4 Vehicle Reliability

5.4.1 Constraint Definition

The reliability of a launch vehicle expresses the probability of successfully completing the mission. Failure to complete the mission can result from in-flight accidental or self-destruct explosions or from delivering the payload to the incorrect orbital altitude and inclination. The second classification of a failure can also be labeled as a partial success if the spacecraft can achieve its intended orbital position through its own maneuvering system. However, such maneuvers consume vital propellant and reduce the spacecraft's operating life. In other situations, the spacecraft may not be able to reach its desired position, but can still be used to perform part of the mission in a degraded state or can be reprogrammed to complete an entirely new mission. Finally, there are instances where the spacecraft cannot reach its desired orbit and is therefore unable to complete any of its intended or secondary missions and it is ruled as a complete mission failure.

Launch reliabilities vary from vehicle to vehicle although typically average around 85 percent. Historically, vehicles that have been in operation for several years and have completed more than 10 launches have had much higher average reliabilities as time and experience increase. Heritage vehicles that are based on previous launch systems or represent incremental improvements over existing systems tend to have better reliabilities although there are exceptions. Standard reliabilities are simply determined by calculating the number of successful flights over the total number of flights attempted. However, other measures of reliability which discount the first several flights as "tests" are also used in industry. Vehicles with long series of successes are typically viewed more favorably than vehicles with only several attempts even if the more experienced vehicle has a lower absolute reliability. Figure 5-3 shows the current reliabilities for many of the world's launch vehicles.

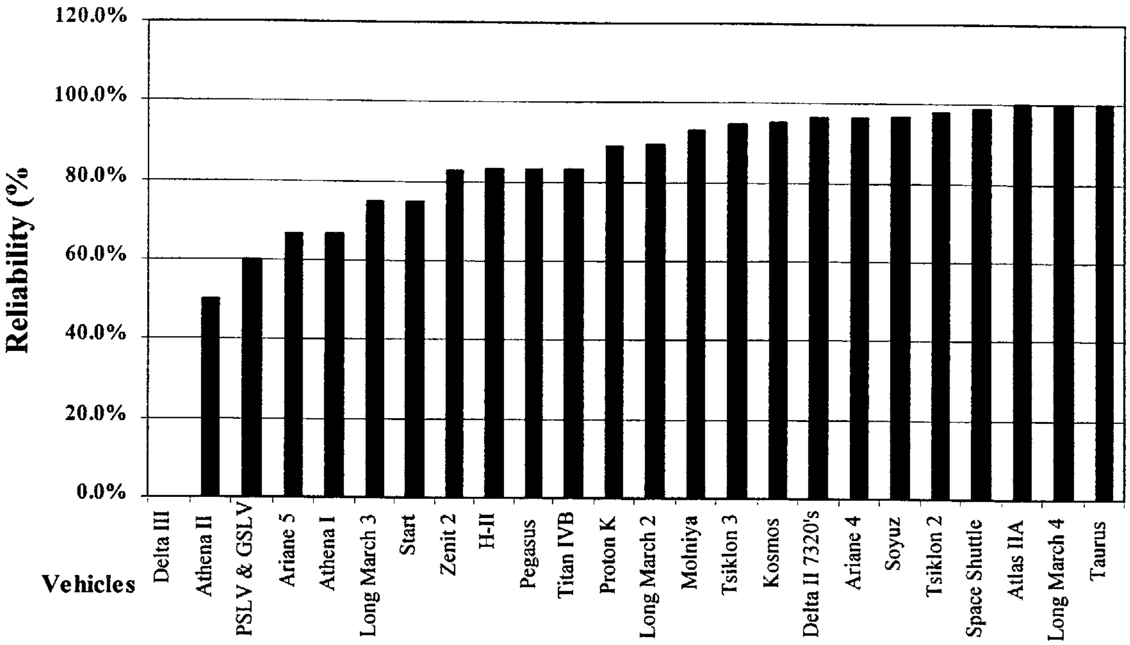

FIGURE 5-3 RELIABILITIES FOR CURRENT LAUNCH VEHICLES [16]

5.4.2 Impact of Vehicle Reliability on Spacecraft Design

On September 9, 1998, a Ukrainian Zenit 2 rocket carrying 12 Globalstar mobile telecommunications satellites lost control 272 seconds into its flight when the main rocket motors suddenly shutdown sending all 12 spacecraft smashing down to Earth. Globalstar had planned to conduct three more missions with the Zenit vehicle to deploy 36 of the 48 spacecraft in its low Earth orbit communications constellation. The Zenit loss had a significant impact on Globalstar's constellation deployment strategy affecting the composition and the number of launches required to deliver the entire constellation to orbit. With eight spacecraft already successfully launched aboard two Delta II's, Globalstar decided to launch the remaining spacecraft in groups of four aboard a mix of Delta II's and Russian Soyuz'. Instead of the initial six planned launches, Globalstar required a total of 14 launches lasting through February 2000 and the constellation was eventually activated in October 1999 behind schedule and with only 40 spacecraft in orbit.

Vehicle failures that destroy critical spacecraft or large numbers of a constellation also have psychological affects. One company reported a $2 billion decrease in market cap following the loss of an important spacecraft. Additionally, in the case of a new system like Globalstar's, the company's success depends on signing up millions of subscribers. With the cost of satellite mobile phones averaging over $1000 per unit, highly publicized loses of spacecraft hurt the companies' image and could dissuade potential subscribers from purchasing the expensive handset and signing up for service until they are sure that the service will be around for awhile.

Beyond impacts from complete failures and spectacular explosions, launch vehicle reliability can have many other affects on space systems. On Christmas Day 1997, a spacecraft known as AsiaSat-3 lifted-off aboard a Russian Proton launch vehicle. After settling into a support orbit, the Proton's fourth stage ignited six hours and 18 minutes into the mission in order to transfer the spacecraft from the parking orbit to geostationary orbit. One second into the planned 110 second burn, the Proton fourth stage shut-off prematurely after ignition sending the communications and television spacecraft owned by Asia Satellite Telecommunications Company into an unusable, highly elliptical and inclined orbit. Even though the spacecraft was completely functional, AsiaSat filed an insurance claim and the insurers declared the satellite a total loss. In March 1998, AsiaSat ordered a replacement satellite from Hughes which was lifted into orbit one year later in March 1999 aboard another Proton vehicle, 15 months after anticipated. Although AsiaSat-3 was supposed to replace AsiaSat-1 which had been in orbit since 1990, the 15 month delay postponed the rollout of new capabilities for its customers, potentially influencing company revenues and market share. Additionally, AsiaSat's telecommunications license related to the spectrum allocated for its mission was revoked in June 1998.

In April of 1998, Hughes Global Services reached an agreement with the insurers to attempt a rescue mission to salvage the AsiaSat spacecraft agreeing to share any profits with the insurers. Renamed HGS-1, engineers as Hughes and the Aerospace Corporation devised an unique plan to use a gravity assist around the Moon to flatten and circularize the spacecraft's orbit. During the process of two lunar flyby's, the spacecraft was able to be stabilize the spacecraft's orbit. While the spacecraft will produce some revenues for Hughes and the insurers through selling limited communications services the spacecraft will also have an extremely short life to generate these revenues based on the fuel expended during the correction burns.

For the period between 1997 and 2000, the insurance sector was forced to payout, on average, over $400 million per year for launch vehicle related failures. The effect numerous failures in the launch industry directly translates into increased spacecraft insurance rates already averaging 15 percent to 30 percent of the launch costs. Besides adding absolute cost, insurance premiums vary from vehicle to vehicle depending on the insurance companies assessment of the vehicle's operational reliability. Thus, differences in insurance rates can influence vehicle selection. Future insurance problems are seen on the horizon as more unproven vehicles come onto the market in the heavy-lift category capable of lifting multiple spacecraft or larger, complex and expensive spacecraft. By 2002, there will be "five launch vehicles capable of carrying payloads worth more than half the value of total annual insurance industry premiums."[28]

Relatively low vehicle reliabilities (compared to other transportation systems) have also contributed to the high degree of risk aversion among spacecraft customers. Conservative customers drive spacecraft designs by refusing to use new technologies and components. Customers want the benefits of the new technology but are unwilling to be the first to "try it out." The probability that they will lose a spacecraft during launch or once in orbit fuels this tendency towards conservative designs and implies that the commercial will take an evolutionary approach towards new designs.

Vehicle reliability is intimately linked the impacts discussed in the previous section on availability. Conservative customers are unwilling to limit spacecraft designs to a single vehicle option even if it offers superior performance or lower cost. This contributes to a slow acceptance of new launch capabilities. Thus, vehicle reliability fuels concerns over vehicle availability and ultimately affects spacecraft development.

5.4.3 Summary of Reliability Impacts

Launch vehicle reliability defines the probability of successfully completing the space transportation mission with failures including in-flight explosions and delivering a payload to the incorrect orbital altitude or inclination. The potential for losing a spacecraft during transport leads to high insurance premiums, production of back-up hardware and spares, and distributing constellation spacecraft across several launch vehicle families (requiring compatibility designs).

Additionally, spacecraft placed into incorrect orbits must consume crucial propellant during special trajectory corrections burns which reduce spacecraft operational life.

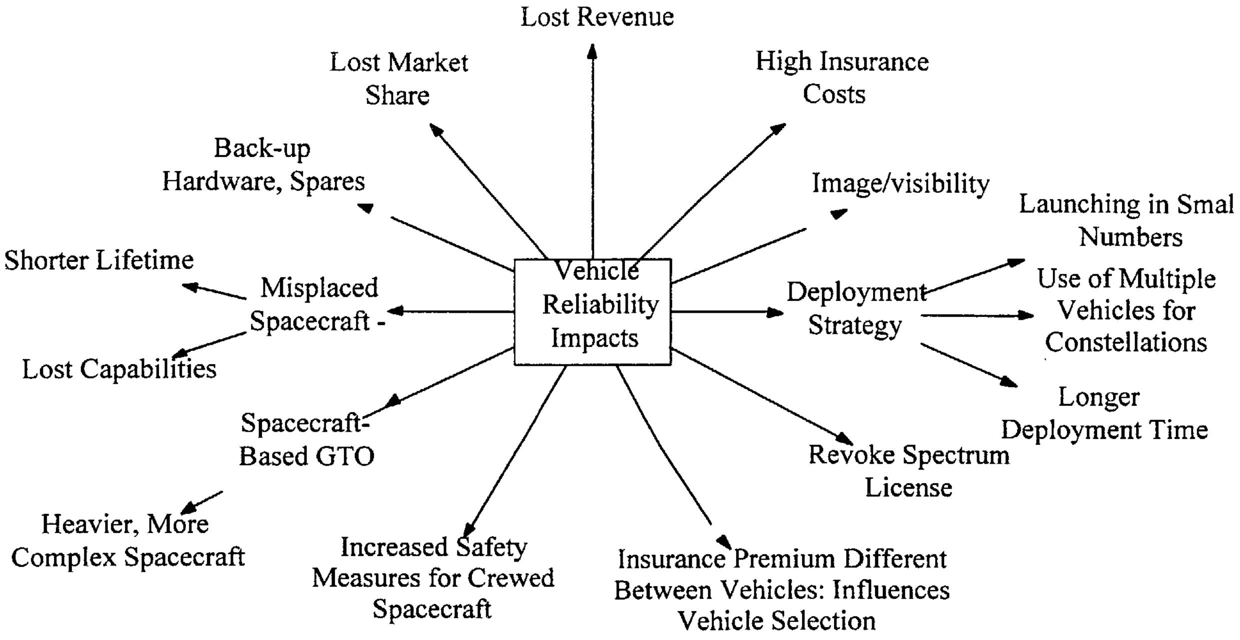

FIGURE 5-4 RELIABILITY IMPACTS

CHAPTER 6 DISCUSSION OF COST CONSTRAINTS

6.1 Constraint Definition

The most influential and often cited launch constraint is cost. Compared to any other mode of transportation, launching objects into space is by far the most expensive. The costs associated with space access and payload delivery varies significantly depending primarily on the payload size and the orbital destination. It is also important to note that the exact launch costs for a particular vehicle will vary slightly from launch to launch depending on mission-specific equipment. These costs, also known as "drive-away" costs (reference to auto extras), include add-ons and extra features that are not included in the base vehicle price and cover equipment and operations such as special payload adapters, thrust augmentation to increase lift capacity, unique separation procedures or telemetry requirements and among many others.

6.2 Cost Breakdown

Launch costs are typically measured by two methods, vehicle procurement price and price per unit mass. The vehicle procurement price is the absolute cost of purchasing the launch vehicle for a single payload. For current vehicles, costs are roughly a function of the lift capacity of the launch vehicle with cost increasing at a fairly linear rate as shown in Figure 6-1. The two rightmost points identify the US Space Shuttle (the only reusable launch vehicle) and the Titan IV which is being retired in 2002.

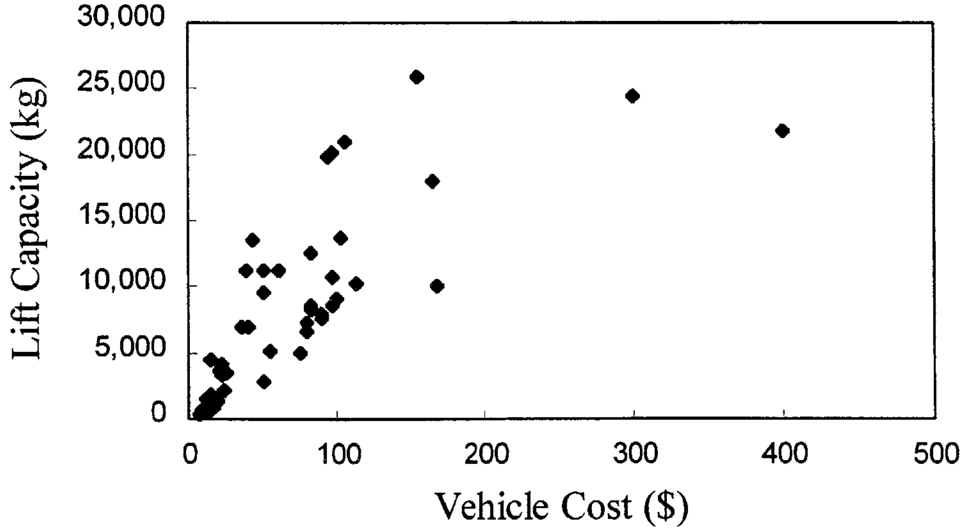

FIGURE 6-1 LAUNCH PRICES BY VEHICLE [16]

Launch vehicle costs range from the least expensive Orbital Sciences Pegasus vehicle at $15 million per flight up to the most expensive Lockheed Martin Titan IV vehicle at $400 million. Another cost measurement that is often quoted is the price per kilogram. For low Earth orbit launches, the average price is $9,800 per kilogram while the average price to geostationary orbit is $26,500 per kilogram.

The cost of space access has remarkably remained relatively flat since the early 1970's.[29] The lowest US space transportation costs were achieved by the Saturn V booster which delivered the Apollo astronauts to the Moon and has been retired from service for over 25 years. Compared to today's costs, the Saturn V was able to deliver hardware to space for an estimated $8,400 per kilogram. Of course, the Saturn V was also able to lift 127,00 kilograms to low Earth orbit or more than 5 times the largest lift capacity available today. The Saturn V launch vehicle was an outlier in the lift capacity historical trend as economies of scale significantly contributed to such a low cost. Following retirement of the Saturn V, prices returned to their previous levels and remained constant until the early 1990's. Increased international competition helped to drive US launch prices down. Figure 6-2 shows the history of launch costs since the early 1960's.

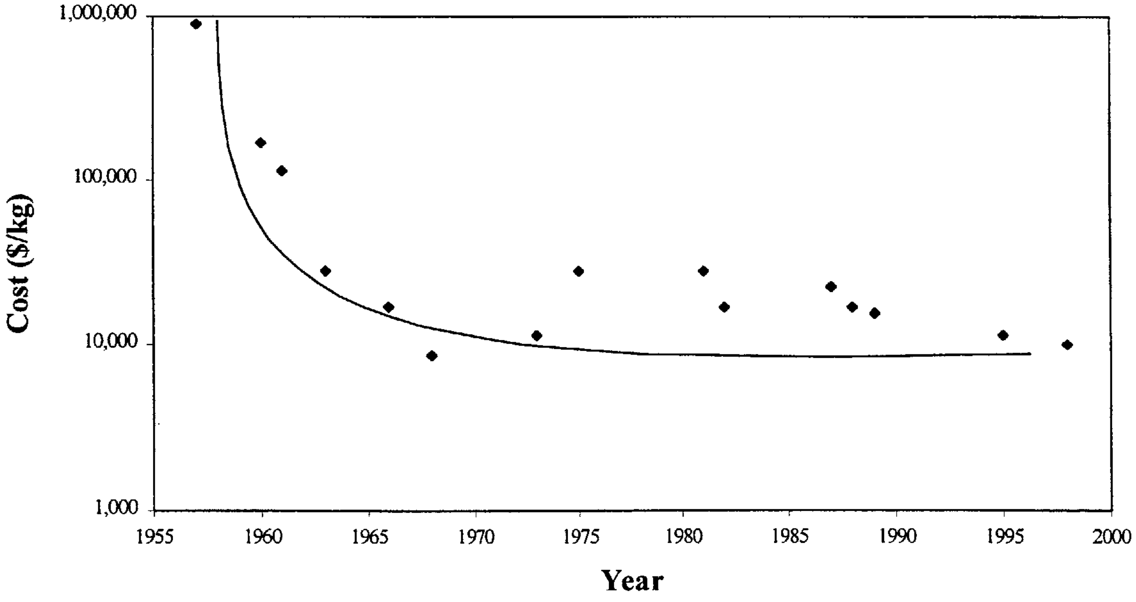

FIGURE 6-2 HISTORICAL LAUNCH PRICES [29]

As was mentioned in Chapter 2, there are several ways to divide up the total life-cycle costs of a space program. Dividing costs among the different architecture segments varies depending on the type and duration of each mission. Typically, however, the launch segment will consume roughly 30 to 40 percent of the program costs but can range anywhere from 15 to 75 percent in extreme cases. On average, when launch insurance is included, the launch process consumes 50 percent of the total program budget. Although spacecraft are expensive to design and manufacture, revolutionary changes in how satellites are designed and produced has been demonstrated by companies such as Iridium and Globalstar. These companies have shown that production and deployment cycle times and per unit costs can be driven down by utilizing radical design, test, and production methodologies. According to commercial industry officials, the percentage of the total budget that launch consumes is growing to more than 50 percent as satellites have seen a 4 to 5 times improvement in cost efficiency over the last 10 years.

6.3 Launch Cost Drivers

There are many factors which contribute to high launch costs. Launch costs can be divided between recurring and non-recurring costs. For expendable vehicles, recurring costs include production of all major hardware (engines, structure, electronics, etc), propellant, insurance, and labor costs. Non-recurring covers initial research and development and infrastructure development costs. For reusable vehicles the bulk of recurring costs are in the labor necessary for maintenance and preparation as well as for propellant and insurance. Non-recurring costs include research and development, vehicle production, and infrastructure costs. However, the primary reason for high launch costs is the low flight rates. Multi-billion dollar upfront development costs are difficult to recoup when a vehicle flies only 10 times per year. Paying of research and development and infrastructure costs can take decades, without even starting to pay off interest on debt or making a profit. Figure 6-3 shows the relationship between the flight rate and the cost per kilogram to orbit. Clearly the best way to reduce launch costs is to push the flight rate up past 1,000 flight per year. However, high flight rates require high demand.

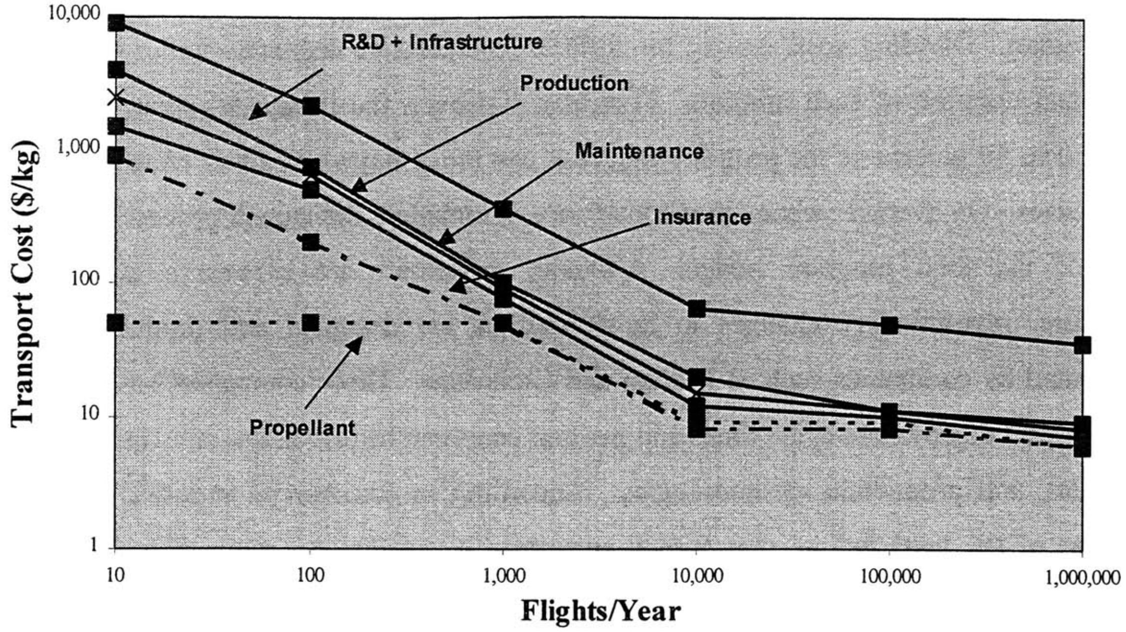

FIGURE 6-3 FLIGHT RATE VERSUS LAUNCH COSTS [30]

6.4 Impact of Launch Costs on Spacecraft Design

The high cost of launch has several significant effects on space projects. One of the most explicit examples of this is the limitation of the quantity and scope of a new space missions. With average launch costs around $75 million per mission, an organization with a $500 million budget is automatically limited to at most seven missions, without even considering the cost of building and operating the spacecraft. With the least expensive launch vehicle costing around $14 million per mission, the impact of launch costs is felt most strongly by small, inexpensive spacecraft systems. In these cases, the cost of launch can consume greater than 50 percent of the program budget and has an enormous influence on the potential scope of the mission. Furthermore, several innovative programs over the past 20 years have been able to reduce the cost of developing spacecraft systems while transportation costs have roughly remained flat or slightly increased (Figure 6-2).

Several studies have looked at the potential increase in the quantity and scope of spacecraft missions resulting from significantly reduced launch costs. The "Future Spacelift Requirements Study" prepared by the Aerospace Corporation looked a wide range of new space market opportunities that low launch costs could enable. The study identified 76 new space initiatives that could come to market within the next two decades. Each of the 76 projects identified was also evaluated to determine what level of cost reduction would be necessary for market plausibility. The results showed that a 3x reduction in costs enabled 14 percent of these missions, a 10x reduction enabled 21 percent of these missions and a 100x reduction enabled 80 percent of these missions. [31] Figure 6-4 shows the increase in scope illustrated by the projected number of new spacecraft missions.

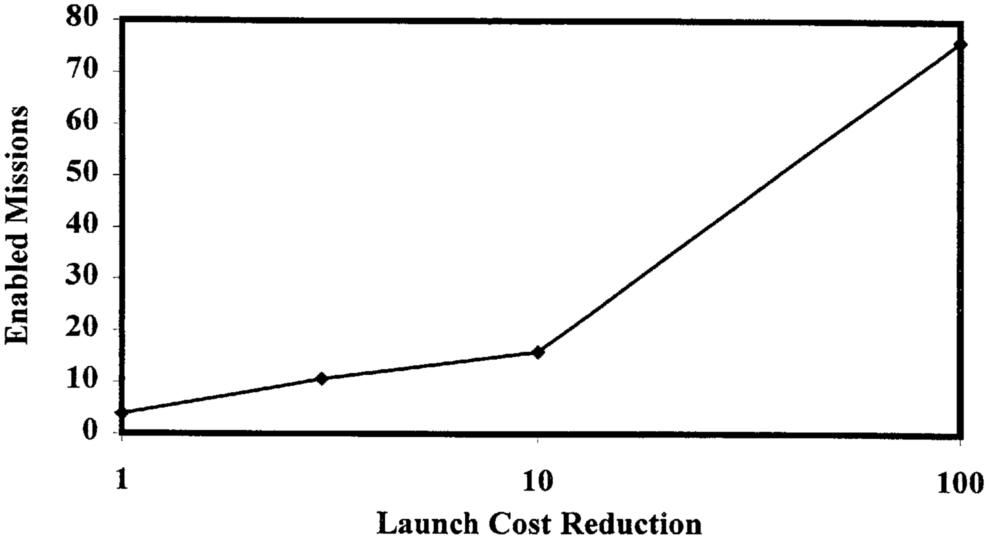

FIGURE 6-4 THE IMPACT OF LAUNCH COST REDUCTION ON NEW MISSIONS [31]

Beyond scope increases, reduced launch costs also have the potential to increase the actual quantity of spacecraft developed and deployed. Studies such as the "Future Spacelift Requirements Study" suggest that the price elasticity of demand for launch services follows a kinked function curve. Under this scenario, demand for a larger number of missions will increase very slightly for price reductions between the current $10,000 per kilogram and $1,000 per kilogram. In this region, the price elasticity of demand is near zero (inelastic) and significant price decreases have little to no effect on the quantity demanded. Once below $1,000 per kilogram, the demand curve begins to become more elastic with each unit price decrease generating an increase in demand. Part of the small increase is due to lower launch costs helping to close the business case of new missions that currently do not quite show positive net present values. A further order of magnitude reduction to around $100 per kilogram suggests that the market becomes increasingly elastic with smaller price reductions generating larger increases in demand. Figure 6-5 shows the kinked price elasticity of demand curve for launch services. This scenarios, while somewhat speculative, is typical of markets with high initial costs and characterizes the early aviation industry.

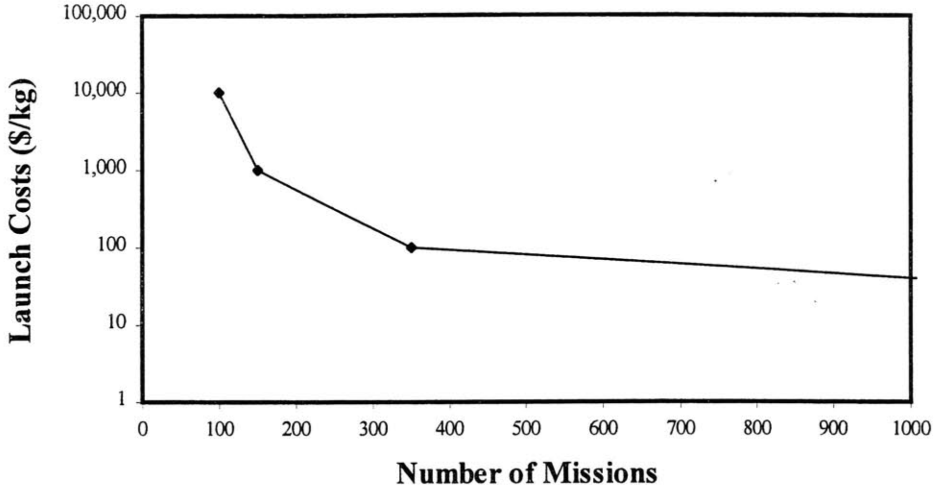

FIGURE 6-5 PRICE ELASTICITY OF DEMAND FOR LAUNCH SERVICES

One of the most important impacts of launch costs is the vicious cycle discussed in Chapter 1 where spacecraft missions need low transportation costs in order to be viable and more numerous, yet launch systems need more missions (higher flight rate) to reduce per flight costs and encourage additional funding for further improvements. In addition to suppressing demand, high launch costs also create the "high cost of failure" paradigm.

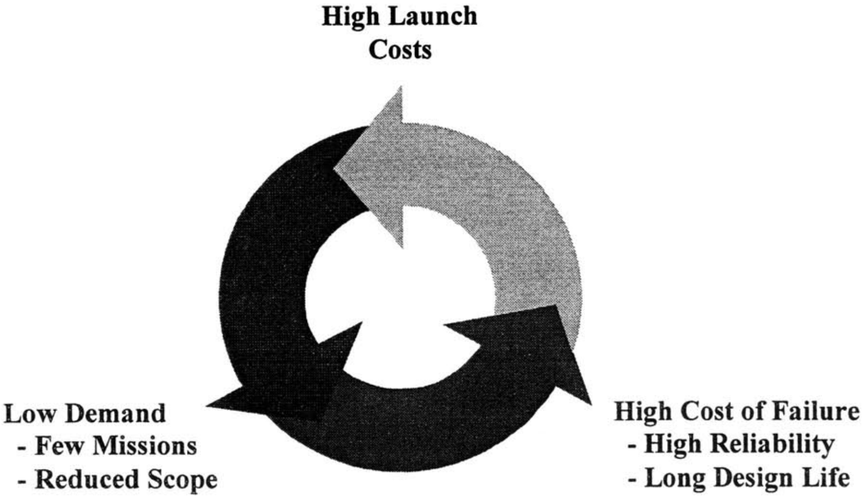

FIGURE 6-6 THE SPACECRAFT – LAUNCH VEHICLE VICIOUS CIRCLE [2]

The "high cost of failure" paradigm has secondary effects which also influence spacecraft system development. The high cost of failure mindset combined with lengthy vehicle procurement timelines and the inability to perform maintenance or servicing on-orbit drives high spacecraft reliability and high spacecraft functionality. Achieving high reliability requires extensive testing and qualifying processes which add significant costs and time to spacecraft development. It also suppresses the desire to insert many new technologies that have not yet been proven.

Along with high reliability, spacecraft designers faced with limited number of missions are pushed to stretch the functionality of each mission. Stretching mission functionality increases spacecraft system complexity and ultimately cost. In this context, system complexity refers to an index based on multiple measurable factors (number of mission objectives, number of parts, lines of code, degree of system inputs/outputs, etc). The actual relationship between complexity and cost has been found to follow the traditional exponential growth pattern, where small increases in complexity produce large increases in cost.[32]

Referring back to the vicious cycle, high launch costs limit the number of missions that can be funded leading to limits in vehicle and subsystem production volumes. Low production volumes eliminate the benefits of spreading non-recurring or fixed costs (R&D, equipment, etc) over multiple spacecraft system units. The potential cost reduction enabled through the transition to large production runs has been documented in the automobile and aircraft industries and most recently in the case of Iridium. [33] Additionally, switching to a automobile-style production system has also demonstrated the ability to improve product quality by emphasizing the process and design while minimizing end-stage testing. The largest obstacle to applying this rationale to spacecraft systems is that the demand for large quantities of the same spacecraft does not exist. Low lot sizes have also discouraged many suppliers from entering the market and driven many out of it. The electronics industry has been fighting aerospace's small quantity, high requirement parts for years by driving prices up to push space companies towards using COTS parts. In one example, an electronic part that cost less than $1 to produce and retailed for around $2.00, was sold at a price exceeding $1,500 because of extreme requirements for loads testing, radiation hardening, and other obscure spacecraft requirements. Additionally, many times even if more than one unit is purchased it is done over several years. One industry designer provided an example of a situation where a set of six components were purchased at a rate of one per year for six years at a cost of $2 million per component. Because of the cost of setup and tooling the purchase price could have been reduced by 50 percent to $1 million each had all of the components been purchased at once.

High launch costs impact companies replenishment strategies by driving spacecraft towards longer design lifetimes to avoid spending additional funds launching replacement satellites. There is also an arbitrage-like characteristic to launch prices involving differences between costs for delivery to LEO versus delivery to GEO. Several industry officials quoted that using a launch vehicle to get to GEO is twice as expensive as including a special boost stage on the spacecraft to make the final orbital altitude increase by itself. This forces spacecraft designers to address orbital transfer issues and in the process reduces available volume and mass when the boost stage is included.

6.5 Summary of Cost Impacts

Cost constraints result from the exorbitant price of purchasing a launch vehicle and are further amplified by insurance costs, range fees, and "drive-away" costs associated with mission-unique hardware. Excessive costs limit the number and scope of space missions, impede new market applications, and create a general "high cost of failure" mentality. The high cost of failure mindset discourages technology insertion, pushes high spacecraft reliabilities and testing, and causes developers to stretch spacecraft functionality. High launch costs also affect replenishment strategies pushing longer spacecraft lifetimes to avoid spend additional funds launching a replacement satellite. The summation of these cost impacts creates a vicious cycle for the space industry where spacecraft missions need low transportation costs in order to be viable and more numerous, yet launch systems need more missions (higher flight rate) to reduce per flight costs and encourage additional funding for further improvements.

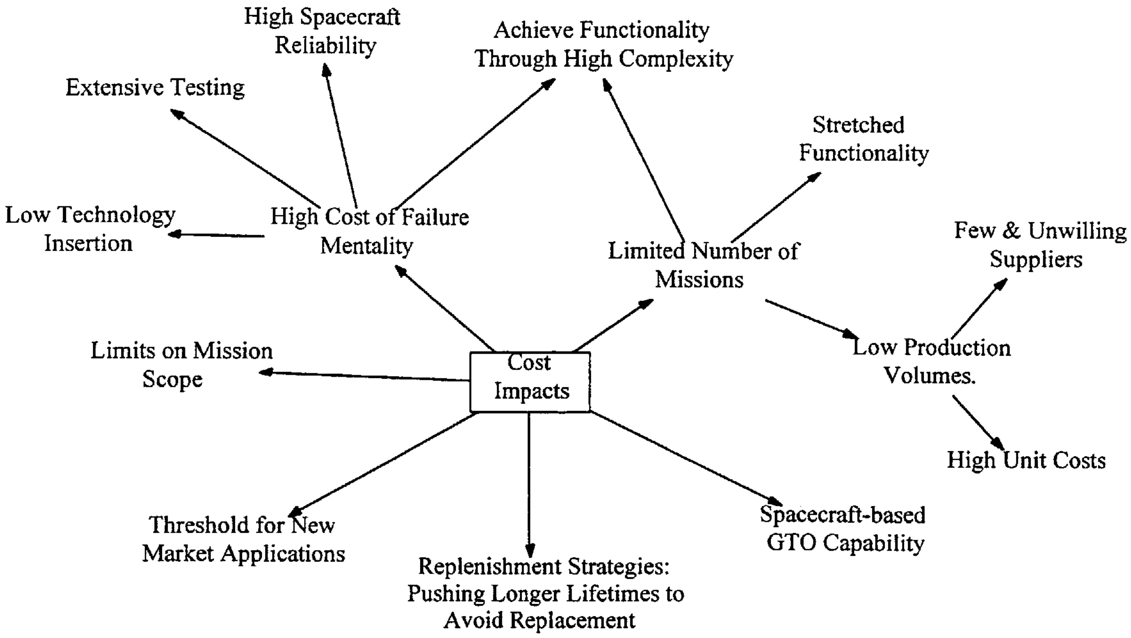

FIGURE 6-7 COST IMPACTS

CHAPTER 7 DISCUSSION OF POLICY CONSTRAINTS

7.1 Overview of Policy Constraints

While spacecraft developers are notorious for innovative and creative solutions to the very tangible technical, operational, and cost constraints they encounter, some of the most difficult constraints to manage exist in an intangible form and come through the launch vehicle from the realm of policy. What makes these policy constraints so difficult to address is that in contrast to technical and operational constraints, policy issues tend to be abstract and difficult to precisely define. Unlike engineering solutions where a "correct" or "optimal" solution can be verified by data and equations, policy solutions are rarely as straightforward and are virtually impossible to determine as being "correct." Policy constraints in the form of government regulations, national policy platforms, and strategic planning roadmaps for research and development can influence spacecraft system design. Ironically, current policy regarding future launch vehicle development is primarily responsible for determining the future technical, operational, and cost constraints.

This chapter focuses on how US national space transportation policy can influence the design and development of spacecraft systems. In contrast to the three previous chapters, this chapter takes a slightly approach to addressing the impact of policy constraints on spacecraft design. The chapter layout is shown in Figure 7-1. To better understand the role that policy plays in the design of spacecraft systems, it is first necessary to define the policy goals and the key players responsible for creating and implementing these polices. With the policy stage set, three policy topics are individually introduced each providing a historical synopsis of the major issues, a discussion of the current situation, and an analysis of how the existing policies impact spacecraft design. The three policy constraints that are addressed are:

> **Launch Quotas:** Limits on the number and pricing of foreign vehicles used to launch US payloads
>
> **Launch Vehicle Selection:** Mandated, pre-design choices of launch vehicles and prohibited use of foreign launch vehicles for US military and science missions
>
> **New Vehicle Development:** Decisions on future launch vehicle technologies and capabilities that will be available to the spacecraft community

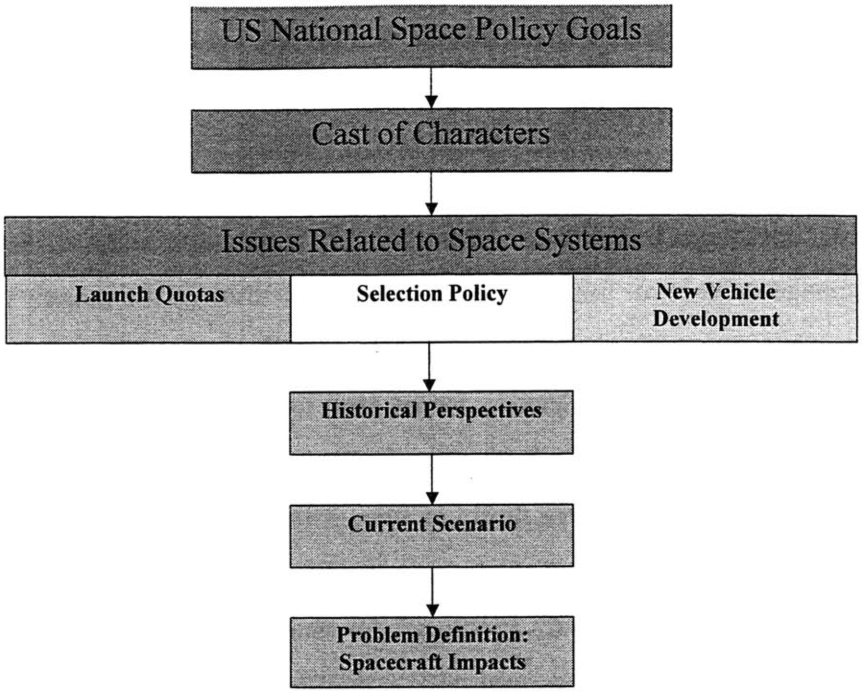

FIGURE 7-1 OUTLINE OF POLICY CHAPTER

The following overview of the US space transportation goals and the discussion of the cast of characters involved in the space transportation market serves to provide traceability and rationale for current policies. An understanding of the objectives that motivated the development of a particular space transportation policy puts the policy's impact on spacecraft development into perspective. Additionally, identifying the cast of characters, their roles, and their policy positions provides context for their policy reactions.

7.2 US National Space Transportation Policy Goals

The current space transportation policy was formulated by the National Science and Technology Council under the Clinton Administration. The National Space Transportation Policy released in August 1994 and the National Space Policy released in September 1996 highlight the objectives and implementation guidelines for achieving the United States' principal mission in space:

> "to maintain a leadership role in space by supporting a strong, stable and balanced national space program that serves our goals in national security, foreign policy, economic growth, environmental stewardship, and scientific and technical excellence." [34]

Drawing on these two recent policy documents, the key government objectives for the US space transportation industry are to:[35,36]

1) **Sustain and modernize** the existing space transportation infrastructure, capabilities, and the technology base to provide reliable and cost effective launch vehicle production and operational capabilities to meet national security, civil, and commercial requirements.

2) **Develop new technologies** through efficient investment of R&D resources to support future decisions on the development of next generation space transportation systems that greatly reduce the cost of space access while improving their reliability, operability, responsiveness, and safety.

3) **Leverage commercial sector capabilities** by encouraging the cost-effective use of commercially provided US products and services that meet government mission requirements, expanding the private sector role in federal space transportation R&D decisions, and supporting state and private sector investments in and use of space technologies to expand space markets and applications.

4) **Promote international cooperation** by opening US markets to the use of foreign launch systems, endorsing joint ventures that capitalize on foreign technologies and processes without becoming dependent on them, and maintaining stable and friendly political and trade-relations with partners and allies.

5) **Control ICBM proliferation** by limiting the use and spread of missile technologies and ensuring that launch technologies are used for peaceful space launch purposes.

6) **Foster commercial sector competitiveness** by preventing the adverse impacts of using excess US ballistic missile assets on the commercial sector, protecting US firms from non-market-based economies offering irrationally discounted launch prices, and considering commercial needs and in the formulation of US space transportation policies.

7.3 Key Stakeholders in the Space Transportation Industry

The development of the US space transportation policy involves a wide array of stakeholders. These stakeholders each play unique roles in the policy process from formulation through implementation of the policy plan. Four key roles can be identified: decision makers, influence brokers, implementers, and the affected. In this situation, the term affected refers organizations whose daily activities are affected (either positively or negatively) by the policy implementation. Organizations can and do play multiple roles throughout the policy process. The formulation of the policy plan occurs during an iterative dialogue between the influence brokers and the decision makers. Influence brokers provide both unbiased and biased information and options in an attempt to move policy in a particular direction. The role of the decision maker is to sift through this information to determine the final policy direction and the parties responsible for implementation. Table 7-1 outlines the different organizations involved, their objectives and responsibilities (related to launch), and their role(s) in the policy process.

TABLE 7-1 CAST OF CHARACTERS IN THE SPACE TRANSPORTATION MARKET

Stakeholder	Objectives/ Responsibilities	Policy Role(s)
Department of Defense	**Objective: Maintain national security & control of space** - Improvement & evolution of current US expendable launch vehicle fleet - Maintain capability to operate systems, infrastructure	Influencer Implementer Affected
National Aeronautics and Space Administration	**Objective: Conduct human exploration of space** - Provide improvement & operation of space shuttle system - Lead agency for technology develop for next generation RLV	Influencer Implementer Affected
Department of Transportation and Commerce	**Objective: Promote competitive commercial launch capability** - Identifying & promoting innovative types of arrangements between government & private sector	Influencer
US Launch Service Providers (prime contractors & suppliers)	**Objective: Maximize shareholder value; Profit** - Production of vehicle components & systems - Delivery of the customer's payload to desired orbit	Affected Influencer
US Spacecraft Developers (prime contractors & suppliers)	**Objective: Maximize shareholder value; Profit** - Production of spacecraft & payload - Manage until routine on-orbit operations & customer handoff	Affected Influencer
US Spacecraft Operators (Customers: scientists, military, commercial)	**Objective: Maximize shareholder value; Profit** - Operation of spacecraft & offer services to end users	Affected Influencer
US Congress: OMB	**Objective: Serve US public & government interests** - Allocation of funds for science & technology development	Decision Maker
White House Advisors: Office of Science & Technology Policy; National Science & Technology Council	**Objective: Provide scientific & technological analysis & judgment for the President** - Develop & implement sound science & technology policies & budgets - Work with the private sector to ensure Federal investments in science & technology contribute to economic prosperity, environmental quality, & national security	Decision Maker Influencer
Federal Aviation Administration	**Objective: Safe, secure, & efficient aerospace system for US** - Certification, regulation, & surveillance - Accident prevention - Safety Information Sharing & Analysis: Develop partnerships with the aviation community to share data & information supporting safe, secure aviation.	Decision Maker Implementer
Insurance Community	**Objective: Maximize shareholder value; Profit** - Provide financial protection for launch & spacecraft developers & payload customer in the event of an accident	Affected Influencer
Launch Range Operators (Government & Commercial)	**Objective: Safe operation of launch range; Profit** - Operate & maintain range equipment & facilities - Develop new range operations technologies	Affected Influencer
Foreign Launch & Spacecraft Providers & Operators	**Objective: Maximize shareholder value; Profit** - Produce, launch, & operate spacecraft systems	Affected

Formulating a set of policies that will completely satisfy the objectives of every stakeholder is highly unlikely. Thus, difficult trades and compromises must be made. Ultimately, the resulting policy will have impacts on all stakeholders, some positive and some negative. The essence of the space transportation policy focuses on the achieving the goals outlined in Section 7.2. However, in satisfying these goals of the launch segment, there are ramifications for other parts of the aerospace industry, mainly the spacecraft segment. The following sections discuss three policy issues that were formulated to achieve space transportation objectives yet have an adverse impact on spacecraft systems and are therefore deemed constraints.

7.4 Government Regulation: Launch Quotas

7.4.1 Constraint Definition

Launch quotas are government mandated limitations on the purchase of foreign launch vehicles be US spacecraft firms. As an instrument of foreign trade policy, quotas establish non-tariff barriers to international commerce in that they do not directly levy a tax or tariff on the foreign good. Instead, launch quotas place a limit on the number of US satellites that can be launched on foreign vehicles during a specified period and the price at which these vehicles are procured. The goal of these quotas is to protect US launch firms from unfair international market practices, consistent with goals number 1 and 6 in Section 7.2.

7.4.2 Historical Perspectives

With the fall of the Soviet Union in the early 1990's came increased concern over the possibility of non-economic-based launch systems entering the global commercial market. Russia and the Ukraine had a stable of launch vehicles that were eager to transform themselves into for-profit entities when Soviet government funding started to dry up. Throughout history, Russia has pursued a different approach to launch than the rest of the rest of the world. While US companies consumed precious launch pad time on the order of months by vertically erecting their vehicles right on the launch stand, Russia pioneered horizontal vehicle integration. Completed Russian rockets were rolled up to the launch stand via railroad, quickly erected, and launched within a matter of days. Russia also focused on achieving much higher flight rates, trading economies-of-scale cost reductions for slightly lower reliabilities. From 1970 through 1990, the Soviet Union averaged 90 plus launches a year compared to only 25 for the United

States. In fact, over the first 40 years of the space era, the Soviet Union performed 2,822 launches compared to the US's 979 and Europe's 211.[16] This difference in philosophy caused problems for US launch firms when the Soviet Union fell and the former government launch companies were free to turn to the private markets. Steady growth in the geostationary commercial launch services market combined with a growing trend towards LEO satellite constellations each requiring tens of launches could not alleviate US launch companies' concerns over Russia's market entrance. Many US firms worried that not only would the Russian launch companies be able to charge a lower price and capture significant market share, but they would also be easily able to handle the large number of new launches without having to build up additional production facilities (one of the factors that could slow a cheaper competitor from gaining greater market share).

Faced with growing concerns, the two largest launch companies at the time, McDonnell Douglas with its line of Delta vehicles and General Dynamics with its Atlas line, approached the US Congress for support. The result was a set of agreements with the governments of Russia, China, and the Ukraine that would set a limit on the number of launches each country could conduct for US customers to geostationary orbit. US launch companies were still recovering from the wild fluctuations in the mid 1980's when they were initially pushed out of business by the space shuttle only to be quickly revamped and brought back online following the Challenger disaster. The launch quotas were aimed at helping US companies regain their footing and compete on the global playing field. Additionally, national security concerns over maintaining a strong and reliable launch capability motivated Congress' actions.

The first agreement, signed into law in September 1993, granted Russia the right to launch eight US spacecraft to geostationary orbit during the period of 1994 through the end of the year 2000. Additionally, the agreement specified that the Russian launch companies could not charge a price more than 7.5 percent lower than the prevailing US launch prices for similar services. Roughly a year and a half later, a similar agreement was reached with the People's Republic of China granting a total of eleven launches to GEO from the date of signing through December 2001. However, increased demand for launches to geostationary orbit led lawmakers to insert a clause in the Chinese agreement allowing an additional 11 launches in the event that US demand for

GEO launches exceeded 20 per year. A similar extension was granted to the Russians in January 1996 which increased their quota to 15 launches and increased the price limit to 15 percent below prevailing US prices. Two additional agreements were signed with the Ukraine allowing five launches to wholly-owned Ukrainian companies and an additional 11 for the Sea Launch international joint venture whose members include the US based Boeing Company, the Ukrainian-based Yuzhnoye/PO Yuzhmash, and the Russian-based RSC Energia.[37]

7.4.3 Current Scenario

In 1998, 15 spacecraft and launch vehicle corporations came together to form the Satellite Industry Association (SIA) and delivered a letter to Vice President Al Gore requesting that the launch quotas be dropped but the price limits remain. In June 2000, President Clinton announced the end of the trade agreement with Ukraine effectively lifting all quotas on Ukrainian vehicles. As stated by President Clinton, "this decision eliminates launch quotas and gives US firms greater opportunity to enter into commercial space launch joint ventures with Ukrainian partners without limit."[38] It is interesting to note that this policy decision was not based on a burgeoning GEO satellite market or the adverse impact that quotas had on US spacecraft markets. With demand for Ukrainian vehicles well below quota limits, the final decision by the Clinton administration was essentially symbolic in showing support for the Ukraine's positive steps in missile non-proliferation, fostering closer ties between US and Ukrainian firms, and enabling important rocket technology transfer back to the US.

In December of 2000, the launch quotas for Russia were allowed to expire without an extension to the initial agreement. While many US and foreign firms were pleased with this result, some firms still lobbied for the quotas to be extended. US rocket makers such as Pratt and Whitney and Aerojet were concerned over the practice of using Russian and Ukrainian rocket engines on US vehicles such as the new Lockheed Martin Atlas V. US engine firms saw the quotas as the only method of protecting themselves from the superior and less expensive foreign rivals. With the expiration of launch quotas for both Russia and the Ukraine, both countries were free to sell as many vehicles as they wanted and at prices that they determined. At present, the Chinese quotas are set to expire in December 2001.

7.4.4 Impact of Quotas on Spacecraft Design

There are two key instruments to the US policy on the use of foreign launch vehicles: 1) the limit on the number of US satellites that can be launched on foreign vehicles and 2) the price at which these vehicles can be procured. While the initial policy was developed in an effort to make sure the US launch industry stayed healthy and could compete in the world market, the policy takes a very one-sided view of the US space market trading benefits for the launch vehicle companies against benefits for the spacecraft sector. Both the quota and the price restriction, essentially a non-tariff trade barrier, have a significant influence on the space system development.

The impact of price control is fairly straightforward. Drawing on economics theory, the government essentially setup price supports or price floors for launch services available to US customers. The effect is that prices are held above their equilibrium levels. The end result of such price floors is a combination of excess supply and reduced demand shown in Figure 7-2 at point 1. The global launch market experienced excess supply with more companies interested to launching payloads than payloads for them to launch. The spacecraft developers' demand also was lower than its equilibrium levels because of the artificially held-up prices. In most economic scenarios involving government price fixing, the excess supply from such a government instituted policy is absorbed by the government agency. This is typical of price supports in industries that are considered of national importance such as agriculture. However, this did not happen because the excess supply was existed in the foreign market. While many US launch companies were able to book orders, the Russian, Ukrainian, and Chinese companies were forced to deal with the excess capacity and eventually agreed to the quotas and higher prices to sell their vehicles.

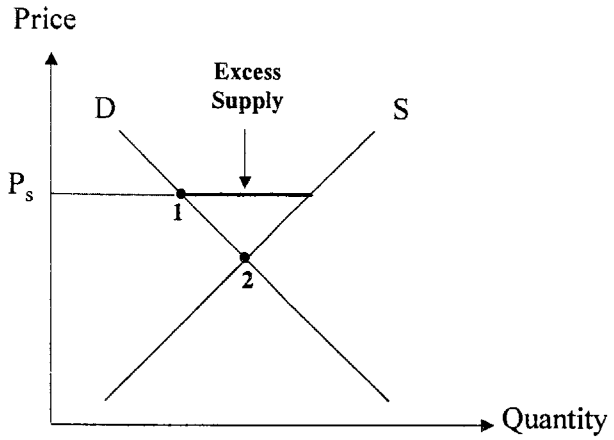

FIGURE 7-2 ECONOMIC IMPACT OF LAUNCH QUOTAS IN THE MARKET[13]

More important, from a US standpoint, than the excess supply of foreign vehicles is the influence of the price floors on spacecraft demand. Had the foreign launch companies been allowed to offer their services at much lower prices, it is highly likely that demand for these services would have increased, moving from point 1 to point 2 in Figure 7-2. The increase in demand, while difficult to predict an actual number, is extremely probably given the significant portion of program costs that launch consumes and the likely discount in the price of foreign vehicles. With some programs spending more than 50 percent of their budget on launch services, the availability of lower launch costs would have enabled missions which under existing US prices the business case did not close. In the long run, some of this increased demand would have been diverted back to US vehicles. Additionally, the increase in the spacecraft market could have been substantial if the discounted foreign prices came in below the critical threshold described in Chapter 6 where the elasticity of demand changes from being almost completely inelastic to being very elastic. Lawmakers attempting to protect the US launch industry actually hurt the spacecraft industry.

The US government's desire to try to protect its launch industry from potential dumping practices by foreign, non-economic-based launch companies does make economic sense. Without any restrictions, foreign companies could charge extremely low prices to capture significant amounts of the US and world market. The end result would be huge loses for US launch companies and a likely decrease in the US launch capabilities, sparking concerns over US national security issues. However, the consequence of this price floor is that it does not give any incentive to the US companies to attempt to lower their prices over the long term. US launch companies have a difficult choice to make. On the one hand, if they reduce prices to match the foreign competitors, the foreign competitors can continue to lower their prices 15 percent below the US prices. Taking this route could lead to a vicious price reduction spiral which would benefit the spacecraft community but probably destroy the US launch industry. The other option is to offer a better service to lure customers with higher reliability or performance. While the benefits of this are obvious, the drawback is that prices remain high. So the end result of the price controls is a likely increase in service without immediate or long-term price relief. While performance, reliability, and other service attributes are important, as mentioned above, cost can be a deciding factor in closing the business case for a new market opportunity.

Beyond price impacts for spacecraft developers, the quotas also affected the selection of vehicles available to US customers. In the late 1980's, prior to the initial agreement with the Russians, the average annual launch rate for US commercial payloads to GEO was eight. Forecasts predicted 56 spacecraft would be launched during the agreement period from 1993 through 2000. Thus, 1-of-8 US spacecraft would be able to purchase a Russian vehicle if they wanted to. This represents a significant limitation on selection and creates an auction-like environment for Russian vehicles. However, the initial estimates were too low and in the mid 1990's the number of launches to GEO grew significantly. In 1999 alone, 21 commercial communications satellites (28 total) were launched into geostationary orbit with the total between 1989 and 1999 at 182 spacecraft. The ratio of US spacecraft allowed to be launched on Russian vehicles would have been reduced to 1-of-23 without the quota extension but instead was closer to 1-of-17 with the extension. Similar scenarios can be worked through for Russian and Ukrainian vehicles. Taking all of the quota limits combined, US payloads had access to 35 foreign vehicles before extensions and a total of 53 with extensions. This means that somewhere between 1-of-3 and 1-of-5 US spacecraft could use a foreign vehicle. Yet, not all vehicles are the same and some are more desired than others. The end result in any case is a limitation on selection.

While the quotas on the number of foreign rockets available for purchase affected the price and selection available for US spacecraft developers (with all of the technical ramifications) it also had the potential to create a much more dangerous situation. Prior to the late 1990's, the US spacecraft industry was significantly ahead of foreign spacecraft producers. This forced most US and foreign service providers to purchase US spacecraft which had better performance capabilities and were less expensive. The US spacecraft industry enjoyed a near monopoly in securing contracts for large geosynchronous spacecrafts. In the late 1990's, however, other countries' spacecraft designers started to catch-up. This provided additional options for foreign countries interested in avoiding the US government-imposed launch constraints and securing less expensive launches. Limits on the number of US satellites that could go on Russian rockets meant that a foreign service provider, in an attempt to reduce overall costs, might choose a more expensive foreign-made spacecraft and launch it on a cheaper Russian rocket. This would allow them to completely circumnavigate the quota issue as well as other US imposed technology transfer regulations.

Another major development was the increase in popularity of using LEO orbits to perform some of the same GEO missions. The initial launch agreements only handled payloads headed for geosynchronous orbits and not low Earth orbits. As the LEO markets rapidly grew with the arrival of massive constellations such as Iridium's 66 satellite constellation and Globalstar's 52 satellite constellation, US launchers began to worry that Russian and Ukrainian stockpiles of ICBM's could be put into service, severely undercutting US prices and capturing a significant portion of the un-quota-protected LEO market. In response, US companies initiated international joint venture partnerships pairing US and Russian/Ukrainian launch companies. This further complicated the GEO quota-regulated situation by blurring the categorization of companies as being foreign versus domestic. US firms seized the opportunity to utilize and learn from superior Russian and Ukrainian rocket technology yet were stung by their own previously lobbied for quota protection system.

7.4.5 Summary of Launch Quotas Impacts

Government regulations can have both positive and negative impacts on the space system market usually as a trade-off between the launch industry and the spacecraft industry. It is tough to completely satisfy organizations from both sectors. The impacts discussed above show how policy geared towards the launch industry can ultimately have a substantial impact on spacecraft systems. Equally true is the possibility of spacecraft focused policy affecting the launch industry.

In defining the future policy, emphasis should be placed on proactive versus reactive policies. Launch quotas and price controls are reactive policies which were put in place to protect US markets. The mere fact that the US markets needed to be protected pointed to a more profound problem that should be addressed. The fact that Russia has much better rocket technology begs the question why? The answer is simple. In the last 30 years (up until 1999), Russia has developed 45 different rocket engines while the US has developed only one, the Space Shuttle Main Engine. [39] While the potential prices that Russia, Ukraine, and China might have charged without quotas and price controls in place would probably be considered too low, or below the appropriate market equilibrium, it is also likely that the US prices were probably too high, or above market equilibrium and should come down over time. This is further supported by the discussion in Chapter 6 of the stagnating launch prices in the US from 1975 through 1993 when foreign competition entered the picture. The primary space system impacts of the US governments launch quota regulations:

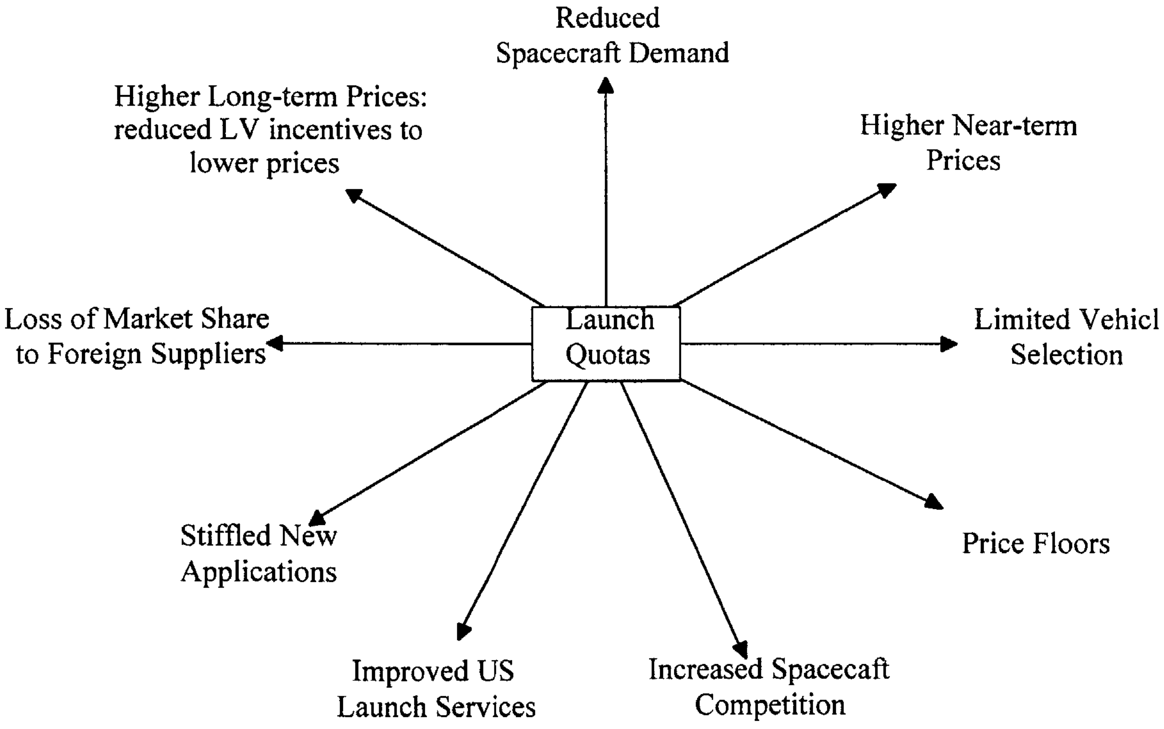

FIGURE 7-3 IMPACT OF LAUNCH QUOTA POLICY ON SPACE SYSTEMS

7.5 Vehicle Selection

7.5.1 Constraint Definition

The process used to select a launch vehicle for a specific spacecraft mission involves a wide array of technical, operational, and political parameters. While technical and operational parameters initially define the trade space for applicable vehicles narrowing the selection possibilities, the final verdict relies on a policy decision. Mission type and the managing organization play a significant role in this process. While the number of launch vehicles available is not countless, there are enough vehicles so that the majority of missions have several options.

During the selection process, different attributes, or constraints, of the launch vehicle are considered over time. For example, initial factors considered might include lift capacity or volume available. Using these attributes, it is possible for the spacecraft designer to define the trade-space and identify how many vehicles might fit the spacecraft systems specifications. A second set of attributes such as cost, reliability or country of origin then helps contrast the remaining candidates. The diversity of most space missions combined with the complex interactions/ coupling of launch constraints make each vehicle selection a unique process.

While there is no formal selection process that can be applied across all missions, the discriminating factors/constraints can be broken down into three categories depending on their degree of influence and level of rigidity, as specified in Chapter 3. First tier factors have substantial design impacts and are either impossible or extremely difficult to trade-off. Second tier constraints also have significant design impacts, usually can be traded, and are the most influential in making the final choice from the suitable vehicles. The third tier factors usually do not have a large influence on the selection decision but can be traded and do impact the spacecraft design following selection. As previously mentioned, diversity across space missions and requirements can alter which tier a constraint falls under. For example, while loads and environments are traditionally a third tier factor, there are cases where certain launch vehicles have substantially different physical environments that the loads become a second tier factor and can be principally responsible for a selection decision. Table 7-2 shows the typical characteristics/constraints that are considered in selecting a vehicle by tier.

TABLE 7-2 TIERED STRUCTURE OF LAUNCH VEHICLE SELECTION CRITERIA

Tier # 1	**Tier # 2**	**Tier # 3**
Government Regulations	Cost	Loads
Availability	Reliability	Environments
Lift Capacity	Partnerships	Schedule
Volume Available	Insurance	Launch location
Orbital Location		Interfaces

7.5.1.1 First Tier Constraints

For Tier 1 constraints, most cannot be traded. Government regulations might stipulate that only a US vehicle can be used or quotas can eliminate the potential of using a foreign vehicle. Availability is also a firm, non-tradable constraint. Even if a vehicle's characteristics, cost, loads, etc, perfectly match a spacecraft, if the vehicle is offline for some reason, it is simply not possible to order or procure (at least not in near term). Mass and volume limits can also be fixed constraints if the approximate weight of the spacecraft is known early in the design selection phase. A spacecraft forecast to weigh at least 2,000 kilograms and measure 4 meters in diameter simply cannot fit on a vehicle designed to lift 500 kilograms with a fairing only 3 meters across. Finally, some vehicles because of launch location or performance specifications cannot deliver payloads into certain orbits such as polar or geostationary.

7.5.1.2 Second Tier Constraints

Second tier constraints have some flexibility. While programs do have limited budgets, it is possible to spend less on other aspects such as the spacecraft or operations in order to spend more on launch or vice versa. Many times spacecraft developers set a minimum reliability level or the amount of risk they are willing to take based on the value and importance of the space mission. However, the firmness of this threshold depends on the risk profile of the space mission. While the loss of a spacecraft is a considerable financial blow to all programs, a special spacecraft requiring ten years of development and bound for Jupiter has a different risk profile from a simple LEO communications spacecraft. To save costs or move up a launch date, some programs will make a trade with reliability.

Vehicle reliabilities can also be subjective. A vehicle that failed during its first three flights but has since achieved 20 successful flights is not viewed the same as a vehicle who made 20 successful flights but lost the last three even though they have the same mathematical reliability record. Ownership also plays a substantial role as a spacecraft owner might see reliability as tier 1 (only accepting vehicles with reliabilities above 99 percent) while the spacecraft designer would see launch reliability as second tier constraint. Insurance costs are also flexible, depending on the value of the spacecraft and the reliability of the vehicle selected. Partnership constraints refer to situations involving international joint ventures or consortia that might initially agree to launch a specified number of spacecraft on a vehicle from each country. This type of agreement is also flexible and can be traded.

7.5.1.3 Third Tier Constraints

Although third tier constraints can influence the final decision, they are usually the ones that designers accommodate or "live with." Third tier factors do not drive selection, instead they come into play as cost adjustments and design drivers. Industry tends to address these in an attempt to satisfy and encourage repeat customers. While there are physical differences among launch providers, it is rare to see vehicle parameters too far off the average for risk of losing customers. Thus, things like loads, interfaces, and environments which could be deciding factors are usually not because vehicles tend to migrate toward a central standard. Launch locations refers to the launcher country of origin. If a spacecraft is allowed to launch on a foreign vehicle, technology transfer regulations dictate specific procedures and technology protection mechanisms which must be put into place affecting the vehicle design. Additional costs are also incurred to pay travel, accommodations, and service fees for the required US Air Force Lt Col escort responsible for overseeing all domestic payloads launched on foreign vehicles. Finally, although launch manifests fill up years in advance, the ability to negotiate schedule changes or possibly changing dates with another payload allow some schedule flexibility.

7.5.2 Historical Perspectives

Following the extremely successful Apollo program, NASA embarked on a quest to develop an aircraft-like launch system offering complete reusablility, low operations costs, high reliability, and quick launch schedules. Belief in the prospects of the new system were so high that space transportation policy was set to eventually transition all US payloads, both government and commercial, to the US Space Transportation System (STS), or the Space Shuttle Fleet. As the shuttle was set to enter service 1981, the three primary US expendable launch vehicle systems prepared to close down operations. Figure 7-4 shows the significant decline between 1975 and 1985 from 26 launches per year to 7. During the same period, the space shuttle came online and began to ramp up its flight rate from 2 in 1981 to 9 in 1985 (Figure 7-5).

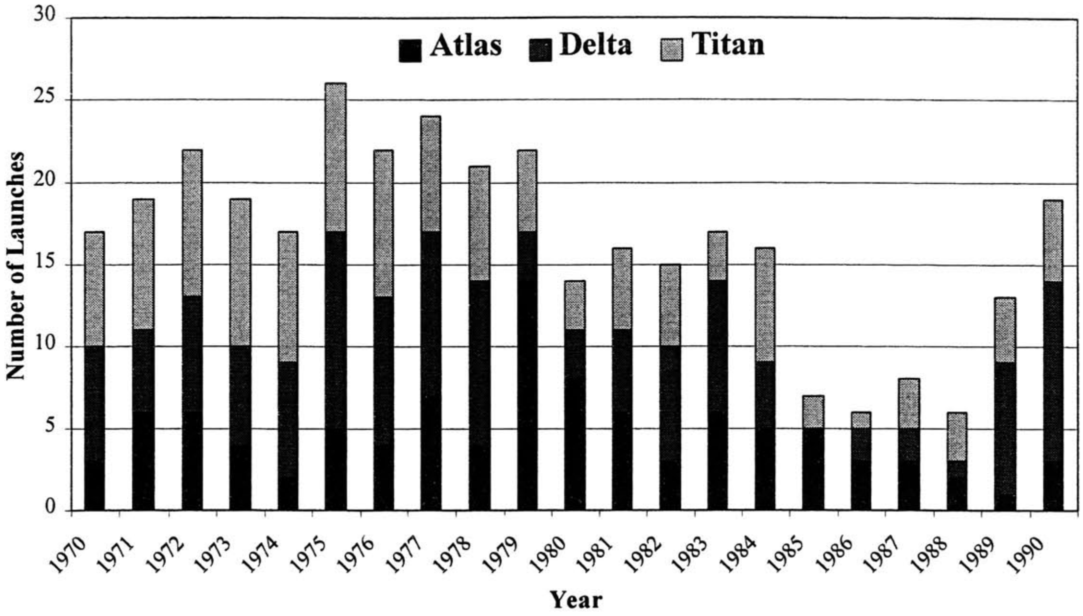

FIGURE 7-4 LAUNCHES ON THREE MAIN US EXPENDABLE VEHICLES[16]

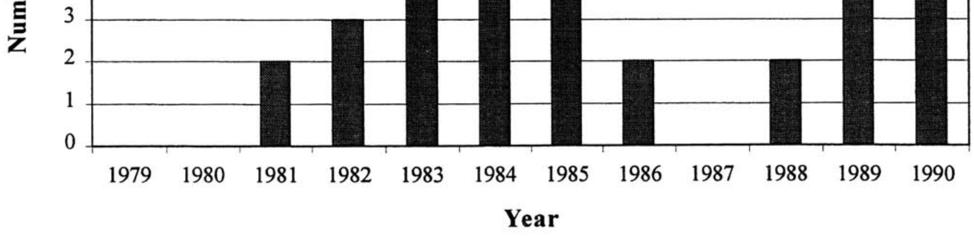

FIGURE 7-5 SHUTTLE LAUNCHES

A strategy requiring all spacecraft to fly on a single launch system is inherently risky. The loss of space shuttle Challenger in January 1986 is ample proof of the significant flaws in this policy. In the wake of the Challenger accident, non-government payloads were restricted from using the shuttle. With the shuttle program offline for over 32 months, both government and commercial payloads were forced to look for alternative routes into space. Foreign launch vehicles such as the Ariane gained market share while the US commercial expendables took several years to regain normal operations. When the shuttle came back online, the majority of flights served the science community as the military decided to adopt a policy of maintaining a wider selection of expendable vehicles.

7.5.3 Current Scenario

Currently, all US military missions are restricted to using US domestically owned, produced, and operated expendable launch vehicles. The rationale for this policy (consistent with goals 1 and 5 in Section 7.2) involves maintaining complete control over military assets and operations, supporting assured strategic launch capabilities, and denying foreign access to advanced military technologies to both allies and rivals in order to sustain US military superiority and protect national security. Military programs traditionally provide what industry labels Government Furnished Equipment (GFE). Government Furnished Equipment refers to situations where the military program office responsible for running a particular mission will approach a spacecraft developer with a launch vehicle already procured or on contract. Potential to trade vehicles is low even if less expensive opportunities arise. Recent examples of this include advanced procurement of a precise number of launches on each of the Boeing Delta IV and the Lockheed Martin Atlas V Evolved Expendable Launch Vehicles (EELV). Well in advance of design requirements, specific missions were committed to either of the vehicles. In one mission requiring three launches, designers were forced to design for both vehicles with two satellites manifested on one vehicle and one on the other. This adds costs in that they must design the spacecraft to accommodate the constraints of both vehicles which are unique enough to affect program costs an schedule.

Non-military government missions flown by NASA, NOAA, and other civil organizations are also usually restricted to using US vehicles. These missions typically have slightly more flexibility to select among available US options although GFE issues also occur. For international scientific collaboration funded by multiple countries, mission planners have more flexibility to select foreign launchers. Several joint NASA-ESA Mars missions have looked into options of using US vehicles or flying piggyback on the large ESA Ariane vehicle. Hardware, supplies, and personnel launches aboard both the US shuttle and the Russian Soyuz rocket for the International Space Station exemplifies the selection flexibility offered to science missions.

In the commercial world, companies have much more freedom in selecting either US or foreign vehicles, although as outlined in the previous section, there can be limits on the number of vehicles that may be used from a particular foreign country. Flexibility in commercial selections follows a wide range of scenarios. Selection can be completely flexible in the case of turn-key solution requests. In this situation the customer waives any selection authority and simply asks for a capability and the spacecraft developer arranges everything from launch through operations. Other times commercial ventures may stipulate that they would like to purchase vehicle 'X' because they have used it in the past and were comfortable with its performance. Or a company may specify a particular vehicle that they refuse to use as Globalstar did for the Zenit 2 vehicle after losing 12 spacecraft on a single launch (discussed in Section 5.4.2). Finally, there are situations where a company is part of an international consortium and as part of a business agreement or contract, they have specified that so many spacecraft would be launched on a vehicle from each country. This is typical of large communications constellations that also hope to capture customers in various countries. A US built spacecraft for an international communications company that wants to place a ground station and offer service in China might decide to launch several elements of its constellation on a Long March vehicle as part of negotiations for market access and to improve local publicity. Commercial launch companies also sometimes start joint ventures with spacecraft firms where the launch service provider invests in the spacecraft system provided it is launched on one of its rockets. Finally, in some cases the spacecraft developer, the launch vehicle, and the end operator are all owned by a single entity and the company's vehicle selection is dictated by a policy to use its own assets.

7.5.4 Impact of Selection Policy on Spacecraft Design

Prior to selection of a vehicle, the ability to make design trades is high. At this point, the spacecraft system has an incredible degree of flexibility. For an individual spacecraft, the system can grow, shrink, or change in a myriad of ways to meet initial or altered mission requirements. For a constellation of spacecraft, architectural decisions can change from deploying 10 small spacecraft equally distributing mission functionality to single mothership approach with one large spacecraft coordinating functionality across 2 or 3 daughter satellites. The ability to make trades at the system level opens up a range of possibilities that might enable meeting mission requirements for lower costs, shorter schedules, or with improved system characteristics. Figure 7-6 demonstrates how a space system architecture might change from design iteration A through D as different launch attributes are weighed and considered and traded across system boundaries.

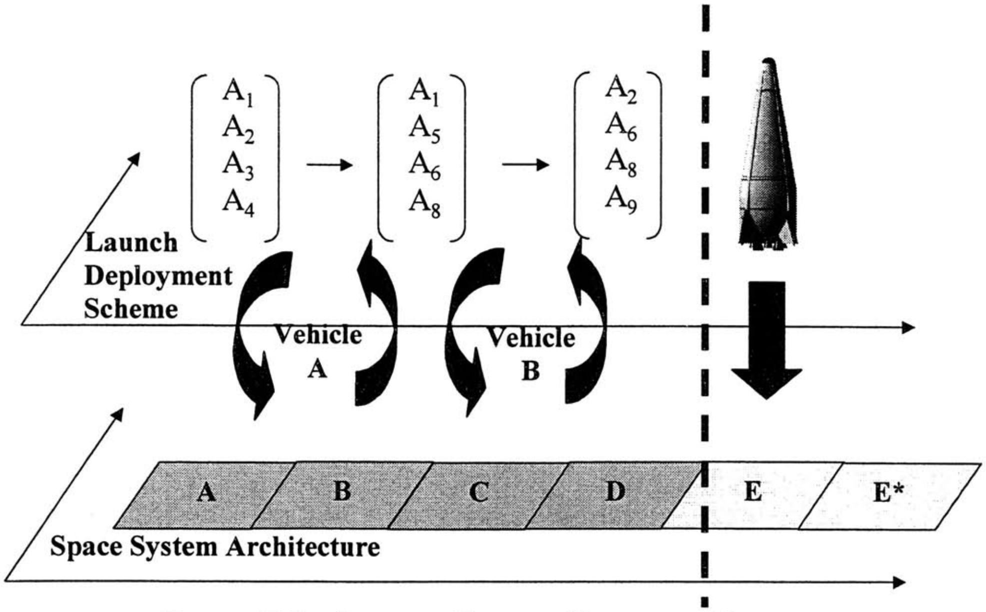

FIGURE 7-6 LAUNCH VEHICLE SELECTION PROCESS

Once the vehicle is selected (design E), the vehicle constraints become fixed and it is not possible to make trades between launch and the spacecraft. Thus, changes to the spacecraft, moving from E to E* represents sub-system changes within launch constraint limits (some slight changes can be made such as damping loads with special adapters, etc but not without penalties). Design trades and optimization can only occur between the spacecraft bus elements and the payload. As was demonstrated in Chapter 4, with semi-generic spacecraft buses, the payload is usually affected most reducing performance capabilities. The interaction changes from a dynamic system with feedback loops between the spacecraft and the launch vehicle to a one-way flow of launch constraints imposed on the spacecraft system design, represented in Figure 7-7.

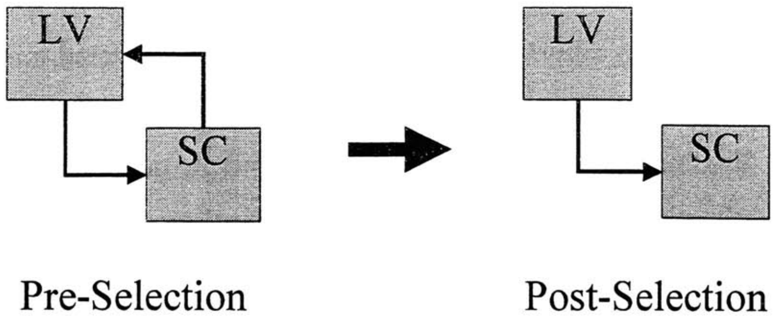

FIGURE 7-7 LAUNCH – SPACECRAFT INFLUENCE CHANGES FOLLOWING SELECTION

In the early space shuttle era circa 1985, the selection line in Figure 7-6 was located at the extreme left for all commercial, civil, and military missions. Following the Challenger accident, the military relaxed to some extent moving the line slightly to the right. However, most military programs are still far to the left, dictating which vehicles will be used among a limited set of choices. Figure 7-8 shows a comparison of today's military, civil, and commercial vehicle selection policy compared to that under the shuttle program.

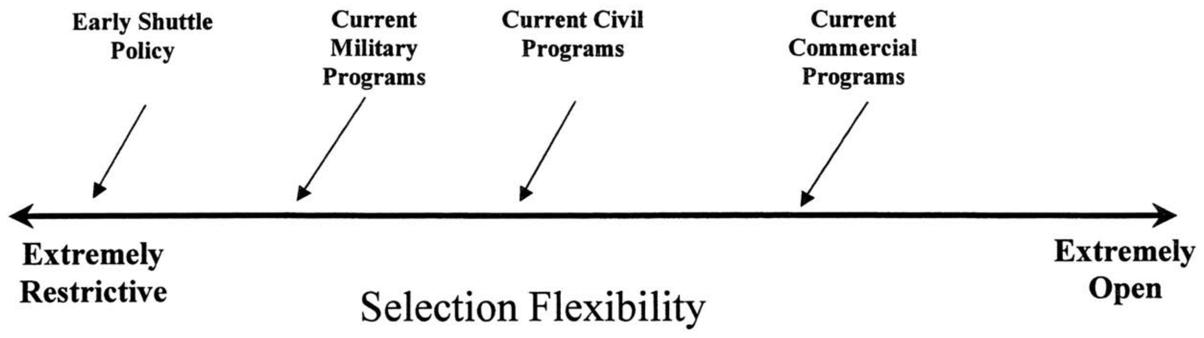

FIGURE 7-8 SELECTION FLEXIBILITY SCALE

The selection of the launch vehicle has some unique impacts on spacecraft system design. In the case of a military or science mission that is told what vehicle will be procured for the program, the selection defines the physical constraints imposed by the vehicle. At this point, the designers face the following situation: "we have x kilograms to use, how shall we budget between subsystems?" This approach to spacecraft design, although very common, is quite backward.

The user needs and utility profile should lead to a process where spacecraft architecture, launch strategies, and on-orbit operations are traded to maximize customer utility/value for an agreed upon cost and schedule. However, forced into a launch system does not allow the designer to perform these trades.

Altering a selection decision far into a program can also have significant design impacts. Choosing to switch launch vehicles because of a recent launch failure or political pressures (such as forced trade sanctions reflecting political conflicts) can have enormous design consequences, especially since most spacecraft are optimized for a single vehicle. Changing vehicles obviously involves potential mass, volume, and loads parameters differences. However, even if another vehicle is found that meets these requirements, other factors such the need to change the spacecraft center of mass to balance one the new vehicle or structural changes related to where the spacecraft fits in the fairing can also must be addressed. One recent example is the NASA LAPSE program which was required from day one to be designed for use on an Orbital Sciences' Pegasus vehicle. As the loads impact discussion in Chapter 3 laid out, the unique horizontal integration and horizontal launch regime for the Pegasus vehicle leads to very specific design choices. Moving the LAPSE mission to another vehicle, one that is processed and launched vertically, leads to a significant design changes to parts the spacecraft structural system.

In the commercial communications world, use of a generic spacecraft buses continues to gain acceptance. Most firms develop a set of two to four spacecraft buses that are designed to each capture a distinct parts of the market. Customers approach the designer with a required capability and through a series of discussions, the two sides determine which pre-designed bus will fit the mission. This may mean the customer accepts slightly less capability to use a smaller bus or slightly more capability for a larger bus. This move to a more modular approach can reduce design and manufacturing costs while fixing a large portion of the spacecraft design upfront. As mentioned in Chapter 3, using a fixed, pre-designed bus does transfers the burden of weight and volume reductions to the payload in the event that the spacecraft overshoots design limits. Thus, the risks of losing spacecraft capability must be weighed against the lower cost of generic buses. Generic buses are not as widely for military and science missions due to unique mission requirements.

However, the most important aspect of generic commercial buses related to launch is that they are designed to be compliant with a range of vehicles. New buses are designed to fit a range of vehicle envelopes, weight classes, and loads environments. As newer launch vehicles move closer to common standards, this will continue to benefit generic bus systems. For example, the oldest active Boeing spacecraft bus, the 376, is configured to fit on a Delta II or as a dual manifest on the Ariane IV and the newer Boeing 601 fits on an Atlas II, Delta III, or a dual manifest Ariane V. The newest Boeing spacecraft, 702, was designed to fit on a Delta III, a Delta IV, an Atlas III, and an Atlas V. Thus, in the commercial world, spacecraft owners can actually purchase the launch vehicle much later in the program (although they must be concerned with getting on the launch manifest). In a commercial market environment, this flexibility is extremely important to manage dynamic market changes.

7.5.5 Summary Vehicle Selection Impacts

The policy used to select the launch vehicle as well as the actual selection has significant affects on spacecraft system design and development. Selection policies set to maintain launch capabilities or to lower program costs many times have unintended or unforeseen consequences. In contrast, the ramifications of some policies, such as forcing all spacecraft onto a single vehicle, have clear impacts but were ignored for lack of sound judgment. The primary space system impacts of launch selection and selection policy:

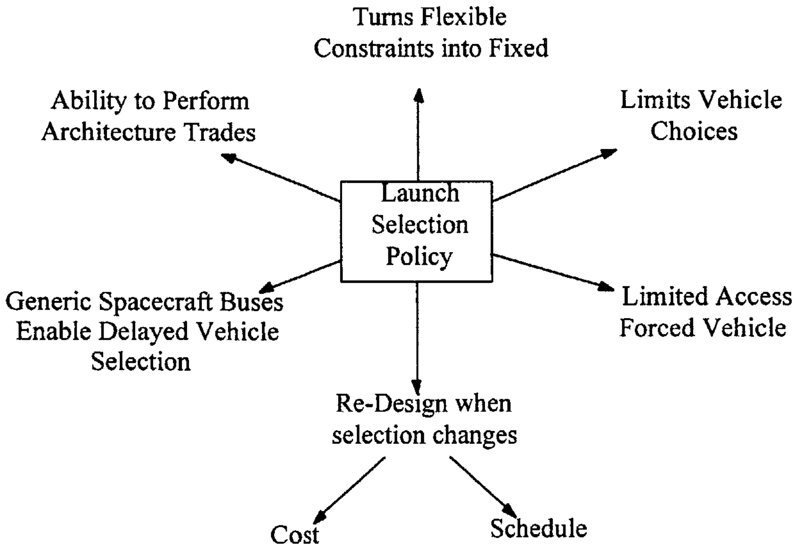

FIGURE 7-9 LAUNCH SELECTION POLICY IMPACTS

7.6 *Government Future Space Transportation Policy*

7.6.1 Overview of R&D Policy

The current set of launch constraints owe their existence to past research and development policy. Vehicles currently online today trace their history back to both commercial and government decisions at least 10 years ago, some much more. Market conditions and future forecasts drove policy decisions determining what modifications to make to existing vehicles, what functionality would be necessary for future vehicles, and what new technology would be necessary to invest in. Timelines and budgets are then coordinated to attain the determined goals. In this manner, R&D and strategic planning policy have a significant impact on technical and operational launch vehicle characteristics and thus, constraints. Looking forward, current R&D policy decisions will ultimately have a significant impact on future spacecraft systems.

In order to understand how future launch vehicle constraints will impact spacecraft system design and development, it is necessary to fathom the direction that launch vehicles themselves are taking and utilize this understanding to look ahead at the possible ramifications for future spacecraft systems. The following discussion assesses the US government's space transportation research and development policy examining previous federal programs to stimulate advanced vehicle development, the current policy, and its potential impact on future spacecraft systems.

7.6.2 Historical Perspectives

Space transportation policy in the US can be broken down into three clear periods of policy direction. From the beginning of the space era in 1957 through the end of Apollo, space transportation policy followed as an extension of military ballistic missile programs. From 1972 through 1986, the prevailing policy focused on developing a single vehicle to meet all space access needs through the US Space Transportation System (STS) or the space shuttle. Work on expendables gradually declined as it was believed that reusable launch vehicles were the future. Following the Challenger accident in 1986, this policy was replaced with a diversification strategy focused on bringing expendable vehicles back online for commercial and military programs and reserving the reusable shuttle for science missions. This final period, lasting up through 2001, could be labeled the "period of policy confusion" with space transportation policy lacking consistency. Over the last 15 years, policy changes have led to a continual migration from program to program in an attempt to offer a range of options but also seeking the elusive "holy grail" of space access: the low cost, high reliability, fully reusable Single Stage to Orbit (SSTO) vehicle. NASA's Space Launch Initiative launched in early 2001 represents the newest chapter in the "policy confusion" period.

7.6.2.1 US Space Policy Historical Perspectives: 1960 to 1972

The first launch vehicle programs grew out of the shadow of the military's ballistic missile programs from the 1940's and 1950's. Te first set of vehicles used in the late 1950's and early 1960's were actually converted Intercontinental Ballistic Missiles (ICBM's). The first real rocket development occurred during the build-up for the Apollo program which resulted in the mammoth Saturn series of vehicle which eventually delivered the Apollo astronauts to the Moon.

7.6.2.2 US Space Policy Historical Perspectives: 1972 to 1986

Towards the end of the highly successful Apollo program, NASA began to structure a new set of goals aimed at the continued human exploration of space. Eager to maintain a consistent budget, NASA realized that a new large-scale program was necessary to fill the gap when the Apollo program came to a close. The prevailing opinion supported the development of a space station in low earth orbit to enable long duration stays in space and to pave the way for future space colonization of the Moon and eventually Mars and beyond. In order to accomplish these goals, the first logical step was the development of a robust and cost-effective means for reaching orbit for personnel and extremely large amounts of cargo. Thus, the idea of a space taxi was conceived and the Space Transportation System (STS) or the space shuttle program was born. Requirements for the space shuttle were derived from its potential missions to the space station. Additionally, NASA envisioned a vehicle so advanced that it would be able to handle military as well as commercial needs for space access.

Amid budgetary pressures and requirements arguments, the space shuttle morphed from a completely reusable system to a partially reusable system. When the initial $5 billion budget proved to be too low, the US Congress held firm forcing NASA to live within its specified funding profile. As a result, NASA backed away from a completely reusable vehicle and re-designed the program around a reusable orbiter supported by an external fuel tank and two solid rockets. Without previous experience in reusable system design, the forecasts for performance and cost were based on numerous questionable assumptions. Additionally, in trying to meet the wide range of military, civil, and commercial missions, the vehicle suffered from divergent requirements. NASA's desire for a man-rated vehicle required substantial amounts of certification and safety checks in direct conflict with the military and commercial's need for inexpensive and quick access to space. Without having built a vehicle for operation in the past, NASA managers placed the majority of emphasis on the technical performance believing that the operations specifications would not pose a significant challenge compared to the performance parameters. These assumptions proved to be vastly incorrect. Table 7-3 shows the expected and actual performance and operational goals of the STS program. All performance requirements were met within 10 percent of specifications, while all operational parameters were off by more than an order of magnitude.

TABLE 7-3 COMPARISON OF ESTIMATED TO ACTUAL STS CHARACTERISTICS

	Expected	Actual
Performance Goals		
• Payload	65,000 lbs	60,000 lbs
• Cross Range	1100-1500 mi	1265 mi
• SSME Isp	455 sec	455 sec
• SSME Thrust	470,000 lbs (Vacuum)	470,000 lbs (Vacuum)
Operational Goals		
• Turn-around Time	10 days	80-100 Days
• Launch Rate	60 per year	6-8 year
• Cost/Flight (1970 $'s)	$10.5 million	$160- 180 mil

*Adapted from internal study by The Aerospace Corporation, 1995.

These numbers started to become clear in the mid 1980's as NASA realized how difficult it would be for the shuttle to ever reach its specified operational characteristics. The loss of the Challenger made this hope impossible as NASA began to focus much more keenly on shuttle safety. Following the Challenger failure, NASA, the military, and the commercial sector quickly realized the mistake of relying on a single vehicle and set a new policy for the future. Clearly performance is important. However, the impact of other system constraints must not be completely sacrificed for performance. The end result was that even though the shuttle was a technological marvel, it was not able to complete its mission and achieve its key cost and schedule goals.

7.6.2.3 US Space Policy Historical Perspectives: 1986 to Present

Following the Space Shuttle accident, the US entered an extended period of space transportation policy confusion that was characterized by the formulation and destruction of program after program without clear objectives and a constant changing of responsibilities. Not wanting to revisit the time when the US had only one option for space access, many of the old expendable launch systems were brought back online to handle both the commercial and military space access needs. The shuttle system was restricted from flying commercial missions, flew very few military ones, and became the workhorse for scientific missions and eventually space station construction. Ironically, it has ended up finally fulfilling one of its intended tasks, only 20 years after commencement.

With the old expendables up and running to support the commercial and military markets, the government once again turned to the quest for the elusive aircraft-like launch system. The most ambitious of these was the National Aerospace Plane (NASP). Originally a classified Air Force vehicle under the designation X-30, the NASP program grew out of an Advanced Research Projects Agency (DARPA) project called Copper Canyon running from 1982 to 1985. Under the Reagan administration, the program was publicized as a commercial civilian program to succeed the shuttle and gained fame as "an Orient Express that could take off from Dulles Airport and accelerate up to twenty-five times the speed of sound, attaining low earth orbit or flying to Tokyo within two hours."[40] Initial plans called for a $3.1 billion program becoming operational in 1993.

The NASP program focused on the marriage of aircraft and rocket technologies to create a vehicle that could take-off and land like and airplane, yet also exit the atmosphere and operate in space for extended periods of time. The ambitious program hinged on the development of a highly advanced propulsion system combining a hypersonic airbreathing engine for atmospheric flight with a more traditional rocket engine for orbital insertion. The technical difficulties of developing the NASP vehicle, from the high temperature materials to the mach 10 plus ramjet/scramjet engine, proved to be insurmountable as the program crumbled beneath its own budget and technology weight. The program was finally cancelled in late 1993 after more than a decade of work when final cost projections topped $17 billion and the first flight date was pushed back to 2001.

Around the same time frame as NASP, two new expendable launch vehicles programs also were established called the American Launch System (ALS) and the National Launch System (NLS). The ALS was initiated by the Air Force in an attempt to develop a highly reliable, high flight rate, heavy-lift launch (50,000 to 100,000 kilogram range) vehicle able to reduce costs by a factor of 10. This lift capability was justified for "launching elements of a ballistic missile defense system and to alleviate payload design weight constraints.[40] Additionally, ALS was viewed as a potential "space truck" for heavy commercial satellites and sending bulk supplies to a space station. The program started in 1987 with seven contractors receiving small multi-million dollar awards ($5 million) to draft conceptual designs to meet the Air Forces mission requirements with operational capabilities expected by 1998. A changing climate toward the Strategic Defense Initiative (SDI), the decision to use US commercial vehicles for the majority of the military's launch needs, and a $15 billion price tag killed the program in early 1990.

The NLS began in 1991 with the recommendation from the president's National Space Council for "a joint DOD/NASA program to develop and procure a family of launch vehicles and supporting infrastructure to meet civil, commercial, and national security needs by providing NASA and the DOD with a capability to deliver a wide range of payloads to low-Earth orbit at a low cost and with improved reliability." [41] Military leaders were adamant about relying on a single system and questioned the "combat readiness, sustainability, and force structure" of the US's current fleet of vehicles. Key program objectives included developing a family of launch vehicles based on common building blocks/modules that could be combined into different vehicles without changing subsystems or redoing major qualification tests, making critical subsystems such as the propulsion system multi-use and recoverable, and achieving high reliability (98 percent plus), high launch-on-schedule rate (95 percent plus), high vehicle availability (90 percent plus), 30 day or less launch response time, a surge capability that will accommodate seven payloads within a five-day period, and significantly reducing operating costs. [42] With an estimated cost of $10.5 billion, the program was never able to get off the ground as decision makers in congress shied away from the high development cost of a new system in favor of maintaining the status quo.

Following the NASP, ALS, and NLS programs, the National Space Transportation Policy was drafted in 1994 taking a slightly different approach by pushing more development work towards the commercial sector and separating responsibilities for expendables and reusables between the military and NASA, respectively. The military was charged with assisting commercial companies in developing the next generation of expendable vehicles that could be used for military and commercial purposes and offered slightly lower costs (25 percent improvement) and higher reliabilities (97 percent plus). The Evolved Expendable Launch Vehicle (EELV) program arose in 1995 with the goal of an operational vehicle by 2001. The fear of having only a single new vehicle forced the decision to support two programs, awarding 75 percent of future military launches to Boeing Delta IV and the remaining 25 percent of launches to Lockheed Martin's Atlas V program. The EELV program shared much in common with the NLS. The notion of developing a vehicle family for varying weight classes, using common modules among these vehicles, and pushing schedule and operational performance characteristics pulled almost directly from the NLS design philosophy.

NASA was tasked with developing an advanced reusable vehicle to replace the aging shuttle and once again pursue aircraft-like operations. With three main contractors vying for the $1 billion program award, NASA choose to pursue the most radical design and focused on making the leap to single-stage-to-orbit (SSTO). Lockheed Martin won the X-33 competition with its sub-scale prototype SSTO liftingbody design utilizing a revolutionary aerospike engine which unlike traditional bell nozzles for rockets uses atmospheric pressure to contain exhaust plume and is able to optimize the exit nozzle area for various flight regimes. Program goals called for order of magnitude reductions in costs and schedule, two orders of magnitude improvement in reliability, and first flight by the end of the 1990's. Based on a successful test program, Lockheed proposed the commercial development of a full-scale vehicle called the Venturestar. Plagued with schedule overruns and technical problems, mostly with avant-garde all composite fuel tank, the program ran out of funds in early 2001 and was not extended additional financing.

In addition to the X-33, NASA also initiated several other smaller RLV programs to demonstrate key reusable system technologies such as automated guidance and navigation, high temperature materials, rapid ground processing techniques, and integrated vehicle health monitoring systems. Orbital Sciences won the X-34 contract for a set of three key technology demonstrator flight test vehicles and the development of a crew escape vehicle (X-38) to replace the Russian Soyuz capsules as the lifeboat for the International Space Station. Remnants of the NASP high-speed airbreathing propulsion systems development were transitioned to the X-43 Hyper X program run by the NASA Langley Research Center to demonstrate key hypersonic flight technologies. along with another test vehicle program (X-40) run by Boeing and the Air Force to validate re-entry technologies.

7.6.3 Current Scenario: Space Launch Initiative

In June of 2000, NASA announced the formation of new program, the Space Launch Initiative (SLI). Few details were initially released including the program budget of $4.5 billion spread over five years and the program objectives: lowering costs, improving reliability, and reducing schedules. The Space Launch Initiative was initially sold to Congress as a cornerstone program to develop a safe, reliable, and inexpensive space transportation system for the benefit of civil, commercial, and military space organizations. Each of these entities perform extremely important missions, yet their missions are very unique. While they all share common primary goals such as reliable and inexpensive space access, their secondary goals diverge considerably. Managing this divergence, the failure of previous programs, is the key to SLI success. Space transportation is a complex undertaking and trying to develop a vehicle that can be all things to all people only leads to greater complexity, greater cost, and a reduced probability of meeting key objectives.

Initial reactions concluded that SLI actually would end up as a shuttle upgrade program and a bail-out plan for the current cost overrun family of X-vehicles. Official cancellation of the X-33, X-34, and X-38 programs in February 2001 along with statements assuring these programs would not receive SLI funding quelled these rumors. but also raised a more important question: How can SLI succeed where the seven previous programs failed?

7.6.4 Impacts of Space Transportation Policy on Spacecraft Design

A complete analysis of the Space Launch Initiative is not possible at this point because key features beyond budget and timeframe have not yet been released. However, based on its initial mission statement, it is possible to explore how different paths and outcomes of SLI will impact spacecraft development. For the Space Launch Initiative to succeed it must fight several very severe problems in the launch industry. The method used to attack these problems and the success in solving them will ultimately determine the launch constraints that future spacecraft must design within.

Several of the most difficult problems involve tackling the launch constraints that have been discussed in-depth in Chapters 4, 5, and 6. Issues such as foreign competition (dumping from non-economic-based companies), extremely high development costs, high-profile spacecraft market failures, and very uncertain markets for space systems pose significant obstacles. Perhaps the most crucial challenge is technology. The NASP and X-33 programs clearly demonstrated that the technical capability to build an inexpensive SSTO vehicle is neither currently available nor achievable for less than $10 billion, if not more. Initial policy statements from the SLI program have pointed to NASA's desire to take a step back from SSTO and first accomplish inexpensive and reliable Two Stage To Orbit (TSTO) vehicles. While these issues are obvious and have been understood for the last two decades, there are several other less tangible issues that must be addressed.

The most substantial impact that SLI can have on future spacecraft development is the future launch environment that it creates. One possible future is a government-dominated launch market. Prior to the 1990's, the majority of activity in space was government-based. Commercial companies did produce hardware, however, they rarely were in the position of buyer or owner. This situation has changed dramatically in the last ten years where in 1997, commercial expenditures on space exceeded government spending for the first time. Space has evolved from the government-focused, two member Cold War contest into a multi-country, multi-organization market. SLI must address this change in market composition and address the question of the appropriate role for government space transportation. If SLI results in a government- dominated launch market, this will let government launch criteria drive future vehicle capabilities and limit vehicle choices for spacecraft developers and will.

With NASA in charge of SLI, it is more likely that the program will be run in favor of meeting NASA-specific objectives and requirements. NASA's current objectives focus on improved human spaceflight with unique requirements that call for "the ability to return payloads from low-Earth orbit, support and servicing of complex space platforms, rendezvous and dock with the space station, conduct an emergency crew rescue mission within two days of an incident, support 5-7 crew members in orbit for seven days with EVA capability, and support 3-7 crew members for 5-15 days to conduct station-like research." [43] While both the military and the commercial world would not object to having such capabilities, they would clearly rather spend time and money on achieving significant improvements in cost, reliability, and schedule dependability than on these type of capabilities. Commercial and military missions require a commercially competitive, low-cost, reliable launcher for unmanned spacecraft. Human-rating a launch vehicle requires an extensive certification safety process that will overwhelm cost savings even if best practices and lessons learned shuttle are implemented. By focusing SLI's risk reduction on meeting NASA post-shuttle human spaceflight objectives the program will be pulled in opposing directions.[43] The danger of this is a move to incremental changes. A vehicle that can safely fly humans will only be able to achieve incremental improvements in costs and reliability. Thus, in additional to providing crew capabilities, launch would move from $10,000 per kilogram costs, 80 days schedules, and 98 percent reliability to $1,000 per kilogram, 10 days schedules, and 99.9 percent reliability. But one order of magnitude improvements may not be enough to spark changes in commercial spacecraft markets or address key military objectives.

Another pressing concern is the incumbent issue. The power of large incumbents in the launch market limit the entrance of new vehicles offering better capabilities and more selection options for spacecraft developers. The military has gone to great lengths to maintain a launch capability for national security reasons. In maintaining this capability, they have also helped to reinforce the market position of two commercial launch companies. Faced with stable market shares and long-term military contracts, there is little incentive to pursue revolutionary, expensive R&D programs to capture a small and uncertain additional market share. Content with the status quo and concerned with next quarters financial performance, the risk reward scenario does not justify pending billions of dollars on a new vehicle (does not make economic sense). Many start-up space transportation firms have openly accused the government of suppressing commercial vehicle development through funding large government programs that will unfairly complete in the commercial market. With the government involved in developing vehicles, these firms have found it difficult to raise financing in the capital markets. The inability of these firms to compete and survive ultimately limits the selection available to spacecraft developers.

A second incumbent issue involves the shuttle. Once the shuttle has finished its space station construction duties, besides crew and station cargo transport, it will no longer have a clear secondary mission to justify its high operational costs. With NASA claming it can fly the shuttle until 2030, the issue of competition with commercial vehicles will eventually arise. One of the main problems going forward is the shuttle flight rate issue. With shuttle operations consuming $3 billion a year irregardless of flight rate, pressure to fill the shuttle manifest will mount. Should the shuttle stay operational past 2010, the possibility that it could steal missions for the other commercial vehicles thereby limiting their ability to compete and ultimately affecting the spacecraft market.

Another issue plaguing new vehicle development and restraining significantly improved launch capabilities available to spacecraft is the high degree of risk aversion now prevalent in the aerospace industry. As was discussed in Chapter 1, the high cost of failure also impacts the launch development business. With billions of dollars required to develop technology, start production, and operation many firms are simply not willing to take the risk. The risk aversion on the commercial side is understandable. However, the risk aversion on the government's side detrimental to new technology development and the ability to achieve multiple orders of magnitude improvement in launch capabilities. With high profile failures such as the billion dollar Mars Observer in 1992 and the Mars Climate Surveyor in 1999, NASA has lost sight of the risk reward equation. Some of the greatest strides made in space transportation back in the 1960's came amid numerous rocket failures. The Orbital Sciences led X-34 program mentioned in section 7.6.2 to demonstrate new RLV operational technologies is a perfect example of the current risk aversion in NASA. Understanding program risk, Orbital Sciences developed three separate vehicles for the event that one or even two were lost. However, following the Mars mission loses, NASA headquarters decided it could not afford another widely publicized failure. Thus, 80 percent of the way into the program, NASA decided to change the requirements for the vehicles and demanded extra safety and reliability additions. The result was an obvious cost and schedule overrun for the program. NASA then canceled the program for the same cost and schedule overruns that it created. Success or failure of one or more of the vehicles would have most likely yielded significant technical return and lessons learned.

In order for the new US space transportation policy to be effective, it needs to address not only the technical issues, but also the policy issues discussed above. In addressing its key challenges:

- Extremely high development costs
- Uncertain markets
- Immature technology
- Foreign competition (dumping from non-economic-based companies),
- Uncertain government role, inconsistent policy, agency leader
- Capital fundraising raising problems
- Incumbent issues: lack of revolutionary change incentives
- Risk aversion: magnified fear of failure
- Shuttle competition for payloads and resources

The Space Launch Initiative cannot loose sight of the reason behind developing new launch systems, to provide better capabilities for unmanned and manned spacecraft systems. The path and success of this program will ultimately define the new launch constraints that spacecraft designers in the future must manage.

7.6.5 Summary of Space Transportation Policy Impacts

Future launch vehicle improvement strategies are responsible for determining the future physical, operational, and cost constraints. New vehicle development which does not address the change in market composition from a government-dominated space environment to one where government and commercial coexist favors government requirements and limits new vehicle entrants/selection options. Figure 7-10 outlines the impacts of new space transportation R&D policy on the future of spacecraft development.

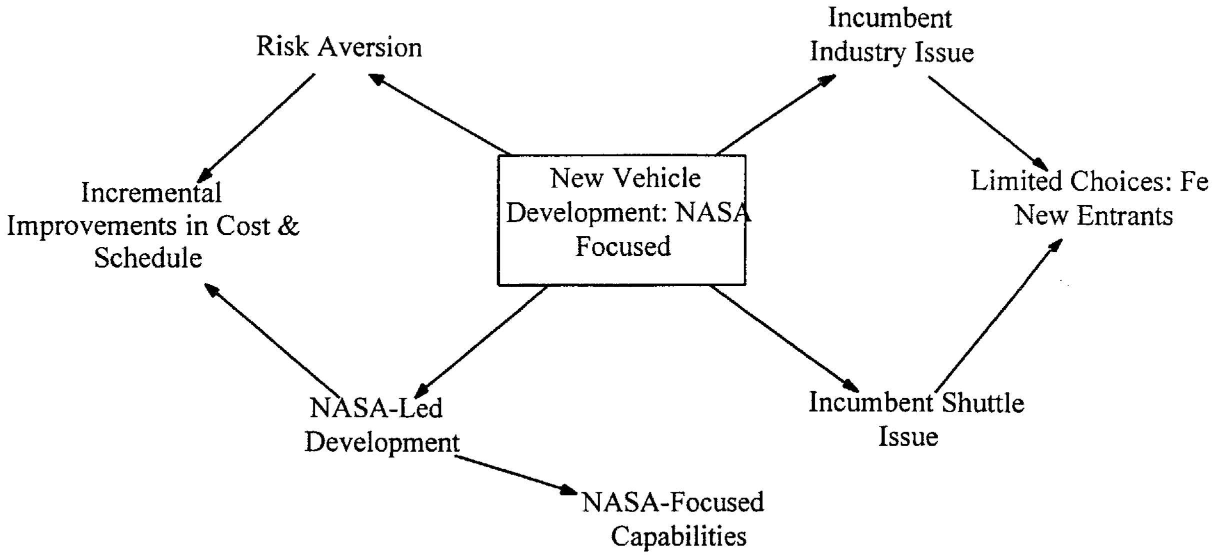

FIGURE 7-10 R&D IMPACTS ON SPACECRAFT DESIGN

CHAPTER 8 IMPLICATIONS OF RELAXED CONSTRAINTS

8.1 Overview of Implications

The notion of a "paradigm shift" was first introduced by Thomas Kuhn in his famous work titled "The Structure of Scientific Revolutions." Kuhn's work demonstrated how the majority of significant scientific breakthroughs occurred when scientists and engineers ignored history and traditional manners of thinking and approached an existing problem from a new vantage point or frame-of-reference. Today, the word paradigm is synonymous with other frame-of-reference terms such as model, theory, perception, and assumption. One of the best examples of adopting a unique paradigm was the highly regarded Lockheed Skunk Works. From the 1940's through the 1970's, the Skunk Works produced astonishing technological breakthroughs in aircraft development in record time by approaching each project with the philosophy that traditional rules should be forgotten.

The introduction of a significantly improved launch vehicle represents a disruptive technology that has the potential to instigate a paradigm shift in the development and deployment of space systems unlike any innovation since the early 1960's. The reason behind this shift will not only be technical, but also philosophical. The importance of lower costs launchers is secondary to what improved space access enables. Space systems are expensive because spacecraft are expensive, launchers are expensive, operations are expensive, and technology development is expensive. Reducing the cost one aspect, while important, will not solve the deeper problem. As this research has demonstrated, there is a significant link between the launcher and the spacecraft. Launch vehicles have significant design and development impacts on space systems. Thus, changes in one element have profound impacts on the other that when reinforced create a positive feedback loop which counters the vicious cycle explained in Chapter 1.

This chapter explores the implications of relaxing launch vehicle constraints on spacecraft system architecture and subsystem design. A range of architecture options that are currently constrained by launch constraints are identified and a simple mathematical model exploring the potential impact of reduced launch constraints on one of the outlined architecture options is presented.

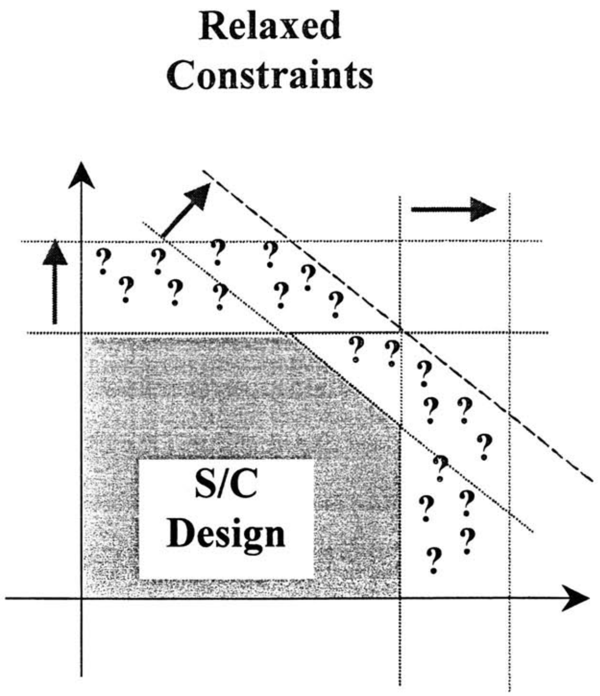

FIGURE 8-1 IMPLICATIONS OF RELAXED CONSTRAINTS

8.2 Historical Perspectives for Change

Throughout the first four decades of space travel, venturing into orbit was viewed as only the realm of large governments and big projects. The exorbitant costs associated with R&D and transportation limited space to organizations with deep pockets. Even as commercial companies began to alter their view of space from the role of supporter, simply developing hardware sell to the government, to the role of operator and profiteer, the notion that space was still a government endeavor was very entrenched. Over the last five years, this viewpoint has started to change as companies like Iridium, Globalstar, and DirectTV began testing the waters of completely commercial ventures and taking there business case direct to consumers. While many of these ventures failed or have struggled to compete with terrestrial alternatives, the arrival of significantly improved launch systems will not only enable better and cheaper access to space, but will also allow spacecraft developers to alter their approach to the design and development of spacecraft systems. Pushing for larger, 15 year plus lifetime, single spacecraft may yield to small, serviceable spacecraft that function in distributed teams and can quickly be configured to meet changing market conditions.

Until recently, there have been few challenges and changes to methodology behind space systems development. The dominant design philosophies for both spacecraft and launch vehicles established circa 1960 have remained intact with minor, incremental alterations. Launch vehicles are still based on ballistic missile technology and the basic design of spacecraft, although much larger and heavier, strongly resemble the first artificial satellites launch by the US and the USSR in the late 1950's.

8.3 Changes Under Relaxed Constraints

In combination with other forces at work in the spacecraft community including the growth of commercial markets, the miniaturization of components (nanotechnology), and adoption of lean production principles, improved launch capabilities will be a key enabler to implement radical spacecraft design philosophies which up until this point did not make economic sense. Thus, improved launch will be part of a set of disruptive technologies that forever change the frame of reference for how we design and develop space systems. Up to this point, emphasis has been placed on elucidating the current set of launch constraints and their impact on space systems. With this background, it is possible to look ahead instead of behind and start to consider what changes to these constraints mean for space systems.

Table 8-1 outlines several potential spacecraft system architectures presenting the benefits associated with these architectures and the launch constraints that currently either restrict or obstruct their use. The list is not meant to be exhaustive. For example,

TABLE 8-1 ARCHITECTURE OPTIONS

Architecture Option	Description/ Benefits	Launch Constraint Barriers
Modular Spacecraft "LegoSat"	**Standardized pre-designed subsystems & components** - Reduced development time - Leverage testing: only qualify once, pre-test all possible configurations - Reduced parts & design costs: larger lot sizes, scale economics - Multiple configurations	- Volume limitations - Costs - Interfaces: standardized connections - Mass: Cannot weight minimize
Serviceable Spacecraft "RenewSat"	**Replacement of on-board consumables** - In-orbit maintenance to repair or replace failed components - Replenish fuel or other consumables - Servicing to upgrade capabilities	- Cost - Vehicle performance: rendezvous & autonomous robotic ops - Vehicle schedules: LOD & service at irregular times - Availability: going offline strands spacecraft
Reusable Spacecraft "SalvageSat"	**Carry out mission, return from space, re-configure & re-launch** - Save design time - Save design cost: reuse expensive hardware - Perform same or different mission	- Cost - Vehicle performance: rendezvous, capture, & re-entry - Reentry loads & thermal environment - Government regulation - Mass - Volume
Recurrent Replenishment Spacecraft "SwapSat"	**Reduced design lifetimes & faster replenishment scenarios** - More capability on-orbit sooner - Increased technology insertion - Reduce obsolescence problem - Lower per spacecraft costs	- Costs - Mass - Volume - Vehicle schedules: LOD & ability to service at set & irregular times
Satellite-Level Redundancy Systems "SparesSat"	**High system reliability through numerous on-orbit spares to replace failed s/c** - Cost savings through high production volumes - Schedule savings in design, test, qualifying - Ability to use extensive COTS, single string designs	- Costs - Volume: multiple-manifesting - Vehicle schedules many & frequent launches
Short Life/Short Notice Space Systems "SuccinctSat"	**Launch with little notice, perform intended mission, & then disposed** - Quick initial capabilities - Quick augmentation	- Costs - Vehicle schedules: LOD & ability to service at set & irregular times
Heavier-than-Required Spacecraft "FatSat"	**Use additional mass to lower component costs not increase capability** - Lower costs, non-optimized, previously developed components, COTS - Reduced testing, previously space qualified - Reduced development time	- Mass: cannot mass minimize/optimize - Volume - Cost

8.4 *Recurrent Replenishment Spacecraft: Case Study of SwapSat*

"The worst thing you can do is have to leave off propellant, this kills lifetime"
Industry Spacecraft Developer Quote, January 2001

This is the current industry philosophy. The first satellites launched in the late 1950's had lifetimes measured in days. Explorer I, lofted on January 31, 1958, had a maximum useful life of 105 days. As satellite technology and design improved, the push for longer and longer operating lifetimes has grown tremendously to the point that today's geosynchronous spacecraft are expected to last at least 15 years. The initial GOES-1 spacecraft, launched in 1977, was just recently retired after 24 years of service. Previous sections outlined the wide range of possible impacts that improved launch capability might have on the design and development of future space systems. Trying to model all of these possibilities is outside the scope of this research. However, in an attempt to provide a more definitive answer to the second primary thesis question, a simple model was created to consider the impact of reduced launch constraints on the statement presented above. The primary objective of the model is not to answer what will definitely occur, but to explore what is possible.

The model is based on a simple question: Under different launch conditions, would it make sense to not maximize spacecraft lifetime and instead trade spacecraft lifetime for greater initial capabilities. A typical geosynchronous spacecraft program was used as a baseline case where a trade was made between the amount of propellant on board (primary lifetime determinant) and the number of communications transponders (primary revenue generation determinant). Under one scenario, a spacecraft placed into orbit for 15 years generates a constant stream of revenue. The second scenario involves designing a spacecraft with a shorter lifespan, but containing a larger number of transponders capable of generating a larger revenue stream. However, in order to complete the same mission, the shorter lifetime spacecraft must be replaced one or more times, depending on design lifespan. Thus, one program exhibits low recurring cost /low recurring revenue while the other exhibits higher recurring cost/higher recurring revenue.

1) Long lifetime spacecraft/ fewer transponders
2) Shorter lifetime spacecraft/ more transponders

8.4.1 Rationale and Limits for Spacecraft Lifetimes

As mentioned previously, spacecraft lifetimes have been increasing for the last 40 years and now, depending on the mission vary from 1 year to 15 years. The standard that most customers demand for geostationary spacecraft is a 15-year minimum. It was reported that rarely do customers demand more than 15 years but also rarely will they accept less. The desire to design spacecraft for such long lifetimes is motivated by launch constraints such as high cost, long schedules, and low reliability. With a high percentage of spacecraft failures occurring during the first year of operation and then tailoring-off until the end of design lifetimes, it makes sense that spacecraft developers would want to avoid continually going through the risky and expensive launch process. By designing spacecraft to last for upwards of 15 years, the impact of launch vehicle costs and schedules on the spacecraft program can be minimized.

Several factors determine the expected lifetime of a satellite. The most significant driver for current systems is the amount of propellant supply included Spacecraft lifetime is primarily determined by the supply of propellant. Once a spacecraft depletes its fuel source it is impossible to control and position the satellite for performing its mission, even if all other systems are functioning properly. Other features that can limit lifetime include failures of critical mechanisms such as reaction wheels and degradation of power generation, power storage, and thermal protection capabilities. The harsh space environment subjects spacecraft to extreme temperature fluctuations, radiation, and debris impacts that wear spacecraft surfaces and components.

8.4.2 Model Basics

The model created is based on a geostationary communication satellite completing a 30-year mission. Two unique spacecraft systems were considered. The first is the traditional, long-life spacecraft program. The second spacecraft is designed to perform the same mission but is designed to be replaced on a more frequent basis with design lifetimes for each spacecraft varied from 1 to 15 years. Table 8-2 presents the details of the two spacecraft designs.

TABLE 8-2 SPACECRAFT MODEL BASICS

Attribute	Spacecraft #1	Spacecraft #2
Lifetime	15 years	1 to 15 years
Ku Transponders	32	32 to 84
# of Replacements	2	2 to 30
Operations Costs	5 % Non-recurring	8 % Non-recurring
Per Spacecraft Cost	$150 million	90 % Learning curve

The key difference between these spacecraft is that spacecraft #2 has a larger number of transponders than spacecraft #1. Assuming that each spacecraft is limited to the same final weight, the inclusion of these additional transponders and their supporting equipment is enabled by reducing the amount of propellant on the spacecraft, thereby limiting lifetime.

Model Parameters

- Discount rate: 10 %
- Revenue per transponder: $900,000 per year
- Add some reduction for buying in bulk or more frequent buys
- Tradable Mass: 1,376 pounds
- Fuel Use Rate: 60 pounds of fuel per year
- Spacecraft Dry Weight: 6,424 pounds (without communications payload)

Assumptions

- Each spacecraft has the same launch mass
- Volume restrictions for adding additional transponders are waived

For each spacecraft design, the Net Present Value return was calculated. The NPV measures the time-weighted difference between the revenues and costs according to the following equation:

$$NPV = \sum_{t=1}^{n} \frac{\left(Cost(t)_{Recurring} + Cost(t)_{Nonrecurring}\right)}{(1+r)^{t}}$$

In this case, r is the discount rate, t is the mission lifetime, recurring costs includes operations, and nonrecurring includes spacecraft production and launch. Figure 8-2 shows the financial inflows and outflows for the two spacecraft programs assuming spacecraft #2 is designed with a five-year lifetime and must be replaced every fifth year. The key aspect of this figure is that spacecraft #1 only has substantial costs in years 1 and 16 to replace the spacecraft. In contrast, spacecraft #2 has substantial outflows in years 1, 6, 11, 16, 21, and 26. The difference, however, is that the revenue for spacecraft #2 is substantially higher than for spacecraft #1 reflecting that the addition of 40 additional revenue producing transponders. These transponders were enabled by reducing the amount of propellant on-board.

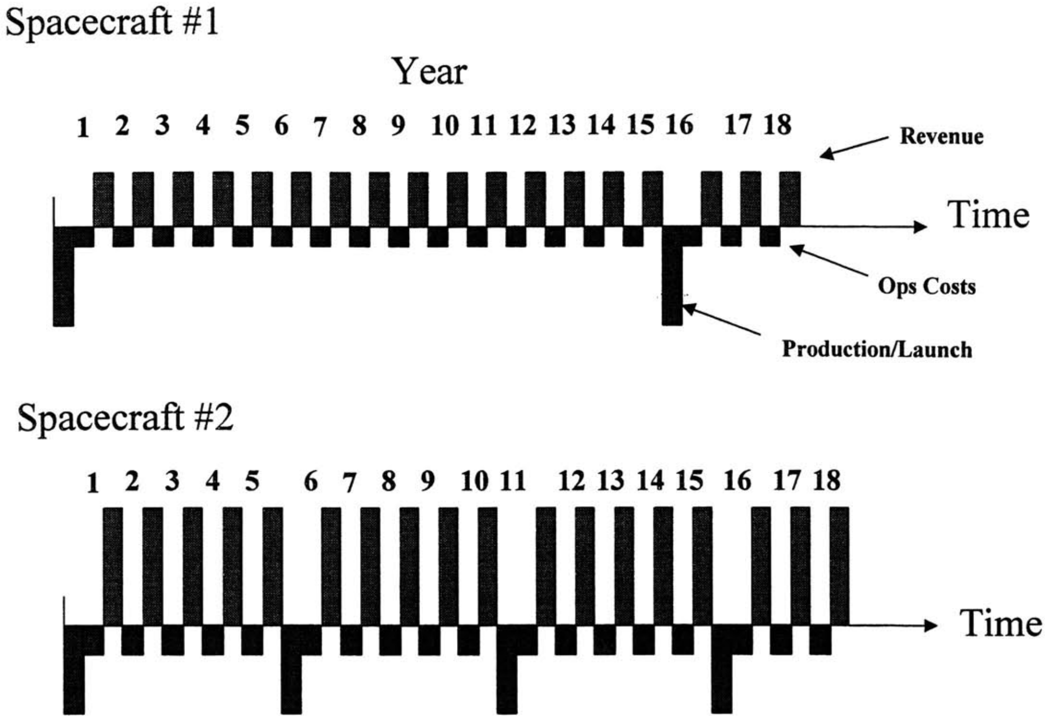

FIGURE 8-2 NET PRESENT VALUE ANALYSIS

In running the model, two parameters were varied across a defined range. The lifetime of spacecraft #2 was varied from 1 year through 15 years and the launch costs were varied from $50,000 per kilogram down to $10 per kilogram.

8.4.3 Model Results

The initial results of the model are shown in Figure 8-3. Each curve corresponds to a specific launch cost on a dollar per kilogram basis ranging from $50,000 per kilogram (lowest curve) to $10 per kilogram (highest curve). For each launch cost level, the NPV of the communications spacecraft mission is plotted as a function of the spacecraft lifetime. For example, for the $25,000 per kilogram curve (second lowest), the highest NPV results when the spacecraft is designed with an eight-year intended lifetime. It was found that as the price of launch decreases, the optimal spacecraft design lifetime for maximizing NPV also decreases. Based on current launch prices in the $25,000 per kilogram range to geostationary orbit, the optimal design lifetime of eight years suggests that today's GEO spacecraft which are designed for 15 years might be over-designed in terms of life expectancy and could yield a higher return, according to NPV, by trading lifetime for additional transponders. As launch prices continue to fall, it makes sense to replace spacecraft more frequently with higher initial and sustained revenues covering additional spacecraft production and launch costs.

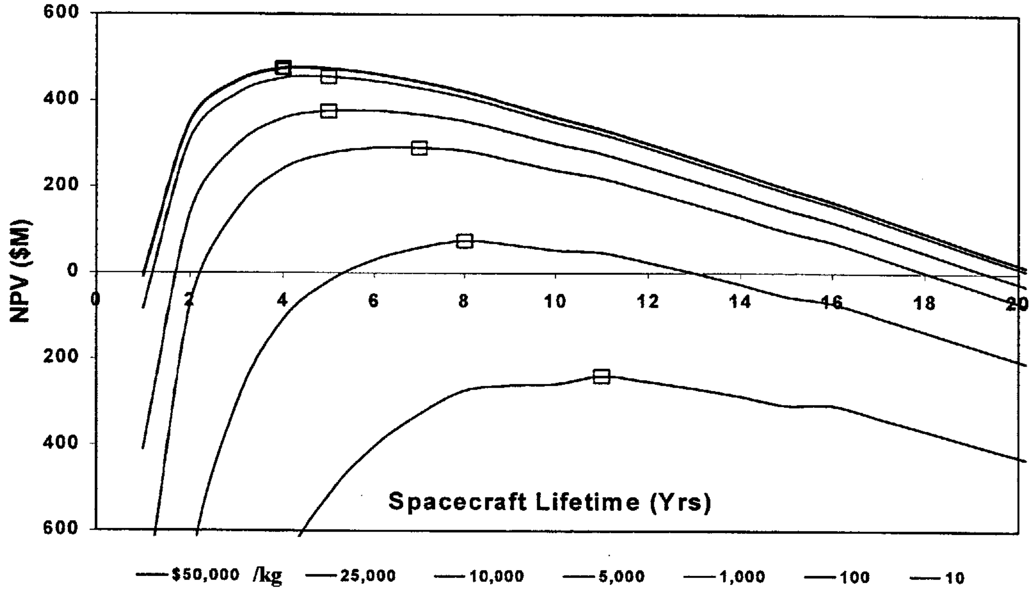

FIGURE 8-3 OPTIMAL SPACECRAFT DESIGN LIFE BASED ON VARIABLE LAUNCH COSTS

As the launch price comes down, it is also important to note that their relative weight of launch costs as a portion of the total cost drops significantly. As the fraction of the total cost spent on launch decreases, weight minimization and other costly design practices may not drive spacecraft design decisions and additional trades between the launch vehicle and the spacecraft are enabled.

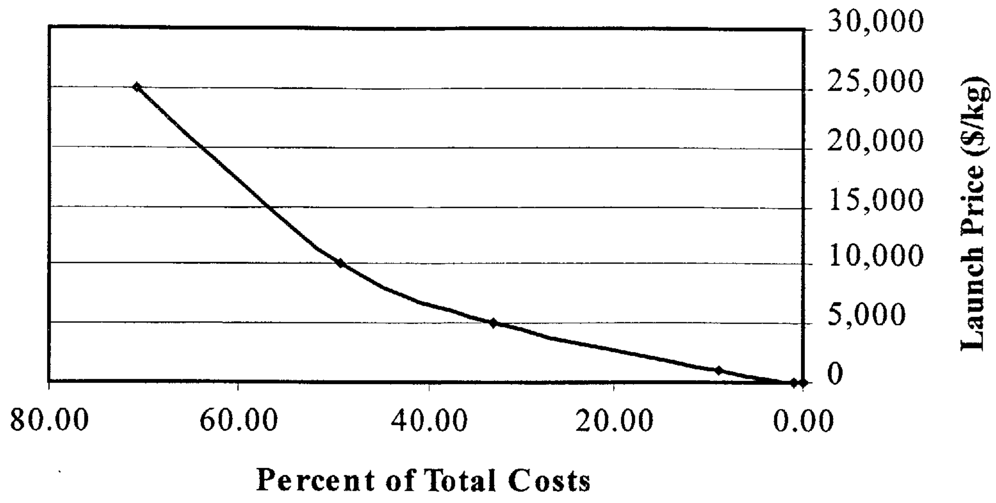

FIGURE 8-4 LAUNCH COSTS AS PERCENT OF TOTAL COSTS

8.4.4 Benefits of Recurrent Replenishment Spacecraft: SwapSat

The are several advantages to implementing a reduced lifetime (higher replacement rate) satellite system. The following benefits are identified:

System Obsolescence and Improvements for Back Compatibility: The necessity to interact with older existing systems can drive design choices for current systems limiting the capability of the new system. Longer life spacecraft mean that the technology in use is much older than new. Moving to shorter lifetimes and more frequent replacements means these technology/compatibility gaps will be reduced and can be planned for more effectively. Dealing with parts obsceneness is also a major concern. With longer life spacecraft replacement of a 15 year-old spacecraft requires almost a complete redesign and qualification. Many the parts supplier or developer no longer exists or the expertise is gone.

New Technology: Shorter lifetime spacecraft also encourage more rapid technology insertion. Previously, technology on-orbit could be extremely old. Two to four years in development plus 15 on orbit equates to 20-year old technology in operation. Compared to the high technology computer industry, this would be the equivalent of using a PC with a X-286 chip running at 10 MHz with less than 1 meg of storage.

Managing Dynamic Market: Shorter lifetime spacecraft allow flexibility to adapt or alter spacecraft functionality and capabilities to cope with dynamic and changing marketplaces. Recent examples of failed satellite communications programs like Iridium and Globalstar were attributed to not be able to quickly address changing market conditions and the rapid rise of the cellular phone industry.

Employee Benefits: More rapid replacement of spacecraft also increases employee/designer knowledge and experience. An engineer is able to work on five to ten spacecraft designs programs over a career versus one or two. An environment of constant changes, new spacecraft development, and new missions also enables increased excitement and is more alluring for younger engineers now in great demand in the aerospace industry.

8.4.5 Barriers to Recurrent Replenishment Spacecraft

While there are some definite advantages to shorter lifetime spacecraft, enabling these benefits requires significant changes to launch vehicle and spacecraft capabilities. The following launch vehicle constraints represent the most significant barriers to enabling such a design architecture.

Launch Costs: Current launch costs are too high to make frequent replenishment a feasible strategy. As shown in Figure 8-3, as the price of launch decreases and launch consumes a smaller percentage of program costs, designing for a shorter expected lifetime begins to become economically viable.

Vehicle Schedules: Frequent replenishment of spacecraft will require launch vehicles that can not only launch more frequently, but also launch on shorter notice.

CHAPTER 9 FINDINGS AND CONCLUSIONS

9.1 Thesis Overview

The primary goal of the thesis was to explore the symbiotic relationship between launch systems and space systems. A myriad of launch constraints were identified and explained which spanned across technical, operational, budgetary, and policy themes. The impact of each constraint on space system design and development, both by itself and coupled with other constraints, was substantiated and supported by historical examples from military, commercial, and civil space missions. Finally, through a set of rudimentary models and simple thought experiments, potential changes to space system design and development in the wake of launch systems improvements were proposed. This final chapter seeks to highlight the key findings of this work, present a summary of conclusions, and describe potential future work to build upon this research and further explore the launch – spacecraft interface.

9.2 Conclusions

9.2.1 Summary of Impacts

Four constraints themes were identified: physical, operational, cost, and policy. Each theme contained several types of specific launch vehicle constraints which each had a range of impacts on the design and development of spacecraft systems. These impacts are summarized below.

9.2.1.1 Physical Constraint Impacts

Physical constraints deal primarily with limitations based on physics and the laws of nature. The following sections highlight the key spacecraft design and development impacts resulting from lift capacity, fairing volume, loads and environments, and system interface constraints.

> **Lift Capacity:** Mass boundaries induce weight minimization philosophies which, in the iterative spacecraft design process, can lead to expensive late-design phase weight reduction practices. Weight restrictions also influence component and materials selection, sub-system redundancy and reliability strategies, and propellant levels that ultimately drove spacecraft lifetime. The increased use of generic, 'untouchable' spacecraft buses has significant influences on payload capabilities as weight reduction practices generally affect the payload.

Fairing Volume: Volume restrictions affect the geometry of key spacecraft sub-systems such as the size and number of antennas and available power based on the sizing of solar arrays and batteries. Limited volume also encourage complicated stacking designs for multi-manifest launches and complex deployable mechanisms allowing components to be compressed during ascent and unfurled once in orbit.

Launch Loads and Environments: Loads impact spacecraft structural designs, requiring high margins of safety and driving structures to consume a high fraction of the spacecraft's dry weight (15 to 25%). Excessive loads are also the primary driver for expensive spacecraft "shake" testing environments including vibration, acoustic, and shock analysis. The forces experienced during launch are so severe, that calibration of spacecraft instruments and systems must be done in-orbit versus on the ground. To compensate for these forces and environments, special damping and insulation systems must be developed consuming already limited mass and volume resources. The spacecraft designer must also perform complex coupled loads analyses and be keenly aware of avoiding launch vehicle natural vibration frequencies and modes.

System Interfaces: Systems interfaces require special coordination between the spacecraft designer and the launch firm to make sure communications are secure. Locations of access ports determine what areas of the spacecraft will be available following encapsulation and where integration testing connections must be located. Lack of standards across many vehicles leads to mission unique support and connection structures that consume valuable mass and volume. Multi-manifested launches also require design coordination between associated spacecraft.

9.2.1.2 Operational Constraint Impacts

Operational launch constraints impact not only the design of space systems, but also the deployment and operations of space systems. The following sections highlight the key spacecraft design and development impacts resulting from launch vehicle schedule length and delays, availability, and reliability constraints.

Schedule Length and Delays: Schedule delays can result in lost revenue and potential market share to competitors, national security vulnerability for quickly replacing damaged or destroyed spacecraft, and missing narrow launch windows for interplanetary science missions. Lengthy contracting schedules force early vehicle selection and procurement to reserve spots on vehicle and range manifests. This reduces the amount of design trades that can be made between the spacecraft and launch vehicle. Finally, lack of "launch-on-demand" capabilities leads to designs with excess capabilities to handle both routine mission functions and sporadic, possibly unnecessary mission functions versus designs for routine mission functions only producing vulnerability and potential capability deficiencies.

Vehicle Availability: Concerns over vehicle availability drive spacecraft designs to multiple vehicle compatibility, lead to expensive re-designs following a vehicle going "offline," and create a conservative spacecraft community where developers resist designing for new vehicles with superior capabilities until a potential replacement vehicle is also available.

Launch Vehicle Reliability: The potential for losing a spacecraft during transport leads to high insurance premiums, production of back-up hardware and spares, and distributing constellation spacecraft across several launch vehicle families (requiring compatibility designs). Additionally, spacecraft placed into incorrect orbits must consume crucial propellant during special trajectory corrections burns which reduce spacecraft operational life.

9.2.1.3 Cost Constraint Impacts

The high cost of purchasing a launch vehicle is further amplified by insurance costs, range fees, and "drive-away" costs associated with mission-unique hardware. The following section highlights the main impacts resulting from launch vehicle cost constraints.

Vehicle Procurement Costs: Excessive costs limit the number and scope of space missions, impede new market applications, and create a general "high cost of failure" mentality. The high cost of failure mindset discourages technology insertion, pushes high spacecraft reliabilities and testing, and causes developers to stretch spacecraft functionality. High launch costs also affect replenishment strategies pushing longer spacecraft lifetimes to avoid spend additional funds launching a replacement satellite. The summation of these cost impacts creates a vicious cycle for the space industry where spacecraft missions need low transportation costs in order to be viable and more numerous, yet launch systems need more missions (higher flight rate) to reduce per flight costs and encourage additional funding for further improvements.

9.2.1.4 Policy Constraint Impacts

Policy constraints affect spacecraft design and deployment through government space transportation regulations, management practices and procedures, politics and international relations, and future launch vehicle improvement strategies.

Government Regulations: Launch quotas create price floors which keep both near term and long-term prices high, limit vehicle selection, allow foreign spacecraft firms to increase market share at domestic spacecraft firms' expense, and curb new space applications and demand.

Selection Policies: Forced early vehicle selection limits the ability to perform architecture trades, limits vehicle choices, transforms flexible constraints into fixed constraints, causes costly re-design processes, and can lead to offline availability issues.

R&D Strategy: Future launch vehicle improvement strategies are responsible for determining the future physical, operational, and cost constraints. New vehicle development which does not address the change in market composition from a government-dominated space environment to one where government and commercial coexist favors government requirements and limits new vehicle entrants/selection options.

9.2.2 Key Findings

9.2.2.1 Architecture versus Subsystem Impacts

In general, it was found that physical constraints had a more direct impact on individual spacecraft and subsystem design while operational and policy had more influence on the higher level architectural design decisions. Most design impacts also resulted from the coupling of two or more launch constraints, further complicating the ability to make effective design trades.

9.2.2.2 High Cost of Failure Mentality

Launch vehicle constraints are a major contributor to the high cost of failure mentality prevalent in the spacecraft community. This mindset is the result of the coupling of high launch costs, low vehicle reliabilities, and lengthy vehicle schedules. Conservative customers have a strong bias towards vehicles with multiple substitutes and avoid designing spacecraft for new vehicles even if they offer superior performance or lower costs. Fear of a vehicle going offline stops spacecraft designers from utilizing the improved capabilities of a new vehicle until secondary options are available. This slow acceptance of new capabilities points to a condition that industry change depends on more than one vehicle offering improved capabilities. Enabling significant changes in the design of spacecraft systems will require two or more improved vehicles with close to equal capabilities.

9.2.2.3 Scalability Issues

The current structure of launch lift capabilities and costs creates a step function characteristic that encourages weight minimization practices and impedes making launch vehicle versus spacecraft trades. While spacecraft can easily grow or shrink by a kilogram or 10, the launch vehicle cannot. Lift capacity follows a standard step-function characteristic with each rung separated by hundreds if not thousands of kilograms. Unlike spacecraft, launch vehicles do not have the ability to easily grow capacity on the scale of less than 100 kilograms. The inability to simply choose another vehicle with a slightly higher lift capability reinforces the necessity to go through costly weight reduction processes to stay on the initially selected vehicle.

9.2.2.4 Unprepared for New Vehicle Capabilities

Many spacecraft technologies and processes required to effectively utilize new launch vehicle capabilities do not exist. For example, the ability to utilize launch-on-demand (LOD) capabilities is limited by the fact that spacecraft typically require months to calibrate instruments, perform diagnostics and system checks, and initialize systems for routine operations, not to mention possible spending months in transit to the final orbital location. Thus, taking advantage of new capabilities created by relaxing some launch vehicle constraints (enabling LOD or on-orbit servicing) is inhibited and requires comparable improvements to spacecraft design technologies and processes.

9.2.2.5 Constraint Priority Depends on Program and Personnel

All of the spacecraft designers interviewed agreed that launch constraints played a role in spacecraft design. Besides cost and weight, most differed on what they believed were the most important constraint from adapters, access panel locations, and integration software to propellant slosh during ascent, fairing shape complaints, and separation mechanisms. Not surprising is the fact that constraint priorities mirrored spacecraft designer functionality and meeting unique mission requirements. Structural engineers cited loads as the most significant constraint while electrical engineers cited communications and adapter interfaces. Many designers also discussed a disconnect between the top attributes for selection of the launch vehicle and the most significant design drivers. In many cases, these were not the same constraints leading to a situation where management's views of the importance of launch constraints differed from the design engineers.

9.2.2.6 Tier Structure of Launch Constraints

Many designers spoke of an "inequality" of launch constraints, with some holding much more weight than others. Launch constraints can be loosely separated into three tiers depending on their degree of influence on launch vehicle selection and level of rigidity. First tier constraints, such as political restrictions or physical limitations such as lift capacity or volume, have substantial design impacts and are either impossible or extremely difficult to trade-off. Second tier constraints have significant design impacts, usually can be traded, and are the most influential in making the final choice from the suitable vehicles. The third tier factors do not have a large influence on the selection decision but can be traded and do impact the spacecraft design following selection.

9.2.2.7 Minimal Inter-Enterprise Trades

Most spacecraft designers pointed to early selection of the launch vehicle (transforming flexible constraints into fixed constraints) limited the possibility of trades between the launch vehicle and the spacecraft, amplifying the impact of the constraints. Late stage re-design to conform to vehicle constraints adds significant cost and leads to unnecessary customization.

9.3 Future Work

The interface between launch vehicles and spacecraft is an extremely complex and large subject with a wide array of additional topics that should be explored. Below is a brief list of a few additional topics requiring research effort.

Efficient Utilization of New Launch Capabilities: An analysis of the spacecraft technologies and processes required to effectively utilize new launch vehicle capabilities would be extremely useful for identifying future technology R&D investment priorities.

Non-Mass Optimized Spacecraft: A model assessing the costs and benefits of a non-mass optimized spacecraft under reduced launch vehicle cost structure would explore the possibility of making substantial design trades between the launch vehicle and the spacecraft system.

Sensitivity of New Markets to Launch Costs: A more detailed market study of the price elasticity of demand of spacecraft systems in relation to launch costs would provide firm price targets for launch cost reduction and would enable improved analysis of the business prospects of new launch vehicle developments.

Launch Infrastructure: A study of the impact of new launch capabilities on the nation's launch ranges is necessary. This should focus on what ground processing technology, equipment, and policy will be required to enable the efficient range operations. In addition, a policy assessment of the range responsibilities should address the role of the military and commercial firms in the range operation and ownership.

Price Scalability: Development of strategies and technologies that reduce the step function attributes of launch prices should be pursued. Technologies to assist multiple payload launches as well as technologies to help the vehicle itself scale with mass and volume capabilities. The ability to purchase one-half or one quarter of a vehicle's capacity will help smooth out the price step function. This requires more interface standardization and a change in design philosophy for more efficient dual manifest designs.

9.4 Closing

The introduction of a significantly improved launch vehicle will represent a disruptive technology that has the potential to instigate a paradigm shift in the development and deployment of space systems unlike any innovation since the early 1960's. Firms that understand how to best adapt and utilize the new capabilities will thrive while those that do not will loose market share and their competitive advantage. The reason behind this shift will not only be technical, but also philosophical. The importance of lower cost launchers is secondary to what improved space access enables. Space systems are expensive because spacecraft are expensive, launchers are expensive, operations are expensive, and technology development is expensive. As this research has demonstrated, there is a symbiotic link between the characteristics of the launcher and the design and development of the space system. Changes in one element have profound impacts on the other that when reinforced, create a positive feedback loop which counters the vicious cycle.

Appendix A: Lean Thinking

The elimination of *Muda,* the Japanese word for waste, lies at the heart of the Lean Aerospace Initiative (LAI), a research partnership formed at the Massachusetts Institute of Technology. LAI was launched in 1993 as a consortium of partners from industry, government, and academia to apply the "Lean" production concepts pioneered by Eiji Toyoda and Taiichi Ohno at the Toyota Motor Company in the early 1950's to the US aircraft industry. The success of Japan's automobile industry following World War II is often attributed to the creation and adoption of "Lean" principles. Over the last decade, many US industries have also begun to adopt these lean practices in an attempt to become more efficient in creating value for the consumer and increasing company profits. MIT has established several initiatives for the automobile and aerospace industries to put these philosophies into practice. Positive results in the automobile and aircraft sectors sparked LAI to create the Test and Space Operations Group in 1998 in order to explore the application of lean philosophies to the space sector.

The guiding principles behind Lean were initially introduced to US businesses through *The Machine That Changed the World* by Womack, Jones, and Roos.[44] As members of the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology, Womack et al visited automobile plants in Japan, Germany, and the United States in order to compare and contrast manufacturing strategies. "IMVP applied the word lean to describe a revolutionary manufacturing approach in contrast to the conventional mass production approach. Lean included concepts of Total Quality Management, Continuous Improvement, Integrated Product Development, and Just-in-Time Inventory Control." [6]

Principles of Lean

The term Muda is generally used to refer to any activity that uses resources without creating value. Creating value for the customer drives all phases of design, testing, manufacturing, and operations. The term "Lean" has been coined to symbolize activities and processes that minimize waste, are responsive to change, promote continuous improvement, efficiently utilize system resources, and in short deliver the right thing, to the right place, at the right time. In contrast to other management techniques, lean is a philosophy for creating value not a step by step approach that must be strictly followed. Results from IMVP and LAI have demonstrated that lean can be effectively applied to different industries and processes when viewed as a way of thinking and improving processes versus being a process itself.

One of the principle concepts of lean is the identification of the Value Stream. The Value Stream captures the set of all specific activities required to create a specific product, service, or combination of the two. Creation of a Value Stream Map helps to graphically represent all process activities and allows the classification of these activities into three identifiers: 1) steps which unambiguously create value, 2) steps which create no value but are unavoidable with current technologies and assets (Type 1 *waste*), and 3) steps which create no value and are immediately avoidable (Type 2 *waste*). Value Stream Analysis is essential for identifying waste and "seeing" where value is created. [45]

Lean Enterprise Model

The Lean Enterprise Model (LEM) presents the Lean Aerospace Initiative's view of lean and is a starting point for understanding the lean paradigm. Through Meta-Principles, Enterprise Principles, Overarching Practices, and Enterprise Metrics, the LEM expresses the fundamental concepts of lean that apply to the aircraft and space businesses as well as many other industries. Figure 4 shows a diagram of the LEM.

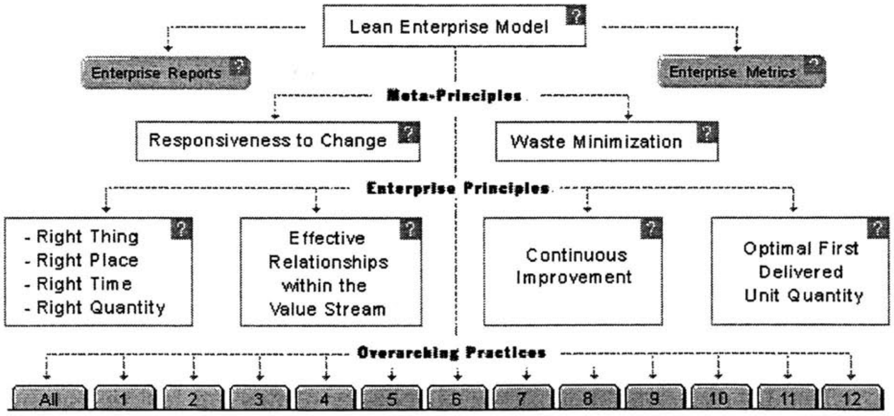

FIGURE 9-1 THE LEAN ENTERPRISE MODEL[46]

For context, the enterprise refers to the broad range of stakeholders that contribute to creating value for the consumer. The enterprise encompasses organizations or elements spanning from design and manufacturing to sales, marketing, and finance. A major tenet of lean is the emphasis on continuous improvement and striving for perfection. Perfection represents a ideal alignment of all components of the enterprise to provide maximum value to the consumer and stakeholders (value is defined in context of receiving entity). While it is realized that absolute perfection is not achievable, it is the awareness/recognition of the value created by constant advancement/ progress and the journey toward perfection that is important.

Managing Constraints as a Lean Enabler

Understanding the impact of external constraints on product design and development represents a lean enabler. In reference to the LEM, the research questions addressed in this thesis fall under the meta principles of waste minimization and responsiveness to change. Additionally, looking across system boundaries, between the launch vehicle and the spacecraft, exemplifies the system-level view crucial to integrating the space enterprise.

> **Enterprise View:** Constraints cut across system boundaries and exist at the heart of interactions between systems and their subsystems. Understanding how one systems' constraints influence another system (or one organization's constraints impact another) allows the designer to operate at the higher supersystem or enterprise-level. At this level, trades can be made across system boundaries striving to bring the enterprise to an optimum while leaving most subsystems at sub-optimal conditions. Optimizing at the enterprise level leads to total value maximization.
>
> **Waste Minimization:** As will be demonstrated in the following chapters, launch constraints lead to many design decisions that limit value creation. More importantly, many times launch constraints are responsible for system re-designs and wasteful design practices that increasing costs and schedule (Type I waste). Understanding constraints is an enabler to doing more with less, efficiently allocating limited resources, an central tenet of Lean.
>
> **Responsiveness to Change:** Analysis of the implications of relaxed launch constraints on space system design and development looks forward using knowledge of constraint impacts to form the basis of technology roadmaps. By outlining which technologies and capabilities will be necessary to effectively utilize the new launch systems quickly once they become available, these roadmaps help space system designers respond to change and focus on enabling continuous improvement.

Appendix B: General Observations from Interviews

9.4.1.2 Tier Structure of Launch Constraints

Launch constraints can be loosely separated into three tiers depending on their degree of influence on launch vehicle selection and level of rigidity. First tier constraints, such as political restrictions or physical limitations such as lift capacity or volume, have substantial design impacts and are either impossible or extremely difficult to trade-off. Second tier constraints also have significant design impacts, usually can be traded, and are the most influential in making the final choice from the suitable vehicles. The third tier factors usually do not have a large influence in the selection decision but can be traded and do impact the spacecraft design following selection.

9.4.1.3 Minimal Inter-Enterprise Trades

In general, most current spacecraft designers do few trades between the spacecraft and launch vehicle because early selected vehicles limit the possibility of trades and a dearth of quantitative tools and applicable methodologies for performing complex trades. Design is extremely compartmentalized with most spacecraft being design optimized for a specific vehicle. (spacecraft level versus architecture level optimization) Late stage re-designs to conform to vehicle constraints adds significant cost and leads to unnecessary customization. shielded from other elements of the space system enterprise.

9.4.1.4 Policy Driven Early Selection

Military programs have little flexibility in vehicle selection because of a "procure domestic vehicle only" policy. Additionally, even this little flexibility is removed with pre-design single vehicle assignment (ie program X will be on a Delta II) Early selection eliminates architecture trades.

9.4.1.5 Vehicle Standardization

The EELV program has improved standardization among US vehicles for loads and interfaces especially for the heaviest-lift class. Standardization with foreign vehicles has improved very little. Customer concern over standard interfaces allowing multiple vehicle options is a driving force for higher standardization in the commercial market. Vehicles that are too far from the mean loose customers who do not want to lock into a single vehicle choice. NASA was labeled as the most likely to have special needs requiring interfaces changes.

9.4.1.6 Capability First - Always

In response to the question "If additional lift capability were available for the same lift cost would you consider choosing larger, but less expensive components to save spacecraft costs?" Overwhelming response was no, would push for greater spacecraft capability. Commercial and military were most adamant about more capability.

9.4.1.7 Conservative Customers

Current situation with such high per unit costs and long manifest schedules make operator customers extremely conservative. Customers risk aversion is labeled as key design driver Many spacecraft developers spoke of clashing with the customer over putting on new technology/ components. Customers wanted benefits of new technology but were not willing to be the first to "try it out." Strong preference for qualified, pre-flown designs. Prevailing theme: Commercial will take an evolutionary approach.

9.4.1.8 Single Improved Vehicle → Slow Acceptance and Capability Utilization

Conservative customers are not willing to limit spacecraft designs to a single vehicle option even if it offers superior performance or lower cost. Ariane V cited as example of vehicle spacecraft developers avoid. The Ariane V offers substantial lift capability (over 6,800 kilograms to GTO), however, it is the only vehicle currently able to lift such large payloads (besides the Shuttle which is off limits to commercial payloads). Designers have shied away until another option in the 6,800 kilogram plus category is online. This points to a condition that industry change depends on more than one vehicle offering improved capabilities. Fear of a vehicle going offline (STS/Milstar example) will stop spacecraft designers from utilizing new capabilities until secondary options are available. Best environment for space system market and design changes needs two or more improved vehicles with close to equal capabilities.

9.4.1.9 Constraint Priority Depends on Program and Personnel

All spacecraft designers agreed that launch constraints played a role in spacecraft design. Besides cost and weight, most differed on what they believed were the most important constraint from adapters, access panel locations, and integration software to propellant slosh during ascent, fairing shape complaints, and separation mechanisms. Constraint priority mirrored spacecraft designer functionality with structural engineers citing loads as the most significant constraint and electrical engineers citing communications and adapter interfaces. Also, top attributes for selection are not always the same as biggest design drivers.

9.4.1.10 Old-Vehicle Bias

Selection preference for older proven systems with records over new systems was widely mentioned. Need for testing phase similar to aircraft to prove operational status was mentioned as a desire for new systems.

9.4.1.11 Scalability Issues

The current structure of launch lift capabilities creates a step function characteristic that encourages weight optimization and minimization. While spacecraft can easily grow or shrink by a kilogram or 10, the launch vehicle cannot. Lift capacity follows a standard step-function characteristic with each rung separated by hundreds if not thousands of kilograms. Unlike spacecraft, launch vehicles do not have the ability to easily grow capacity on the scale of less than 100 kilograms. The average weight differences between one vehicle and the next size up is 620 kilograms. However, this assumes access/availability to all global vehicles. Considering just US vehicles raises the average weight step to 1334 kilograms. The inability to simply choose another vehicle with a slightly higher lift capability reinforces the necessity to go through costly weight reduction processes.

9.4.1.12 $100 per pound Threshold

Most designers agreed that significant changes in spacecraft design philosophies and new markets would not change until launch price approached the $100 per pound level. Several industry studies pegged substantial new market creation in the $300 to $600 per pound range.

9.4.1.13 Vendor Situation

Many designer mentioned parts suppliers problems with vendors reluctantly accepting orders for small lot sizes with extensive load, environmental, and reliability requirements. Many attempted to raise prices (up to 1000x) to drive orders away. Has led to few suppliers for many components such as 1 or two vendors for Earth sensors. Single, complex spacecraft strategies along with launch and space environment constraints are responsible.

9.4.1.14 Readiness level

The current industry technology readiness to efficiently utilize improved launch capabilities is low. Commercial industry was much more near-term focused on vehicles that are currently available and acknowledge that very few exploratory studies and analysis had been performed to look at more radical design philosophies or the launch capabilities that would be required to support them.

9.4.1.15 Weight Based Cost Models

Spacecraft cost models and methodologies are entirely weight based with a positive relationship between weight and cost. Design trades based on using heavier COTS or previously designed hardware that is not optimized for the mission under consideration are extremely difficult to make. Additionally, weight-based cost models reinforce the weight minimization, weight optimization paradigm.

9.4.1.16 Strong Barriers to Generic Satellites

While they are becoming increasing used in commercial industry, there is some push-back to the use of generic spacecraft. Designers stressed the need to design for environments and vehicles that the spacecraft may not see. A struggle exist between highly skilled engineers not wanting to become assembly line workers. There is a strong personal preference for having some decision input and more customized work where they can treat the project as their own creation. Employee Benefits: More current knowledge, happier with more new missions, more dynamic environment

9.4.1.17 Prepare the Customer for Change

The high cost of failure has created an extremely risk averse customer environment. Spacecraft developers have a difficult time pushing new technology insertion as the customer drives the design. Several spacecraft developers mentioned that the customer is "not as technically knowledgeable as in the past" and there is more frequent personnel changeover with "managers coming in mid-project, needing to be educated, and then being reassigned just when they are up to speed." This limits long range vision and there is "rarely a customer who sees the grand picture." When changes in launch capabilities reduce the high cost of failure, it will be vital to prepare the customer for an environment where architectures and new technologies do not carry the same risk profile.

9.4.1.18 Government Technology Leadership

The high cost of technology development for launch and space systems requires government involvement. The commercial world will follow evolutionary changes because the risk-reward scenario for radical technologies is not economically appropriate Evolutionary development by industry must be supported with revolutionary development by the government. Federal research funds should be continually focused on the next generation of technologies leaving refinement to industry.

9.4.1.19 Standardize Interface Policy

Convergence of mechanical and electrical connections standards will allow payloads to be designed for the mission versus being designed for the vehicle. It also allows easier transition between vehicles. The key is to standardization success is involving several major players to adopt these standards so that others wishing to enter the market must also adopt. Standardization in the EELV program has made progress towards this goal.

Appendix C: Interview Questionnaire

1. In the programs that you have worked on, what were the main factors (4 - 7) that drove system costs and program schedule?
    - What differences have you observed across commercial, civil, and/or military programs?

2. What type of studies or design trades have you or your company performed in the past looking that the relationship between launch systems and spacecraft systems?

3. What drove the selection of the launch vehicle (what process was used) for the program(s) you worked on?
    - Which launch characteristics had the largest influence on the space mission and system design? Cost, Reliability, Integration or Interfaces, Schedule Dependability, Performance Capability, Availability, Other
    - How does this process differ between commercial versus government programs?
    - How does this process differ over single versus constellation architectures?

4. At what point in the program(s) was the final launch vehicle selected and roughly what percent of the spacecraft design was frozen prior to this selection?
    - How did the design evolve after this?
    - Were there any substantial changes to the spacecraft or architecture design that were driven (to a large degree) by the launch system cost or capabilities?
    - Any differences between commercial versus government payloads? Leo versus Geo?

5. Considering primary sub-systems, which tended to:
    - Grow or consume the most of weight and volume margins
    - Go through the most design iterations, most design changes, or require alterations to reduce size or mass
    - Have the most options to consider, variety of alternatives of different price, size, reliability, etc
    - Overrun cost budget allocation
    - Forced you to often pick up the launch vehicle specs

6. Consider a scenario where launch costs are extremely low (say $25/lb), launch on demand exists, and there is enormous launch mass capability available (greater than 100,000 lbs), what do you think might change in the design of space architecture? Push on:
    - Modular design
    - Technology insertion rate, rate of innovation, willingness to try new things
    - Expected spacecraft lifetime (replacement rate)
    - Spacecraft reliability
    - Spacecraft development time
    - Spacecraft Sub-systems (weight, volume, etc)
    - Reusability & Serviceability

7. What are your thoughts on?
    - Launch on demand
    - Designing payloads with shorter lifetimes and replacing them more frequently
        - What are the primary differences between long/short lifetime S/C?
        - How do costs change with expected S/C lifetime or development time?
        - What limits the potential lifetime?
        - Pros and cons (more technology innovation)
    - Using extra mass capability to reduce cost versus improve performance?
        - What about choosing heavier, less expensive components over light, expensive?
    - Allowing lower reliability but launching more spares?
        - Mainly for constellations
    - Any impact on design of systems in the past decade when mass capability has increased?
    - Using several inexpensive satellites instead of a single expensive one

8. What existing space markets would benefit most from reduced launch costs? Why?
    - Commercial versus government
    - Single satellite versus constellation
    - Leo versus Geo

9. What new markets would open up or what if launch prices decreased? Why?
    - What levels of cost, capacity, reliability do you think are necessary to enable these?

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