

**Designing Sustainable Heavy Lift Launch Vehicle Architectures
Adaptability, Lock-In, and System Evolution**

by,

Matthew Robin Silver

B.A., Williams College, 2001

S.M., International Space University, 2002

Submitted to the Engineering Systems Division and the
Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the degrees of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

and

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

at the
Massachusetts Institute of Technology
September, 2005

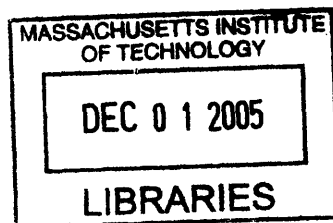
© 2005 Massachusetts Institute of Technology
All rights reserved

Signature of Author.....
Department of Aeronautics and Astronautics; Engineering Systems Division
July 29, 2005

Certified by.....
Jeffery Hoffman
Professor of the Practice of Aerospace Engineering
Thesis Supervisor

Accepted by.....
Jaime Peraire
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Accepted by.....
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program



BARKER

Designing Sustainable Heavy Lift Launch Vehicle Architectures Adaptability, Lock-In, and System Evolution

by,

Matthew Robin Silver

Submitted to the Engineering Systems Division and the
Department of Aeronautics and Astronautics on July 29, 2005
in Partial Fulfillment of the Requirements for the degrees of
Master of Science in Aeronautics and Astronautics and
Master of Science in Technology and Policy at the
Massachusetts Institute of Technology

ABSTRACT

Long term human space exploration depends on the development of a sustainable heavy lift launch vehicle (HLLV). But what exactly is *sustainability* in the context of launch systems and how can it be addressed in the design process? A HLLV must balance myriad technical and programmatic factors such as performance, reliability, cost, geographical configuration, logistics and assembly, as well as in-space issues such as mass and manifesting requirements for Lunar and Mars missions, and rendezvous and docking capability. The problem is further complicated by uncertainties in demand and differing stakeholder incentives. The military significance of space launch creates security externalities that often constrain design; “standing armies” of technicians and operators throughout the country affect industry and political interests; and scientific goals are often at odds with all three. The multi-dimensional nature of the design problem suggests that sustainability is best addressed at the system architecture level, where direct links can be made between technical and non-technical aspects of system operation.

This thesis examines the problem of designing sustainable heavy lift architectures in three ways: First, recent advances in systems architecture are synthesized as they apply to heavy lift launch. Sustainability is defined more precisely, as are the counterbalancing dynamics of adaptability and architectural lock-in. Second, cases are studied to understand how the previously defined concepts have played out in practice. The evolution of system architectures leading to the development of the last heavy lift vehicle, Saturn V, is analyzed; and the problem of reducing cost in the modern launch industry is examined from a political-economic perspective. Finally, insights from these studies together with recent advances in engineering economy are used to develop quantitative models to compare architectures. An analytic model is created to evaluate mission cost and risk as a function of vehicle capacity and in-space requirements. A discrete model based on real-options thinking is developed to compare Space Shuttle-derived and Evolved Expendable Launch Vehicle (EELV) derived architectures.

Thesis Supervisor:
Professor Jeffrey Hoffman
Department of Aeronautics and Astronautics

ACKNOWLEDGMENTS

The past two years at MIT have been exciting and eye-opening. I would first like to thank my family and friends for all their help and support. Without them I would probably be in a very different place—Harvard even.

I would like to thank Professor Jeff Hoffman for his advice in writing this thesis, as well as his inspiring stories about what space exploration is really like. I am also greatly indebted to Professor Olivier de Weck and Professor Ed Crawley, both for their academic guidance and support, and for their confidence in giving me the opportunity to contribute to such an exciting research topic.

I am grateful to Garry Martin at NASA Headquarters for supporting this research and putting me through grad school, but also for his encouragement and genuine interest in students and the future of space exploration. Together with the rest of the former Space Architecture Office, he made my summer at HQ truly fun and rewarding.

Finally, I would like to say a big thanks to Sydney Miller at TPP for always being there to help with basic MIT issues. She received the “Golden Band-Aide” award from students in the past, but I think an upgrade to Platinum may be in order.

CONTENTS

1. Introduction.....	15
1.1 Motivation.....	16
1.2 Approach.....	18
2. Designing Complex Systems	22
2.1 Introduction.....	22
2.2 Architecture.....	22
2.2.1 Spatial Architecture	23
2.2.2 Organizational Architecture.....	24
2.2.3 Operational Architecture.....	25
2.2.4 Value Networks	27
2.3 Some Notes on Design.....	29
2.4 Bounded Rationality and Imperfect Information.....	30
2.5 Technology as Knowledge: The Importance of Learning	32
2.6 Conclusion	33
3. Sustainability, Lock-In, Adaptability.....	36
3.1 Introduction.....	36
3.2 Defining Sustainability	36
3.3 The Iron Triangle, with a Twist.....	38
3.3.1 Benefit.....	38
3.3.2 Cost	40
3.3.3 Risk	41
3.4 Uncertainty.....	42
3.4.1 Policy Uncertainty	43
3.4.2 Budgetary Uncertainty	43
3.4.3 Technical Uncertainty.....	44

3.5	The coupling of Architecture, Politics, and Organization	45
3.6	Adaptation, Lock-In, and Vehicle Evolution	48
3.6.1	Adaptation.....	48
3.7	Path-Dependence & Lock-In	50
3.7.1	Causes of Lock-In: Switching Cost & Sunk Cost Hysteresis	51
3.8	Conclusion	56
4.	Origins & Evolution of U.S. Rocket Programs	59
4.1	Introduction.....	59
4.2	Skepticism and Experimentation—Rocket Programs in the 1940s	60
4.2.1	Influential Studies	61
4.2.2	Early Flight Programs	62
4.2.3	MX-774.....	64
4.3	The Cold War Heats Up: Rocket Programs in the 1950s	65
4.3.1	The Redstone Short Range Ballistic Missile	66
4.3.2	Jupiter.....	67
4.3.3	Juno	68
4.4	Air Force Missiles to Three Main Lines: Atlas, Titan, Delta	70
4.4.1	Atlas	70
4.4.2	Titan	73
4.4.3	Delta/Thor	74
4.5	Launching Early Manned Programs: Mercury, Gemini	75
4.6	Launching Apollo: The Saturn V.....	76
4.6.1	LOR verse EOR	77
4.6.2	The Saturn V	79
4.6.3	Logistics.....	82
4.7	Conclusion	83
5.	Government Policy and Innovation in the Modern Launch Industry.....	89
5.1	Introduction.....	89
5.2	The Political Economy of Launch	90
5.3	Military Roots: Legacy Costs	91
5.4	Development of an Industry and Government Failure	93

5.5	Industry Structure.....	95
5.6	Potential Remedies.....	99
5.7	Conclusion	101
6.	Analytic Model of HLLV Capacity, Cost & Risk	104
6.1	Introduction.....	104
6.2	Principle Trades	105
6.3	General Trends in Cost and Risk	107
6.3.1	Launch Cost	107
6.4	Development Cost.....	108
6.5	Risk implications of Single vs. Multiple Launch.....	109
6.6	Incorporating Risk into Cost.....	111
6.6.1	Expected Cost	111
6.7	Payload Cost as a Function of Capacity	112
6.8	Architecture Launch Cost vs. Capacity	113
6.9	Sensitivity Analysis	114
6.9.1	Learning Curves.....	114
6.9.2	Launch and Docking Reliability	115
6.10	Conclusion	117
6.11	Future Work	118
7.	Comparing Shuttle and EELV Derived Architectures.....	121
7.1	Introduction.....	121
7.2	Real Options Thinking.....	122
7.3	Elements of Life-Cycle Cost.....	124
7.3.1	Modeling Uncertainty in Demand	126
7.4	Shuttle-Derived verses EELV-Derived Architectures	128
7.4.1	Shuttle-Derived Costs	130
7.4.2	EELV-Derived Costs	131
7.4.3	Discount Rate.....	133
7.4.4	Summary of the Model	133
7.4.5	Results.....	135
7.5	Discussion.....	138

8. Conclusion	141
8.1 Sustainability and Complex Systems Design	142
8.2 Path Dependence and Lock-In.....	143
8.3 Analytic Launch Model	144
8.4 SDV verses EELVD	145
Bibliography	147

LIST OF FIGURES

FIGURE 1: NESTED HIERARCHY OF SUB-SYSTEM ARCHITECTURES FOR A LAUNCH SYSTEM	24
FIGURE 2: NESTED HIERARCHY OF SUB-SYSTEM ARCHITECTURES.....	25
FIGURE 3: POTENTIAL OPERATIONAL ARCHITECTURE OF SHORT STAY LUNAR MISSION	26
FIGURE 4: OPM REPRESENTATION OF THE HIGH-LEVEL GOAL OF A LAUNCH VEHICLE.	27
FIGURE 5: INTERACTION OF SYSTEM, GOAL, ENVIRONMENT.	29
FIGURE 6: THE IRON TRIANGLE: BALANCING COST, RISK, AND BENEFIT	38
FIGURE 7: NASA BUDGETARY FLUCTUATIONS IN 1996 DOLLARS.....	44
FIGURE 8: INTERACTION OF POLITICAL, ORGANIZATIONAL, AND TECHNICAL FACTORS.....	45
FIGURE 9: TRANSLATING POLICY PARAMETER AFFECTS INTO THE TECHNICAL DOMAIN.....	46
FIGURE 10: FOUR PRINCIPAL FACTORS AFFECTING THE DECISION TO SWITCH.....	55
FIGURE 11: NAVAHO CRUISE MISSILE TEST LAUNCH, 1957	64
FIGURE 12: MX-774 TEST MISSILE.	65
FIGURE 13: VANGUARD MISSILE, EXPLODING ON THE PAD. JUPITER AT LAUNCH.....	69
FIGURE 14: ATLAS MA-BOOSTERS PERFORMANCE EVOLUTION.....	72
FIGURE 15: THE MERCURY-ATLAS, LAUNCHING	73
FIGURE 16: THE H-1 ENGINE	75
FIGURE 17: SATURN V CONFIGURATION.	81
FIGURE 18: CHICKEN AND EGG PROBLEM IN THE LAUNCH INDUSTRY.	90
FIGURE 19: TRENDS IN EXPENDABLE VEHICLE LAUNCH COST SINCE 1960.	92
FIGURE 20: GOVERNMENT AND COMMERCIAL PAYLOADS LAUNCHES 1957 TO 2001	96
FIGURE 21: CONSOLIDATION IN THE AEROSPACE INDUSTRY, 1980 TO 2001	97
FIGURE 22: PUBLIC SPACE TRAVEL ESTIMATES.....	99
FIGURE 23: LAUNCH CAPACITY, PAYLOAD COST, AND RELIABILITY.....	107
FIGURE 24: RELATIONSHIP OF LAUNCH COST TO LEO CAPACITY FOR US	108
FIGURE 28: CRYOGENIC KICK-STAGE COST VS. PRODUCTION RATE.....	113

FIGURE 29: TOTAL EXPECTED ARCHITECTURE COST V CAPACITY.	114
FIGURE 30: TOTAL LAUNCH COST V CAPACITY AT DIFFERENT LEARNING CURVES.	115
FIGURE 31: EXPECTED LAUNCH COST V AR&D RELIABILITY.	116
FIGURE 32: EXPECTED LAUNCH COST V PAYLOAD COST	117
FIGURE 33: ELEMENTS OF LAUNCH VEHICLE LIFE CYCLE COST.	124
FIGURE 35: TWO PLANS FOR HEAVY LIFT LAUNCH; SDV VS EELVD	129
FIGURE 36: DECISION TREE VIEW OF EXPECTED-COST CALCULATION	134
FIGURE 37: DISCOUNTED LIFE-CYCLE COST COMPARISON	136
FIGURE 38: DISCOUNTED LIFE-CYCLE COST COMPARISON, WITHOUT RAMP-UP	136
FIGURE 39: MODEL RESULTS WITHOUT RAMP-UP.	137

LIST OF TABLES

TABLE 1: SAMPLE SCENARIOS AFFECTING LAUNCH VEHICLE LIFE-CYCLE	49
TABLE 2: PROGRAM TIMELINE	86
TABLE 3: COMPETING COST AND RISK FACTORS OF SMALLER AND BIGGER LAUNCHERS..	106
TABLE 4: DIFFERENCE BETWEEN 40MT AND 80MT ARCHITECTURE LAUNCH COST.	116
TABLE 5: SDV DEVELOPMENT COSTS	130
TABLE 6: SDV 4-SEGMENT VARIABLE RECURRING COSTS	130
TABLE 7: SDV 5-SEGMENT VARIABLE RECURRING COSTS	130
TABLE 8: SDV “RAMP-UP”	131
TABLE 9: DEVELOPMENT COST SPREAD	132
TABLE 10: EELVD DEVELOPMENT COSTS	132
TABLE 11: HIGH DEMAND SCENARIO	135
TABLE 12: MEDIUM DEMAND SCENARIO	135
TABLE 13: LOW DEMAND SCENARIO	135

1. Introduction

It is increasingly recognized that large-scale, complex systems cannot be designed independent of the social, political, and economic context in which they operate. Given their size, cost, and complexity, space systems are often cited as paradigmatic examples of this need. The harshness of the space environment demands tremendous reliability and control at multiple levels, with systems designed and coordinated by thousands of people throughout the country. Simply ensuring that they work is a tremendous challenge. However, our expanding experience with space enterprise demonstrates that often the non-physical constraints in the operating environment such as programmatic and organizational issues, economics, or politics, are as important or more to a system's long-term success. These factors are best addressed at the architectural design level, where direct links can be made between them and technical aspects of the system. To do this rigorously, new frameworks, tools, and methods to are needed.

An architectural approach is particularly important for designing a heavy lift launch vehicle (HLLV) to support human exploration missions to the Moon, Mars, and beyond. Earth to Orbit launch forms the bedrock of all space activities. Increased vehicle size usually entails added complexity. A successful transportation system will balance myriad factors such as vehicle size, reliability, configuration, logistics, and cost, as well as in-space issues such as Lunar and Martian mission mass and manifesting, rendezvous and docking capability, and transfer trajectories. Optimization is further complicated by the fact that a vehicle program serves different purposes to different groups. The military significance of space launch creates security externalities that often constrain design. "Standing armies" of technicians and operators throughout the country and complex

supplier relationships affect industry and political interests. Finally, scientific goals can at times be at odds with these groups. While difficult to quantify, these interests often have significant impact on both the design and evolution of vehicle programs. A properly designed vehicle will ensure that, to the extent possible, such forces work for, rather than against, our long-term goals in space.

This thesis examines the problem of designing sustainable heavy lift launch vehicles from an architectural perspective. Because of the multi-dimensional nature of the problem, it is examined from multiple angles. Basic issues in the design of complex systems, and definitions of sustainability, adaptability, and lock-in, are synthesized as they apply to heavy lift launch. Case studies verify how these concepts shed light on the long-term evolution of past vehicle programs, the development of the last heavy lift launch Vehicle for lunar exploration, the Saturn V, as well as the problems of reducing cost in the modern launch market. An analytic model is developed to evaluate high-level trades of launch capacity, cost, risk, and in-space design. A discrete model is also developed to compare Space Shuttle Derived Heavy Lift Vehicles, to EELV-derived heavy lift vehicles using Real Options Thinking.

1.1 Motivation

A key enabling capability for human space exploration is Earth to Orbit transportation. When last called upon to explore a solar system body with humans, NASA created the now legendary Saturn V vehicle. Five 1.7 million pounds thrust F-1 engines in its first stage, five 232,000 pounds thrust J-2 engines in its second stage, and one J-2 engine in a third stage which doubled as a trans-lunar injection stage, gave the Saturn V lifting capacity of roughly 260,000 pounds to low earth orbit.¹ While the Saturn V was ultimately successful, the decision to go with an “all-up” architecture to low Earth Orbit (LEO) was not at all evident in the early 1960’s. Many worried about the reliability of one massive vehicle and some proposed to split the Lunar payload into pieces and assemble them in orbit. As a new exploration vision takes shape at NASA, the critical

question looms again: What size launch vehicle will best enable the human exploration of the Moon and Mars?

The *sustainability* of a launch system is central to the decision. By the President's own words the Exploration Vision will be long-term and continuous;² initial efforts must develop skills and techniques necessary to sustain further exploration, and the ultimate goal is extended human presence on bodies outside of Earth orbit. But it is important to note that sustainability has implications beyond NASA. As the recent Aldridge Report notes, a central goal for the long-term exploration of space is the development of a robust space industry independent of government intervention.³

More than simply ensuring the continuation of NASA programs, this involves structuring programs and incentives adequately to encourage outside participation. Similarly, because political winds are likely to change throughout the exploration system life-cycle, a sustainable program must be designed to maintain, among other attributes, *relevance* to the government, American people, and other stakeholders, through time. A better understanding of vehicle sustainability will create more value for stakeholders over time, increase the return on taxpayer investment, and increase the likelihood that our long-term goals in space are realized.

As NASA organizes to return men to the Moon, Mars, and beyond, it is therefore imperative that it considers the long-term sustainability of various vehicle architectures, and space systems in general. What contributes and detracts from it? And how can sustainability be provided for through design decisions made today?

NASA and other entities in the government have, of course, designed successful vehicles in the past. Lessons learned with regard to the sustainability of past vehicle programs should be used to design new systems. However, the indefinite duration of the current exploration visions complicates the picture. Unlike the Apollo program, in which one goal generated an unchanging rank-ordering of metrics for all subsystems (i.e. safety first, cost last), the open-ended nature of the current plan means that priorities, sub-goals, and

technology will likely change while systems are operational. NASA needs new tools and concepts to design and compare systems for operation in these conditions.

1.2 Approach

Designing sustainable launch vehicle systems is a multi-parameter task that requires balancing performance and programmatic factors. Consideration must be paid to launch vehicles, the launch facilities, payloads, and payload accommodations as well as programmatic factors such as workforce requirements and program cost.⁴ The latter have overtly political implications. The coupling of political and organizational factors with technical design also has implications for program adaptability. System Architecture affects issues such as organizational inertia, political incentives, economic trades, and overall system reliability, all of which influence switching costs and create “path-dependencies” in the vehicle evolution. Unfortunately, these latter factors are rarely incorporated into the design and advanced planning stages of vehicle development.

These design challenges demands an understanding of how launch system architectures couple to uncertainty in the technical, economic and political realms. By extension, in order to compare different system architectures with respect to their sustainability, system designers must understand how various designs can *adapt* to new needs and operational environments. To be sure, such analysis will draw on traditional systems engineering tools, and the basic cost-risk-benefit triangle. But new concepts and tools are needed to understand which system is *more sustainable* than the next.

Motivated by these problems, this thesis examines the question sustainability in launch systems, from an architectural perspective. Given the complexity and scope of the problem, a large portion of the work involves how best to *frame* the design problem, that alternative launch systems can be compared. Chapters 2 and 3 provide a theoretical basis for such comparison. Chapter two synthesizes recent advances in systems theory and design theory as they apply to space systems. Chapter three defines *sustainability* in the

context of launch systems, including the need for adaptability, and the role of switching costs and lock-in.

Chapter four examines the sustainability of past vehicle architectures, focusing on how political, economic and technical factors affected the initial development and evolution of launch vehicles architectures. These case studies follow the evolution of early programs from ballistic missile systems into the three main modern launch vehicle lines in use today: Atlas, Delta, Titan.¹ The affect of past designs on the development of the Saturn V heavy lift vehicle is also examined, as well the relationship of the Saturn program to overall Apollo program goals.

Chapter five analyzes the modern launch industry, with a focus on NASA's role in encouraging innovation. Specifically, it examines the political economy of the launch industry in an effort to understand why the cost of space launch has not fallen over the past half-century, and whether NASA policies have helped or hurt in this regard. Recommendations for policies that may encourage the development of entrepreneurial activities are made.

The frameworks and concepts developed in chapters two through five are applied in chapter six and seven to modeling the heavy lift decision from an architectural perspective. Chapter six presents an analytic model of launch cost and risk as a function of capacity. This includes the trade-off between launching large vehicles with ground assembly, or smaller vehicles with in-space assembly. The goal of this model is to determine the desirable vehicle size for lunar and mars missions from a cost and risk perspective and also to understand what factors most affect a launch vehicles' contribution to overall mission cost and risk.

Chapter seven uses "real options thinking" to model the forthcoming decision on whether to use Shuttle-Derive or EELV-derived components in a new heavy lift vehicle.

¹ Though of course the Titan is currently being phased out, and Lockheed Martin and Boeing have recently signed a joint venture to operate the EELVs based on Atlas and Delta rockets together.

Chapter 1: Introduction

Specifically, the question is framed as an option on EELV vehicles: either a shuttle derived vehicle can be created for Lunar and Mars missions, or a smaller EELV-derived system can be created for lunar missions with the option to expand capacity for larger missions. Major factors affecting this decision are discussed, together with possible design options.

Chapter Endnotes

¹ Bilstein, Roger E. *Stages to Saturn: A Technological History of the Apollo/Saturn Vehicles*. NASA History Series. Published by Scientific and Technical Information Branch, National Aeronautics and Space Administration. Washington, DC. 1980

² Remarks by President Bush on U.S. Space Policy. NASA Headquarters, January 14, 2004. See: <http://www.whitehouse.gov/news/releases/2004/01/20040114-3.html>

³ Report of the President's Commission on the Implementation of United States Space Exploration Policy: "Journey to Inspire Innovate, and Discover." June, 2004

⁴ Ryan, Robert, et al. "Fundamentals and Issues in Launch Vehicle Design." *Journal of Spacecraft and Rockets*. Vol. 34, No 2., March-April 1997

2. Designing Complex Systems

2.1 Introduction

The design of complex systems such as launch vehicles differs from more basic design in important ways. Issues such as bounded rationality, the importance of learning, ubiquitous uncertainty and imperfect information, emergent phenomenon, and the existence of multiple stakeholders, all acutely affect conception, design, testing and operations of such systems. It is increasingly recognized that these issues are best addressed at the level of the system architecture, and a new discipline is rapidly emerging to understand how best this should be done. This chapter therefore presents some fundamental concepts and recent advances in systems architecting and complex systems design, as a basis for investigating specific issues in the design of sustainable heavy lift launch vehicles. While the concepts apply to heavy lift vehicles, they are generic to the design of complex engineered systems.

2.2 Architecture

What does it mean to design a system's architecture? A system can be defined as a collection of interrelated elements with functionality greater than the sum of independent element functions.¹ The term "system architecture" refers to the invariant properties of a system, defined as a unique association of form and process.^{2,3} The system architecture thus defines the *relationships between constituent elements* of the system, whether in spatial, organizational, or operational terms.⁴ Spatial architecture defines relationships of

Chapter 2: Designing Complex Systems

subsystem parts in space; organizational architecture identifies the unique interconnection of subsystems processes; operational architecture refers to the sequence of operations conducted to accomplish a mission. All three views are related.

The focus on defining and understanding relationships, rather than objects themselves, is a critical element of architecting systems, worth emphasizing in the context of rocket design. The concept of creating a “rocket system” as an integrated whole emerged as early as the 1950s, when military necessity called for rapid development of complete weapons systems.⁵ General Bernard Schriever, a major player in the development of ballistic missiles and launch vehicles, called this a “program package,” emphasizing its *management and technical* implications.⁶

While subsystems may vary, architecture will remain unchanged if new subsystems perform the same functions using the same interfaces. Said another way, architecture is blind to subsystem characteristics if interfaces are appropriately designed. Describing a system in terms of these invariant characteristics therefore greatly simplifies the high-level design of the system because it avoids detailed subsystem design. It allows constituent parts to be organized and analyzed without recourse to exceedingly complex calculations and representations of subsystem characteristics. Importantly, it also allows systems with similar architectures, but different constituent elements to be compared. As Herbert Simon writes: “Resemblance in behavior of systems without identity of inner systems is particularly feasible if aspects in which we are interested arise out of the *organization of the parts*, independently of all but a few properties of the individual components.”⁷ The following presents more specific examples.

2.2.1 Spatial Architecture

The word architecture most commonly brings to mind buildings. The architecture of a building defines the *spatial* relationship between walls, floor, roof, and other constituent elements of the building. Under this definition, using I-beams for support rather than, say, wood reflects an engineering, rather than architectural, decision. The architect must know constraints and properties of different materials in order to know what forms might be

possible, but beyond this he defines only the invariant spatial relationships in his plans (the forms); engineering executes the design plans, ensures that they “work” (in this case, that the building will stand).

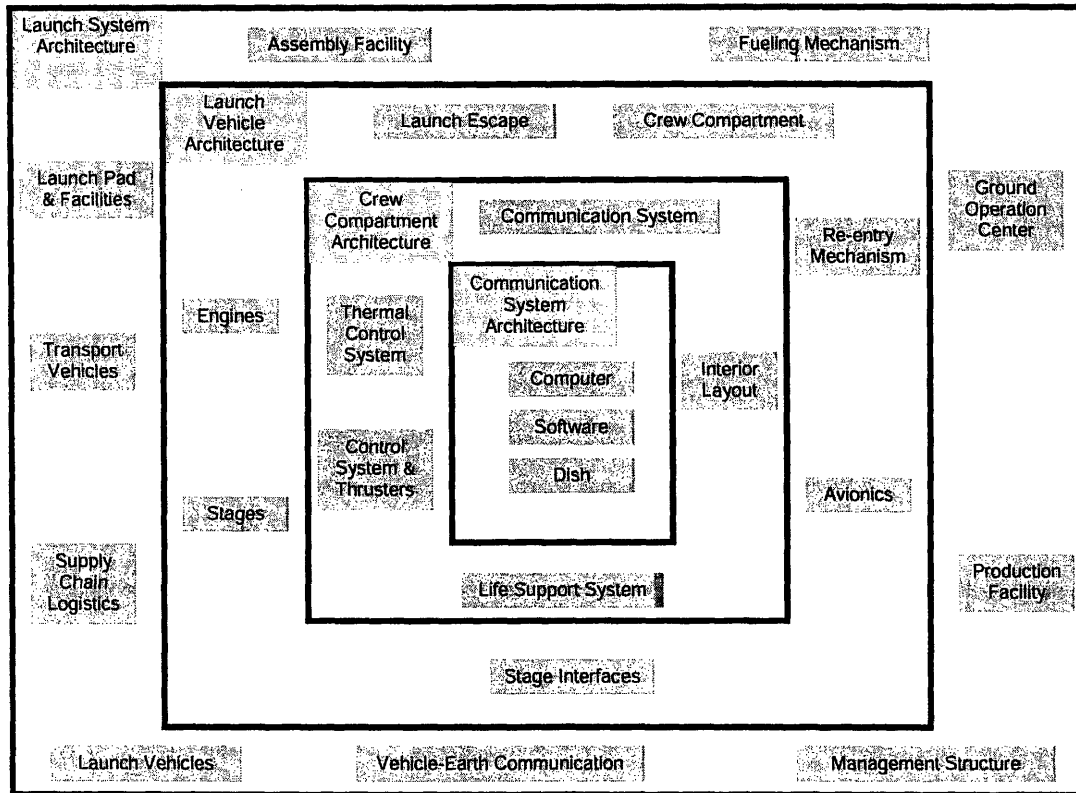


Figure 1: Nested hierarchy of sub-system architectures for a launch system, along one line of the tree. Subsystems are not exhaustive. (Modeled after Christenson, 1993)

2.2.2 Organizational Architecture

Complex Systems are often, if not always, created through a hierarchical assimilation of component parts. The system is thus composed of multiple levels of sub-systems, each of which interact to produce a specific function for a higher level. Each level corresponds to a unique organization of subsystems, from whose interaction higher-level function emerges.⁸ Each sub-system, all the way down to the atomic level, can be defined in terms of the *process or function* that it executes, rather than its material form.⁹ The unique, relationship of these processes at each level defines the organizational architecture of that

level of the product or system. Figure 1 and Figure 2 illustrate two views of the organizational architecture of a launch system. It is important to note that the architectural elements of these figures include the function of the subsystems, and their interconnection—not the specific technology of the subsystems themselves.

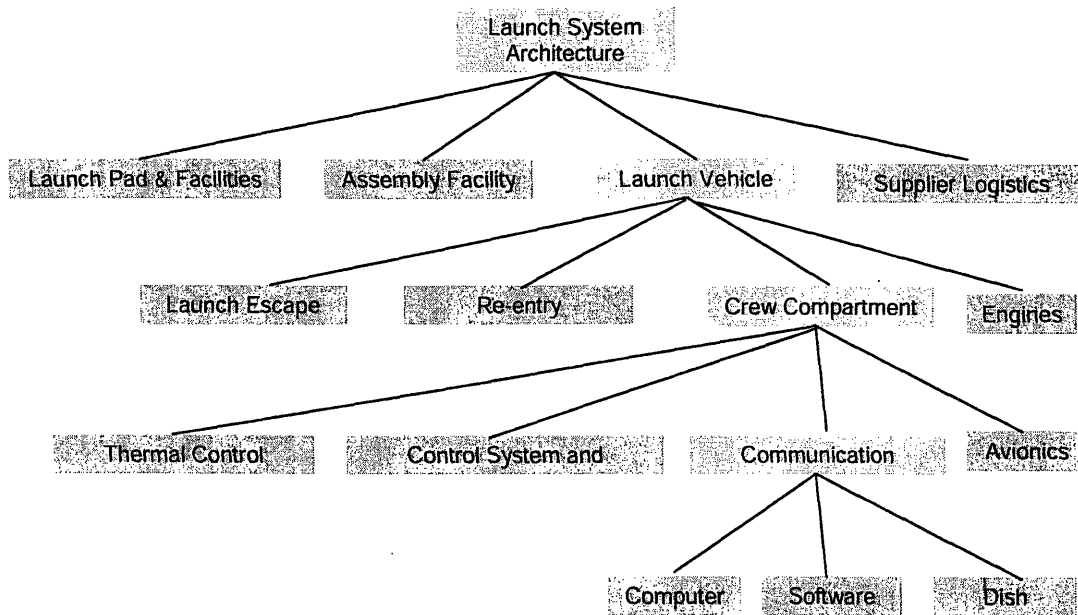


Figure 2: Nested hierarchy of sub-system architectures, along one line of the tree. Subsystems are not exhaustive.

2.2.3 Operational Architecture

Exploration Systems often perform tasks in *sequences*, in pursuit of a function or goal. The nature and relationship of these sequences defines the operational architecture of the system.¹⁰ An often-sited operational architecture design decision involved whether to use Lunar-Orbit-Rendezvous (LOR) or Earth-Orbit-Rendezvous in the first manned mission to the moon. While each had relative advantages, LOR was eventually chosen.

All three architectural views are intimately related. Figure 3 illustrates an operational view of a short-stay lunar mission. It calls for two ETO launches, Earth-Orbit assembly of a lunar excursion module (LEM) and crew exploration vehicle (CEV), injection of the stack, descent of a lunar and rendezvous in lunar orbit, and a CEV return with ballistic

Chapter 2: Designing Complex Systems

trajectory. Because it associates specific forms with specific processes, this sequence automatically defines the organizational architecture as well: The CEV will not descend to the lunar surface, and an expendable LEM is needed. A crew service module provides independent functions as well. The size and shape (spatial architecture) of all of these forms are constrained, if not partly defined, by their functional requirements.

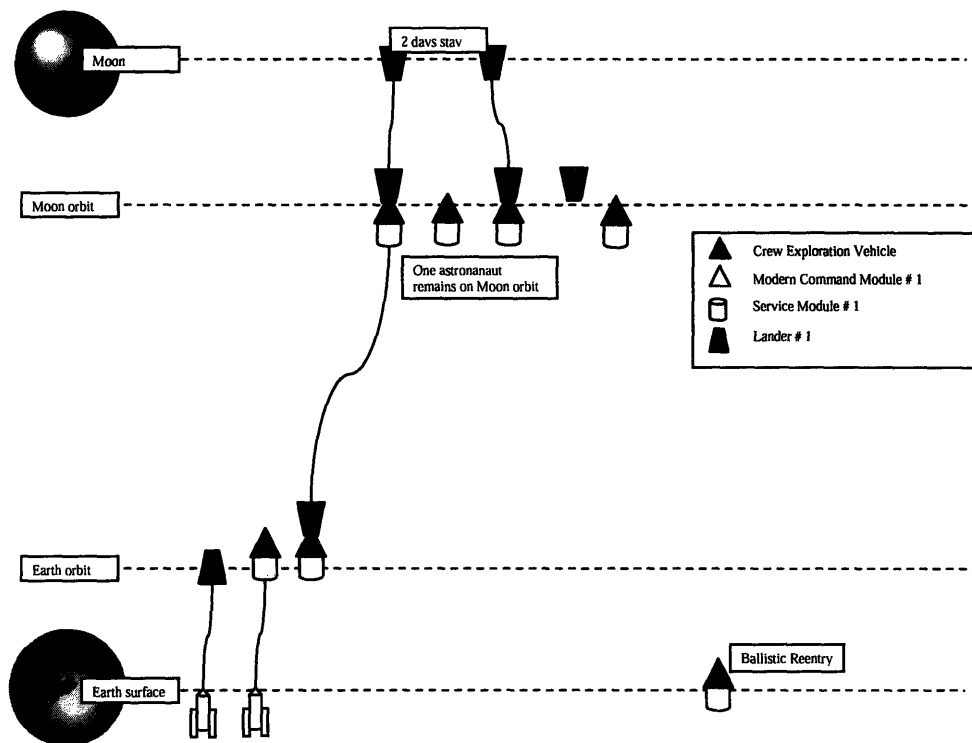


Figure 3: Potential operational architecture of short stay Lunar Mission

System architectures can thus be represented in many ways. One increasingly used method of representation is Object Process Methodology (OPM). OPM associates objects with process, and enables both to be associated with attributes. Figure 4 illustrates a high-level representation of the goal of a launch vehicle, using OPM. Read through it states NASA must design "A transporter using existing technology where possible, that will transport humans and cargo from Earth to LEO and back to Earth, economically and safely, in order to enable the Exploration Vision."

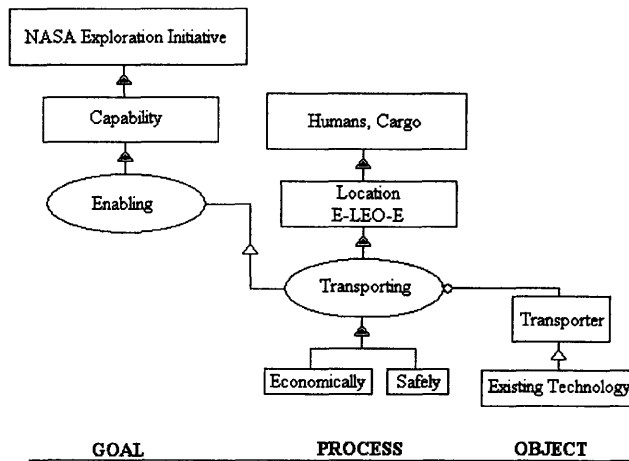


Figure 4: OPM representation of the high-level goal of a launch vehicle.

2.2.4 Value Networks

The hierarchical decomposition illustrated in Figure 1 above mirrors the design of the organization which will build the system. That is, groups of people associated with designing, building and operating subsystems, gain expertise in their area and communicate most often with groups on their level or those directly adjacent. Recent scholarship in product architecture emphasizes the importance of this coupling between the organization and the technical system for design, operation, and innovation.¹¹ Hans Christensen has called the combination a *value-network*, noting that what determines design and incentives to innovate in a given network is often the specific rank-ordering of metrics determined at the highest-level of the system.¹² Associating the term “technological paradigm” with system architecture, he writes:

“The scope and boundaries of a value network are defined by the dominant technological paradigm and the corresponding technological trajectory employed at the higher levels of the network...the very definition of value is a function of the dominant technological paradigm in the ultimate system of use in the value network. The metrics by which value is assessed will therefore differ across networks. Specifically, associated with each network is a unique rank-ordering of the importance of various performance attributes, which rank-ordering differs from that employed in other value networks.”¹³

Chapter 2: Designing Complex Systems

Thus, a system architecture has significant implications for the way that value is understood at the subsystem level, for it dictates the rank ordering of metrics by which to measure improvement. This, in turn, dictates the direction of innovation. While straightforward, this observation is critical to thinking about the sustainability of complex systems. For it makes clear that simple architectural decisions have extraordinarily complex social implications, including the way that knowledge is accumulated and the design choices made by thousands of engineers at lower levels. These issues are enforced by an established pattern of contractor and sub-contractor communication, and the development of expertise. A simple example involves whether to use H2/LOX or RP1/LOX as propellant for the HLLV booster stage. While such a decision could be framed as a performance/economic trade on the vehicle, it also programmatic and supplier implications that touch industries outside of Aerospace, and could define radically different cost-profiles for future NASA development projects. Such decisions, while technical in nature, should be made with a firm understanding of the programmatic implications.

For private industry, highest-level metrics correspond to perceived market needs. For NASA, they are determined by the end-goal of the system, and take the form of early design requirements. The end-goal of the entire exploration system could be said to reflect the needs of the “political marketplace” to which NASA caters. This includes military, political, and industry priorities, which should be a reflection of national priorities. Like a market niche, such needs are liable to change before the system is obsolete.

The value-network perspective is important to this thesis for two reasons: First, it puts emphasis on the need to design the system holistically, with regard to programmatic and organizational elements that will likely affect the vehicle throughout its life-cycle. Second, it provides a framework to explicitly link system-level change (i.e. change in metrics) to changes in the environment (i.e. political or economic goals). That is, by associating general needs with specific rank-orders of metrics, a concrete link can be

made between political and organizational realities and uncertainties, system design, and system sustainability. This will be elaborated upon below.

2.3 Some Notes on Design

Especially when billions of dollars are at stake, a complex system's design often represents the outcome of multiple conceptions, refinements, and negotiations.¹⁴ If we are to supplement the activity of design with tools, then, the process of design must be understood at a basic level. This section begins with a discussion of the very basics of *design*, including limitations in the design process and how simulation can help.

The activity of “design” can be defined simply as the process of matching the characteristic of an artifact or system with its environment, in order to achieve a goal.¹⁵ As such, quite often the most difficult aspect of designing involves correctly defining the environment or context in which the system will operate—for once this has been accomplished, creating something to fit this context becomes more akin to mechanistic execution than anything else.¹⁶ For space systems, much effort is paid to characterizing and compensating for the extreme harshness of the physical environment in which the system will operate. But as noted, economic, organizational, and political factors also create important environmental constraints and uncertainties.¹⁷

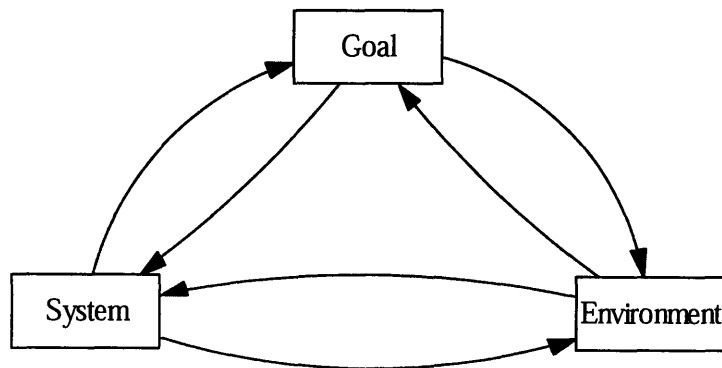


Figure 5: Interaction of System, Goal, Environment.

Chapter 2: Designing Complex Systems

Figure 5 illustrates the interconnection between the system, goal and environment. While intuitively clear, this can serve as a powerful template to organize design thinking. For example, a consideration for system “sustainability” will include an understanding of how factors in each of the three categories change through time and how these changes influence the other categories. Systematically thinking through these interactions can be greatly simplified by considering that all changes occur in one of the three categories, and their impacts, often formalize through equations, are represented along the arrows.

For example, discovering water on Mars changes the state of knowledge of the *environment*, and this will likely translate to *new goals* with required modifications in the *system*. Similarly, political or geopolitical shifts, in the environment may alter the perceived value of exploration which has an impact on available resources. Less obviously, characteristics of the system can impact the goal and the environment. Technological limitations restrict exploration targets, and existing funding channels are quite often difficult to alter. Thus, the goal may not easily be changed in response to environmental changes.

While rather abstract, this kind of thinking can have very concrete implications for system design. Assigning probabilities to different scenarios, for example, can help determine whether a vehicle capable of lifting 80 metric tons or 100 metric tons to LEO, will prove more valuable over its life-cycle. Such scenarios will thus be elaborated upon in the following chapter.

2.4 Bounded Rationality and Imperfect Information

System designers must conceive solutions in a fog of *imperfect information* and *bounded rationality*. Information is imperfect because aspects of the system, environment or goal are unknowable or are known with limited precision. Bounded rationality stems from basic limits to cognition, regardless of the kind of information present. Though related in affect, these are distinct issues that must be addressed independently.

Chapter 2: Designing Complex Systems

Herbert Simon, a Nobel laureate in economics and pioneer in theories of bounded rationality, has noted that rationality is limited for three main reasons:¹⁸

1. It is impossible to have complete knowledge and anticipations of the consequences of a decision
2. Values can only be imperfectly anticipated
3. Only a few possible alternative solutions ever come to mind

These issues must be distinguished from basic issues of imperfect information, which has to do more with limitations in collecting data or the inability to know a specific piece of information. For example, we do not know now whether there is enough water in the lunar poles to support a human settlement on the moon for extended periods of time. This is imperfect information. We cannot conceive of every possible method to extract water—this is bounded rationality.

The basic distinction between system, environment, and goal outlined above, can help understand the implications of this definition for system design:

In System:

- Imperfect Information: Complex interaction cannot always be inferred from knowledge of parts
- Bounded Rationality: Only a few of the possible alternative solutions ever come to mind

In Environment:

- Imperfect Information: Forecasts are always wrong. New information comes in often from the environment
- Bounded Rationality: One cannot have complete knowledge of the strategic consequences of a decision (or design)

In Goal:

Chapter 2: Designing Complex Systems

- Imperfect Information: Values/needs can only be imperfectly anticipated
- Bounded Rationality: It is impossible to consider all consequences of actions/designs

The distinction between imperfect information and bounded rationality is important because, though similar in affect, mediating strategies for each are very different. Information can be perfected through testing or well planned strategies. It is less clear how to address problems of bounded rationality.

Computational models can help increase rationality in some of these areas, but not in others. Enumerating thousands or millions of architectural combinations, for example, addresses Simon's third point about what limits rationality. But the second and first point are much more difficult. Models are only as good as their assumptions. And at the heart of it, estimates about future values or about the consequences of a given action will always be nothing more than assumptions.

2.5 Technology as Knowledge: The Importance of Learning

The historian of Technology, Edward Constant, has noted: "Technology, like instinct, is knowledge tested against the environment."¹⁹ When lay-people think of space-systems and technology in general they often think of physical artifacts such as rockets. But a longer-term view proves Constant's definition to be much more useful. For especially when a system is complex, learning dominates design and operations. This knowledge then changes the cost-structure of future alternatives, making some paths cheaper and others more expensive. In turn, the evolution of a complex program is more accurately conceptualized as the evolution of a knowledge-base, with physical artifacts created to suite different needs.

That learning dominates the development of complex systems is proven in part by the importance of testing. Quite often, subsystem and system-level tests are the most costly aspect of DDT&E.²⁰ This is due in large part to "emergent phenomena" which are

Chapter 2: Designing Complex Systems

difficult to predict before a system is integrated. An example of emergent phenomena in heavy lift vehicle systems was the “pogo” action discovered during testing of the Saturn V. “Pogo” was the name given to unexpected axial vibrations which were traced to the coupling of aerodynamics, propulsion systems and tank design. Significant redesign of each was needed to remedy the situation.²¹ Retiring these development learning costs creates significant incentives to continue operating existing vehicle configurations.

Learning has profound affects for production and operations as well. It is well documented that learning decreases the cost of production significantly, and this is incorporated into economic models through *learning curves*. The same is true for operations, which become streamlined and increasingly efficient as uncertainties are reduced. Changing modes of production or operations, then, constitutes not only new design and production costs, but new learning costs. There is evidently a balance between switching these modes to decrease cost, and keeping them the same to take advantage of learning, which greatly influences the sustainability of a program.

These factors will be further addressed in later chapters on modeling. Suffice to note that the fact that technology, especially when dealing with complex systems, is knowledge tested against the environment has important implications for sustainability. It emphasizes the social component to sustaining systems. It also implies that a large part of the developing sustainable systems involves, among other factors, maintaining a base of knowledge at minimum cost in the face of change.

2.6 Conclusion

The previous discussion reveals a string of interrelated issues that are crucial to consider in the design of a complex system such as a launch vehicle:

- We need to clearly understand the context/environment in which the system will operate, including political and economics and technical uncertainties, in order to design a sustainable system.

Chapter 2: Designing Complex Systems

- A complex system can be defined as a value-network in which value is uniquely determined by rank-ordering of metrics created by the highest-level goal of the system. A value network encompasses both technical and organizational elements of the system.
- Bounded rationality means that modeling a decision can be useful in some ways, not in others. Basic problems associated with imperfect information are difficult to overcome through modeling. This increases the need for flexibility and adaptability.
- Technological development can be defined as the evolution of a knowledge base.
- This greatly increases the importance of learning, and leads to issues such as technological lock-in, with implications for long-term dynamics. It also implies that a large part of the developing sustainable systems involves, among other factors, maintaining a base of knowledge at minimum cost in the face of change.
- All of these issues will be examined in more detail, as they apply to launch systems, in the following chapters.

Chapter 2: Designing Complex Systems

Chapter Endnotes

- 1 Crawley, Edward. Lecture notes from 16.89 Space Systems Design Class. Spring, 2004
- 2 Koo, Benjamin. "A Meta Language for Systems Architecture." Phd Thesis. MIT, 2005
- 3 Alexander, Christopher. Notes on the Synthesis of Form. Harvard University Press, Cambridge, MA. 1964
- 4 Christensen, Clayton M. The Innovators Dilemma. HaperCollins Publishers Inc., New York, NY. 1997
- 5 Emme, Eugene M. (editor). The History of Rocket Technology; Essays on Research, Development, and Utility. Wayne State University Press. Detroit, Mich. 1964
- ⁶ Emme, 1964
- 7 Simon, Herbert A. The Sciences of the Artificial; Third Edition. MIT Press. Cambridge MA 1996 p. 17
- 8 Crawley, 2004
- 9 Simon, 1996, P. 5
- 10 Crawley, 2004
- 11 Henderson, Rebecca M. et al. "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firms." Administrative Science Quarterly (35), 1990, p. 9-30
- 12 Christenson, 1997
- 13 Christenson, 1997
- 14 Klein, Hans. "System Development in the Federal Government: How Technology Influences Outcomes," Policy Studies Journal, vol. 28, no. 2, 2000.
- 15 Simon, 1996, p. 5
- 16 Christopher, 1964. p. 15
- 17 Weigal, Annalisa et al. "Interaction of Policy Choices and Technical Requirements for a Space Transportation Infrastructure." Acta Astronautica, vol 52 no. 7 (2003), 551-562.
- 18 Simon, Herbert. Administrative Behavior, Fourth Edition. The Free Press. New York, NY, 1997
- 19 Constant, Edward II. The Origins of the Turbojet Revolution. Johns Hopkins University Press, Baltimore, MD, c1980.
- 20 Constant, 1980
- 21 Bilstein, Roger E. Stages to Saturn: A Technological History of the Apollo/Saturn Vehicles. NASA History Series. Published by Scientific and Technical Information Branch, National Aeronautics and Space Administration. Washington, DC. 1980

3. Sustainability, Lock-In, Adaptability

“Once inefficient systems are developed and placed in operation, further life-cycle cost trades become heavily biased in favor of the inefficient technology—its development costs and risks having been retired. Compared to new technologies that must still be developed, an existing capability has a huge advantage. Thus, once investments are made in inferior designs, they tend to have a very long life”

--Robert Shishko, “Space Station Lessons Learned”

3.1 Introduction

The previous chapter presented some concepts that are critical to designing sustainable complex systems, and sustainable launch systems. The following chapter examines with more precision what *sustainability* is in the context of launch vehicle design, and what else might be needed to compare alternative architectures on these terms. It begins with a definition of sustainability for space systems. It then discusses the impact of life-cycle dynamics and multiple forms of uncertainty. Finally, it discusses the related attributes of architectural adaptability/flexibility and architectural lock-in, both of which are critical factors in program evolution. The chapter concludes with a simple model for incorporating these concepts into a design decision.

3.2 Defining Sustainability

To sustain means literally to “support,” and an effort is sustainable if it is able to be continuously supported. What about a system, however, enables it to be continuously supported? To answer this question we must better understand specific attributes of space systems, as well as issues that may hinder their continued support.

Chapter 3: Sustainability, Lock-In, Adaptability

Two additional definitions will be useful for this analysis. First, the Bruntland Report of 1987, widely credited with coining the term “sustainable development,” claims that an effort is sustainable if it “meets the needs of the present without compromising the ability of future generations to meet their own needs.”¹ By analogy, we might say that a space system is sustainable if it achieves preset exploration goals without compromising long-term exploration goals. Second, “Red” and “Blue” team reports conducted at NASA in the spring of 2004 characterized sustainability in terms of the ability to “transcend individual institutional, political, and programmatic cycles as well as unanticipated events.”² This emphasizes the need to cope with uncertainty. We therefore have three interrelated determinants of a sustainable system:

Sustainability: An exploration system or subsystem is sustainable if it has the capacity to be continuously supported at the political, economic, and technical level.

Corollary 1: A system or subsystem is sustainable if it can react to, or manage, uncertainties in the political, economic and technical domains.

Corollary 2: A system is sustainable if it does not hinder future goals.

By extension, a given architecture is more sustainable than another if it accomplishes the tasks defined above better than another, according to some metric. However, it is important to stress the difference between the sustainability of a system and the sustainability of a goal. In the final analysis, we are concerned with sustainability because we want the exploration of space to continue, regardless of which system is used, and we want the eventual development of a robust space industry independent of government intervention. *Corollary 2* is therefore critical, for we want to design a launch system that benefits the overall exploration vision. A large launch vehicle should not prevent the development of systems and practices that might contribute to the future evolution of the industry. These might include entrepreneurial ventures, or the development of advanced technologies.

Sustainability, then, by definition refers to the highest-level goals of a system. A given launch vehicle architecture may be changed many times or continuously adapted, but

Chapter 3: Sustainability, Lock-In, Adaptability

relative sustainability is a question of the end goal. Both corollary 1 and corollary 2 are thus equally important and somewhat conflicting. Our goal is to strike a balance between creating a sustainable vehicle program and “sustainably” supporting the exploration vision.

3.3 The Iron Triangle, with a Twist

Systems engineering is largely about balancing cost, risk, and benefit. The interconnection of these factors is often depicted via the “iron triangle,” shown in Figure 6. A successful system will create value for its stakeholders at acceptable levels of cost and risk. A consideration for sustainability implies simply extending this paradigm to take into account how cost, risk, and benefit, may change through time. Because elements of both the system and the environment are likely to change, a system must adapt to ensure that uncertainties do not allow the cost, risk, or benefit, to fall outside of allowable margins.

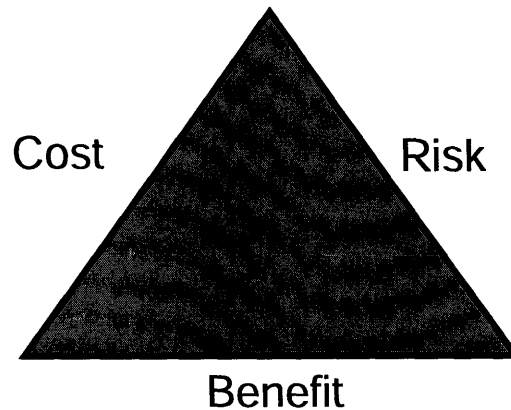


Figure 6: The Iron Triangle: balancing cost, risk, and benefit

3.3.1 Benefit

Value, of course, is in the eye of the beholder. In order to understand the benefit exploration systems and the launch systems that support them, we must know both who

Chapter 3: Sustainability, Lock-In, Adaptability

the stake-holders of the system are, and how benefit is defined. The following provides a policy-level overview of exploration system stakeholders and benefits, in order to frame the basic problem of sustainability. More detailed analysis of risks and benefits associated with launch vehicles is provided in following chapters.

For the exploration system, let us define the stakeholders as *members of communities with the direct ability to provide financing and/or material support for exploration and/or those communities which benefit directly from exploration deliverables*. While it might be reasonable to consider the entire US population, or even the World population, as holding a “stake” in the exploration of space, we can make the limiting assumption that the needs and desires of the public will be represented adequately through the US congress—for if the US government decides not to fund space exploration, it will not take place. By extension, the representative bodies of international participants are stakeholders. Thus, the stakeholders for Space Exploration will include the following:

- The US Congress
- Relevant branches of the US Military and Security establishment
- NASA
- International Sates and Agencies cooperating in the Exploration Vision
- The Scientific Community
- Industry contractors and subcontractors, including entrepreneurs
- Educators

The question remains, what are the “deliverables” from which these groups benefit? Recent work at MIT suggests that at the highest level, the main value-added deliverable of exploration is knowledge, in various forms.³ Knowledge can be categorized based on type, each of which are valued differently by various stakeholders. Categories of knowledge include:

- Human experience of space and interplanetary exploration
- Scientific data

Chapter 3: Sustainability, Lock-In, Adaptability

- Space system design knowledge
- System production knowledge
- Space system operational knowledge and experience

Knowledge flows from the system to stakeholders through different channels. Human experience is communicated to the public through the media, news, and other means. Scientific data is generated at different points during exploration missions, and transmitted back to earth through the communications architecture or as samples. Experience with space technology accumulates in industry and government groups, and can be used in different applications thereafter. In this regard, whether knowledge gained is of the system or of the environment is secondary to whether or not it has value.

In short, stake-holders invest in space exploration to gain various kinds of knowledge. Of course, at the launch-system level, the benefit is a bit more concrete. Launch systems provide earth to orbit transportation to enable exploration with certain costs and risks. Stake-holders may invest in a launch system without interest in the broader goal of exploration. This is particularly true for the military and industry, who will likely be more concerned with operational capability and revenue generating capability, than with actually exploring. This can, in turn, affect the acceptable costs and risks associated with a vehicle program. More specific benefits, costs, and risks associated with vehicle architectures are discussed in the chapter on modeling.

3.3.2 Cost

Given stakeholder support, an exploration system must continuously fall within an allocated budget in order to be sustainable. In other words, it must be *affordable*. The question of how much budget to allocate to various systems in the exploration technology portfolio is complex and demands considerable attention and analysis. Earth to Orbit transportation consumes a large portion of NASA's total budget. Even with zero flights, for example, the Space Shuttle Program costs nearly three billion dollars, or 20% of NASA's budget.

Chapter 3: Sustainability, Lock-In, Adaptability

Basic vehicle program costs can be broken into development, fixed recurring, and variable recurring. Development includes DDT&E, fixed recurring can be thought of as the cost of maintaining a program with zero flights. This includes labor, facilities, program management, and whatever production is required to keep lines open. Variable recurring includes all costs associated with flying vehicles, which vary accord to demand. The details of these cost-structures will be addressed in the chapter on modeling.

An important issue concerning funding vehicle programs involves whether to build in-house or out-contract. In the past, when a particular transportation industry has been too immature to satisfy Government needs, the government has been faced with the choice of creating the infrastructure itself, or helping private industry mature.⁴ NASA is faced with this same problem with respect to ETO launch.

Building in-house, means that NASA will pay directly for design, development, and operations of the vehicle. In this scenario, NASA would be able to retire the various costs of building the system, and pay only operations costs downstream. Out-contracting would mean that NASA pays a private contractor for DDT&E and then pays a price for launch including amortized development costs and profit. In this scenario NASA must pay for profit, but the private entity could sell launches on the commercial market. These scenarios are examined in more detail below.

These options constitute a radical difference in incentives for various parties. Government workers often have an incentive to “fill up” a budget and force expenditure to exactly equal investment, because if a program is under-budget, it risks being funded less the following year.⁵ Private programs, on the other hand, often look to cut costs, but this is sometimes even at the expense of safety.

3.3.3 Risk

Both the real and perceived risk associated with exploration is directly tied to its benefits and costs and will greatly affect overall sustainability. While there are many different kinds of risk, it can be generally said that if the perceived risk of exploration is too high

Chapter 3: Sustainability, Lock-In, Adaptability

given a goal, funding will be with-held or the goal will be recast. Risk tolerance can be divided into three main areas:⁶

- Development risk: during design, test integration of architecture components
- Planning risk: willingness to exploit more or less known system margins while planning an exploration mission
- Operations risk: willingness to take risk during operations.

By definition, risk-free exploration does not exist. System designers must balance the risk associated with architectural form, schedule, and operations, in order to achieve system objectives. Risk tolerance can change throughout a system life cycle, and thus change how a given system is operated.

A key trade with respect to launch risk is associated with in-space assembly. A large vehicle enables more ground assembly and fewer pieces, which generally reduces mission risk in orbit but may increase launch risk. A smaller vehicle is generally more reliable at launch and has lower fixed recurring costs, but will require more launches and more in-space assembly which can be costly and risky. The relationship of reliability to capacity, however, is not fully understood. This issue is addressed in the chapters on modeling.

3.4 Uncertainty

A multi-year, multi-billion dollar program in the US Government must expect to face changes of objectives, budget allocations, and technical performance. In order for an exploration system to be sustainable, then, it must be able to operate in an environment of considerable uncertainty throughout its life-cycle. Beyond balancing benefit, cost, and risk for multiple stake-holders, designing for sustainability implies identifying sources of uncertainty and managing them through up-front system attributes. The following section introduces various kinds of uncertainty that will impact an exploration system and launch vehicle.

Chapter 3: Sustainability, Lock-In, Adaptability

3.4.1 Policy Uncertainty

Policy uncertainty can take the form of changes in objectives or the regulatory environment in which a system must operate. It stems from the dynamic nature of the US government, and the need for space systems to suit both national/strategic and political/tactical interests. Government programs are re-assessed on a yearly basis in terms of national priorities and, in some cases, performance. Changes in the political and geopolitical environment can alter the perception of the value of exploration activities. An important aspect of policy sustainability is thus the ability to maintain relevance, and continue operations, in the face of shifting objectives and regulatory environments.

To take one example, while the decision to build the Space Station Freedom was motivated largely by Cold War concerns, the fall of the Berlin Wall transformed the ailing project into a symbol for international peace and cooperation.⁷ To the extent possible, system designers should consider the implications of such changes for system operation. If a policy decision to focus on Mars rather than the Moon is likely in the near term, current designs should be extensible to both objectives. Similarly, if international cooperation is based on uncertain agreements, alternatives to international participation on the critical path of development should be available.

3.4.2 Budgetary Uncertainty

Shifting political priorities also create changes in funding. During its years of development and operations, a programs budget may oscillate unpredictably. Figure 7 illustrates how NASA's budget fluctuates over time.

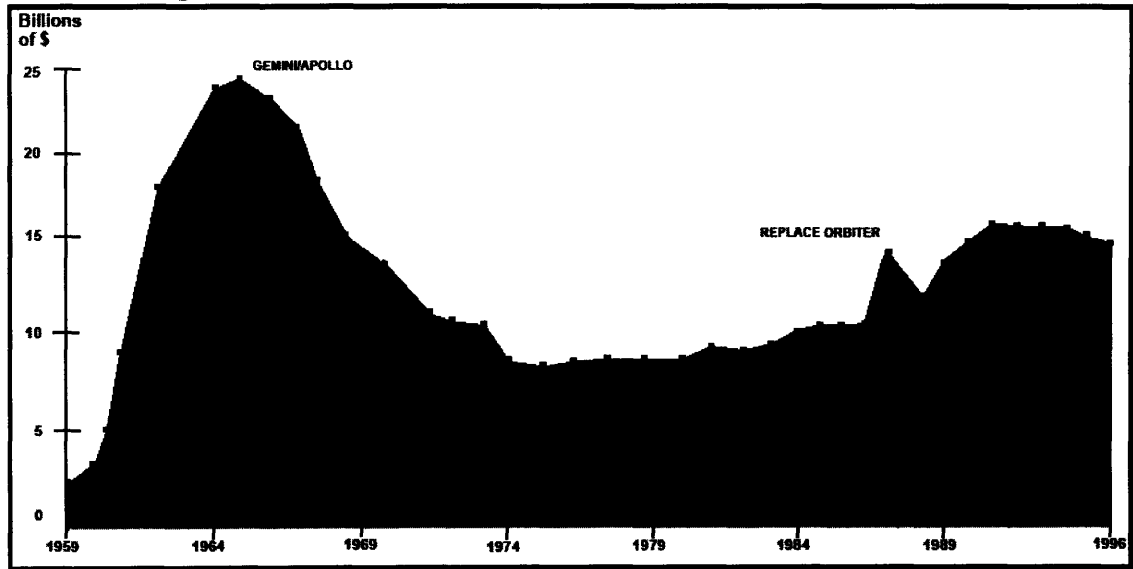


Figure 7: NASA budgetary fluctuations in 1996 dollars (courtesy <http://history.nasa.gov>)

A flexible system will maintain exploration capability even in the face of budgetary fluctuations, whether through changes in schedule, scale of operations, or by other means.

The ability of a vehicle program to cope with budgetary pressure is a function of its cost profile, including the development, fixed recurring, and variable recurring components. A program with low fixed recurring cost can more easily withstand periods of low budget or low launch rates however, quite often such capability comes at the expense of higher development and/or variable recurring costs. The affect of these ratios on HLLV development are examined in chapters five and six.

3.4.3 *Technical Uncertainty*

An exploration system must support and maintain human and robotic activity at various fronts of exploration, and incorporate technological advances to continuously improve system performance without major operational changes. Further, any highly complex system is likely to fail at some point during its life cycle. A sustainable system will be one that is robust to failures, both small and large, and one that can incorporate advances in technology with minimum disruptions to overall objectives.

3.5 The coupling of Architecture, Politics, and Organization

Our definition of sustainability emphasizes the fact that a given architecture should not hinder future exploration goals. While a large complex system must react to changing political, budgetary, organizational, and technical uncertainties aspects of systems can themselves impact the environment. Once in development and operation, a multi-billion-dollar system will mediate political interests, organizational decisions, and technical alternatives, creating potential sources of stability and positive feedback-loops, as well as sources of uncertainty. Early decisions that create high switching costs or large infrastructure sites, can “lock-in” architectural configurations and influence the objectives and development path of later systems.⁸ A sustainable design will be one in which, to the greatest extent possible, the dynamics behind political, technical, and financial sources of stability support, rather than hinder, system development and operations. The relationship between these three broad domains is shown in Figure 8.

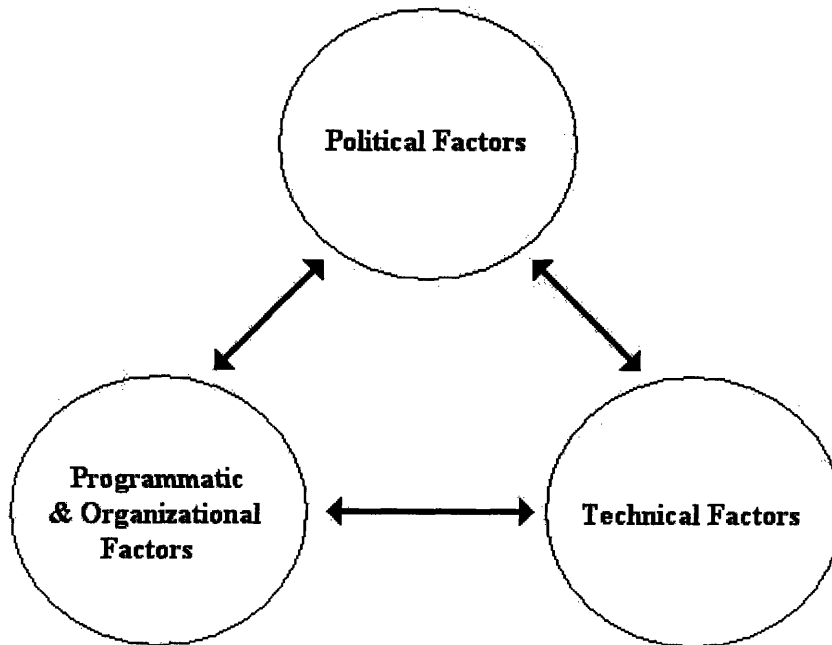


Figure 8: Interaction of political, organizational, and technical factors

Hans Klein has suggested that the characteristics of a technological system and development program can facilitate or impede coalition politics, thereby reducing or

Chapter 3: Sustainability, Lock-In, Adaptability

exacerbating conflicts between politics and program administration.⁹ Technology and politics are linked when program administrators translate political forces into design requirements. Once developed, a given system architecture together with its supporting facilities can become “locked-in” and perpetuated through later designs. The space shuttle, for example, made use of facilities designed partly as the result of short-term political wrangling conducted during the Apollo era.¹⁰

Annalisa Weigel and Daniel Hastings have similarly stressed that space transportation infrastructures are affected as much by political considerations as technical problems. It is thus imperative to understand the coupling of both domains if a system is to operate successfully in the “politico-technical” arena. Figure 9 is an “influence diagram” used to understand such coupling.

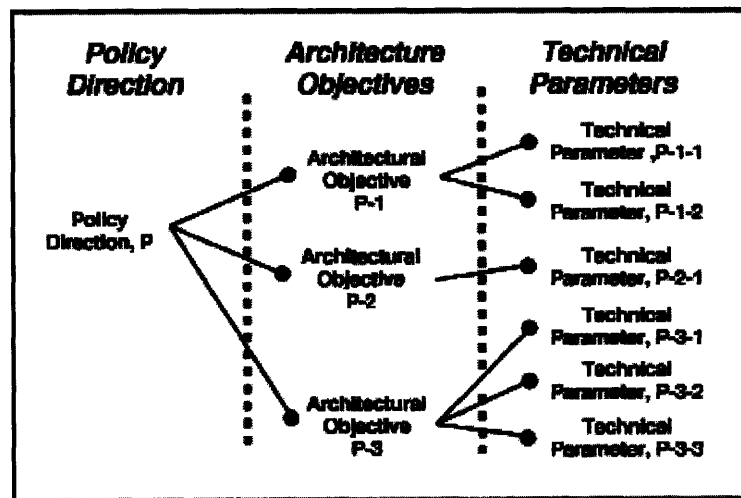


Figure 9: Translating policy parameter affects into the technical domain: an influence diagram (courtesy, Weigel and Hastings, 2003)

Finally, *organizational performance* and technical design are closely linked. Organizational structure of technically complex systems can impact system reliability by hindering individual’s abilities to learn from their mistakes.¹¹ In the extreme, a badly designed organization can create “quite erroneous worlds in [the] minds” of system operators and managers.¹² Diane Vaughan has similarly noted that the “the microscopic world of daily decisions” can create almost imperceptible changes in organizational

Chapter 3: Sustainability, Lock-In, Adaptability

culture over time, with important consequences for safety. Her term, the “normalization of deviance,” encompasses the way in which expectations can change and aberrations become accepted, through continual exposure to anomalies. While difficult to quantify, understanding the long-term impact of architectural design on such organizational issues can greatly impact sustainability.

Beyond affecting political incentives and organizational habits, a given architectural configuration has important implications for innovation. We have already discussed the way in which an architecture, defined as a value network, creates a rank-order of metrics which affects sub-system innovation. Similarly, James Utterback has noted that the innovative potential of a firm is intimately tied to socio-technical factors. He writes:

“Any firm’s potential for technical innovation can be considered as a function of its environment—including economic, social, and political factors, the state of development of technology, and information about technology. Barriers to flows of people and information between the firm and its environment will limit its knowledge of market needs, new and existing technology, and government programs, incentives, and regulations, thus limiting the potential for innovation as seen by the firm. Characteristics of the firm itself, including its resources, personnel, and patterns of communication and decision-making, will determine the degree to which it meets its perceived potential for innovation.”¹³

Utterback’s observations, together with the concept of value networks, emphasize the need to design architecture with consideration for social factors such as communication, information processing, and incentives. This will have implications for issues such as what to design in house, and what to out-contract, where to locate facilities, and which kinds of core technologies are used.

In short, the political and organizational context in which a space-system operates not only affects, but is affected by, the system architecture. While these interactions are difficult to quantify, they have profound affects on system evolution and sustainability. An operational system, together with its subsystems, creates patterns of communication and activity which influence reliability, innovation, and other important issues. It also creates patterns of spending with important political repercussions. Finally, expensive systems become the foundation for future developments, restricting some options and encouraging others. This latter aspect of system evolution is examined in-depth in the following chapter on case-studies.

3.6 Adaptation, Lock-In, and Vehicle Evolution

The above discussion suggests how complicated it can be to design a system with consideration for sustainability. The system must be changeable in reaction to various uncertainties, many of which are very difficult to quantify, and it must be robust to others. Much recent research has centered around measuring a system's ability to achieve these objectives. Investigated measures and metrics Many terms have been used to define a system's ability to achieve such objectives. These include: adaptability, flexibility, robustness, and extensibility. Together, these are known as the "ilities" and their resemblance quite often generates more confusion than clarity. In many ways this is merely a matter of semantics.

3.6.1 Adaptation

This thesis will use the umbrella term, *adaptation*, to describe a system's ability to react to changes in the goal or environment. More specifically, we can use the biological notion that a system is adaptable if it addresses change while keeping "essential variables within acceptable limits."¹⁴ For space systems, we can define the "essential variables" as the basic triangle of cost, risk, and benefit. While "acceptable limits" may change as circumstances change, this basic definition holds.

In a simplified model of adaptation, a vehicle system serves one purpose with a given rank-order of metrics, then change occurs, and the entire system must respond. For simplicity, we can assume that a given architecture can be changed in two basic ways: incrementally or radically. Incremental change involves changing a subsystem, while keeping architectural relationships intact. Radical or architectural change means completely changing the relationships between subsystems. Much recent scholarship has examined the organizational and social aspects of architectural and incremental change, mostly with respect to product architectures.¹⁵

Architectural change often results from either a change in overall goal, or a radical innovation. For example, because NASA has changed its overall goals in space we now

Chapter 3: Sustainability, Lock-In, Adaptability

need a vehicle capable of lifting larger masses of cargo to IMLEO at less cost than the shuttle. As a result, proposals have been made to adapt existing shuttle hardware to create a shuttle derived heavy lift vehicle. Because the shuttle cannot be used for the new goal at acceptable levels of costs, adaptation is needed. This is an example of radical change as a result of a goal change.

Radical innovation also calls for new vehicle architectures. For example, if nuclear thermal rockets were perfected in a safe manner, a non-chemical vehicle architecture would likely replace anything designed in the near term. This would entail new hardware, different payload accommodations, new launch pads, and new logistics: in short, a new architecture.

These initial distinctions, while very rudimentary, point the way towards designing systems for adaptability. We want to create architectures that can serve multiple goals or respond to likely innovations, at minimum cost. This means creating system components that can form the basis for multiple architectures, without radical change. This strategy is often called platforming. The difficulty, of course, is that such flexibility comes at the expense of performance.

Scenario planning is one way to begin evaluating architectures along these lines. Scenario planning involves creating different scenarios that are likely to affect a space system, and then testing how well different architectures react. Table 1 presents example scenarios, with some resulting impacts on the launch system. Chapter six will demonstrate more accurately how to translate use decision tree analysis to quantifiable the impact of such scenarios on the system.

Table 1: Sample scenarios affecting launch vehicle life-cycle

Example Scenario	Result	Impact on Launch System
Water in Lunar Pole	Change Exploration Goal	Increase IMLEO Needed
Nuclear Thermal Engine Dev.	Drop Cost Increase performance	Increase ETO Capacity
Foreign War	Cut Budget	Reduce # of Launches
System Failure	Decrease Risk Threshold	Increase Cost

Chapter 3: Sustainability, Lock-In, Adaptability

While designing a system to be adaptive will surely improve that architecture's sustainability, sometimes facilitating subsystem change can actually lock-in suboptimal technologies. Organizational and political incentives will ensure that existing system will be used if possible, sometimes at the expense of innovation and/or efficiency. This phenomenon is known as lock-in and must be understood before one can design for architectural adaptation.

3.7 Path-Dependence & Lock-In

"A process of economic allocation is called *path dependent* when the sequence of allocations depends not only on fundamental, *a priori* determinants—typically listed as technology, factor endowments, preferences, and institutions—but also on particular contingent events. Instead of converging to a determinate, predictable, unique equilibrium, such processes have multiple potential equilibriums, and which one is selected depends on the specific history of the process."¹⁶

Path dependence and lock-in are two related technological phenomena that strongly affect space systems. *Path-dependence* refers to the fact that future options are constrained by past decisions. A system's "development path," for example, is a function of future needs, existing technology, and developed hardware. *Lock-in* is a prominent cause of path dependence. It occurs when inferior architectures are difficult to change due to incentives to continue operating fielded systems. Path dependence and lock-in are relevant to the current discussion because they affect the ability of an agency to achieve long-term goals. In order to design an adaptable launch vehicle, the forces affecting path dependence and lock-in must be understood. Importantly, they are often impossible to quantify.

As the quote above this section stresses, path-dependence occurs when multiple architectural configurations can be applied to a given situation and the one chosen is a function of previous decisions and contingent aspects of the design environment. While ideally a given technology is optimized for a given goal, the reality with complex systems is that more often political goals and existing capability meet halfway. This is due to institutional and organizational factors, as well as economic and technical issues such as

Chapter 3: Sustainability, Lock-In, Adaptability

sunk costs and network affects. To take one example, early rocket programs were designed for rapid deployment and reliability, with little regard for operations cost. Once their DDT&E have been retired, there were strong organizational and political incentives to address new goals with derivatives of these systems.

Thus, a major source of path-dependence involves the combination of contingent events during design, and the fact that existing design represent an equilibrium from which it is difficult to deviate. With respect to space systems we might call this a political-economic-technical equilibrium.

The continuation of a given system architectures is prolonged by *lock-in*, which refers to the fact that fielded system architectures are very difficult to change. Multiple examples of lock-in have been sited in consumer technologies, the most famous involving VHS verse Beta-Max as a standard for VCRs. A second example involves the persistent use of the “qwerty” key-board configuration which was originally designed to slow down typing.¹⁷

Lock-in strongly affects space-systems. The high capital cost and complexity of space systems creates strong incentives to continue existing modes of development and operation. An example of this is the current debate surrounding Shuttle-derived verses EELV-derived HLLV architectures. Much operational and development risk and costs associated with shuttle components have been retired, creating a strong incentives to continue their use rather than develop a newer system based on EELV components. There are also political incentives to keep jobs in existing programs. In many ways, any final vehicle configuration will be a triumph of political clout, rather than technology—for it is relatively clear that both EELV and Shuttle vehicles have the capability to support exploration missions.

3.7.1 Causes of Lock-In: Switching Cost & Sunk Cost Hysteresis

The basic causes of path-dependence and lock-in are multidimensional, which is partly why they are very hard to control. These causes, however, can be encapsulated by the

Chapter 3: Sustainability, Lock-In, Adaptability

concept of *switching-cost*. For underlying this discussion is the assumption that two architectures, or technologies, are being compared, and a decision must be made regarding whether to *switch* from one to the other. While the cost of switching to a new technology or architecture is often purely economic, it can also include be social or political.

Sunk Cost

The most concrete form of switching costs is the re-investment and risk associated with design, development and learning. A suboptimal technology can compare favorably to an optimal technology simply because development cost and risk, and learning curves, have been retired. Herbert Simon states this clearly, in reference to the metric system verse English system of measurement:

“A society starting from scratch and familiar with both systems would surely prefer the metric to the English System. But if future benefits are discounted at some rate of interest, it might never be economical to switch from the one system, once adopted, to the other...The evolution and future of such systems can only be understood from a knowledge of their histories”¹⁸

Very similar dynamics affect the evolution of space systems, as Robert Shishko has noted with respect to the Space Station:

“Once inefficient systems are developed and placed in operation, further life-cycle cost trades become heavily biased in favor of the inefficient technology—its development costs and risks having been retired. Compared to new technologies that must still be developed, an existing capability has a huge advantage. Thus, once investments are made in inferior designs, they tend to have a very long life”¹⁹

The incentive to put off switching due to sunk costs and risks is amplified when there is uncertainty in the operating environment and investment is irreversible. Uncertainty in future demand or operating needs creates further asymmetries between existing and future systems because even if costs of a new system were equal to those of an existing system after sunk costs and risks were considered, there would still be the possibility that this comparison would change once investment began. It is always possible to put off investment in a new system to see how this uncertainty plays out, however, once new investments begin this cannot be recouped. In reality, then, the total expenditures for a

Chapter 3: Sustainability, Lock-In, Adaptability

new system, including new DDT&E and learning, must clear a “hurdle rate” to overcome the affect of uncertainty.²⁰

The affect of this hurdle rate on investment in uncertain environments has been termed “Sunk Cost Hysteresis” by economists. The appellation refers to the fact that capital can remain active even after the economic environment which brought it about has changed. One way to address hysteresis is to design options into the architecture which allow rapid response to environmental change without significant new investment. This is the basis for *real options analysis*, which is addressed more directly in later chapters.

Network Affects

Switching costs are amplified by *network affects*. The term *network affect*, refers to the fact that the value of some technologies increases as more people use it.²¹ As Christenson has noted, value is property of networks not technologies.²² That is, the benefit of a technology stems from its relationship to other processes and needs, the totality of which defines a value network. The examples above concerning the metric system, the qwerty keyboard, and VHS tapes all involve network affects. As more people use them, the value of these technologies increase, and more technologies are invented around them. Technologies that exhibit network affects are difficult to change because changing them requires changing all technologies which use them in their network. Further, without significant numbers of new adopters, the incentives to switch to a new architecture are often fairly low.

Standards and Interfaces

It should be noted that all of the technologies described above that exhibit strong network affects can be considered *standards*. They define interfaces between various parts of the value network, whether human-computer, tape-reader, or units of measurement. This is significant because we have defined the architecture of a system as the relationship between forms and processes and, by extension, the nature of *interfaces* defines the architecture. Once an architecture has been defined, improvements can be made to subsystems while keeping the same interface. Improvements to the *architecture*, however,

Chapter 3: Sustainability, Lock-In, Adaptability

cannot often be made without changing all of the interfaces and thus changing all subsystems.

Learning

Besides sunk cost hysteresis, and network affects, basic limits to rationality and learning represent a major cause of architectural lock-in. Learning, of course, has significant economic impact for development and operations. This is incorporated into economic models via the learning curve. Switching to a new system demands paying down this learning again.

Learning, however, has implications beyond economics. As previously noted, defining an architecture enables engineers to focus on more detailed problems at the subsystem level, without constantly having to make design decisions about the whole system. This leads to the build-up of expertise in a given area and crystallizes channels of communication along certain lines. As a result, solutions to past problems have a strong influence on the nature of current and future problems, and it is very difficult to advocate changing these relationships all at once.

Basic cultural factors related to learning also influence the direction that an organization can be taken. As one author has noted:

"Technology infusion is not simply about having an accurate accounting scheme, however; there are significant cultural barriers that often inhibit progress. Spacecraft engineering teams are understandably reticent when faced with the task of embedding a complex new technology in a product with firm cost and delivery targets. Technology developers are often unfamiliar with the process of building equipment that must operate in the field with high levels of reliability."²³

All of these factors are basic causes for the broader symptom of political and organizational inertia. *Inertia* refers to the tendency for organizational structures to perpetuate themselves. As previously stated, a system architecture crystallizes the standard operating procedures in an organization, and thus the organizational environment. This, in turn, defines the allocation of resources needed to maintain that

Chapter 3: Sustainability, Lock-In, Adaptability

organization. Changing the architecture or a core technology means re-allocating jobs and resources. Constant has stated this problem clearly:

“Proponents of new systems are put in the unenviable position not only of having to transform theory so that it applies to technology but also having to argue de novo for certain features of their proposals without backing from either existent scientific theory or technological practice.”²⁴

Inertia therefore has both an organizational and a political component. From an agency perspective, it often stems from basic efforts to protect bureaucratic “turf” or pursue agendas through existing hierarchies. From a political perspective, congressmen have strong incentives to keep jobs in their district. This combination of political and agency incentives can be very difficult to overcome.

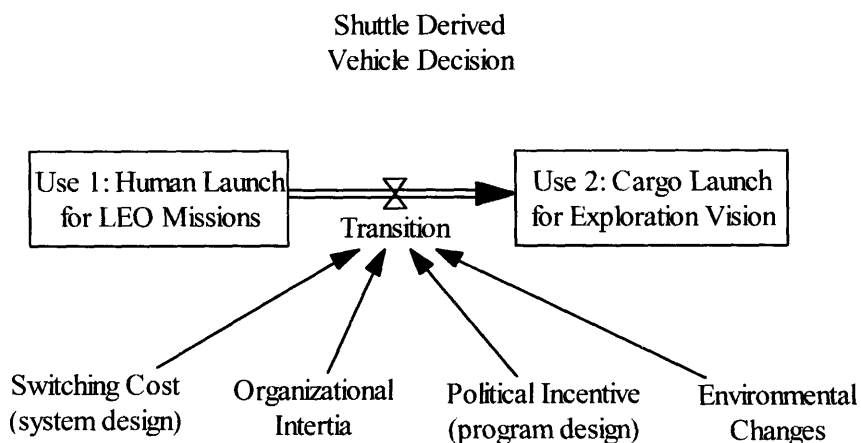


Figure 10: Four principal factors affecting the decision to develop a new system or modify an old system. As applied to Shuttle Derived Vehicles.

These observations emphasize the multidimensional nature of lock-in. Cultural factors, uncertainty, learning, and economics, all create incentives not to change complex technologies. In many ways, designing for sustainability means lowering switching costs associated with moving from one architectural configuration to the next. In this way, the system can react to changes in the environment more easily. Of course, easy switching may not *always* be desirable, in some circumstances a more sustainable architecture will be difficult to switch.

Chapter 3: Sustainability, Lock-In, Adaptability

Figure 10 illustrates the basic issues behind decisions to switch to new system architectures, or modify old architectures. These can be divided into four basic categories: switching cost, organizational inertia, political incentives, and environment. Here environment refers to issues such as the geopolitical climate or scientific knowledge of Mars. The figure implies that the probability that an agency will modify an existing system, rather than create a new one, is a function of these four basic categories. Each of these categories, in turn, is a function of either the systems design, the organizations design, or is completely random.

For example, a system that is easily reconfigured will have low switching costs, which will increase incentives to use it. A program which is spread throughout the country will create stronger political incentives to continue its operation.

3.8 Conclusion

An exploration system or subsystem is sustainable if it has the capacity to be continuously supported at the political, economic, and technical level. *Corollary 1:* A system or subsystem is sustainable if it can react to, or manage, uncertainties in the political, economic and technical domains. *Corollary 2:* A system is sustainable if it does not hinder future goals.

Sustainability necessarily related to the highest level of the system—we are concerned with the sustainability of the goal, not a given architecture or technology. Any metric for sustainability must therefore incorporate a holistic view of system operation.

The highest-level value-added deliverable of space exploration is knowledge, in various forms. Different stakeholders are after different kinds of knowledge. At lower levels, of course, stakeholders are also concerned with economic profit, political significance, and other issues.

At a given time and space there are trade-offs between performance, economics, and risk across the system for a given set of objects and constraints, but these trade-offs are subject to change. Designing for sustainability thus implies creating system attributes that

Chapter 3: Sustainability, Lock-In, Adaptability

allow a system to adapt in or order to keep costs, risks, and benefits within acceptable margins as the environment, system, and goal change.

While ideally a given technology is optimized for a given goal, the reality with complex systems is that more often political goals and existing capability meet halfway. This is the principal reason for path-dependence, which is due to institutional and organizational factors, as well as economic and technical issues such as sunk costs and network affects.

Architectures, as interface standards, become *locked-in* in for myriad reasons. These include sunk-costs, learning curves, and network affects. It is possible to quantify such decision. As a whole, lock-in demonstrates that the system architecture is not only affected by, but also affects, the political and organizational environment in which it operates.

Chapter 3: Sustainability, Lock-In, Adaptability

Chapter Endnotes

- ¹ Quoted from "Technology for a Sustainable Future" July 1994
- ² NASA Red Blue team report, June 2004, Keyword definition page 27
- ³ For a detailed discussion of this value proposition see: "A Paradigm Shift in Design for NASA's New Exploration Initiative." 16.89 Graduate Design Class in Space Systems Engineering, Massachusetts Institute of Technology, Spring, 2004
- ⁴ Shaw, Eric. Economic Analysis of the Space Transportation Architecture Study (STAS) NASA Team. 1999
- ⁵ Pace, Scott. "Merchants and Guardians: Balancing US Interests in Space Commerce." John M. Logsdon and Russell J. Acker, Editors. International Space Policy Forum Publication. Washington DC. 1999
- ⁶ de Weck, Olivier. Lecture Notes, 16.89 Space Systems Design Class. Massachusetts Institute of Technology. Spring, 2004
- ⁷ http://en.wikipedia.org/wiki/International_space_station
- ⁸ Klein, Hans. "System Development in the Federal Government: How Technology Influences Outcomes," Policy Studies Journal, vol. 28, no. 2, 2000.
- ⁹ Klein, 2000
- ¹⁰ Klein, 2000
- ¹¹ Perrow, Charles. Normal Accidents: Living with High Risk Technologies. Princeton University Press. Princeton, NJ. 1999
- ¹² Perrow, 1999
- ¹³ Utterback, James M. "Innovation in Industry and the Diffusion of Technology." *Science, New Series*, Vol. 183, No 4125 (Feb. 15 1974), p. 620-626
- ¹⁴ Ashby, William Ross. Design for a Brain: The Origin of Adaptive Behavior. Science Paperbacks. London, 1966
- ¹⁵ Henderson, Rebecca M. et al. "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firms." *Administrative Science Quarterly* (35), 1990, p. 9-30; Also, Christensen, Clayton M. The Innovators Dilemma. HaperCollins Publishers Inc., New York, NY. 1997
- ¹⁶ Puffert, Douglas J. "Path Dependence, Network Form, and Technological Change" Article in: History Matters: Economic Growth, Technology, and Population. Stanford University Press (November 1, 2003)
- ¹⁷ Liebowitz, SJ, et al. "Path Dependence, Lock-In, and History." *Journal of Law, Economics, and Organization* vol. 1 no. 1. 1985
- ¹⁸ Simon, Herbert A. The Sciences of the Artificial; Third Edition. MIT Press. Cambridge MA 1996
- ¹⁹ Shishko, Robert. Lessons Learned from the Space Station Program: The Role of Life Cycle Cost. Jet Propulsion Laboratory.
- ²⁰ Dixit, Avinash. Investment and Hysteresis. *Journal of Economic Perspectives*—Volume 6, No 1. Winter 1992. P 107, 1992
- ²¹ Katz, Michael. "Systems Competition and Network Effects." *Journal of Economic Perspectives*. Vol 8, no 2, 1984. p 93-115
- ²² Christenson, 1997
- ²³ The Technology Puzzle: Quantitative Methods for Developing Advanced Aerospace Technology, by Liam Sarsfield; RAND, National Security Research Division, 2001.
- ²⁴ Constant, Edward II. The Origins of the Turbojet Revolution. Johns Hopkins University Press, Baltimore, MD, c1980.

4. Origins & Evolution of U.S. Rocket Programs

“The present would be full of all possible futures, if the past had not already projected a pattern upon it.”

-Andre Gide

“To pinpoint the exact beginning of a complex technical program is usually impossible, for more often than not it is a consequence of the scientific-research and engineering process underway on a broad scale, often in diverse areas.”

-Ugene Emme, *The History of U.S. Rocket Technology*

4.1 Introduction

In order to compare heavy lift launch systems, we would like to evaluate the expected costs and risks of different plans, including switching from one plan to another. But as the previous chapter argues, switching is strongly affected by political and economic concerns, as well as external issues. Not all “switches” are possible and their probabilities are a function of technical factors, political and economic circumstance, external events. These must be better understood in order to create a suitable model of switching, and to design sustainable vehicles. This section examines the evolution of launch vehicles in order to understand the nature of these path dependencies, and what it means to switch from one development plan to another.

The history of large launch vehicle programs in the United States illustrates a balance of adaptation and path-dependence previously described. The earliest large U.S. programs include the Navaho, Redstone, Jupiter, Thor and Atlas. These coalesced into the three

Chapter 4: Origins & Evolution of U.S. Rocket Programs

main expendable vehicle lines in use today: Atlas, Delta, and Titan. Years later, hardware, technical expertise, and management techniques created for these programs were used directly in the manned Mercury, Gemini and Apollo programs.

While early vehicles were designed largely for performance and reliability, large sunk costs and varied political pressures, among other factors, created strong incentives to adapt previous programs to future applications rather than develop wholly new systems.

¹ This was true even for later programs which focused on market applications and increasingly balanced cost with performance and risk. As a result, all existing U.S. launch systems, including the Space Shuttle, make use of at least some hardware developed 35 to 50 years ago, whether launch facilities, engine lines, ground stations, or other system elements.²

The following section examines this evolution, including how technical, political, and economic factors constrained or encouraged “switching” to later programs. It should be noted that factual histories of rocket development, including detailed accounts of subsystem development, abound. The goal of the current analysis is to understand the *architectural* evolution of these systems, including how high-level design decisions affected and were affected by the organizational, economic, and political environment. As noted, architecture is defined as the relationship between objects and processes without necessary reference to subsystems design. The following analysis will therefore focus on arrangements, basic performance metrics, and, where possible, costs. Core subsystems, such as engines, are often examined in more detail.

4.2 Skepticism and Experimentation—Rocket Programs in the 1940s

Missile technology advanced significantly during World War II, particularly through German efforts with the V2 rocket. However, like many radical technologies that demand a shift in basic strategy and human organization, the perceived benefits of the technology by military elites remained too low to justify major investment. Vannevar Bush, a high-

Chapter 4: Origins & Evolution of U.S. Rocket Programs

ranking military science director, summarized this feeling well in a statement made soon after the war in 1945:

“There has been a great deal said about a 3,000 mile high-angle rocket. In my opinion such a thing is impossible and will be impossible for many years...I say technically I don't think anybody in the world knows how to do such a thing and I feel confident it will not be done for a very long period of time to come. I think we can leave that out of our thinking.”³

Thus, while the promise of rocket technology was recognized, military elites were skeptical about its benefits verses costs and risks in the near-term. This attitude was enforced by an over-confidence in U.S. military strength relative to the Soviets following victory in World War II, and a public desire to return to “normalcy.”⁴ The result was that post-war US nuclear military strategy remained based on long-range bombers, rather than ballistic missiles. As with many revolutionary technologies, it would take *necessity*, in the form of the Cold War and the Korean War, to prompt a rethinking of this strategy.

4.2.1 Influential Studies

While major investment remained low directly following the war, some notable events and accomplishments did lay the groundwork for future US rocket programs. In particular both the Navy and the Air Force conducted top-secret and influential feasibility studies. In October of 1945, the Navy Bureau of Aeronautics created the Committee for Evaluating Feasibility of Space Rocketry (CEFSR), in order to conduct calculations and profile analysis on liquid Hydrogen-Oxygen (LOX) single-stage satellite launchers. Initial Results were promising, and CEFSR made a strong recommendation that the NAVY begin a satellite launcher test program. Contracts were soon let to the Guggenheim Aeronautical Laborer at Cal-Tech (Now called the Jet Propulsion Laboratory) to test assumptions about the structure/mass ratio and fuel-engine combination. However, for reasons described above, it was quickly concluded that a full satellite launch program was too expensive.⁵

Difficulty funding the Navy concept lead CEFSR personnel to approach the Air Force with the hope of creating a joint Navy/Air-Force test program. Although favorably received, higher-ranking Air Force members shared Vanevar Bush's skepticism regarding

Chapter 4: Origins & Evolution of U.S. Rocket Programs

the feasibility and need for a rocket in the near term. The Air Force declined the CEFSR proposal, but contracted RAND to begin rapid in-house feasibility studies in 1946. The resulting report, "Preliminary Design of an Experimental World-Circling Spaceship," was completed in May 12, 1946. It made some important technical improvements to the Navy concept and proved highly prophetic regarding the larger implications of rocket-propulsion.

Technically, the RAND report contradicted the NAVY conclusion that a single-stage LOX rocket could reach orbital velocity. It added the concept of staging, concluding that three stages were optimum for a LOX propellant. The Rand study also presciently noted that "a satellite vehicle with appropriate instrumentation can be expected to be one of the most potent scientific tools of the Twentieth century....The achievement of a satellite craft by the United States would inflame the imagination of mankind, and would probably produce repercussions in the world comparable to the explosion of the atomic bomb...."⁶ It would take over ten years, an increasingly polarizing Cold War, and a Soviet Satellite launch, before the accuracy of these words was appreciated by high ranking members of the US military and political establishment.

Though recommendations to begin a launch vehicle program were not implemented for some time, these initial studies provided technical specifications and perspective when ICBM programs gained traction in the early 1950s. In particular, the feasibility of some elements of orbital vehicle design conducted at CALCIT, the realization that staging would be crucial, and the recognition of the non-military significance of rocket technology proved important for later work.

4.2.2 Early Flight Programs

If reception to orbiting vehicle concept studies was cool during the 1940's interest in long-range missiles remained sufficiently high to justify some experimentation. Two of the most important projects were the Navaho test vehicle and the MX-744. Both provided critical components to larger programs when the Cold War heated up in the early 1950s.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

The Navaho program was initiated by the Air Force in April of 1946, with the goal of producing a 10,200 km range surface-to-surface cruise missile capable of delivering a 600 lb payload. The prime contractor was the North American Aviation Company, and the engine was sub-contracted to Rocketdyne. At the time, large cruise missiles were considered more practical than ballistic missiles due to the high weight of atomic bombs.⁷ Given the small experience base with the technology, among other factors, requirements were changed often in the following years. It was not until 1950, after significant experimentation that the Air Force firmed up the requirements and called for a 3,600 mile interim vehicle and then a 5,500 operational weapon.⁸

The Navaho system architecture consisted of a rocket-propelled first stage and air-breathing ramjet engines for the second stage. As it turned out, surmounting the aerodynamic problems involved with automated super-sonic flight proved more difficult than creating a ballistic missile. The program was cancelled in the mid 1950s. Still, important strides were made in subsystem design and manufacturing, with implications for later programs. These included experience with super-sonic aerodynamics, development of chem-milling fuel tank fabrication techniques and improved inertial and stellar navigation.

Most importantly, the LOX/RP-1, 135 klb thrust booster stage proved critical for later development programs. Variants of these engines were used directly in the Redstone, Jupiter, Atlas, Thor, and Saturn Programs.

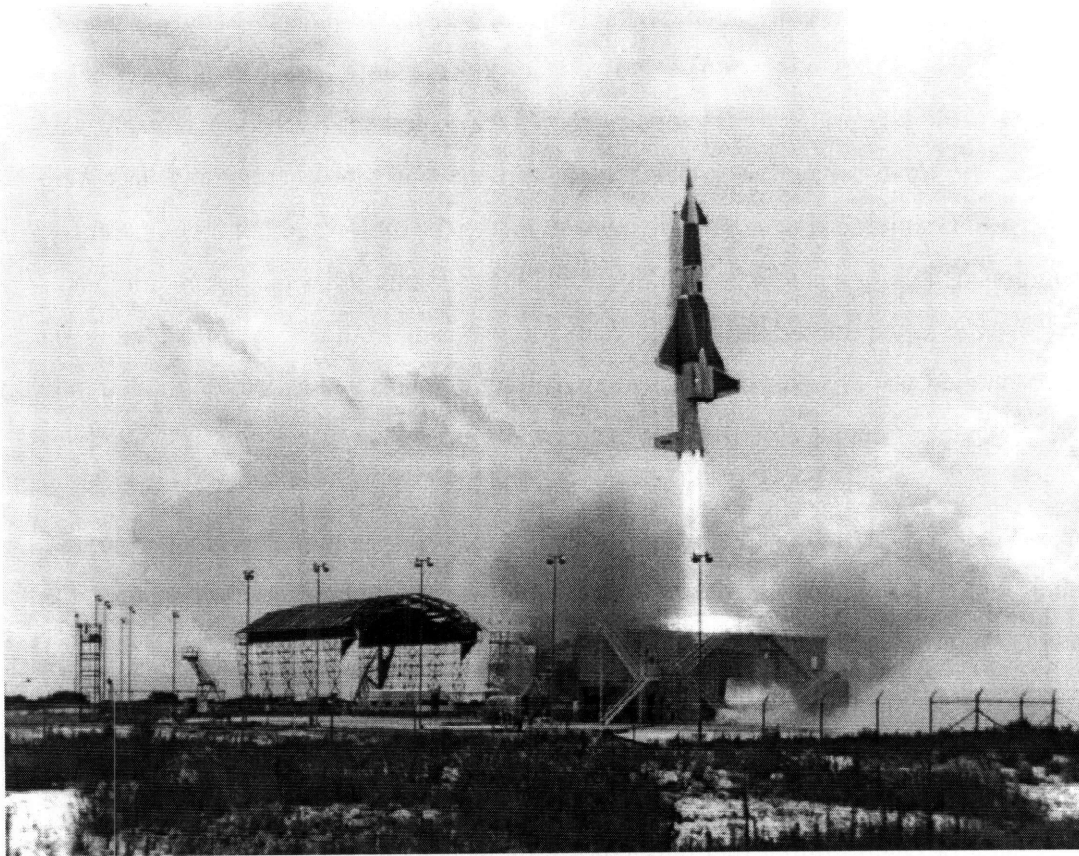


Figure 11: Navaho Cruise Missile Test Launch, 1957. The Navaho Booster engines, seen firing, were used directly in initial Redstone and Atlas designs. (courtesy, www.astronautix.com)

4.2.3 MX-774

Another important pre-1950 test program was the MX-774, which laid the groundwork for what would become the long-lived Atlas Rocket. As noted, reports soon after World War II called for the development of long-range missiles. In 1946 the Air Force awarded Convair, a subsidiary of the Atlas Group, a small contract to begin tests on a 6,000 mile range ballistic missile. This contract was cancelled in 1947 for fear that it was too risky and that it competed with manned-bomber funding.⁹ It was eventually restarted as the MX-1593, and renamed the Atlas Program in 1951.

The Air Force contracted for MX-774 vehicles in three phases. Stage A, the Teetotaler, was a sub-sonic, self-guided cruise missile. Stage B, the Old Fashioned, was a test missile

Chapter 4: Origins & Evolution of U.S. Rocket Programs

using V-2 technology but incorporating new concepts planned for the next phase. Stage C, the Manhattan, was to become an ICBM.¹⁰

The *MX-774* program produced some important innovations still used today. Propellant tanks were fabricated for the first time with a single-walled extra thin stainless steel body, whose structure was maintained by pressure. A separable nose-cone was introduced, removing the need for multiple navigation instruments. Most importantly, the MX-744 pioneered the used of gimbaled engines for control.



Figure 12: MX-774 Test Missile. Nicknamed "The Old Fashioned" for its visual and technical resemblance to the V2 rocket. Courtesy, Astronautix.com

4.3 The Cold War Heats Up: Rocket Programs in the 1950s

Several factors coalesced in the early 1950s to completely change the perceived need for rocket technology. Geopolitically, the Cold War became more serious. The Soviet Union detonated its first nuclear weapon in 1949, shattering the U.S. perception that it maintained insurmountable military superiority. The Korean War began in 1950, and

Chapter 4: Origins & Evolution of U.S. Rocket Programs

money flowed into new weapons systems. In 1953 the U.S. learned that the Soviets had made significant progress with long-range ballistic missiles.¹¹ Technically, a breakthrough in nuclear physics reduced the weight of nuclear bombs, increasing the efficacy of rockets as a delivery mechanism. And perhaps most importantly, a new generation of military leaders were less beholden to the manned-bomber strategy and more comfortable with the transformative implications of rocket technology.

These factors created a sudden and urgent need for fully operational ballistic missile systems. New programs used expertise gained during the 1940s wherever possible. From these large programs came the rockets that would carry the first men into space and to the moon. Eventually, the various architectures would coalesce into the three main U.S. rocket lines: Atlas, Delta, and Titan. Thus, decisions made in the heated atmosphere of the mid 1950s had repercussions throughout the following decades.

4.3.1 The Redstone Short Range Ballistic Missile

The Redstone was the first operational ballistic missile developed in the U.S. and has been called the most important rocket in the history of the U.S. space program. Although only operational for five years, and originally designed as an short range ballistic missile (SRBM), it laid the technical groundwork for almost all future development programs. Modified versions of the Redstone became Jupiter, which was the first intermediate range ballistic missile (IRBM), the Mercury-Redstone, which launched Alan Shepard on the first U.S. manned sub-orbital flight to space, and the Juno, which launched the first U.S. satellite. When the Apollo program began, drawing board designs for the Juno V, were renamed Saturn I.

The Redstone program began in July of 1950 in response to the beginning of the Korean War. The Army Ballistic Missile Agency (ABMA) asked the Ordinance Guided Missile Center at Redstone Arsenal to conduct a feasibility study on a field-deployable 500-mile range rocket capable of carrying a 600 lb nuclear warhead. In an example of how requirement often change to suit technology, the range was soon reduced to 200 miles to accommodate the use of Navaho engines.¹²

Chapter 4: Origins & Evolution of U.S. Rocket Programs

The Arsenal was then home to the Wernher von Braun and his German technical group of about 120 engineers. Much of the experience gained through years of testing the V2 and developing subsystems was put directly to use in the new program. As Von Braun notes, “The [Redstone] development plan evolving from our investigation was based on our experience in rocketry and on available hardware. We decided to adapt to our purpose the liquid propulsion system then used in the Navaho test missile—a North American Aviation (NAA) engine.”¹³

First tested in 1953, the missile was declared operational in 1958 and deployed in West Germany. It was replaced only five years later in 1963 by the Pershing missile. The system was mobile, but required 600 people and many large vehicles to operate a liquid oxygen processing plant.¹⁴ It was powered by up-rated Navaho engines, burning LOX-Alcohol (75% alcohol, 25% water) producing a total of 77,200 lbs of thrust. It was guided by simple inertial guidance developed for the V2, and controlled by vanes moving on pivots attached to fins.

4.3.2 Jupiter

Through the 1950's, the team at the Redstone arsenal was asked to develop increasingly long-range versions of the Redstone rocket. These included the Jupiter A, the Jupiter C (IRBM), Juno ETO vehicles, and the Mercury-Redstone rocket that carried Alan Shepard into sub-orbital space. These developments built progressively on each other, often borrowing from concurrent development programs such as Atlas and Thor/Delta.

The Jupiter Program was initiated by the Army in 1955 as a 1,500 mile Intermediate Range Ballistic Missile (IRBM). It was conceived as a direct successor from the Redstone and evolved incrementally from it. Jupiter test flights actually served to further test Redstone Components.¹⁵

Chapter 4: Origins & Evolution of U.S. Rocket Programs

Jupiter A was essentially a Redstone rocket with some modifications to increase range. The Jupiter C (short for “Composite Reentry Test Vehicle”) was designed to test re-entry technology and constituted an important improvement on the Redstone Rocket. It was a three stage vehicle, with a Redstone missile as a booster stage, 11 clustered Thiokol Baby Sergeant solid rocket motors as second stage, and three clustered Thiokol Baby Sergeant solid rocket motors as third stage. The Thiokol solid motors derived directly from studies conducted in the 1940s at Calcilt (now JPL) contracted partly in response to Air Force studies mentioned above.¹⁶ The Redstone tanks were also enlarged to increase burn-time for the Jupiter C. Perhaps most importantly, the Navaho engines in the first stage were replaced by engines newly developed by Rocketdyne for the Air Force’s Thor IRBM.

4.3.3 Juno

The story behind the birth of the Juno program is indicative of the political and military aspects of system development. The mid 1950’s witnessed mounting tension not only between the U.S. and Soviet Union, but also between military services vying for control of ballistic missile development. In 1955, plans were made to launch a U.S. satellite ahead of the Soviet Union, and a decision loomed over which launch vehicle to use. Von Braun and his team proposed a four stage version of the Jupiter C, called “Project Orbiter.” The Jupiter/Redstone program had been successful to date and Von Braun had by far the most experience with rocket technology. Eisenhower, however, was sensitive to the potential friction generated if the Army were to launch the first U.S. satellite. He thus chose a proposal based on civilian management (though using Navy technology) called Project Vanguard.¹⁷ The politically motivated decision proved disastrous.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

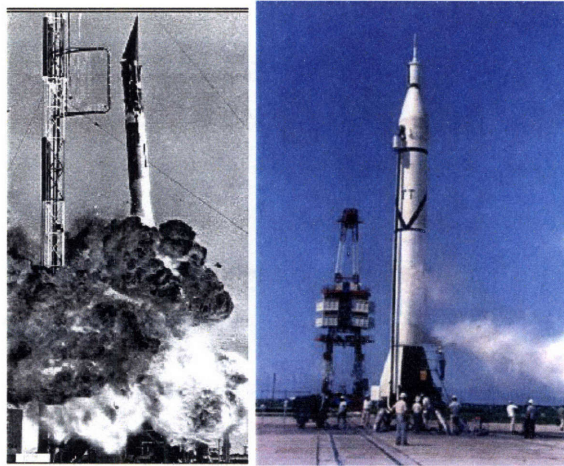


Figure 13: Vanguard Missile, Exploding on the Pad, 1957. Jupiter Missile ready for launch. (courtesy astronautix.com)

While Vanguard test flights failed successively, the ABMA team continued with the Jupiter C test program, and even launched a missile with a dummy fourth stage “in case” it was eventually needed.¹⁸ As one author notes, “The Jupiter C had shown it was perfectly capable of launching a small satellite, yet bureaucracy forbade it to make the attempt.”¹⁹

The political tide turned, however, when in October of 1957, the Soviet Union shocked the world by launching Sputnik. The ABMA was able to convince the Secretary of Defense, Neil McElroy that the up-scaled Jupiter C should be given a chance.(online encyclopedia) After one more failed Vanguard attempt and a delay, the four-stage Jupiter C launched the first U.S. satellite into space. The new line had been christened Juno.²⁰

The Juno line was thus designed by the ABMA to launch the first U.S. satellites into space. Juno I was simply a Redstone rocket with three upper stages including a single-solid-engine fourth stage. It was thus a Jupiter C prior to having changed the propellant to Hydrazine. Juno II was a Jupiter C with the same upper stage as Juno I. As Von Braun notes, the primary goal for these vehicles was development speed and economy of resources—not performance. For Juno II, for example, he writes: “Although Juno II was not an optimum vehicle it provided a quick and economical way to launch a payload over three times as heavy as that lifted by its Redstone predecessor, the Juno I.”²¹

Chapter 4: Origins & Evolution of U.S. Rocket Programs

Including the Jupiter C, a total of nine Jupiter/Junos were launched, with three satellites placed into orbit and three failures. Plans were drawn for Juno III, IV, and V, but these never made it past design stages. Instead, Von Braun's team up-rated the plan for Juno V and suggested a new name: If the Juno line was based on the Jupiter missile, a larger vehicle should be named Saturn, after the planet one step further from the sun.

4.4 Air Force Missiles to Three Main Lines: Atlas, Titan, Delta

From these pre-Apollo years of inter-service rivalry and Cold War urgency emerged the three expendable vehicle lines still in use today: Atlas, Titan, and Delta. All three were originally ICBM programs started by the Air Force in response to the technical, military, and political events of the early 1950's, and later converted into ETO launchers. General Bernard Schriever, widely credited as the visionary architect of the Air Force rocket programs, has noted that the driving factors behind this development were the need for ICBMs and reconnaissance. Given the urgency, initial system architectures borrowed heavily from previous programs such as Navaho, MX-774, and the Army Redstone/Jupiter. Innovations, in turn, were fed back into the latter.²²

4.4.1 Atlas

The Atlas was the first U.S. intercontinental ballistic missile (ICBM). Initiated by the Air Force in 1951, it was based directly on the MX-774 ICBM test program, and used modified Navaho engines (its original name was in fact MX-1593).²³ As with these previous programs, the contractor was Convair with the Propulsion system was subcontracted to Rocketdyne. The Atlas ICBM was operational starting in 1957 and decommissioned in 1964, when it was replaced by more responsive solid-propellant ICBMs.²⁴ During this period, however, significant improvements were made at the system and subsystem level, and the program was transformed to provide Earth to Orbit capability for military applications.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

The evolution of the Atlas vehicle, and in particular the propulsion system, is instructive for the purpose of understanding factors in life-cycle dynamics. Because continuous improvements were being made across the system, initial designs were subject to significant uncertainties in subsystem and payload design. In fact, the Titan program emerged as an ambitious/redundant test plan within the Atlas program, in order to take advantage of recent technical advances and increase probability that an operational ICBM would be forthcoming.²⁵ A significant change in requirements occurred in 1954, when it became clear that nuclear payloads could be made significantly lighter than expected. Later changes occurred as the core vehicle was used to launch payloads to orbit.

As noted, the Atlas was originally designed to carry the heavy nuclear weapons of the day. It used an innovative “stage-and-half” solution: four booster engines were lit together with one sustainer engine in the first stage, and dropped during flight. The stage-and-half provided higher thrust at low altitude where it was needed most. The five engine configuration was scaled down to 3 engines (two boosters, one sustainer) in 1954 when nuclear payloads were made smaller.

The complete propulsion system, including two boosters, one sustainer, and some small engines for control, was called the MA-1. The engines utilized liquid oxygen (LOX)/Kerosene (RP-1) fuel.²⁶ As the Atlas line evolved, The MA-1 became the first stage of the ETO Vehicle, and was successively modified and upgraded to the MA-5A.

The MA-1 engine block was continuously updated through the 1980's. As noted, *MA-1* engines were taken directly from the Navaho program with few modifications, and used on Atlas test vehicles from 1956 to 1958.

MA-2 engines were an up-rated and simplified version of the MA-1 used in the actual Atlas ICBM from 1958 to 1962. They included a simplified start-up and a gas-powered propellant feed for the entire three-engine configuration, delivering a total of 309,000 lb of thrust.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

MA-3 further simplified the assembly process for the *MA-2* engines, by separating the gas-powered propellant feeds for all three engines. This increased the total thrust to 330,000 lbs and also made the engine-system more modular. In case of failure, one engine could be removed and changed rather than the entire stack. The *MA-3* was in production from 1960-1964 and was used on the first Atlas Orbital vehicles.

MA-5 system was a non-military derivative of the *MA-2*. It employed a common gas-powered propellant feed, hypergolic ignition, and an electro-pneumatic start-shutdown system. *MA-5* was used in the Atlas ICBM from 1955 to 1966, and throughout the following decades in the Atlas Launch Vehicle. The engine-pack was actually man-rated in 1963 for use in John Glen's first orbital flight aboard the "Mercury Atlas."

MA-5A An improved version of the *MA-5* was developed in the late 1980's, response to the military directive to launch military payloads on expendable vehicles. The *MA-5A* was essentially an *MA-5* with an improved H-1/RS-27 turbo-pumps, significantly improving thrust and ISP.

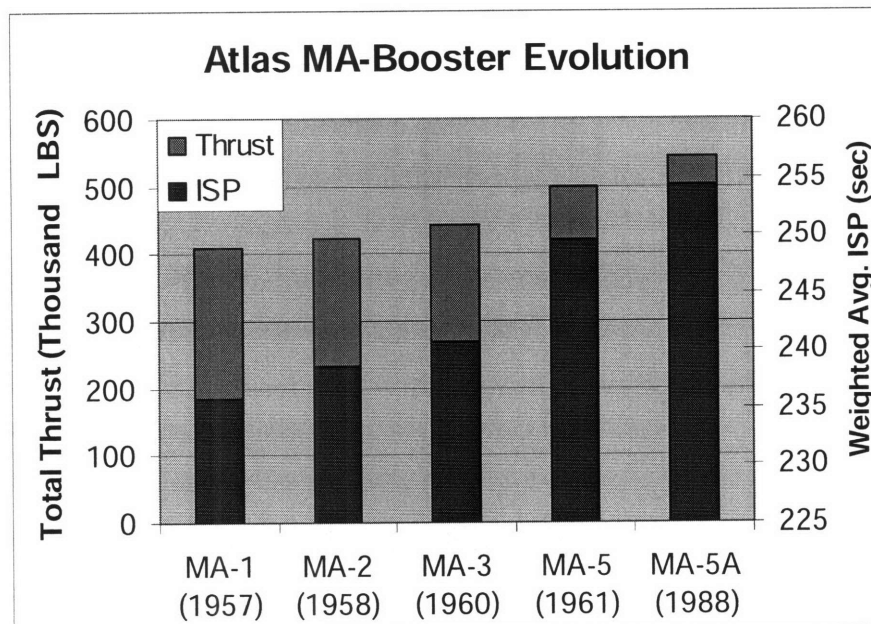


Figure 14: Atlas MA-Boosters Performance Evolution

Chapter 4: Origins & Evolution of U.S. Rocket Programs

Upper stages were added to the Atlas MA-boosters in the 1960's, to create manned and unmanned launch vehicles. The Atlas Centaur, first introduced in 1962, included an MA-3 first stage, and Convair-developed centaur second stage: two Pratt & Whitney engines with 30,000 lbs of thrust. The centaur second stages have been significantly upgraded through the ensuing decades.

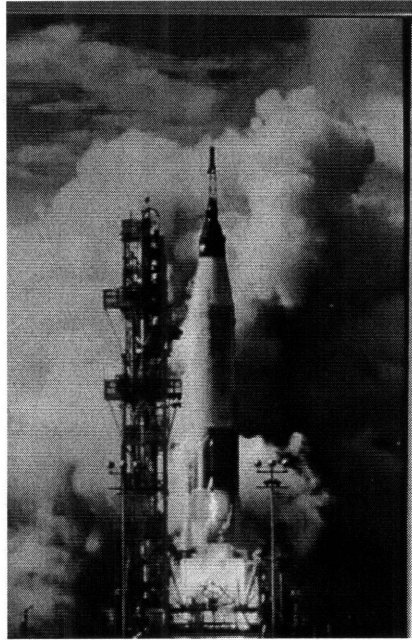


Figure 15: The Mercury-Atlas, launching John Glenn on the first U.S. orbital flight.

4.4.2 Titan

In 1955 the Air Force created the X-11 alternative test-plan within the Atlas program in order to incorporate recent advances in staging and tank design and provide more operating flexibility. The X-11 would come to be called the Titan. Like the Jupiter, the Titan was designed with multiple stages—rather than a “stage and half.” The tank was to be self-supporting light alloy frame.

The Titan first and second stage engines originally burned LOX-RP1 fuel. The first stage consisted of two Aerojet engines, with a combined thrust of 300,000lbs and an ISP of 249 seconds. In 1960, a switch was made to storable N2O4/A-50 propellants. The new vehicle,

Chapter 4: Origins & Evolution of U.S. Rocket Programs

which included numerous improvements including a significant reduction in part number and operating complexity, was called the Titan II. It remained active as an ICBM through the 1980s and was used as a space-launch vehicle for military and eventually commercial launches. The Titan II was also used as a launch vehicle for the Gemini program.

4.4.3 Delta/Thor

The Air Force initiated the Thor intermediate range ballistic missile (IRBM), which eventually became the Delta Launch Vehicle, in the same year as the Titan. Given the urgency of producing an operational missile, the Thor program was likely a hedge against completing an operational ICBM in the near-term. Equally important, however, it reflected an attempt by the Air Force to create an in-house IRBM capability, and therefore sparked intense political maneuvering between the Army and Air-force over control of missile programs.²⁷ The rivalry was put to an end in 1956 by the famous “Wilson memorandum,” in which Secretary of Defense Charles Wilson stripped the Army of all rocket programs with ranges greater than 200 miles.²⁸ As a result the Jupiter missile was transferred from the Army to the Air-Force until its retirement.

The complete Thor system was contracted to Douglas Aircraft, but as with Jupiter, Rocketdyne created the engines. The main Thor engine system called the MB-1 and MB-3 thus also burned LOX-RP-1 fuel and were initially nearly identical to the Jupiter and the Atlas sustainer engines. All three were derived from the Navaho program. The Thor borrowed heavily from the Jupiter and Atlas programs in other respects as well. The re-entry mechanism was copied from the Atlas ICBM, and the inertial guidance system was the same as on the Jupiter.²⁹

In creating the Thor engines Rocketdyne introduced a series of innovations which were later re-incorporated by the Jupiter and Atlas programs. Most notably, the X-1 R&D engine was initiated under the Thor contract and built directly upon the MB-3 arrangement. The X-1 incorporated lessons learned from the Atlas and Jupiter missiles and led to the H-1 engine program which powered the second stage of the Saturn V heavy

Chapter 4: Origins & Evolution of U.S. Rocket Programs

lift vehicle. The H-1 engines later formed the basis from the RS series of upper stages for the Delta Launch vehicles. In essence, the RS series consists of H-1 components repackaged to fit the Thor vehicle arrangement.³⁰

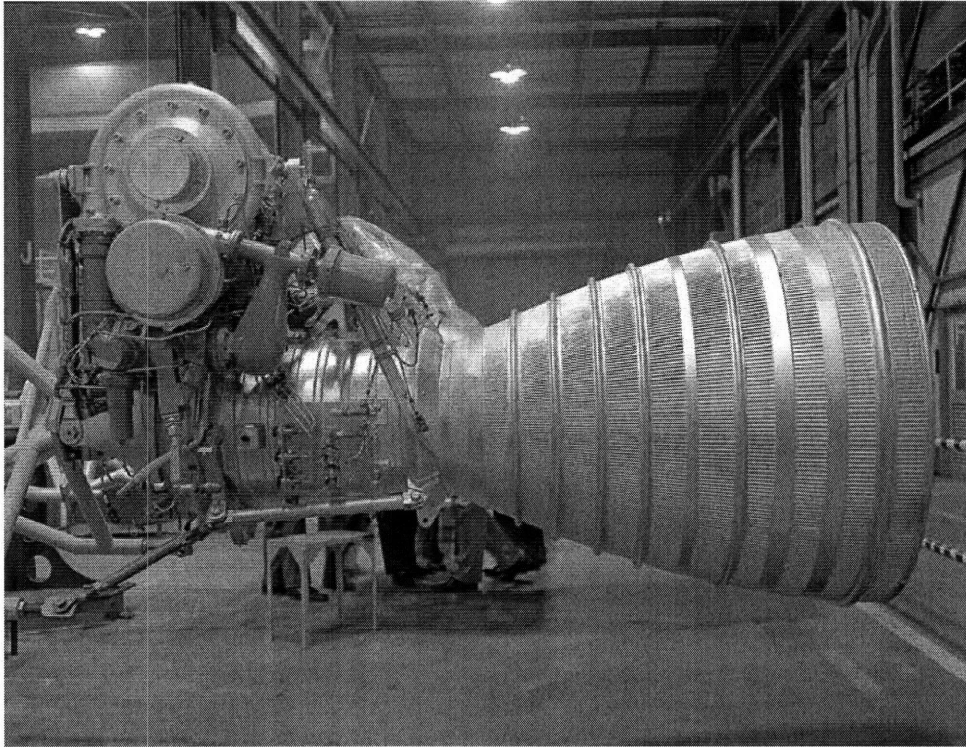


Figure 16: The H-1 Engine

Thus, the Thor program represents an important intermediary between the ICBM programs initiated in the early 1950s, and the heavy lift Saturn vehicle. It built on expertise previously gained, resulting in engines components still considered state of the art today. The Delta program emerged from the Thor IRBM program in 1958, as a carrier for NASA satellites. The Thor had already been outfitted with various upper stages and served as a space launch vehicle for the Air Force. Delta was thus nothing more than the civilian name for a four-stage Thor missile.

4.5 Launching Early Manned Programs: Mercury, Gemini

NASA was created on October 1 1958 and within one-week the Manned Mercury program was approved. The Mercury program was followed by the Gemini Orbital

Chapter 4: Origins & Evolution of U.S. Rocket Programs

program, and then the Apollo lunar program. Significant to the current study, all launch vehicles used for these programs were taken from other programs with minor changes. Of course, the Saturn vehicle represented an enormous increase in scale compared to previous missile programs. Still, it made use of Engines and components refined through production of previous missiles. As previously stated, the Saturn I was essentially a Juno V. And as Von Braun notes, “Many Redstone and Jupiter component could be adapted and used in the new vehicle, and most hardware could be built with existing tools, using established fabrication procedures.”³¹

Mercury was the first manned NASA program, authorized in urgent response to Soviet manned programs. Its first manned suborbital flight utilized the Redstone with some modifications. The larger Atlas was man-rated and used for later flights. The use of existing vehicles drove the Mercury program. As one author notes, “The mercury vehicle was completely dictated by the binding constraints of the max payload capability of the Atlas Booster.”³²

The Gemini program had as its goal the first manned orbital flight, and was later used to test technologies for Apollo. Again, an up-rated off-the shelf launcher was used for Gemini—the Titan II.

4.6 Launching Apollo: The Saturn V

Much has been written about the Saturn V Heavy Lift Vehicle that launched the Apollo astronauts to the moon. In the context of rocket evolution, a few issues are particularly important. First, the early Apollo decision between Lunar Orbit Rendezvous (LOR) and Earth Orbit Rendezvous (EOR) emphasized the coupling of launch-vehicle design to in-space design. That decision solidified heavy lift requirements, with repercussions for decades to come. Second, as previously noted, the original Saturn I launcher was derived directly from the Juno line of space vehicles. Von Braun writes, “Juno V was, in fact, the infant of Saturn.”³³ Some Saturn components, such as the engines, were orders of magnitude more powerful than anything previously built, and represented considerable

Chapter 4: Origins & Evolution of U.S. Rocket Programs

technological development. But these advances were also made in stepping-stone fashion, building on previous expertise.

4.6.1 LOR verse EOR

Initial designs for the launch vehicle fluctuated quite a bit, as much due to bureaucratic wrangling as the reduction of technological uncertainties. Much of the fluctuation revolved around the critical mission architecture decision around Lunar Orbital Rendezvous (LOR), Earth Orbit Rendezvous (EOR), or a straight-up approach named NOVA. The decision had enormous ramifications for both payload and vehicle design, and was therefore debated across agency organizational lines. As one author notes, “The struggle in reaching a final decision also suggested some of the problems to be faced by NASA management when one center had responsibility for the launch vehicle and another organization had the payload. The problems were compounded when both were trying to fashion programs and develop hardware without always knowing what each would require in the end.”³⁴ Thus, technical uncertainties surrounding the LOR-EOR were significant enough to be exploited by opposing political factions within NASA.

The details of these architectures are worth examining for the purpose of understanding heavy lift launch vehicle design decisions. EOR called for launching two payloads on advanced Saturn rockets, one with the crew and the other with the propellant and engines needed for lunar injection, lunar landing, and crew return.³⁵ Under EOR, then, one crew vehicle would serve as the crew quarters, command module, lunar excursion module (LEM), and return vehicle. The NOVA architecture was very similar to the EOR mission architecture, except that both the propellant and crew compartment would be launched together by one very large rocket.

LOR, on the other hand, called for designing two different crew vehicles: one for lunar landing, and one for trans-lunar travel and return. The LEM would separate from the Command Module in lunar orbit, and the descent crew would return to rendezvous with it upon completion of the lunar landing.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

It is worth noting that LOR enabled an important design principle known as independence, which states that each process should be encapsulated in a distinct form. The trans-lunar module was distinct from the LEM, and the even the lunar ascent vehicle could be detached from the LEM, allowing specially designed ascent engines and subsystems. As a whole, then, the three basic benefits of LOR were:³⁶

- Only a specially designed lunar module (the LEM) would actually descend to the Moon's surface.
- Only a portion of that LEM, the so-called "ascent stage," would return to dock with the command module in lunar orbit.
- Only the command module, the Apollo capsule itself, with its protective heat shield, would fall back to Earth.

From a launch vehicle perspective, EOR required two launches of the smaller heavy lift launchers, which could be accomplished with up-rated Atlas rockets currently under development. NOVA required a massive vehicle, but did not demand rendezvous techniques. LOR required a heavy lift vehicle, though less than NOVA, but also required orbital rendezvous technologies. EOR, with a NOVA back-up was thus originally preferred by Wherner von Braun and his colleagues for multiple reasons:

It would use up-rated launchers that were very feasible and nearly ready for launch. It was very similar to the NOVA mission from ETO onward. Thus, both NOVA and EOR could be pursued along two simultaneous development paths, reducing overall development risk. For EOR, the main development risk was Rendezvous techniques. For NOVA the main development risk was building a massive vehicle. Both options could be pursued simultaneously, and a decision to launch all-up or in chunks could be made late.

LOR verse EOR negotiations became increasingly heated through 1962, and multiple committees were established to examine the issue. The technical uncertainties allowed the decision to become rather political. President Kennedy's science advisor, Dr. Jerry Wiesner, for example, was opposed to LOR even after Von Braun had come around to the idea.³⁷ In the end Kennedy supported the LOR decision, notwithstanding Wiesner's

Chapter 4: Origins & Evolution of U.S. Rocket Programs

objections. After a final round of studies, a firm decision to pursue LOR was announced on November 7, 1962.³⁸

The debate surrounding LOR and EOR in the early 60s is significant to the current discussion because it illustrates the interdependence of launch and in-space architecture, and the extent to which political and bureaucratic factions affect architectural decisions. EOR, its supporters stressed, simplified launch vehicle development. LOR, on the other hand, simplified in-space architecture and in particular lunar landing.³⁹ The trade was very hard to carry out because comparative mission reliability was practically impossible to quantify (beyond estimates) and, perhaps more importantly, the advantages of each architecture were *incommensurable*. That is, they maximized different rank-orders of metrics. Thus the decision was more about establishing what was valued most—development risk, landing simplicity, cost—rather than about optimizing an objective function. Values, of course, are inherently political.

4.6.2 The Saturn V

The LOR decision solidified the need for a launch vehicle capable of lifting roughly 250,000 lbs to LEO. Work had already begun on a heavy lift vehicle, using a stepping-stone philosophy based largely on the Juno V design, scaling up existing sub-system components. These were based largely on Redstone and Jupiter missile components and tooling, with plans to up-rate engines and, eventually to create cryogenic upper stages. The plan was to create three vehicles of progressively larger ETO capability: The Saturn I, the Saturn IIB, and the Saturn V.

The basic requirements and configuration for the Saturn vehicles was established in 1959 by a committee chaired by Abe Silverstein and including von Braun, known as the “Saturn Vehicle Team.”⁴⁰ The committee included representatives from NASA, Air Force, ABMA, ARPA, and was charged with preparing “recommendations for the guidance of the development of Saturn, and specifically for selection of upper stage configurations.” The Silverstein committee established the stepping stone program for the three Saturn vehicles. It also made the somewhat controversial decision to embrace

Chapter 4: Origins & Evolution of U.S. Rocket Programs

cryogenic liquid Hydrogen (H₂) technology for the upper stages. This was largely due to Abe Silverstein's conviction, and von Braun's acknowledgement that higher energy propellants were absolutely necessary.⁴¹

The first Saturn in the stepping stone process was based directly on Juno V designs, and included the relatively untried clustering concept. Saturn IB was designed as a test-bed for the Saturn V, and incorporated the Saturn V third stage as its second stage. The Saturn V had three stages, with a five-engine RP-1/LOX booster, 5 liquid hydrogen/LOX J-2 engines in the second stage, and one J-2 engine third stage which doubled as an injection stage. Figure 17 illustrates the Saturn V configuration.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

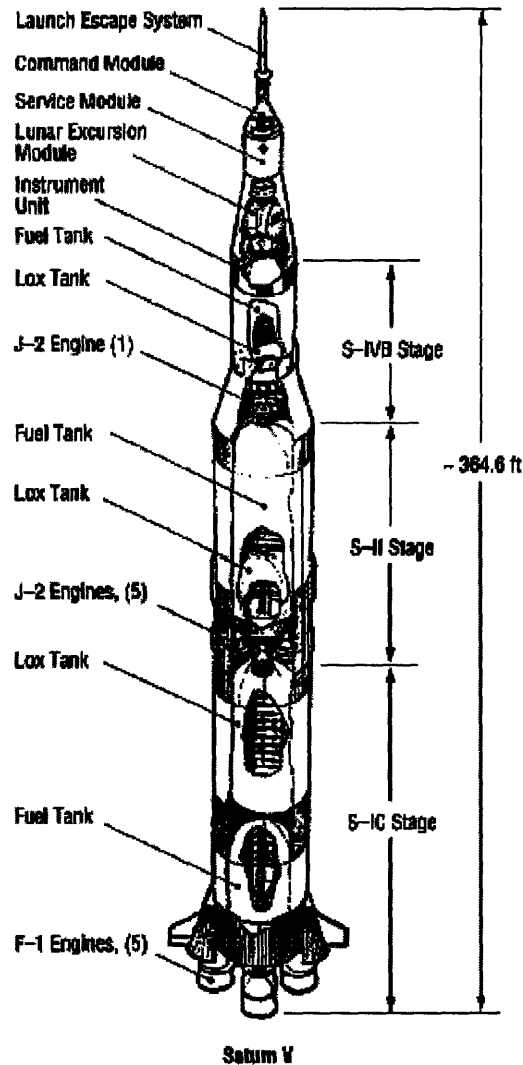


Figure 17: Saturn V configuration. (Courtesy, Ryan et. al)⁴²

Propulsion systems drove the Saturn vehicle design. For the first stage of the Saturn I and IIB, it was decided early on to simplify and improve the Jupiter Thor engines.⁴³ A contract was let to Rocketdyne for this purpose, and the new engine was to be called the H-1. The H1, was built with Jupiter/Thor subsystems and using Jupiter/Thor tooling. In fact, many Thor, Jupiter and Atlas subsystems were used directly including control valves, gas generator system, turbo-pump assembly, and thrust chambers. Further, the tank configuration was created by combining one 105-inch Jupiter tank surrounded by eight 70-inch Redstone tanks.⁴⁴ The H1 produced a maximum of total of 205 klbs of thrust.⁴⁵

Chapter 4: Origins & Evolution of U.S. Rocket Programs

For the Saturn V, NASA opted to create an even larger engine, using RP-1/LOX fuel. In 1958 it contracted Rocketdyne to construct a significantly larger 1.5 million lbs thrust engine. Studies had, in fact, been conducted for engines of this size under Air-Force contracts since 1955. Still, there were significant uncertainties regarding the possibility of such a massive engine, and the final design for the Saturn V did not specify F-1 engines until early 1962.⁴⁶

The use of J-2 liquid hydrogen in the Saturn upper stages represented a considerable technological leap, and demanded significant development. Again, however, efforts built directly upon studies begun years early. In 1945, in fact, the Navy Bureau of Aeronautics began a program to investigate the potential of liquid hydrogen as rocket propellant at Calcit (now JPL). This work benefited the development by Pratt and Whitney of the first operations hydrogen engine, the RL-10, with a thrust of 15 klbs. The Silverstein committee made its decision to pursue a much larger LOX/H₂ engine, partly on the assumption that the RL-10 engine and performance could be scaled.⁴⁷

4.6.3 Logistics

Beyond engines and vehicle design, many lessons from the Apollo/Saturn programs are important for designers today. Logistics, for example, turned out to be more important than initially anticipated. Although logistics programs for launch vehicles had been designed for military operations, NASA managers assumed that no logistics program would be needed for the Saturn. This was because, unlike the military rockets, the Saturn vehicles would be built in relatively small numbers, launched from the same site, and system operators would be professional engineers rather than army technicians. As it turned out, other factors demanded logistical support. These included the size and complexity of the vehicles, the wide geographic dispersal of launch and test sites, the pace of the program, the armies of technicians involved, and the number of suppliers around the country. As Arthur Rudolph, manager of the Manned Space Flight Center's Saturn V Program Office later commented: "We created for ourselves a considerable problem by not allow enough thought and planning toward logistics at the very outset."⁴⁸

Chapter 4: Origins & Evolution of U.S. Rocket Programs

These problems were addressed by creating a high-level logistics management office, which looked in-depth into issues of designing transport, selecting routes, tracking supplies, and coordinating suppliers. By 1966 Rudolph claimed that the logistics tangle was under control, and would not hamper launch operations.

The launch facility was another subsystem designed specially for the Saturn program. NASA made a rather radical decision early on to assemble and check out the vehicle in a Vehicle Assembly Building (VAB) and cart it over to launch, rather than on the launch pad which had been common practice. This was done largely to avoid launch delays in the event of failure.⁴⁹ Facilities at the launch complex thus included: VAB, mobile launcher, crawler-transporter, the crawler-way (road to launch), mobile service structure, and the pad itself.⁵⁰

4.7 Conclusion

- The urgent need for ballistic missiles in the 1950s meant that military planners needed to create a “controlled technical revolution.” Many systems were designed together and are still in use today. As with all such revolutions there was a period of tinkering and many different architectures which were refined into main product lines.
- Decisions made in the 50’s affect us today, so we need to think forward as much as 50 years.
- The development cost not only in dollars, but in time and expertise, created very big incentives to re-use old systems wherever possible. Within the core technology of rocket propulsion, completely new designs are rarely developed—rather, advances are integrated into an existing program, and renamed.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

- Because programs built heavily upon each other, it is very hard to clearly define a “switch.” New programs always use old expertise so what we really have is evolution of a knowledge base, codified into technical artifacts.
- This evolution was strongly influenced by inter-service rivalry and political issues, but also environmental factors, most notably security concerns.
- We are currently witnessing this with respect to the heavy lift launch decision. Given the multiple development needs, the decisions come down to modifying one or another system. Said another way, whatever is most costly to change drives program. Programs fit around subsystems that won’t change. Launch Facilities and logistics create particularly important constraints on future designs. Saturn crawlers and logistics, for example, are still in use today.
- While science and human exploration have also benefited from these efforts, they have never been enough on their own to justify the enormous costs of development and operation, except where they touched directly upon issues of national security. Inter-service politics and external security-related events thus played a major role in the initial design and development of such programs. The period directly following World War II witness a tangle of rocket programs of various sizes, which eventually condensed into the three main lines in operation today: Atlas, Delta, and Titan. All three borrowed from each other—especially the engine development.
- The LOR/EOR debate emphasizes the way that values seep into architectural decisions. EOR, its supporters stressed, simplified launch vehicle development. LOR, on the other hand, simplified in-space architecture and in particular lunar landing. The trade was very hard to carry out because comparative mission reliability was practically impossible to quantify (beyond estimates) and, perhaps more importantly, the advantages of each architecture were *incommensurable*. That is, they maximized different rank-orders of metrics. Thus the decision was as

Chapter 4: Origins & Evolution of U.S. Rocket Programs

much about establishing what was valued most—development risk, landing simplicity, cost—rather than about optimizing an objective function. Values, of course, are inherently political.

Chapter 4: Origins & Evolution of U.S. Rocket Programs

Table 2: Program Timeline

Year	External Event	Program Event
1945	World War II Ends	Navaho Guided Missile Prog. Initiated
1946		MX-774 ICMB Prog. Initiated
1947		MX-774 Cancelled
1948		
1949	USSR Detonates first Atomic Bomb	
1950	Korean War Begins (June)	Redstone IRBM Prog. Initiated (July)
1951		ATLAS ICBM Prog. Initiated
1952		
1953	Nukes made lighter; U.S. learns of soviet missile progress	Atlas Program put on Crash Mode
1954		
1955		Jupiter A (IRBM); Jupiter C/Juno (Orbital Vehicles); Titan Program; Thor IRBM initiated
1956		
1957	Sputnik Launched	Navaho Cancelled
1958		NASA created; Delta Program Created
1959		Silverstein Committee Meets to Address HLLV needs
1960		
1961	Yuri Gagarin becomes first man in orbit	
1962		Atlas-Centaur Launch Vehicle Complete
1963		Redstone Cancelled; Jupiter Cancelled
1964		
1965		
1966		
1967		
1968		
1969		Apollo 11 lands man on Moon

Chapter 4: Origins & Evolution of U.S. Rocket Programs

Chapter Endnotes

-
- ¹ National Research Council. From Earth to Orbit: An Assessment of Transportation Options. National Academy Press. 1991. P 15
- ² From Earth to Orbit, P 15
- ³ Hall, Cargill R. "Early U.S. Satellite Proposals." From: The History of Rocket Technology: Essays on Research, Development, and Utility, Emme, Eugene M. (editor). Wayne State University Press. Detroit, Mich. 1964, p 68
- ⁴ Emme, p 142
- ⁵ Cargill, p 69
- ⁶ RAND engineering report: "Preliminary Design of an Experimental World-Circling Spaceship," Santa Monica, CA. May 1946
- ⁷ Bilstein, Roger E. Stages to Saturn: A Technological History of the Apollo/Saturn Vehicles. NASA History Series. Published by The Scientific and Technical Information Branch, National Aeronautics and Space Administration. Washington, DC. 1980
- ⁸ www.globalsecurity.org/wmd/systems/sm-64.htm
- ⁹ <http://www.daviddarling.info/encyclopedia/V/Vanguard.html>
- ¹⁰ <http://www.astronautix.com>
- ¹¹ Emme, 1964
- ¹² <http://www.spaceline.org/rocketsum/html>
- ¹³ Von Braun, Werner. "Major U.S. Rocket Programs." Chapter 2 of: The History of Rocket Technology: Essays on Research, Development, and Utility, Emme, Eugene M. (editor). Wayne State University Press. Detroit, Mich. 1964, p 68
- ¹⁴ <http://www.spaceline.org>
- ¹⁵ Von Braun, History of Rocket Technology
- ¹⁶ Von Braun, History of Rocket Tech P 112
- ¹⁷ <http://www.daviddarling.info/encyclopedia/V/Vanguard.html>
- ¹⁸ <http://www.daviddarling.info/encyclopedia/V/Vanguard.html>
- ¹⁹ <http://www.daviddarling.info/encyclopedia/V/Vanguard.html>
- ²⁰ <http://www.daviddarling.info/encyclopedia/V/Vanguard.html>
- ²¹ Emme, p 172
- ²² Elements of this discussion take from Emme, 1964
- ²³ [Http://www.spaceline.org](http://www.spaceline.org)
- ²⁴ <http://www.atlasibcm.com/index.php>
- ²⁵ Doyle, Stephen E. (Editor). History of Liquid Rocket Engine Development in the United States: 1955-1980. AAS History Series, Volume 12, AAS Rocket Propulsion History Colloquia, Volume 1. Published by The American Astronautical Society, San Diego, CA, 1992
- ²⁶ <http://www.designation-systems.net/dusrm/m-16.html>
- ²⁷ <http://www.spaceline.org/rocketsum/html>
- ²⁸ <http://www.spaceline.org>
- ²⁹ <http://www.spaceline.org/rocketsum/html>
- ³⁰ Doyle, 1992
- ³¹ Von Braun, 1964, p 104
- ³² Emme, 1964
- ³³ Stages to Saturn, p 63
- ³⁴ Stages to Saturn, p 53
- ³⁵ <http://www.hq.nasa.gov/office/pao/History/monograph4/against.htm>
- ³⁶ <http://www.hq.nasa.gov/office/pao/History/monograph4/against.htm>
- ³⁷ Stages to Saturn, p 67
- ³⁸ Logsdon, John M. (editor), et al. Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program; Volume IV: Accessing Space. NASA History Series, (NASA SP: 4407) Published by the NASA History Division, Washington, D.C.. 1999
- ³⁹ Stages to Saturn, p 62
- ⁴⁰ Stages to Saturn, p 45
- ⁴¹ Stages to Saturn p 52

Chapter 4: Origins & Evolution of U.S. Rocket Programs

⁴² Ryan, Robert, et al. "Fundamentals and Issues in Launch Vehicle Design." *Journal of Spacecraft and Rockets*. Vol. 34, No 2., March-April 1997

⁴³ Von Braun, 1964

⁴⁴ *Stages to Saturn*, p 92

⁴⁵ *Stages to Saturn*, p 98

⁴⁶ *Stages to Saturn*, p 106

⁴⁷ *Stages to Saturn*, p 147

⁴⁸ *Stages to Saturn*, p 290-295

⁴⁹ *Stages to Saturn*, p 290-295

⁵⁰ Benson, Charles. Faherty, William. *Moonport: A History of Apollo Launch Facilities and Operations.* Published by the National Aeronautics and Space Administration, SP-4204 (Washington, 1978)

5. Government Policy and Innovation in the Modern Launch Industry

5.1 Introduction

The previous chapter examined how initial developments with rocket technology contributed the Saturn rocket and eventually coalesced into the three main existing expendable launch vehicle lines: Atlas, Delta, Titan. With the development of the Space Shuttle, government policies began to force these programs towards extinction. The Challenger accident of 1986 reversed this trend, and in the late 1980's the DOD decided to fund the development of new evolved expendable launch vehicle (EELV). These programs, based on Atlas and Delta vehicle architectures, were designed to provide "robust" access to space, and also compete in an emerging commercial marketplace. The marketplace has since shrunk and Lockheed Martin and Boeing, the operators of Atlas and Delta, have recently announced a joint venture to pool resources and reduce cost.

These events raise an important question: why, after 50 years of development, has the cost of spaceflight not dropped? In most major industries, costs drop significantly as experience grows. Spaceflight has not followed this trend.

Initial investigations in this direction reveal a schism in the industry. Established firms like Lockheed Martin and Boeing contend that defense-spending shifts and global competition threaten the very core of their businesses. In contrast, small firms such as Scaled Composites and the now bankrupt Beal Aerospace complain that recent consolidations in the aerospace industry, together with government subsidization of launch vehicles and an overly complex regulatory regime, stifle innovation and created unfair advantages for entrenched firms. Who is correct?

5.2 The Political Economy of Launch

At the core of this debate are questions of both market and government-failure. First, security externalities demand government intervention in the launch industry. While the government would like to lower the cost of launch and thereby catalyze a more vibrant “space-industry,” this objective often conflicts with the military’s need for robust and reliable access to space and the desire to limit foreign access to sensitive technology. Imperfect competition and the dynamics of investment in the launch industry provide a second source of market failure. Like many capitol-intensive industries, the private-space-launch industry suffers from a “chicken-and-egg” problem related to economies of scale. While markets will likely expand if the cost of launch decreases, the cost of launch will decrease only if larger markets create the potential for economies of scale. Figure 18 illustrates the dynamics behind this problem. As a whole, the market risk together with delayed return-on-investment, dissuade sufficient private-sector funding. As with the aviation industry and railroad industry before it, the government must somehow “jump-start” markets through economies of scale.

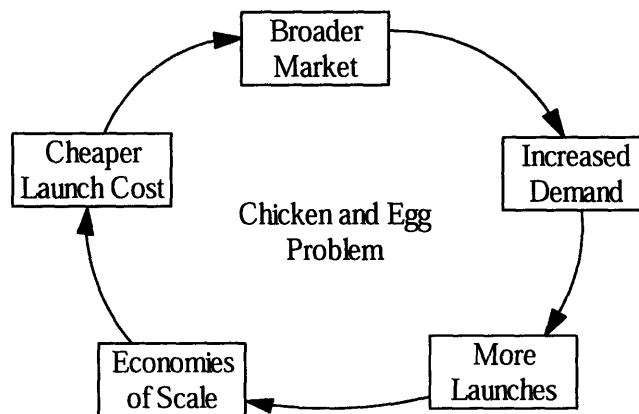


Figure 18: Chicken and Egg Problem in the Launch Industry. The supply and demand are functions of each other.

Both of these problems open the door for government failure. Military interest in the space arena leads to pork-barrel politics and bureaucratic inertia. Economies of scale

Chapter 5: Innovation in the Modern Launch Industry

issues lead to the acceptance of oligopoly, which raises the potential for vast inefficiencies and classic Stiglerian capture problems.

How can these issues be disentangled to provide a proper balance between economic prosperity, technological innovation and national security, in the space-launch industry? An answer must take into account both the history and current state of the launch industry.

5.3 Military Roots: Legacy Costs

The previous chapter examined the military roots of the space launch industry. Like the larger defense industry in which it resides, the industry has long been an oligopoly supplying a monopsony. In the years following World War II, large-government projects motivated largely by security concerns accelerated the development of rocket and ballistic missile technology. As a metaphor for the cutting edge of technology, “rocket science” also had strong symbolic value in the global ideological struggle with the Soviet Union.

Chapter 5: Innovation in the Modern Launch Industry

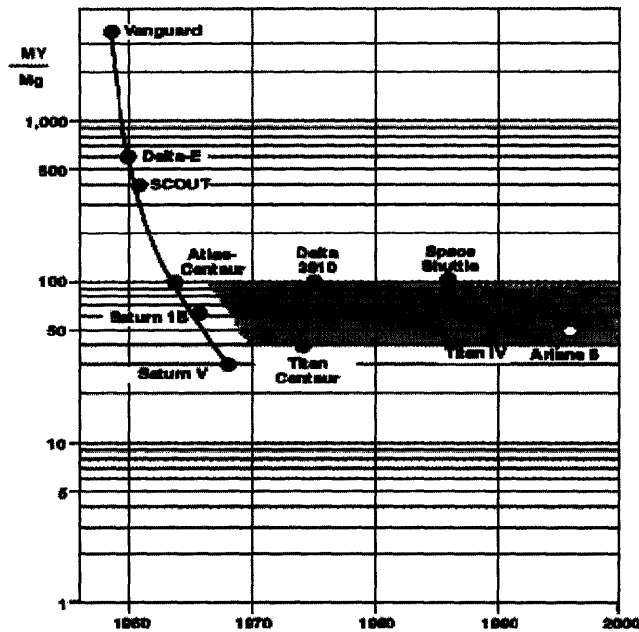


Figure 19: Trends in expendable vehicle launch cost since 1960. Cost is measured in Man-year per mega-gram. Note that costs remain relatively constant from the mid-1960s on. (Courtesy: James R Wertz)

NASA was created largely in response to the Russian launch of sputnik in 1957, as a way to showcase American technological prowess. Beyond putting a man on the moon, its mission was to develop new forms of space-transportation and nurture potential commercial space activity. Concentrated government efforts brought about rapid advance through the 1960s, leading many to predict that space would soon be accessible on a routine and low-cost basis. Forty years later, however, while performance and reliability of rockets has increased significantly, the costs of space-launch has changed little. As Figure 2 illustrates, the cost of placing material into low earth orbit (LEO) is essentially the same as it was in 1960, at about \$10,000 per pound. Government programs designed to create radically new launch technologies, such as the Space Shuttle and more recent Space Launch Initiative, have either failed or actually *raised* the cost of accessing space, and this continues to block potential growth of space-related products, not to mention basic exploration.

5.4 Development of an Industry and Government Failure

Much of this stagnation in cost is likely due to the fact that space-launch has remained an essentially government activity, with little incentive to reduce cost. Military programs often strive for performance objectives with little regard for cost. NASA, and the Congressmen whose districts encompass it, have strong incentives to continue government programs often at the expense of innovation.

While the US Government supported a growing industrial based during the Cold War, a truly private space launch industry—that is, private firms supplying private customers—did not get under way until the late 1980's. The first private launch allegedly occurred on an island in the Gulf of Mexico in 1982.¹ The event created a stir in the Federal Government, since no official licensing system existed for a fully private industry. After some debate concerning the appropriate agency to regulate the industry, the Commercial Space Act (CSA) was passed in 1984, creating the Office of Commercial Space Transportation (OCST) within the Federal Aviation Administration to oversee and help develop the nascent industry.²

Even this “space industry,” however, was essentially a continuation of government practices. Launches were provided by existing production runs of Department of Defense (DOD) expendable vehicles—Atlas, Delta and Titan rockets. Titan rockets are now being phased out. The CSA essentially gave Government contractors the right to sell launches on these rockets using government launch ranges.³ In a sense, then, the Space Act was as an attempt to recoup government development costs. Because the military often stresses performance over cost considerations, Atlas and Delta rockets were not designed for market competition. However, private investors had little incentive to create more competitive systems, since the Atlas and Delta were operating without the need to amortize development costs. In the face of a growing communications satellite market, there was virtually no private investment in new vehicles.

Chapter 5: Innovation in the Modern Launch Industry

When private initiatives did create new opportunities bureaucratic interests often stifled, if not completely extinguished, growth in the industry. A few examples are particularly illuminating. The first involves a small company called American Rocket (AM). Competing Atlas and Delta systems notwithstanding, AM began developing hybrid rocket engines for the commercial launch market in the early 1980s. Hybrids are a relatively old technology which burn solid propellant with a liquid oxidizer. They have disadvantages from a pure performance perspective, but many economic advantages compared to fully cryogenic systems such as the Atlas or Delta. After some initial success, AM managed to attract legitimate private investment, but they also caught NASA's attention. In the name of pioneering all things space-related, the agency put out a request for proposal (RFP) for hybrid rockets, and investors for the private project disbanded. As one FAA employee notes, "A company and investors, venture capitalists, are not willing to put money into a private entity if a government agency is willing to pay somebody else to do that research. They can't compete with it."⁴

While NASA is chartered to aid private development of space, their activities with respect to American Rocket achieved the opposite affect. At the time, AM was a research and development firm. NASA's RFP created the potential for competitors with effectively bottomless resources. Those who issued the RFP evidently believed that NASA's obligations included reducing the cost of government launch systems, which could involve moving from cutting-edge research and development to perfecting lower-cost lower-performance techniques. The trouble is that by funding projects with short-term return on investment, NASA discouraged innovation. This leads to the first policy recommendation of the chapter:

Recommendation 1: NASA should streamline its current agenda and get out of the business of operations. NASA policy should be to *buy* technologies for space operations, and fund research with long return on investment.

A larger example of NASA's dampening affect on the space launch industry involves the bureaucratic politics surrounding the development of the Space Shuttle in the late 1970's.

Chapter 5: Innovation in the Modern Launch Industry

In this case, bureaucratic inertia led to policies that were contradictory and inefficient. On the heels of the spectacularly successful Apollo Program, NASA sold the Space Shuttle Program to Congress as a method to create routine, low-cost access to space. They ran into problems, however, when system-cost-models demonstrated that Shuttle launch would be expensive unless launch rates were high (again, the economies of scale problem). Rather than pursue a new policy, however, bureaucratic maneuvering came to the fore. NASA joined political forces with the Department of Defense, altered the design slightly to incorporate military needs, and proposed that all future government and private payloads be sent to orbit using the Shuttle. While many at Department of Defense worried about dependence on one vehicle for space access, others believed that potential cost savings could be channeled into other DOD programs.⁵ Skeptics were thus “overruled by those in the Pentagon in leadership positions who were convinced that the only way that Congress would approve the development of the Shuttle would be to tie the Shuttle to the imperatives of launching payloads essential to the security of the United States.”⁶ National security was thus a means by which NASA and DOD interests could get their way.

Rather than pursue path-breaking technologies, NASA and the DOD quite often acted as monopolists in the space arena, creating barriers to entry through direct competition with nascent firms and industry players. The development of the Shuttle, together with the policy that all payloads to orbit must be sent on it, essentially extinguished private competition in the launch industry through the 1980s. It was only after the Challenger tragedy of 1986 that policy-makers could no longer ignore the liability associated with tying all launch to one system, and began to develop alternative access to low earth orbit.

5.5 Industry Structure

A reversal of government policy following the Challenger accident, combined with increasing demand from the telecommunications industry revitalized the space launch industry through the 1990s. The Military contracted Boeing and Lockheed to revive Delta and Atlas programs through the new “Evolved Expendable Launch Vehicle” programs,

Chapter 5: Innovation in the Modern Launch Industry

with the dual-goal of ensuring robust space access and serving the commercial market. Figure 20 illustrates the number of government and commercial payloads launched to orbit from 1957 to 2001. The rise in demand for space-related services in the 1990s spurred private investment in satellite manufacturing and other space-related technologies, but higher launch rates did not greatly reduce the cost of private launch. While the reasons for this stagnation are not clear, they raise important questions about the relationship between industry structure and technological innovation.

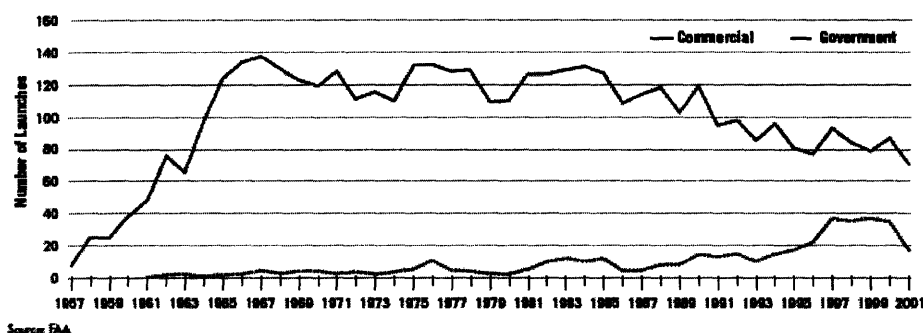


Figure 20: Government and Commercial Payloads launch to orbit 1957 to 2001. Data from the "Final Report of the Commission on the Future of the United States Aerospace Industry."

The current structure of the aerospace industry is the result of a wave of consolidations caused, in part, by reduced defense spending after the end of the Cold War. As **Error! Reference source not found.** illustrates, there are now four major US aerospace firms. Only three of these firms, Boeing, Lockheed Martin, and Northrup Grumman are involved in the satellite launch market. Northrup's involvement stems from acquiring relatively small Pegasus rocket from Orbital Space Planes Inc. The Boeing and Delta programs are much larger.

Chapter 5: Innovation in the Modern Launch Industry

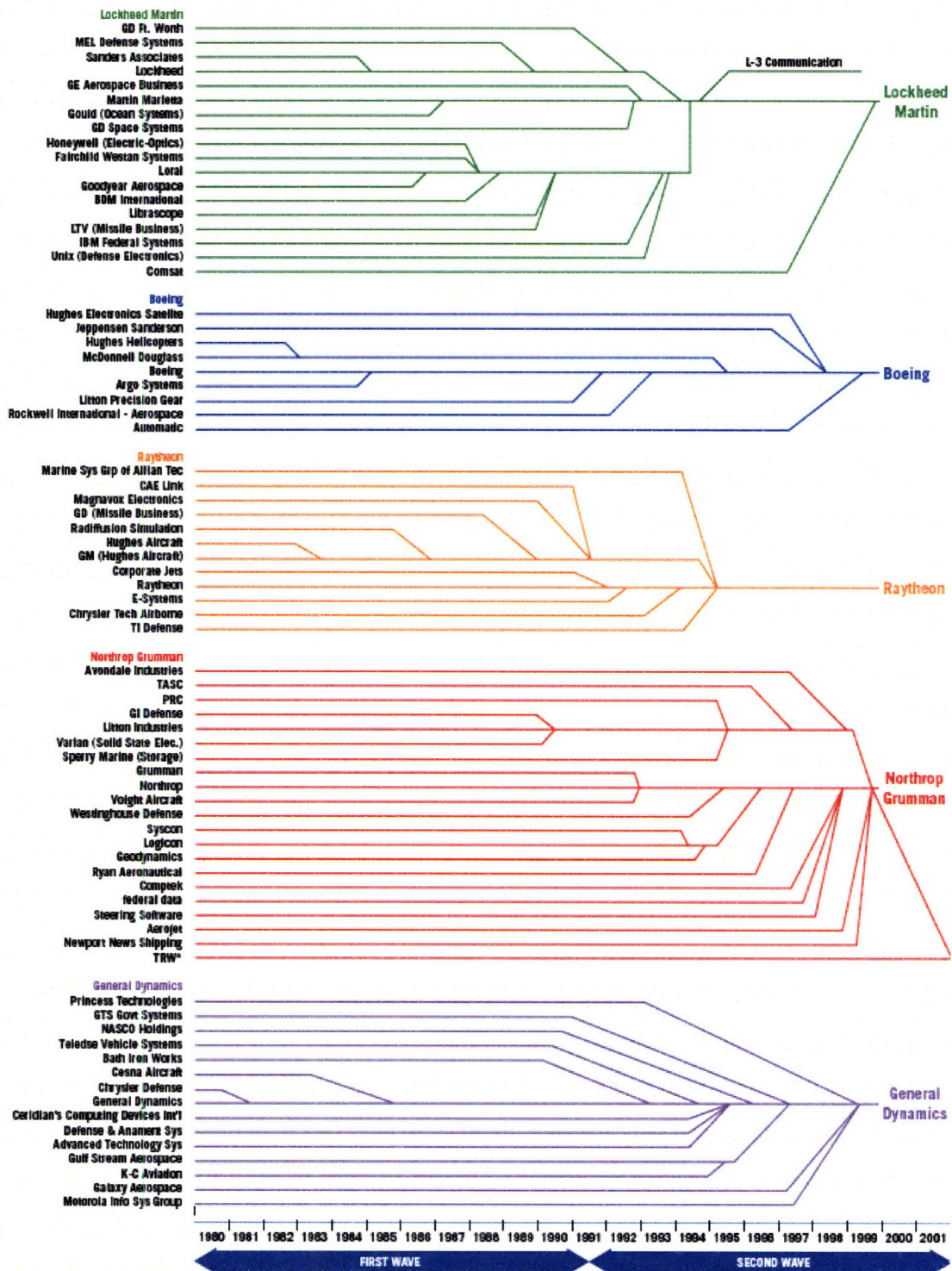


Figure 21: Consolidation in the Aerospace Industry, 1980 to 2001. (courtesy "Final Report of the Commission on the Future of the United States Aerospace Industry.")

Chapter 5: Innovation in the Modern Launch Industry

As noted, the DOD invoked conventional procurement philosophy in creating two lines of launch vehicle supply—the Delta and Atlas programs. While these programs serve national security needs, they were also structured in order to compete in the growing international launch market.⁷ Thus, consolidation together with the need for robust military access and strategic trade concerns, have led to an accepted oligopoly in the industry.

Does this structure harm innovation? On the one hand, it is clear that the market for space launch cannot support many competitors. As the economist Joseph A. Schumpeter and his supporters would likely note, the capitol-intensive nature of the industry combined with the need to capture economies of scale suggest that a duopoly may in fact create more robust competition than a more competitive market. Greater resources may lead to increased spending on research and development. If the private market for space access persists, Lockheed and Boeing will need to continually improve their designs in order to match foreign competition and potential new entrants within the US.

There are, however, a few problems with this argument. First, the concentrated industry structure results in classic Stiglerian capture. Often framing their arguments in terms of industrial-base, strategic trade, or security concerns, Lockheed Martin and Boeing actively lobby Congress and the Administration for rents and advantages. The Aerospace Industries Association (AIA), dominated by Boeing and Lockheed in the launch arena, has argued that government needs to increase, not decrease, its involvement in the industry. In the name of leveling the playing field with international competition, it has asked that the government renew indemnification provisions for launch providers—that is, remove the costs of liability associated with less reliable vehicles—increase spending on basic R&D, and even help industry fix vehicle problems:⁸ As the AIA’s representative has argued publicly before the Senate: “I am also quite concerned about the recent rash of U.S. launch failures....we would like to work in partnership with the federal government, as needed, to remedy our current launch problems, put them behind us, and move on to a period of successful growth in the launch sector.”⁹ Congress often acquiesces to these demands in the name of security and foreign competition.

Chapter 5: Innovation in the Modern Launch Industry

The Atlas and Delta programs, together with heavy rent-seeking, undoubtedly curbs innovation in the industry. Direct aide to existing launch providers increases barriers to entry for new firms. As one entrepreneur noted: “We wonder where the computer industry would be today if the U.S. Government had selected and subsidized one or two personal computer systems when Microsoft Inc. were in their infancy.”¹⁰

5.6 Potential Remedies

Clearing the tangle of bureaucratic wrangling, military concerns, and industry lobbying to bring about needed change in the industry will not be easy. It is clear, however, that increased flight rates are needed, together with proper policies on the part of NASA and the DOD. Many recent reports have noted that a viable tourism space tourism industry could bring about the former. Figure 4 represents one prediction of how public space travel could develop. The question, then, is how to let industry capitalize on this market opportunity?

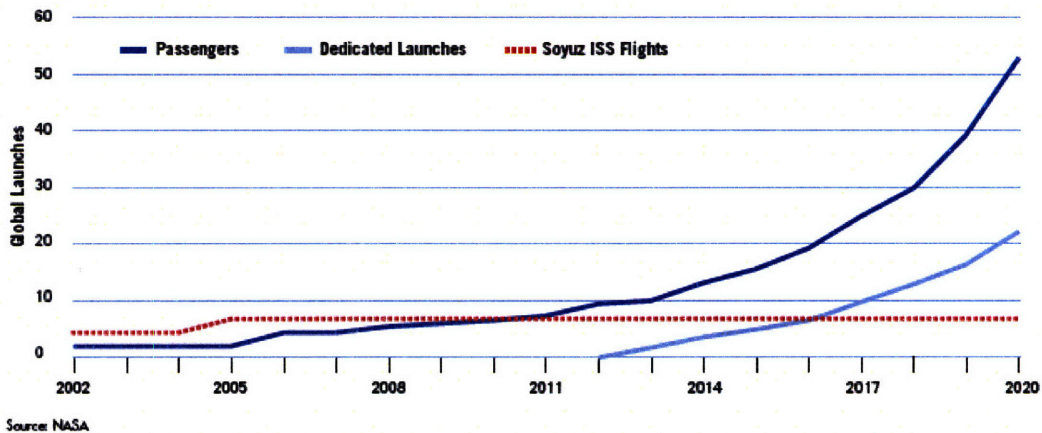


Figure 22: Public Space Travel Estimates. From the "Final Report of the Commission on the Future of the United States Aerospace Industry."

In order for private firms to capture this market, NASA cannot compete with nascent companies. As one space entrepreneur has put it, “The agency needs to be a customer, not an owner. The agency needs to be a multiple transaction thinker, not a single transaction

Chapter 5: Innovation in the Modern Launch Industry

thinker. ...A single transaction thinker tries to squeeze every dime for himself out of a transaction, to the detriment of the other participants.”¹¹ Many NASA policies start from goal of operating technology in space and then move backwards towards doing this at least cost. Stimulating a viable industry requires a change in this paradigm. Ironically, policies established to spur the development of the aircraft industry in the 1930s might be useful. At this time, the US government over-paid for airmail contracts in order to give incentives for private firms to continue manufacturing and eventually reduce costs.¹² While the policy was likely more expensive than creating a government-run airline, it resulted in a vibrant industry after the catalyst of World War II, bringing countless benefits to the US.

Recommendation 2: NASA should become a customer, not a provider of space launch services. In order to stimulate innovation, it should purchase as many launches as possible from burgeoning launch providers, rather than spend money on operations research.

Recommendation 3: NASA should encourage the development of passenger space travel, by tying risks associated with private development to a stable source of alternative demand. It might do this by purchasing all meteorological-related launch, whether sub-orbital or to LEO, from firms that are not part of the current oligopoly.

Successful stimulation of the space-launch industry will also depend on navigating entrenched interests. While military needs will likely maintain the EELV program for a quite some time, this capability should not be pushed onto every market opportunity in the name of reducing cost. Some have noted that the legacy technology associated with these systems leads to legacy costs.¹³ With the tourism market opening, it may be that separating military launch from commercial launch, while initially expensive could lead to increase spending private R&D spending. This would not, however, include launches to very high orbits, since any new vehicles are not likely to support such markets.

Chapter 5: Innovation in the Modern Launch Industry

Recommendation 4: The government should investigate the potential for EELV related vehicles to support Geosynchronous Launch and Military needs only.

This recommendation, however, will also depend on the development of viable alternatives to the EELV vehicles. Needless to say, these should not be developed by government. Instead, incentives should be provided to stimulate private funding of such ventures. NASA's centennial challenges program, which offers prizes for technology demonstrations, is an excellent model in this regard. This leads to the third and final recommendation:

Recommendation 5: NASA should increase funding to the centennial challenges program, and provide significant cash prizes for access to low earth orbit. Such prizes could include guaranteed contracts on a few subsequent government launch opportunities.

5.7 Conclusion

The previous analysis suggests some potential solutions:

Recommendation 1: NASA should streamline its current agenda and get out of the business of operations. NASA policy should be to *buy* technologies for space operations, and fund research with long return on investment.

Recommendation 2: NASA should become a customer, not a provider of space launch services. In order to stimulate innovation, it should purchase as many launches as possible from burgeoning launch providers, rather than spend money on operations research.

Recommendation 3: NASA should encourage the development of passenger space travel, by tying risks associated with private development to a stable source of alternative demand. It might do this by purchasing all meteorological-related launch, whether sub-orbital or to LEO, from firms that are not part of the current oligopoly.

Chapter 5: Innovation in the Modern Launch Industry

Recommendation 4: The government should investigate the potential for EELV related vehicles to support Geosynchronous Launch and Military needs only.

Recommendation 5: NASA should increase funding to the centennial challenges program, and provide significant cash prizes for access to low earth orbit. Such prizes could include guaranteed contracts on a few subsequent government launch opportunities.

Chapter 5: Innovation in the Modern Launch Industry

Chapter Endnotes

¹ Gress, Ron K. "2002 Commercial Space Transportation Lecture Series." From http://ast.faa.gov/files/pdf/gress_complete.pdf

² Gress, 2002

³ Gress, 2002

⁴ Gress, 2002

⁵ Aldridge, E. C. Pete. "Assured Access to Space: The Bureaucratic Space War" Dr. Robert H. Goddar Historical Essay. NASA, c 2003

⁶ Aldridge, c2003

⁷ Aldridge, c 2003

⁸ Douglass, John W. "Removing Barriers to Commercial Space Industry." Testimony Prepared for the U.S. Senate Committee on Commerce, Science and Transportation Subcommittee on Science, Technology, and Space. May, 1999

⁹ Douglass, 1999

¹⁰ Andrew Beal. Quoted in "Rocket Start-up Beal Aerospace out of Business" Reuters News 2000

¹¹ Robert Bigelow. Speech to NASA

¹² Rudolph, Jane Anna. "Globalization of the Aerospace Industry." MIT Thesis, May 2001.

¹³ Musk, Elon. Speech to the Centennial Challenge Workshop. August 2004

6. Analytic Model of HLLV Capacity, Cost & Risk

6.1 Introduction

The problem of designing a heavy lift launch system encompasses, among other things, the cost and performance of the launch system and its impact on in-space-designs and exploration missions for decades to come. From an economic perspective, these complexities can be reduced by framing the decision in terms of capacity choice. Critical factors include competing scale-benefits in production verses at launch, as well as reliability-dependant expected-costs of launch verses in-space-assembly.

Building on the previous discussion, this chapter develops a high-level cost and risk model to evaluate these competing factors against capacity from mission-specific and life-cycle perspectives. The model demonstrates, among other findings, that the risk associated with launching many rockets is balanced by economic impacts of failures in larger rockets. Further, given current technology, economies of scale at launch are the dominant factor in determining overall mission cost, rather than economies of scale in production. However, these findings are sensitive to assumed scale effects and learning curves associated with variations in production rate—suggesting that these variables must be known with greater accuracy for each potential launch system if a sound decision is to be made.

These issues can be addressed by framing the launch problem in terms of *capacity choice*. That is, one can assume launch capacity is a free design variable, in order to evaluate how cost and risk trade against it. In reality the problem will be more discrete due to variations

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

in production costs and system reliability of fielded systems, including the Shuttle and Evolved Expendable Launch Vehicles (EELV). Such factors can be incorporated later.

6.2 Principle Trades

What are the cost and risk trades associated with capacity? Table 3 summarizes the *benefits* of larger versus smaller launches. All else being equal, larger vehicles enable simpler in-space operations and benefits from launch economies of scale; smaller launchers require more modular payloads and on orbit assembly, but benefit from production economies of scale and flexibility in the face of shifting demand. "Economies of scale at launch" refers to cost benefits resulting from larger launches, such as lower mass-fractions and potentially reduced ratios of labor to IMLEO. "Production economies of scale" refer to economic advantages resulting from producing greater numbers of vehicles, such as greater more influential learning curves.

Also, because smaller launchers will typically have smaller fixed recurring cost (in the form of labor and facilities maintenance) they will be more flexible to changes in demand. If expected mission frequency drops substantially it will cost less to maintain a smaller launcher.

Potential Benefits of Larger v Smaller Launchers		
Benefit		Reason for Benefit
COST	Lower cost-per-kilo at launch	Economies of scale at launch
	Lower operations cost	Simpler in-space operations
RISK	Lower in-space risk	Few in space dockings
	Lower schedule risk	Less dependence on high-reliability AR&D
Benefit		Reason for Benefit
COST	Lower Development Cost	Use of existing technology, smaller scale

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

	construction	
	Lower relative production cost per-vehicle	Increased production rate
RISK	Higher reliability at launch	Less complex system, higher production rate
	Lower schedule risk	Lower non-recurring costs lead to greater Flexibility

Table 3: Competing cost and risk factors of smaller and bigger launchers; Bigger is not necessarily better from a cost and risk perspective.

From a risk perspective, larger launchers benefit because—reliability of launch being equal—fewer launches create less chance that a payload will be lost. Smaller launchers, however, benefit from the fact that not all the “eggs are in one basket,” causing a loss at launch to be less catastrophic from an economic perspective. However, it is not clear that reliability is constant as capacity increases. This relationship is critical to a final decision, although it will itself be a function of development budgets.

The architecture of Lunar or Mars exploration will also affect the relative benefits of various capacity launchers from a cost and risk perspective. To begin with, the architecture selected affects average payload cost. Current studies suggest that most mass sent to orbit will be propellant and propulsion modules. Sending such payloads in small amounts may actually *decrease* mission risk by lowering the effect of a catastrophic accident. Further, producing smaller propulsion modules in greater number increases production rates and thus reduces per-unit module costs. Lowering average payload cost might in turn lead to the acceptability of lower launch reliability thus reducing relative development cost. Figure 23 Illustrates this relationship using systems dynamics notation. Note that given a fixed available budget, continued increase in desired launch capacity (perhaps for unrelated reasons such as simplified in-space assembly) will eventually be halted by reliability and cost constraints. The loop thus “balances” with a theoretically identifiable local cost minimum as a function of capacity. Of course, the import of average payload cost is but one factor in the decision.

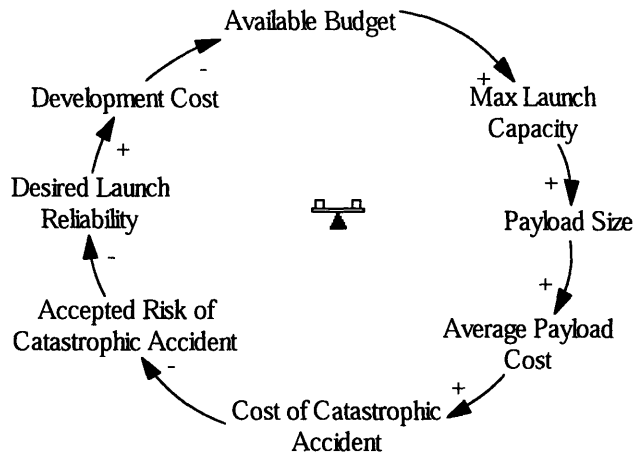


Figure 23: Launch capacity, payload cost, and reliability

The real impact of these trends will of course depend on the specifics of the system developed. It may be, for example, that beyond a certain lift-capacity, complexities in the system cause larger launchers to lose expected economies of scale. It is more useful, however, to address these factors once high-level trades have been evaluated and specific systems chosen for comparison.

It is evident, then, that the problem is rather complex. The outcome depends on a host of interrelated factors, including the reliability of launchers, the average cost of payloads, and the reliability of cheap, fully autonomous docking technologies. Further, inter-agency and extra-agency political forces must be considered in determining a final design.

6.3 General Trends in Cost and Risk

6.3.1 Launch Cost

Can these relationships be quantified? As with other capacity problems, economies of scale suggest that the relationship of size to average launch cost will follow a power law:

$$C_L = A \times L^B \tag{1}$$

Where:

$$C_L = \text{Cost of Launch}$$

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

L = Capacity to LEO (or other orbits)

A and B are coefficients dependant on the type of system

Figure 24 illustrates the relationship for expendable US launchers, as of 2000.¹ This data suggests that, for capacity in kilograms and costs in millions of dollars, these coefficients are currently: $A=0.226$ and $B=.66$ with an error of .96.

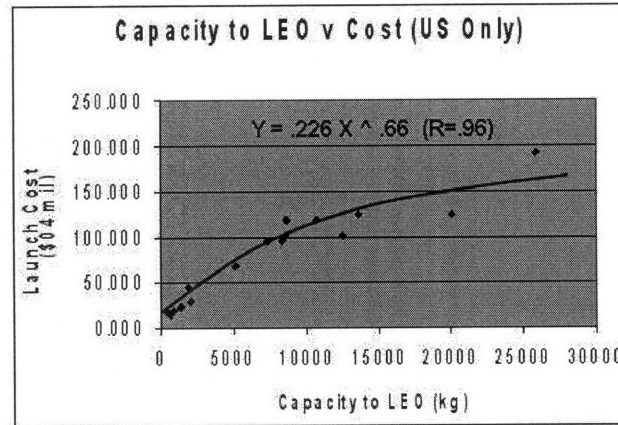


Figure 24: Relationship of launch cost to LEO Capacity for US Launchers. (Data from "International Guide to Launch Vehicle" Isakowitz)

To keep things even, however, it should be noted that the cost of a launch is often highly dependant on the flight rate. If a dedicated exploration launcher is created, the cost of launch will be a function of both capacity and the number of launches (which itself depends on capacity and IMLEO). We can incorporate this by including a simple learning curve, which lowers cost depending on the number launched, and dividing back to get an "average cost per launch." For large capacity launchers, fewer launches will result in less reduction of per-launch costs.

6.4 Development Cost

Development cost follows the opposite trend: larger launchers are more complex and will cost more to develop. Recent studies of the potential for modified industry vehicles suggest that industry developments costs follow a step function, with a large increase in

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

cost at capacities greater than approximately 60 metric tons (mt). It is also possible, however, to convert the Space Shuttle into an expendable heavy lift vehicle. Development cost on a modified shuttle will be lower, due to the fact that a lot of hardware already exists. As previously stated, development cost can also itself be considered a design variable, affecting the reliability of various components, which then impacts operation cost.

6.5 Risk implications of Single vs. Multiple Launch

From a mission perspective, the relative benefit of a larger v smaller launcher will also depend on the risk of launching payloads in small or large numbers. This is affected by the reliability and capacity of the launcher, the reliability of in-orbit docking, and IMLEO required. We can begin to see how capacity affects risk through simple reliability calculations.

Given a reliability of launch, R_L , a reliability of docking, R_D , and launch capacity, L , the reliability of launching a given IMLEO to orbit will be:

$$R_{LD} = R_L^N \times R_D^{(N-1)} \quad (2)$$

Where $N = IMLEO / L$ (Rounded Up)

The assumption here is that given N launches, $N-1$ dockings will occur. In reality, of course, a given architecture may have more than $N-1$ dockings, depending on whether it uses Lunar Orbit rendezvous, Earth Orbit rendezvous on return Earth-return, or other such operational scenarios. These decisions, however, will impact mission reliability regardless of the launcher chosen.

We can now examine how the launch capacity and IMLEO affect the reliability of launching a mission. Figure 26 illustrates how total launch reliability (including launch and assembly) changes with respect to launch capacity for different reliabilities of AR&D,

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

assuming an IMLEO of 150mt and a conservative launcher reliability of 98%. One might note that above a capacity 75 metric tons, the size of the launcher has no impact on mission reliability. This, of course, is because the number of launches remains constant at 2.

The mission reliability does drop significantly when smaller launchers are used. For an AR&D reliability of 0.995, however, (which might be needed if humans are involved at any point in the docking process), a 40mt launcher keeps the mission reliability above 0.90.

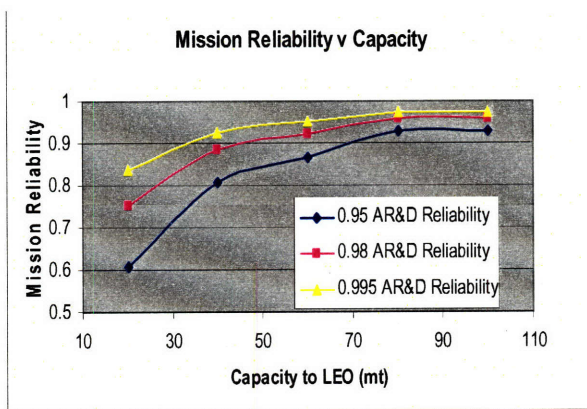


Figure 26: Mission Reliability v Capacity for various AR&D reliabilities. Assumes: IMLEO 150 mt Launcher Reliability of 0.98

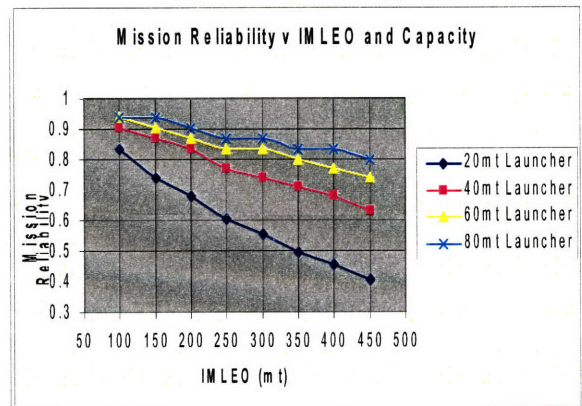


Figure 25: Mission Reliability v IMLEO for various capacity launchers. Assumes: Launch and Autonomous Docking Reliability of .98 Each. "Fractional Launches" not allowed.

Figure 25 illustrates total mission reliability with respect to IMLEO for different capacity launchers, assuming launch and AR&D reliability of 98%. For an IMELO below 120mt, a 40mt launcher decreases mission reliability on the order of 3%, compared to an 80mt launcher. This is an important number, as EELV-derived launchers face a rather sharp rise in the development cost above approximately 40mt. For comparison, a Shuttle derived vehicle has a capacity to LEO on the order of 80mt to 120mt.

This suggests that reliability of launch and docking *should not* be a concern in determining whether to use 40mt or 80mt launchers for lower-mass lunar missions. Depending on the relative development and recurring cost-savings of 40mt EELV-

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

derived system verses an 80mt Shuttle derived vehicle, this may make a case for developing lower-mass lunar missions (perhaps, for example, through the use of reusable in-space vehicles).

6.6 Incorporating Risk into Cost

6.6.1 Expected Cost

From an architectural perspective, the true cost of one launch also depends on the expected cost of losing a launch and/or a payload. A payload can be lost either during launch, or during rendezvous and docking with other architectural components. In-space risk is reduced with the former, launch risk is reduced in the latter. The outcome is a function of launch reliability and number of launches. It is thus also a function of capacity in that capacity affects the number of launches needed for a given architecture, and the average cost of a payload (higher capacity launchers will typically have higher-cost payloads).

To calculate the risk of losing a payload we can use the economic concept of *expected cost*. This must be done both with respect to the probability that a launch will fail, and that docking will fail. Assuming that an extra vehicle is available for launch if a failure should occur, the former will result in the need for one new launcher and one new payload.² Taking this into account the *expected cost* of one launch, C_E , and one mission, C_{EA} , will be:

$$C_E = C_l + (1 - R_l) \times (C_L + M) \quad (3)$$

$$C_{EA} = C_E \times (N \div L) + (1 - R_D^{(N-1)}) \times (C_l + M) \quad (4)$$

Where

C_L = Cost of Launch

R_l = Reliability of launch

R_d = Reliability of Autonomous Rendezvous & Docking

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

$$M = \text{Payload cost}$$

6.7 Payload Cost as a Function of Capacity

The equations above incorporate the cost of a payload, which must be specified before they can be calculated. Launch capacity will simultaneously drive the size of the modules and the number built. If modules are generic (expendable kick-stages, for example) economies of scale will again work against each other: bigger launchers will reduce per-kilo launch costs and increase mission reliability, but smaller modules will reduce per-kilo production costs and make losing one module relatively less import.

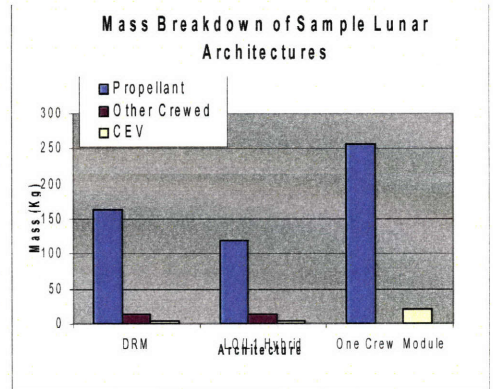


Figure 27: Mass breakdown, 3 candidate lunar missions. (courtesy, MIT 16.89 class report)

For simplicity, we can separate modules into two basic types:

- Pressurized human modules
- Propulsion Modules

For most Lunar and Mars missions the ratio of propellant to pressurized payloads is extremely large. Figure 27 illustrates the amount of propellant and crewed payload for three sample Lunar architectures, based on recent work conducted at the Massachusetts Institute of Technology.² It is clear that, regardless of the chosen Lunar architecture, the majority of mass will be in the form of generic propulsion modules and kick-stages.

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

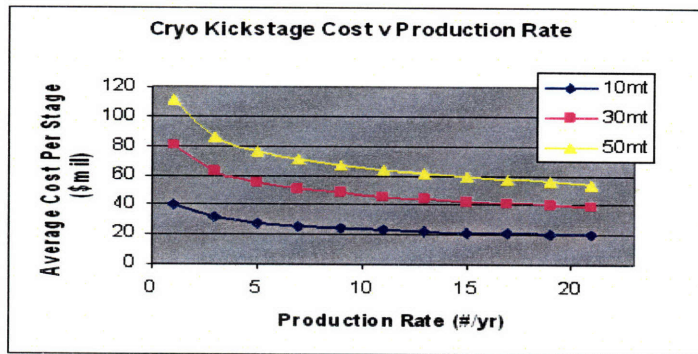


Figure 28: Cryogenic kick-stage cost vs. production rate

Historically, in space propulsion modules have used storable propellants. However, current designs are considering cryogenic-based systems with low or zero boil-off technologies. The cost of both can be estimated using cost estimating relations (CERs) and learning curves.³

Figure 28 graphs propellant kick-stage cost as a function of mass and production rate. It is interesting to note that a production rate of about 8 to 10 per year can significantly reduce per-unit costs. For 40 metric modules, this reduction is on the order of 50%.

6.8 Architecture Launch Cost vs. Capacity

Thus far, it has been maintained that the expected cost of launching a mission (excluding DDT&E cost) will vary with capacity based on the following parameters:

Interrelated Variables:

- IMLEO
- Capacity
- Per Module Cost

Independent variables:

- Launch Reliability
- AR&D Reliability

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

Figure 29 illustrates total *expected architecture costs* for different sized launchers as a function of these variables. It assumes a conservative autonomous docking reliability of 98% and launch reliability of 98%. It demonstrates that after incorporating the risk of failure and ignoring development cost, larger launchers remain more effective from a cost perspective. For each IMLEO graphed, the difference between the launch of a 40mt and 80mt vehicle is on the order of 10%.

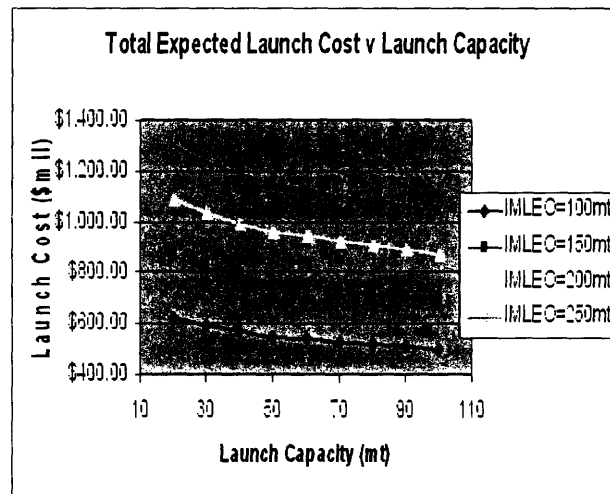


Figure 29: Total Expected Architecture Cost v Capacity. Cost includes risk of failure at launch and/or AR&D. Assumes Launch and AR&D Reliability of 98%. No Development Cost

Figure 29 demonstrates that, from a cost and risk perspective, the *economies of scale for larger vehicles at launch have a larger effect on relative cost than the economies of scale at production for smaller launchers and payloads*, or the risks of assembling may smaller pieces verses fewer larger pieces. While savings from increased production rate for small vehicles evidently flatten the curve, the tradeoff between launch capacity and impact of a catastrophic accident seems to balance itself out. If reliabilities of launch and docking are roughly balanced by payload and launch cost considerations, the main trade-off resulting are economies of scale of launch v economies of scale at production.

6.9 Sensitivity Analysis

6.9.1 Learning Curves

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

Economies of scale in production were estimated using a learning curve of 85%. Figure 30 assumes three lunar missions at 150 metric tons each over three years, with various learning curves. It demonstrates there is in fact a flipping point from *bigger is better* to *bigger is worse*, around a learning curve of about ~80% (lower learning curve factors mean increased savings at increased production rates). Smaller launchers are better at learning curves below 80%, larger is better at learning curves above 80%. Thus, the answer is very sensitive to the savings generated by producing many vehicles. The exact benefits will depend on the ratio of fixed recurring v fixed variable costs (i.e. labor and facilities v launch, operations, and mission costs) for specific systems. This suggests that these ratios must be considered in detail before a final decision is made.

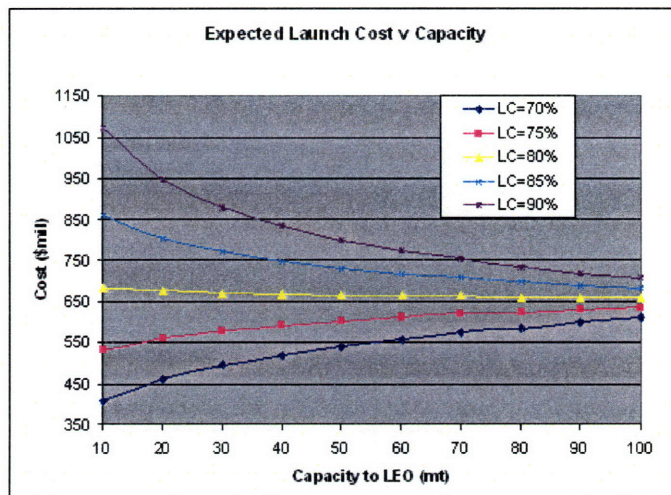


Figure 30: Total launch cost v capacity at different learning curves.

6.9.2 Launch and Docking Reliability

Error! Reference source not found. illustrates how expected architecture cost varies with AR&D reliability, assuming 150 metric tons in orbit, and launch reliability of 98%. It is interesting to note that, while the *difference* between expected cost for large and smaller launchers increases as reliability drops, the *relative cost* of a 40mt v 80mt launcher remains rather constant at ~11%.

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

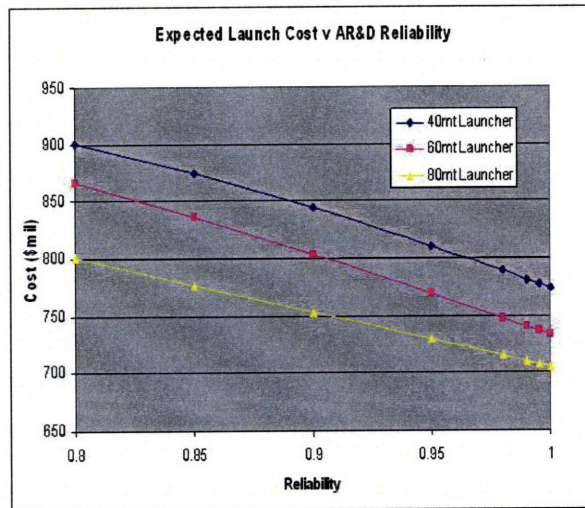


Figure 31: Expected launch cost v AR&D reliability. Assumes IMLEO of 150mt; launch reliability of 98%; all payloads are cryogenic kick-stages.

Table 4: Difference between 40mt and 80mt architecture launch cost.

Difference in Expected Launch Cost	
AR&D Reliability	40mt - 80mt
0.9	\$91.40
0.95	\$81.66
0.98	\$74.04
0.99	\$71.20
0.995	\$69.72
1	\$68.20

This suggests that the benefits of docking once v docking multiple times are counter-balanced by the increased cost of the module being docked for the larger pieces. A failure during docking (resulting in the loss of one module) will be more likely for smaller pieces, but will have a less significant affect on total mission launch cost.

Figure 32 illustrates the relationship of total architecture cost to payload cost, assuming launch and AR&D reliability of 98%. The expected launch cost increases by roughly 8% for 80mt launchers and roughly 12% for 40mt launchers. This, however, is slightly

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

misleading because in reality the total mass and thus cost-per payload will be less for 40mt launchers. Nevertheless, it is important to note that if all payloads cost on the order of \$1 billion dollars, bigger launchers begin to save significantly over smaller launchers.

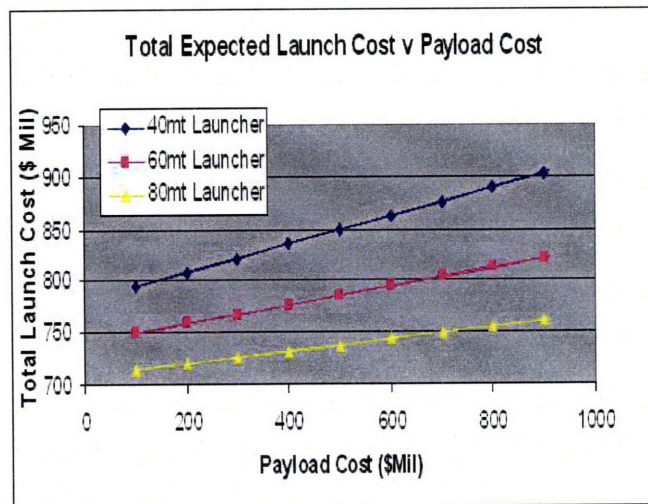


Figure 32: Expected launch cost v payload cost; assumes IMLEO of 150 mt, launch and AR&D reliability of 98%.

6.10 Conclusion

Smaller launchers increase the probability of failure at launch or in-space assembly, but decrease the expected *impact* of a given failure; larger launchers reduce launch risk by launching fewer payloads, but increase impact of a catastrophic failure. Analyzed quantitatively, and assuming generic propulsion modules as payload, these competing factors balance the risk and do not significantly affect the expected-architecture-launch-cost of with smaller v larger vehicles. The impact on expected cost is more important for expensive payloads.

The cost-benefits of different capacity launchers are thus driven by the relationship of economies of scale at launch v economies of scale in production. Larger launchers benefit from the former (more capacity drives down cost-per kilo to orbit), smaller launchers benefit from the latter (increased flight rate and more production).

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

Given current technology levels, larger launchers result in cheaper overall mission cost. However, this finding is sensitive to the learning curves associated with production. If the benefits of increased production are modeled using learning curves, there is a flipping point from “bigger is better” to “bigger is worse” at approximately 80%.

Total expected architecture cost is less sensitive to variations in AR&D reliability. This seems to be because, like launch itself, the economic damages accrued due to failure are less costly when more probable, and less probable when more costly.

6.11 Future Work

The relationship of launch reliability, launch capacity, and development cost, should be investigated in order to more accurately determine the relationship of capacity to expected mission cost. Larger launchers may be inherently less reliable than smaller launchers at comparable development costs, suggesting that the trend of *bigger is better* will be further flattened and potentially reversed.

Cost trends as a function of capacity are highly dependant on the economies of scale in production, which depends on *learning curves* and the *ratio of fixed recurring to variable recurring costs*. These relationships must be understood on a per-system basis in order to make sound life-cycle decisions.

Failure modes for AR&D (loss of mission, loss of module) will have big affect on overall cost and should be known accurately before decision is made.

Chapter 6: Analytic Model of HLLV Capacity, Cost & Risk

Chapter Endnotes

¹ Isakowitz, Steven J. "International Reference Guide to Space Launch Systems, Fourth Edition." AIAA, © 2004, 4th Edition. ISBN: 156347591X

² "A Paradigm Shift in Design for NASA's Space Exploration Initiative." 16.89 Space Systems Engineering Class Report, Massachusetts Institute of Technology. June 2004.

³ Koelle, Dietrich E. "Transcot 7.0; Statistical-Analytical Model for Cost Estimation and Economical Optimization of Space Transportation Systems." TransCost Systems, 2000. ISBN TCS-TR-168

Chapter 7: Comparing Shuttle and EELV Derived Architectures

7. Comparing Shuttle and EELV Derived Architectures

7.1 Introduction

A principle determinant of *comparative* sustainability from an economic perspective involves the pattern of spending associated with development and operations, under various demand scenarios. For example, in the early 1980's cost models demonstrated that the Space Shuttle was more affordable than expendable systems only at inordinately high levels of demand. While political pressures may have induced various groups to advocate for their demand-scenario of choice, the reality, as always, proved unpredictable. All scenarios are best-guesses, lying along a probability distribution which is itself difficult to ascertain.

Real Options Analysis provides a method to design systems that capitalize on, rather than suffer from these inevitable fluctuations in the operating environment. It provides a framework to quantify how system attributes that often decrease optimality in a fixed operating scenario may enhance *flexibility* and thus “life-cycle optimality” over time. The goal of the analysis is to quantify the benefits of designing systems that are more flexible and reactive in the face of uncertainty—and thus more sustainable for long-term endeavors like space exploration.³

This section describes a model of the forthcoming decision on Heavy Lift Launch that uses using “real-options thinking.” The model presented here compares Shuttle-Derived Vehicles (SDV) to EELV-derived architectures (EELVD), under various demand scenarios, in order to answer the following critical question:

³ For a good primer on Real Options, see: de Neufville, Richard. “Architecting Systems Using Real Options.” ESD Working Paper, May 2002.
<http://web.mit.edu/spacearchitects/Archive/Real%20Options%20Working%20Paper.pdf>

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Which is more cost effective from a life-cycle perspective: SDV or EELVD with an option to expand?

This question can be framed as an option on EELV vehicles. Shuttle derived vehicles provide 80+ metric-ton (mt) capability to LEO.¹ However, because preliminary results indicate that a vehicle considerably lower than the 80mt may be adequate for lunar missions, it is conceivable to design a smaller system based on EELV-derived components with the *option to expand for future Mars missions*. These options could take multiple forms, including launch-pad modifications or allowances for additional stages or booster-rockets. While SDV systems have the advantage of having much hardware already built, EELV systems could have the advantage of being smaller, cheaper to maintain, and more agile in the face of change.

7.2 Real Options Thinking

A major goal of Real Options Analysis is the development of a clear, understandable measure of flexibility.² Real options valuation is based directly on the valuation of financial options. While it is not the purpose of this report to examine the details of Real Options Theory, the following information will be useful for understanding the model and analysis below.

An option, whether financial or real, is formally defined as “a right, but not an obligation, to take action now or in the future at a pre-determined price.”³ In finance this takes the form of a contractual agreement to buy or sell a stock at a pre-determined price (called the *strike-price*). The right to buy a stock is called a *call option*. The right to sell is called a *put option*.

Financial options also come in two varieties depending on when they can be exercised. *European Options* must be exercised on a pre-determined date. *American Options* can be exercised anytime before their expiration date. The majority of traded financial options, like real options, are American.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Similarly, a *Real Option* is as an element in the system (or on the system), which allows managers to take an action now or in the future at a pre-determined price. For example, designing EELVs so that they can accommodate varying numbers of booster rockets creates “the right, but not the obligation” to enhance lifting capability if the market demands. Booster rockets, and the design modifications to the main rocket needed to support them, can be defined as an *American Option in the ELLV system*.

Real options can be either *in* a system, or *on* a system. An option *in* a system is a technical construction that provides the ability to change or add something to the system. As noted, booster rockets are options in the EELV system. An option *on* a system entails the right to develop that entire system or program at a given time. For example, certain purchases might need to be made in order to keep the option to develop a Shuttle-Derived vehicle in the future. The actions taken to keep this possibility open can be framed as an option *on* the Shuttle Derived Program.

As all system designers know, options that make a system more flexible come at cost and degradations in system-performance. Real options analysis allows the classic question “how much is this flexibility worth?” to be reframed as: “How much is the Real Option worth?”

There are multiple methods, all more or less complicated, to modeling the value of real options. Suffice to note here that the value of an option stems from three basic features: 1. asymmetric risk 2. Uncertainty in demand 3. The value of information and the discretion of managers. Options have asymmetric because once purchased, they have an upside but practically no downside (other than potential loses in performance which remain fixed). Because the future is uncertain and new information arrives constantly, options give managers the discretion to alter system attributes more flexibly, so they can take advantage of this upside when needed. Valuing real options thus demands an understanding of the level of uncertainty in demand, and the financial and performance costs associate with the system.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

In its simplest instantiation (and quite often, the most appropriate given error-levels in the data and the need for practicality), a decision tree approach can be used. This approach combines the probability that different paths might be taken with the economic concept of “expected cost,” in order to compare the cost of different systems in different scenarios. This will be used for our model, and described in more depth below.

7.3 Elements of Life-Cycle Cost

The value of Real Options is dependant on both the level of uncertainty surrounding critical demand variables (the probability distribution of future demand), and the cost-profile of the systems being deployed. The life-cycle cost of a launch system, as with many other kinds of systems, can be partitioned into three main categories: Development Cost, Fixed Recurring Cost, and Variable Recurring Cost. Figure 33 illustrates the relationship between these costs.

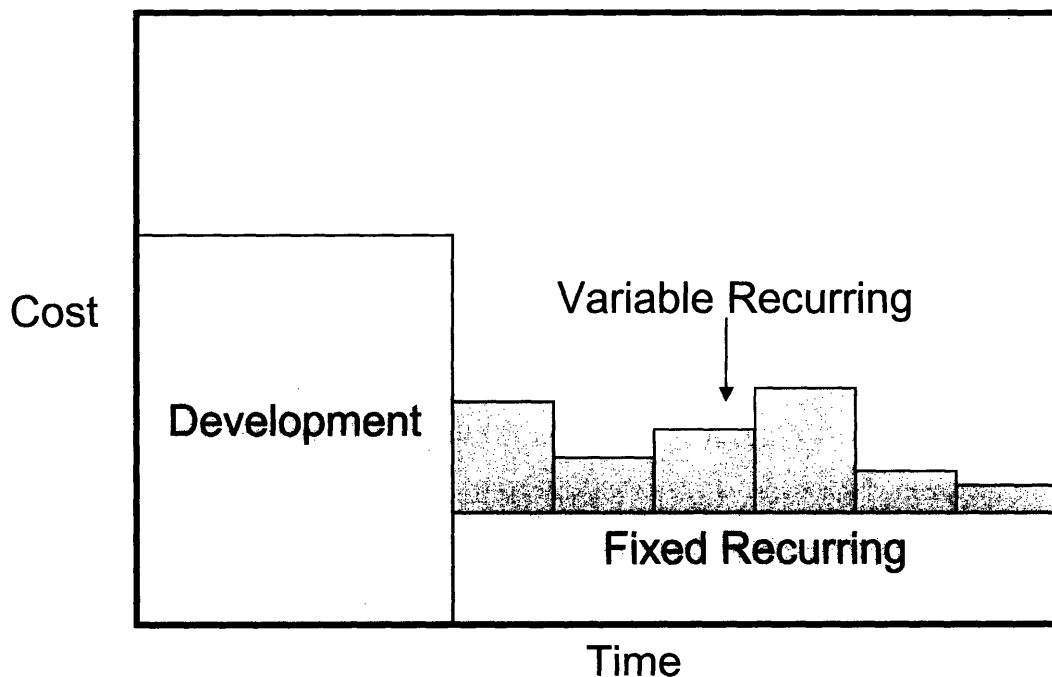


Figure 33: Elements of Launch Vehicle Life Cycle Cost.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Development Cost includes Design, Construction, Testing, and Evaluation of the launch system before it is deployed. It includes all elements of the program prior to operations.

Fixed Recurring Cost includes the cost of maintaining the launch system, regardless of whether there are any launches in a given year. It includes basic program costs such as personnel, management, and facilities maintenance. For expendable vehicles, it can include the cost of producing one vehicle, in order to keep production lines open.

Variable Recurring Cost is the extra cost associated with meeting different levels of demand. It will include, among other elements, the number of vehicles produced, transportation, assembly and payload integration, flight operations, and vehicle recovery (if necessary).

It should be noted that variable recurring cost in our model is not the “cost-per flight” as this value is commonly understood. Cost per flight is traditionally arrived at by adding the variable and fixed recurring costs, and dividing by the number of flights in a given year. The result is that cost-per-flight drops with increasing flight rate due both to a lower ratio of fixed-recurring-cost per flight, and economies of scale in production. For reusable vehicles such as the Space Shuttle, cost-per-flight drops sharply with increased flight-rate because reuse implies that variable recurring cost is lower than for expendable vehicles. Specific assumptions needed to arrive at these costs numbers are addressed in the section on modeling below.

Much can be understood about the sustainability of different programs simply understanding the relative size of these cost-segments. More specifically, the ratio of fixed-recurring to variable recurring cost has a large impact on long-term program costs. A program with low fixed recurring costs will be able to “weather” periods of low demand, without draining the Agency’s budget. Quite often, of course, this low fixed cost comes at the expense of higher variable recurring cost. If relatively high demand is guaranteed, the goal of maintaining a low fixed-recurring cost may be less important than keeping variable costs low.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Maintaining a low fixed recurring cost also has advantages in other ways. Most fixed-recurring costs go toward maintaining the workforce associated with the program, including basic facilities. A larger workforce creates strong political incentives and organizational inertia, which makes change the course of the program more difficult. Keeping the vehicle workforce as small as possible (and by extension, minimizing fixed recurring cost) thus both increase the flexibility of program costs in the face of change, and the flexibility of program direction, as the exploration vision evolves. This general discussion is of course directly transferable to the comparison of Shuttle-Derived and EELV derived systems, and will be elaborated upon in the discussion of model results.

7.3.1 Modeling Uncertainty in Demand

The Heavy Lift Vehicle must meet the ETO needs NASA's exploration vision, while keeping costs as low as possible. Uncertainty in demand is thus a critical factor. This has two main elements: Schedule uncertainty and architectural uncertainty.

Schedule Uncertainty refers to the pattern of missions through time. When will the first lunar mission be launch, and how many will be launched thereafter? When will the first Mars mission be launch and how many thereafter? Depending on the level of fixed recurring costs, schedule uncertainty can greatly affect the life-cycle cost of a vehicle. Ideally, of course, an appropriate vehicle will be developed at a minimum time before it is needed. We can incorporate schedule uncertainty into the model by assuming 3 different schedule scenarios: low, medium, and high.

Architecture Uncertainty has to do with level of IMLEO per mission. Different Lunar and Mars architectures have been proposed, each with different IMLEO. This uncertainty can be modeled probabilistically.

Combining these two sources of uncertainty, we can create a notional decision-tree of the different factors that will affect the relative merits of each plan. The tree in **Error! Reference source not found.** is not exhaustive, but gives an idea of the different

Chapter 7: Comparing Shuttle and EELV Derived Architectures

occurrences that could greatly affect future decisions. Moon 1, 2, 3 and Mars, 1, 2, 3 refer to three possible lunar and Mars architectures.

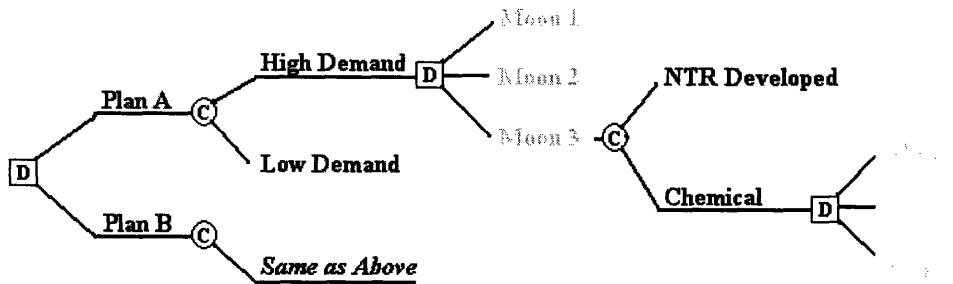


Figure 34: Notional Decision Tree View of Launch System Life-Cycle.

The decision tree has both chance nodes and decision nodes. Chance nodes encompass factors that are beyond the control of system designers. Decision nodes are issues controlled by system designers. As illustrated, it is assumed that the heavy lift decision will be made before critical factors such as the level of demand and the exact lunar and Martian architectures have been established. This may not be the case. If the decision can be postponed, the optimal vehicle for lunar mission could be created, for example. Further, other factors such as the development of nuclear thermal rockets, may greatly affect these later decision points.

Of course, this tree is somewhat idealized. In reality, the various chance points may come before or after the decision points. The important fact is that all of this branch points are currently uncertain, and the relative advantages of different heavy-lift vehicles will change with them.

Also, exact probabilities are difficult to estimate. Our analysis overcomes this problem by examining sensitivities to changes in probabilities. Later analyses should consider using a probability density function for each decision and chance point.

A cost model can now estimate the total life-cycle costs for each plan along each path of the decision tree. By assigning probabilities to the various scenarios, with all of the

Chapter 7: Comparing Shuttle and EELV Derived Architectures

scenarios totaling to a probability of one, we can estimate the expected cost along that path.

7.4 Shuttle-Derived versus EELV-Derived Architectures

Using these distinctions, we can create a discounted cash-flow model to evaluate the cost of different architectures under different demand scenarios. We can do this by creating two different development plans—one using EELV-derived vehicles and the other using SDVs—and comparing their total costs under different demand scenarios. These costs can be coupled to a decision tree representation of the Heavy-Lift decision, and assigned probabilities to calculate expected life-cycle cost.

The first step, then, is to limit the Heavy Lift architectural options for each development plan. Recent NASA studies suggest that a side-mount Shuttle-Derived system, with 4 or 5-segment SRBs is preferable to other configurations along multiple criteria [1]. The same NASA study also estimated costs for various elements of that program. Thus, let us define **Plan A** as follows: Develop a 4 or 5-segment side-mount shuttle derived system, beginning in 2010.

While the shuttle derived vehicles have lifting capacity of 82 and 95 metric tons to LEO, respectively, recent studies suggest that 40-60 metric vehicles should be adequate for lunar missions. This suggests that EELV-derived systems could be designed at this lower range, with the *option to expand to greater values for mars missions*. Thus, let us define **Plan B** as follows: Develop a 34 or 51 metric ton vehicle for lunar missions in 2010 and then develop a larger 100 metric vehicle for Mars-class missions. Figure 35 illustrates plan A and Plan B, using vehicles from the SDV study mentioned above and a recent ETO study conducted at NASA.

-Plan A and B, Vehicles-

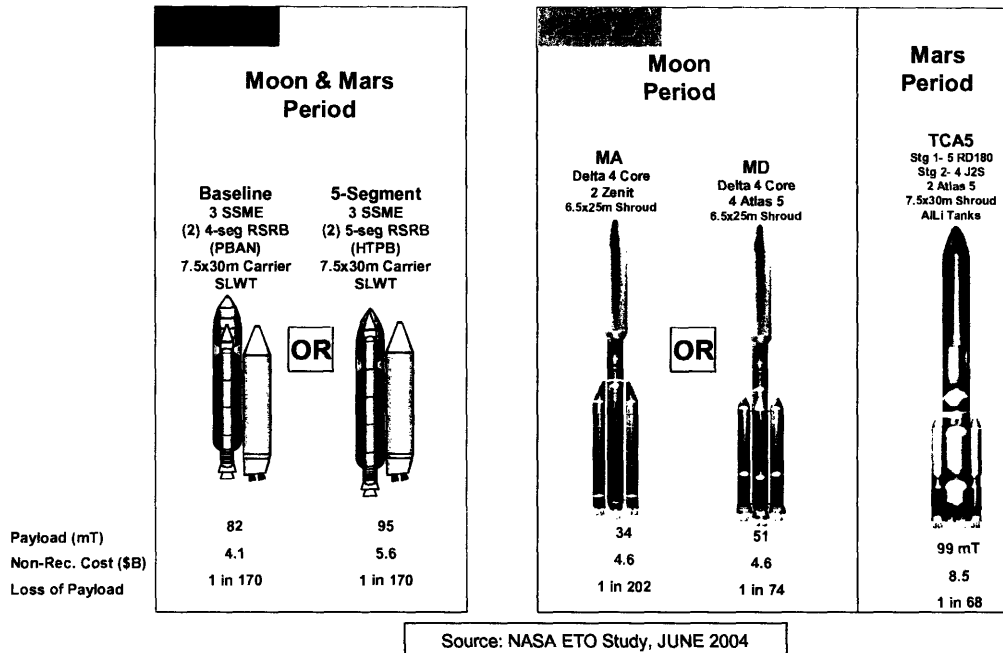


Figure 35: Two Plans for Heavy Lift Launch; SDV vs EELVD

As noted, the second plan constitutes an option to expand. In a traditional Real Options Analysis this plan could be compared to the same plan without the option to expand, thus determining the value of the options. Practically, however, the decision at NASA will involve developing plan A or B.

It is clear that both plans present different advantages. The SDV plans eliminate the need to develop two systems and make use of a lot of existing hardware. The EELV plans reduce fixed-recurring cost initially, by creating a smaller vehicle. They also give managers the discretion to begin building a larger system only when Mars travel is more certain, thus potentially freeing up more money for lunar travel now. The question remains how to estimate the three cost-elements described above for these systems, as a function of demand.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

7.4.1 Shuttle-Derived Costs

As noted, the vehicle options for Plan A were taken from the “Exploration Transportation Team Task 5: Shuttle Derived Vehicles.” Development costs and cost-per flight were estimated in this study for various SDV options. Cost numbers for our model were taken from this study as follows:

Development Cost: Taken from SDV study

Table 5: SDV Development Costs

	Total Dev Cost (\$mil)
SDV 4Seg	\$4,158
SDV 5Seg	\$5,643

Variable Recurring: The SDV study had cost numbers for flight-rates of 1 through 4 per year for each SDV option. These followed a consistent pattern and were extrapolated for flight rates greater than 4.

Table 6: SDV 4-Segment Variable Recurring Costs

SDV 4 Segment Flights/yr	1	2	3	4
Program	\$31	\$47	\$62	\$76
Vehicle	\$767	\$1,275	\$1,757	\$2,226
Launch	\$79	\$81	\$83	\$85
Flight	\$16	\$16	\$16	\$17
Reserves	\$111	\$168	\$220	\$269
Total Cost	\$1,004	\$1,588	\$2,138	\$2,673

Table 7: SDV 5-Segment Variable Recurring Costs

SDV 5 Segment Flights/yr	1	2	3	4
Program	\$32	\$49	\$64	\$79
Vehicle	\$786	\$1,312	\$1,813	\$2,300
Launch	\$93	\$95	\$97	\$99
Flight	\$16	\$16	\$16	\$17
Reserves	\$151	\$248	\$339	\$428

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Total Cost	\$1,077	\$1,720	\$2,330	\$2,923
------------	---------	---------	---------	---------

Fixed Recurring: As noted, this is simply the cost of maintaining the launch-system if there are no-flights in that year. Theoretically it is the program cost (personnel, facilities, etc.) + the cost of producing one vehicle, ignoring the cost of launch and operations. Therefore, this cost includes the following from the tables above: 1 vehicle per year (to keep production lines open) + Program costs (personnel, etc). Launch, ops, and reserve cost not included.

Pre-Development Ramp-Up: In order to keep the possibility of developing a shuttle derived vehicle, certain long-lead-time purchases will need to be made very soon. It is not clear the exact costs of these purchases. We have therefore estimated a “ramp-up” of increasing funds through 2009, when development begins, and run the analysis with and without this ramp-up. The ramp-up is as follows:

Table 8: SDV “Ramp-Up”

Year	Cost (\$million)
2006	200
2007	400
2008	600
2009	800
2010	1000

It should be noted that it was unclear how much this ramp-up would be, and how much of it should be billed to the SDV program, rather than the Shuttle Program. This question is beyond the control of the current analyses so, as stated, results were run with and without ramp-up.

7.4.2 EELV-Derived Costs

Vehicle options for Plan B were taken from a recent NASA study called: Vehicle options taken from: “ETO Trade Study for Future Moon-Mars Exploration,” Presented at NASA

Chapter 7: Comparing Shuttle and EELV Derived Architectures

HQ, June 16, 2004. This study including development and recurring cost. However, because we want recurring cost as a function of demand, another value was needed.

We have already discussed in chapter 5 how the cost-per flight for large EELVs can be extrapolated from past cost. As with other capacity problems, economies of scale suggest that the relationship of size to average launch cost will follow a power law. We therefore have the following estimates for our cost elements:

Development Cost: Taken from ETO study, spread over 5 years and phased in same proportion as shuttle development cost:

Table 9: Development Cost Spread

Year	1	2	3	4	5
~ % Total Dev. Cost	7.5%	25%	35%	25%	7.5%

Table 10: EELVD Development Costs

	Dev. Cost (\$mil)
34mt Delta IV Core and Zenit	\$4,600
51mt Delta V Core 4 Atlas 5	\$4,600
99mt TCA5	\$8,500

Variable Recurring: Cost Per flight * Number of flights. Cost per flight is a function of capacity based on *power law* relationship using data from "International Guide to Launch Vehicles," by Isokawitz.⁴ Only U.S. launchers included. No learning curves assumed for increased production rates.

$$\text{LaunchCost} = 0.226 \times C^{0.66} \quad (\text{\$million})$$

Where C = Capacity in Kilograms

Fixed Recurring: The cost is modeled here as 89% of the cost of a single launch, based on a similar relationship between variable-recurring and fixed-recurring cost for Shuttle Derived Vehicles. (See next section)

Chapter 7: Comparing Shuttle and EELV Derived Architectures

7.4.3 Discount Rate

The present value of a plan depends both on the amount of money spent, and when that money is spent. Discounting non-inflated costs takes into account the opportunity cost of investing sooner rather than later. If a plan enables us to push costs backward in time, for example, this has real value because we can use the money freed up now to move other priorities along (i.e. development of nuclear propulsion, etc).

More formally, we must note that the discount rate has two factors: interest and inflation. Interest represents the opportunity cost of investing now. If future costs are nominal--that is, in inflated dollars--they need to be reduced by both inflation and interest to get a one-to-one relationship with today's dollars. This is done using a "nominal discount rate." If future costs are "real" (that is, in constant-year dollars--as in our model), we only need to account for interest. This means we use the "real discount rate," which is the nominal rate minus inflation. These issues are explained in the OMB circular that sets forth the rates for government-project NPV analysis:

http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html

There may be some debate as to how much "opportunity cost" should be counted in a NASA NPV analysis. Many studies appear to discount by inflation, or a "real" discount rate of 0. This means that future costs in constant-year dollars would not be discounted. This does not, however, provide for sound decision-making. Discounting at inflation ignores the benefits derived from having more discretion over future spending, including the very real benefit of being able to invest money now on other projects (such as nuclear thermal rockets). Thus, for the purpose of the heavy lift decision, it is most appropriate to use a "real discount rate" provided by the OMB circular. However, as this represents opportunity cost of investing it is difficult to estimate exactly and should be varied to determine sensitivity to discount.

7.4.4 Summary of the Model

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Method of Analysis: Discounted cash flow models were created for four distinct development plans and computed under various demand scenarios. Major cost elements are: Development, Fixed-Recurring, Variable Recurring. The life-cycle costs for these plans were computed under three distinct demand scenarios: low, medium, and high.

Probabilities were assigned to the three plans, and *expected life-cycle costs calculated*. Pair-wise sensitivity analyses were run, as the probabilities between low-medium and medium-high varied between zero and one. The figure below illustrates the decision tree view of one of the medium to high pair-wise analysis.

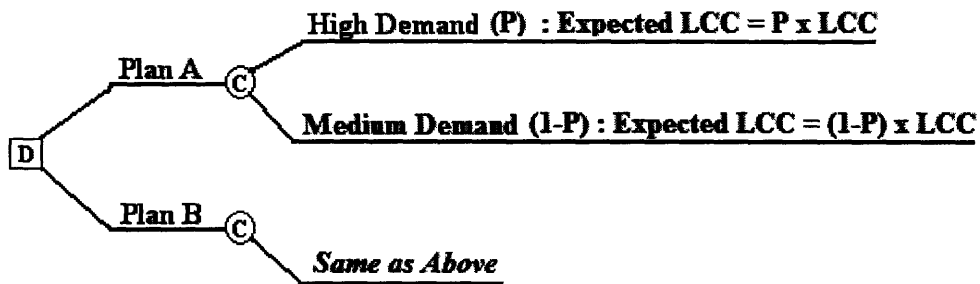


Figure 36: Decision Tree view of Expected-Cost Calculation

The Plans: Two basic vehicle architectures were evaluated, each with two iterations. All plans assume development begins in 2010. The plans are:

Plan A.1: 4 Segment Side-Mount Shuttle-Derived launcher developed in 2010

Plan A.2: 5 Segment Side-Mount Shuttle Derived Launch developed in 2010

Plan B.1: 51 mt EELV-Derived launcher in 2010; Upgraded to 100mt for Mars Missions.

Plan B.2: 34 mt EELVD launch begun in 2010; Upgraded to 100mt for Mars Missions.

Demand Scenarios: Launch Demand Scenarios were taken from the current MIT CE&R study estimates. They include low, medium, and high launch demand scenarios for a baseline Moon and to Mars architecture, each resulting in a set of IMLEOs each year until 2030. As noted, the architecture itself should also be varied probabilistically. This

Chapter 7: Comparing Shuttle and EELV Derived Architectures

will be conducted in further analyses. Specifically, the demand scenarios are as follows. Year is at the top and the IMLEO is at the bottom.

Table 11: High Demand Scenario

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CTS	Cargo	Habitat	Cargo	Mars PD	CTS	Mars PD	Cargo	Mars PD	CTS	Mars PD	Cargo	Mars PD	CTS	Mars PD
		CTS	CTS			Crew	CTS	Crew		Crew	CTS	Crew		Crew
127	100	344	227	403	127	673	227	673	127	673	227	673	127	673

Table 12: Medium Demand Scenario

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CTS	Cargo	Habitat	Cargo	Mars PD		Mars PD		Mars PD		Mars PD		Mars PD		Mars PD
		CTS	CTS			Crew		Crew		Crew		Crew		Crew
127	100	344	227	403		673		673		673		673		673

Table 13: Low Demand Scenario

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	CTS		Cargo	Habitat		Cargo		Mars PD		Mars PD		Mars PD		Mars PD
				CTS		CTS				Crew		Crew		Crew
	127		100	344		227		403		673		673		673

7.4.5 Results

Life cycle costs were calculated with and without the ramp-up costs for the Shuttle Derived program. Figure 37 illustrates total discounted life-cycle costs for the four plans, with shuttle ramp-up costs included. Two facts are most striking: First, both Shuttle Derived plans are more expensive than EELV-derived plans across all scenarios. Second, the relative benefit of EELV derived vehicles increases as demand increases. Factors affecting this comparison are addressed below.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

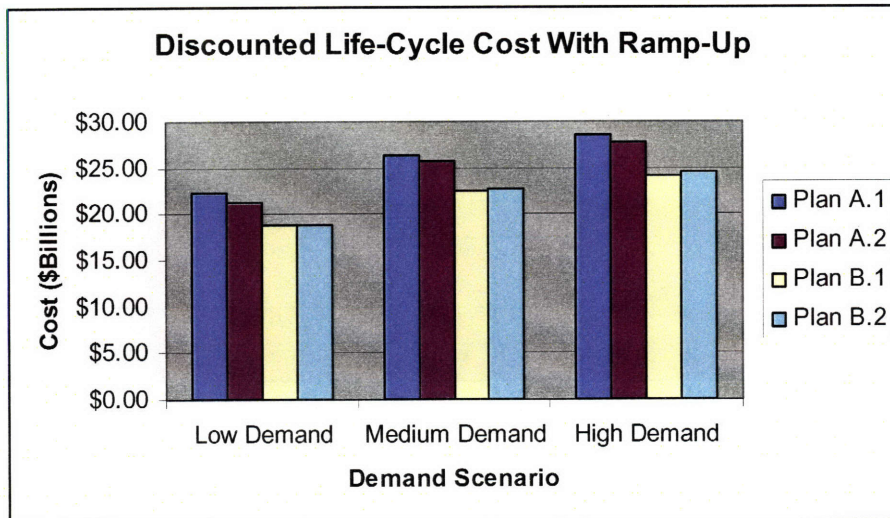


Figure 37: Discounted Life-Cycle Cost Comparison, With Shuttle Ramp-Up Costs. 3.5% Discount Rate.

Figure 38 presents discounted life-cycle cost of the four plans without shuttle ramp-up costs. Here, the Shuttle-Derived plan with 5-segment SRBs is better than all other plans at low demand. At higher demand, EELV-derived vehicles again beat SDVs. It is important to note that the lack of ramp-up costs removes approximately \$3 billion dollars in development-related costs. The exact cost of the ramp-up must be known with more precision if a sound decision is to be made.

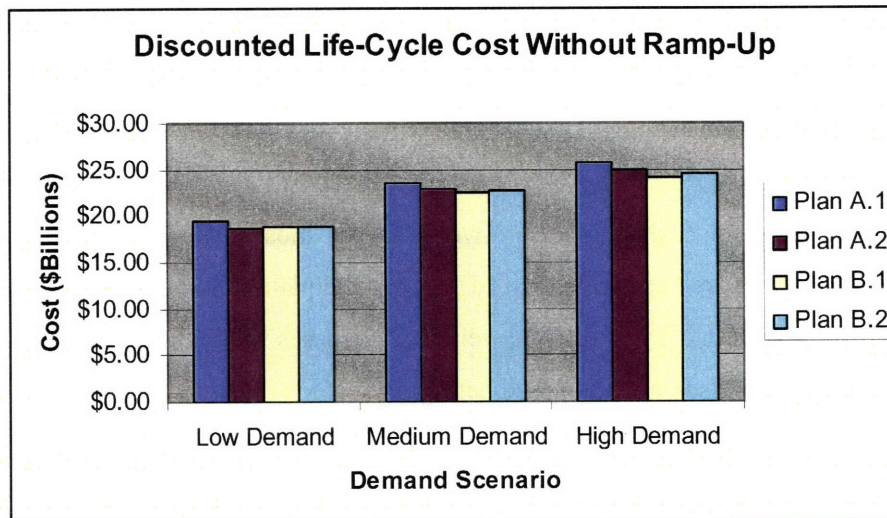


Figure 38: Discounted Life-Cycle Cost Comparison, Without Shuttle Ramp-Up Costs. 3.5% Discount Rate.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Probabilistic Analysis: The only cross-over point in this analysis thus exists between low and medium or low and high demand, with shuttle ramp-up costs *not* included. A decision-tree approach can be used to calculate expected life-cycle costs as a function of the probability that one of these demand scenarios will occur. To do this we need a probability density function (PDF). We can estimate the PDF as uniform, although in reality it will probably be skewed. Future analyses will include a different non-uniform PDFs. It must be noted, however, that a uniform PDF creates a linear relationship between probability of demand scenario and cost. The result is a linear extrapolation from high to low-demand life-cycle costs.

Figure 39 illustrates the expected life-cycle cost of a the four plans, as a function of the probability that a low versus high demand scenario will occur. It demonstrates that when there is approximately *15% chance of high demand or greater*, EELV-derived plans are superior to the Shuttle-Derived Plan A.2.

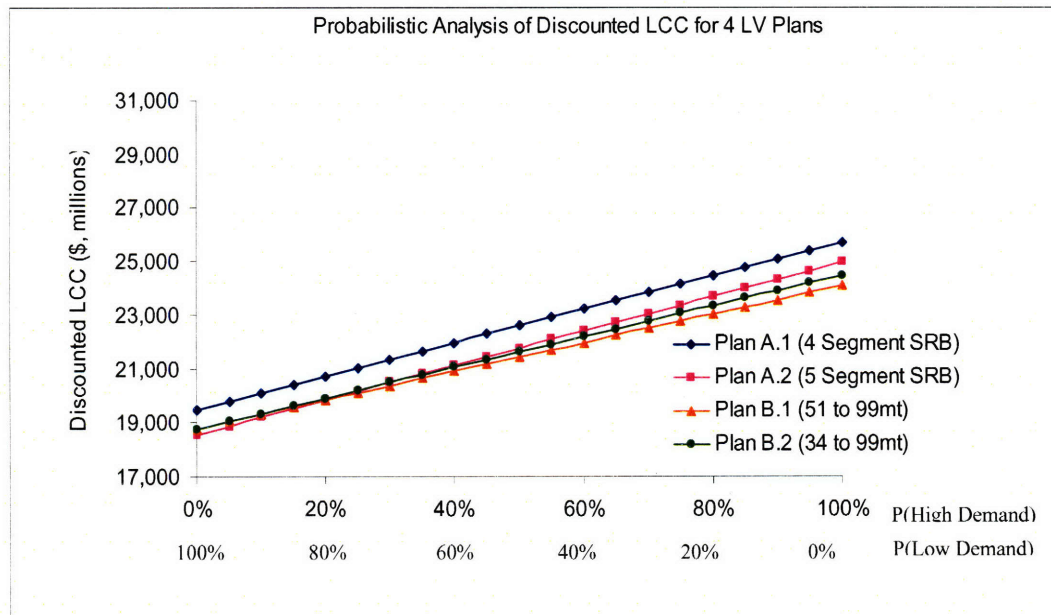


Figure 39: Model Results without ramp-up; 3.5% discount rate; Low to High Demand.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

7.5 Discussion

According to our assumptions, if the ramp-up is included, the Shuttle-Derived programs are clearly more expensive over their life-cycle than EELV-derived systems. If an SDV ramp-up is not included, SDV vehicles are more cost-effective than EELVD under lower-demand scenarios, however, EELVD are still less costly than SDV at medium and high demand levels. The cross-over point here is approximately 85% chance or greater that a low demand scenario will occur.

Various factors influence these outcomes. Smaller launchers benefit over a wider range of scenarios because fixed recurring costs are lower, so total costs follow demand more exactly than for shuttle-derived vehicles. SDV plans benefit because they require only one development effort, while EELVD plans required a development effort prior to both lunar and mars missions. However, the single development effort of the SDV comes at the expense of higher fixed recurring and variable recurring costs. An SDV vehicle is likely larger than needed for lunar missions, and this means that a larger vehicle is built and maintained sooner. Also, it is relatively safe to say that an 80+mt SDV would be built purely for NASA missions, while an EELVD may be created around a core of vehicles and expertise which transfers to the commercial and military domain. This may relax the fixed recurring costs (in the form of personnel and facilities) for NASA when demand is low.

The immediate question arises as to how sensitive the results are to changes in assumptions. Sensitivity analysis has been conducted on a first version of this model. These analyses suggest that final results are less sensitive to changes in architecture (that is, changes in IMLEO for each mission) and changes in discount rate, than they are to changes in the schedule of demand.⁵ Sensitivity to changes in demand, however, increases with discount rate. Therefore, it may be prudent to establish which discount rate will be used when making the decision. Sensitivity to IMLEO using updated lunar and mars architectures is currently being included in a third version of the model.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Options on EELV: It must be noted that, although all cost numbers are uncertain, a critical category of EELV costs were likely over-estimated. Plan B.1 or B.2 were designed as initial systems with options to expand, however, the development cost of the expansion was modeled as an independent development effort. Options to expand that would be built into EELV-derived systems, however, would lower the cost of this second effort. These might include modifying launch facilities to accommodate a Mars-Class launch when pad mods for the smaller launch were conducted. Also, designing a launcher with the ability to accommodate an additional stage or large additional boosters may. These possibilities should be examined in more detail.

Chapter 7: Comparing Shuttle and EELV Derived Architectures

Chapter Endnotes

¹ "Exploration Transportation Team Task 5: Shuttle Derived Vehicles." Presented by Steve Davis. NASA HQ. Spring 2004

² De Neufville, Richard. "Systems Analysis for Design." Class Notes, 2003

³ De Neufville, Richard. "Systems Analysis for Design." Class Notes, 2003

⁴ Isakowitz, Steven J. "International Reference Guide to Space Launch Systems, Fourth Edition." AIAA, © 2004, 4th Edition. ISBN: 156347591X

⁵ This is based on work done at NASA HQ in the summer of 2004, for which a presentation was made to the NASA Space Architecture Office.

8. Conclusion

Designing heavy lift launch vehicles for sustainability is a multidimensional problem demanding consideration for technical performance, risk and reliability as a function of architectural attributes, economic profiles, as well as less quantitative factors such as programmatic inertia, and political incentives. This thesis explored how these issues relate to a systems architecture and system evolution from theoretical and historical perspectives, and how political-economic forces have shaped the evolution of the modern launch industry. These insights, together with recent research into systems architecture and engineering economy were used to create an analytic cost and risk model and a discrete model using real options thinking to comparing Shuttle-derived and EELV-derived heavy lift vehicles.

The models demonstrate that, given current assumptions, bigger expendable vehicles have cost advantages over smaller vehicles if demand is known with reasonable precision. These advantages are rather sensitive to the learning rate associated with production and launch operations. The discrete real-options model demonstrated that if designed with options to expand, EELV derived architectures may be increasingly cost-effective under uncertain demand. This appears to be due largely to lower fixed recurring costs associated with smaller programs, and the discretion to push larger production backwards in time as demand is resolved more clearly.

The sensitivity of these models, however, reveals some issues that should be resolved. The reliability, cost, and failure-modes of in-orbit-assembly is one particularly crucial determinant of the viability of smaller heavy lift vehicles. Similarly, the reliability of launch systems as a function of capacity is poorly understood. A final crucial variable involves learning curves associated with production and launch operations. These will

likely vary across architectures, with important consequences for long-term comparative affordability.

From a less quantitative perspective, it is clear that multi-billion dollar systems demonstrate very strong path dependence, caused in part by entrenched organizational and political interests. Security externalities associated with space launch further warps the economics of the launch industry, quite often resulting in policies that explicitly thwart open competition. A key to the long term exploration of space is the development of a vibrant earth to orbit launch industry. While NASA organizes to return to the Moon and Mars and beyond, it should be particularly sensitive to the affects of launch system designs on the nascent private launch industry.

The following section summarizes some of the key point discussed throughout the thesis concerning sustainability and launch vehicle design:

8.1 Sustainability and Complex Systems Design

- A complex system can be defined as a value-network in which value is uniquely determined by rank-ordering of metrics created by the highest-level goal of the system. A value network encompasses both technical and organizational elements of the system.
- Technological development can be defined as the evolution of a knowledge base. This greatly increases the importance of learning, and better explains issues such as technological lock-in. It also implies that a large part of the developing sustainable systems involves, among other factors, maintaining a base of knowledge at minimum cost in the face of change.
- Sustainability is necessarily related to the highest level of the system—we are concerned with the sustainability of the goal, not a given architecture or

technology. Any metric for sustainability must therefore incorporate a holistic view of system operation.

- At a given time and space there are trade-offs between performance, economics, and risk across the system for a given set of objects and constraints, but these trade-offs are subject to change. Designing for sustainability thus implies creating system attributes that allow a system to adapt in or order to keep costs, risks, and benefits within acceptable margins as the environment, system, and goal change.

8.2 Path Dependence and Lock-In

- While ideally a given technology is optimized for a given goal, the reality with complex systems is that more often political goals and existing capability meet halfway. This is the principal reason for path-dependence, which is due to institutional and organizational factors, as well as economic and technical issues such as sunk costs and network affects.
- Architectures, as interface standards, become *locked-in* in for myriad reasons. These include sunk-costs, learning curves, and network affects. It is possible to quantify such decisions using theories of sunk-cost hysteresis and real options analysis. As a whole, lock-in demonstrates that the system architecture is not only affected by, but also affects, the political and organizational environment in which it operates.
- The development cost in dollars, time and expertise, of large ballistic missile programs in the 1950s and 1960s created very big incentives to re-use old systems wherever possible. It is very hard to clearly define a “switch” with respect to launch vehicle systems because it is not clear where a program starts and stops, notwithstanding official names. New programs always use old expertise so what we really have is evolution of a knowledge base, codified into technical artifacts.

- Decisions made up to fifty years ago still affect current space systems, so we should be thinking at least that far ahead with our current planning.
- Leading up to the development of the Saturn V, this evolution was strongly influenced by inter-service rivalry and political issues, but also environmental factors, most notably security concerns.
- Whatever is most costly to change often drove program evolution. Launch Facilities and logistics create particularly important constraints on future designs. Saturn crawlers and logistics, for example, are still in use today.
- The LOR/EOR debate emphasizes the way that values seep into architectural decisions. The trade was very hard to carry out because comparative mission reliability was practically impossible to quantify (beyond estimates) and, perhaps more importantly, the advantages of each architecture was *incommensurable* with those of the other. That is, they maximized different rank-orders of metrics. Thus the decision was as much about establishing what was valued most as optimizing an objective function. Values, of course, are inherently political.

8.3 Analytic Launch Model

- Smaller launchers increase the probability of failure at launch or in-space assembly, but decrease the expected *impact* of a given failure; larger launchers reduce launch risk by launching fewer payloads, but increase impact of a catastrophic failure. Analyzed quantitatively, and assuming generic propulsion modules as payload, these competing factors balance the risk and do not significantly affect the expected-architecture-launch-cost of with smaller v larger vehicles. The impact on expected cost is more important for expensive payloads.

Chapter 8: Conclusion

- The cost-benefits of different capacity launchers are thus driven by the relationship of economies of scale at launch versus economies of scale in production. Larger launchers benefit from the former (more capacity drives down cost-per kilo to orbit), smaller launchers benefit from the latter (increased flight rate and more production).
- Given current technology levels, larger launchers result in cheaper overall mission cost. However, this finding is sensitive to the learning curves associated with production. If the benefits of increased production are modeled using learning curves, there is a flipping point from “bigger is better” to “bigger is worse” at approximately 80%.
- Total expected architecture cost is less sensitive to variations in AR&D reliability. This seems to be because, like launch itself, the economic damages accrued due to failure are less costly when more probable, and less probable when more costly.

8.4 SDV verses EELVD

- According to our assumptions, Shuttle-Derived programs are clearly more expensive over their life-cycle than EELV-derived systems. If an SDV ramp-up is not included, SDV vehicles are more cost-effective than EELVD under lower-demand scenarios, however, EELVD are still less costly than SDV at medium and high demand levels. The cross-over point here is approximately 85% chance or greater that a low demand scenario will occur.
- Smaller launchers benefit over a wider range of scenarios because fixed recurring costs are lower, so total costs follow demand more exactly than for shuttle-derived vehicles.
- SDV plans benefit because they require only one development effort, while EELVD plans required a development effort prior to both lunar and mars missions.

Chapter 8: Conclusion

However, the single development effort of the SDV comes at the expense of higher fixed recurring and variable recurring costs. An SDV vehicle is likely larger than needed for lunar missions, and this means that a larger vehicle is built and maintained sooner.

Bibliography

Alexander, Christopher. Notes on the Synthesis of Form. Harvard University Press, Cambridge, MA. 1964

Aldridge, E. C. Pete. "Assured Access to Space: The Bureaucratic Space War" Dr. Robert H. Goddard Historical Essay. NASA, c 2003

Ashby, William Ross. Design for a Brain: The Origin of Adaptive Behavior. Science Paperbacks. London, 1966

Beal, Andrew. Quoted in "Rocket Start-up Beal Aerospace out of Business" Reuters News 2000

Benson, Charles. Faherty, William. Moonport: A History of Apollo Launch Facilities and Operations. Published by the National Aeronautics and Space Administration, SP-4204 (Washington, 1978)

Bilstein, Roger E. Stages to Saturn: A Technological History of the Apollo/Saturn Vehicles. NASA History Series. Published by Scientific and Technical Information Branch, National Aeronautics and Space Administration. Washington, DC. 1980

Bush, George W. Remarks on U.S. Space Policy. NASA Headquarters, January 14, 2004. See: <http://www.whitehouse.gov/news/releases/2004/01/20040114-3.html>

Christensen, Clayton M. The Innovators Dilemma. HaperCollins Publishers Inc, New York, NY. 1997

Constant, Edward II. The Origins of the Turbojet Revolution. Johns Hopkins University Press, Baltimore, MD, c1980.

Crawley, Edward. Lecture notes from 16.89 Space Systems Design Class. Spring, 2004

Davis, Steve. "Exploration Transportation Team Task 5: Shuttle Derived Vehicles." Presented by Steve Davis. NASA HQ. Spring 2004

Bibliography

- De Neufville, Richard. "Systems Analysis for Design." Class Notes, 2003
- de Weck, Olivier. Lecture Notes, 16.89 Space Systems Design Class. Massachusetts Institute of Technology. Spring, 2004
- Dixit, Avinash. Investment and Hysteresis. *Journal of Economic Perspectives*—Volume 6, No 1. Winter 1992. P 107, 1932
- Douglass, John W. "Removing Barriers to Commercial Space Industry." Testimony Prepared for the U.S. Senate Committee on Commerce, Science and Transportation Subcommittee on Science, Technology, and Space. May, 1999
- Doyle, Stephen E. (Editor). History of Liquid Rocket Engine Development in the United States: 1955-1980. AAS History Series, Volume 12, AAS Rocket Propulsion History Colloquia, Volume 1. Published by The American Astronautical Society, San Diego, CA, 1992
- Emme, Eugene M. (editor). *The History of Rocket Technology; Essays on Research, Development, and Utility*. Wayne State University Press. Detroit, Mich. 1964
- Gress, Ron K. "2002 Commercial Space Transportation Lecture Series." From http://ast.faa.gov/files/pdf/gress_complete.pdf
- Hall, Cargill R. "Early U.S. Satellite Proposals." From: The History of Rocket Technology; Essays on Research, Development, and Utility, Emme, Eugene M. (editor). Wayne State University Press. Detroit, Mich. 1964, p 68
- Henderson, Rebecca M. et al. "Architectural Innovation: The Reconfiguration of Existing Systems and the Failure of Established Firms." *Administrative Science Quarterly* (35), 1990, p. 9-30
- Isakowitz, Steven J. "International Reference Guide to Space Launch Systems, Fourth Edition." AIAA, © 2004, 4th Edition. ISBN: 156347591X
- Katz, Michael. "Systems Competition and Network Effects." *Journal of Economic Perspectives*. Vol 8, no 2, 1984. p 93-115
- Klein, Hans. "System Development in the Federal Government: How Technology Influences Outcomes," *Policy Studies Journal*, vol. 28, no. 2, 2000.
- Koelle, Dietrich E. "Transcot 7.0; Statistical-Analytical Model for Cost Estimation and Economical Optimization of Space Transportation Systems." TransCost Systems, 2000. ISBN TCS-TR-168
- Koo, Benjamin. "A Meta Language for Systems Architecture." Phd Thesis. MIT, 2005

Bibliography

Liebowitz, SJ, et al. "Path Dependence, Lock-In, and History." *Journal of Law, Economics, and Organization* vol. 1 no. 1. 1985

Logsdon, John M. (editor), et al. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program; Volume IV: Accessing Space*. NASA History Series, (NASA SP: 4407) Published by the NASA History Division, Washington, D.C.. 1999

Musk, Elon. Speech to the Centennial Challenge Workshop. August 2004

Pace, Scott. "Merchants and Guardians: Balancing US Interests in Space Commerce." John M. Logsdon and Russell J. Acker, Editors. *International Space Policy Forum* Publication. Washington DC. 1999

Perrow, Charles. Normal Accidents: Living with High Risk Technologies. Princeton University Press. Princeton, NJ. 1999

Puffert, Douglas J. "Path Dependence, Network Form, and Technological Change" Article in: History Matters: Economic Growth, Technology, and Population. Stanford University Press (November 1, 2003)

Rudolph, Jane Anna. "Globalization of the Aerospace Industry." MIT Thesis, May 2001.

Report of the President's Commission on the Implementation of United States Space Exploration Policy: "Journey to Inspire Innovate, and Discover." June, 2004

Ryan, Robert, et al. "Fundamentals and Issues in Launch Vehicle Design." *Journal of Spacecraft and Rockets*. Vol. 34, No 2., March-April

Sarsfield, Liam. "The Technology Puzzle: Quantitative Methods for Developing Advanced Aerospace Technology." RAND, National Security Research Division, 2001.

Shaw, Eric. *Economic Analysis of the Space Transportation Architecture Study (STAS)* NASA Team. 1999

Simon, Herbert A. *The Sciences of the Artificial; Third Edition*. MIT Press. Cambridge MA 1996 p. 17

Simon, Herbert. *Administrative Behavior, Fourth Edition*. The Free Press. New York, NY, 1997

Shishko, Robert. *Lessons Learned from the Space Station Program: The Role of Life Cycle Cost*. Jet Propulsion Laboratory.

Bibliography

Weigal, Annalisa et al. "Interaction of Policy Choices and Technical Requirements for a Space Transportation Infrastructure." *Acta Astronautica*, vol 52 no. 7 (2003), 551-562.

Utterback, James M. "Innovation in Industry and the Diffusion of Technology." *Science*, New Series, Vol. 183, No 4125 (Feb. 15 1974), p. 620-626

16.89 MIT Space Systems Engineering Class. "A Paradigm Shift in Design for NASA's New Exploration Initiative." Massachusetts Institute of Technology. Spring, 2004

National Research Council. From Earth to Orbit: An Assessment of Transportation Options. National Academy Press. 1991. P 15

RAND engineering report: "Preliminary Design of an Experimental World-Circling Spaceship," Santa Monica, CA. May 1946

Von Braun, Werner. "Major U.S. Rocket Programs." Chapter 2 of: The History of Rocket Technology: Essays on Research, Development, and Utility, Emme, Eugene M. (editor). Wayne State University Press. Detroit, Mich. 1964, p 68

Websites

<http://www.astronautix.com>

<http://www.atlasicbm.com/index.php>

<http://www.daviddarling.info>

<http://www.designation-systems.net/dusrm/m-16.html>

<http://www.globalsecurity.org>

<http://www.hq.nasa.gov/>

<http://www.spaceline.org>

<http://en.wikipedia.org>