





**Political Sustainability in the Vision for Space Exploration:  
Articulating the Policy-Technology Feedback Cycle**  
by

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**Abstract**

It is often difficult to forecast the future budgetary environment for today's space systems. Indeed, multiple NASA missions and programs have been put into jeopardy or cancelled outright, due to discrepancies between the expected and actual lifecycle costs. This has resulted in the loss of billions of dollars in taxpayer money spent on false starts. It is therefore in the best interests of all stakeholders, including NASA and the U.S. Congress, to arrive at a solution which will allow NASA's space exploration endeavors to be funded at a politically sustainable level.

Understanding the mechanisms and processes by which a program may exhibit political sustainability is of paramount importance to the space exploration enterprise. In particular, budgetary sustainability has proven to be a driver for The President's Vision for Space Exploration, which instructs NASA to "Implement a sustained and affordable" space exploration program. NASA, as a federal agency, is dependent upon the support of many stakeholders within the US political system, especially the President and members of Congress. Thus, a politically sustainable program must address the needs of these stakeholders.

Based upon strategies for agency-Congress interaction that are derived from the existing political science literature, this thesis proposes to translate policy directives into technical constraints or requirements for the Vision for Space Exploration. The effects of these changes in the technical system are then traced back to determine how they effect the political environment, articulating a feedback-loop that crosses between the political and technical realms.

Thesis Supervisor: Prof. Annalisa L. Weigel

## BIOGRAPHICAL NOTE

David André Broniatowski was born in Cleveland, Ohio, to loving parents in 1982. As if this weren't enough, when he was 18 years old, he was granted his 12-year-old dream of going to MIT. Infected by the space bug since a young age, he jumped at a note in the MIT Admission packet, proclaiming "Mission 2004: The Search for Life on Mars". Thrilled, he immediately enrolled. He's been chasing space ever since, hence the decision to join the Department of Aeronautics and Astronautics, from which he graduated in 2004. Eventually realizing the old adage that "space is politics", he decided to pursue a graduate education in the Technology and Policy Program, concurrently with an Aero/Astro masters degree. After attending the International Space University in Adelaide, Australia in the Summer of 2004, he decided to explore the interaction between the technical and political realms more closely.

Despite this focus, David has been exposed to many different interesting disciplines, leading to the cultivation of a passion for many fields. These include, but are not limited to, decision theory, game theory, neuroscience, control theory, information theory, psychology, chaos, complexity, international law, negotiations, 20<sup>th</sup> century music and invention. If only MIT offered a degree in polymathy...

David has many goals in life. Perhaps the two most exotic (and relevant to this thesis) are as follows: He wants to ensure that there will be another Israeli astronaut. To this end, he would like to be the American liaison to the Israeli Government. Secondly, and perhaps with a little more whimsy, David hopes one day to make contact with an alien species – after all, we can't be alone forever.

## ACKNOWLEDGMENTS

Even when one is a giant, it is often difficult to see beyond one's nose. How much more so is it difficult to see when there are giants standing on one's shoulders? Such is the quandary faced by the men and women of NASA, whose task, and its consequences for the ultimate fate of the human species, is nothing short of titanic, and whose can-do attitude in the face of all adversity reflects the true essence of the American, and indeed the human, spirit. The author can express nothing but appreciation for the zeal, even in toughest times, with which they carry out their mission.

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## ACRONYM GLOSSARY

<b>AMCM</b>	Advanced Mission Cost Model
<b>CAIB</b>	Columbia Accident Investigation Board
<b>CaLV</b>	Cargo Launch Vehicle
<b>CER</b>	Concept Exploration and Refinement
<b>CEV</b>	Crew Exploration Vehicle
<b>CLV</b>	Crew Launch Vehicle
<b>ESAS</b>	Exploration Systems Architecture Study
<b>ET</b>	External Tank
<b>FY</b>	Fiscal Year
<b>ISS</b>	International Space Station
<b>LEO</b>	Low Earth Orbit
<b>NAFCOM</b>	NASA Air Force Cost Model
<b>NASA</b>	National Aeronautics and Space Administration
<b>OMB</b>	Office of Management and Budget
<b>RCC</b>	Reinforced Carbon-Carbon
<b>RCS</b>	Reaction Control System
<b>RFI</b>	Request for Information
<b>SEI</b>	Space Exploration Initiative
<b>SRB</b>	Solid Rocket Booster
<b>SSB</b>	Space Studies Board
<b>SSME</b>	Space Shuttle Main Engine
<b>TOM</b>	Theory of Moves
<b>TPS</b>	Thermal Protection System
<b>VA-HUD</b>	Veterans' Affairs, Housing and Urban Development
<b>VSE</b>	Vision for Space Exploration

## Chapter 1

### INTRODUCTION

#### Historical Context

On February 1<sup>st</sup>, 2003, the Space Shuttle *Columbia* disintegrated upon reentry over the skies of Texas. *Columbia's* seven crew members, Commander Rick D. Husband, William C. McCool, Michael P. Anderson, David M. Brown, Kalpana Chawla, Laurel Blair Salton Clark, and Ilan Ramon, were lost in the accident. In the ensuing search operation, two civilian searchers, Jules F. Mier, and Charles Krenek, were also lost in the line of duty. This had been the second Space Shuttle lost. Responding to a plan set in place following the loss of the Shuttle *Challenger* in 1986, NASA convened the Columbia Accident Investigation Board (CAIB). An intensive examination of data relating to the loss of *Columbia* was undertaken, eventually leading to the discovery of the technical flaw that led to the Shuttle's loss. A piece of foam had fallen off of the Shuttle's external tank, impacting upon the thermal protection system (TPS). This ultimately allowed superheated gas to enter the Shuttle's left wing, leading to the eventual loss of control and the Shuttle's breakup in mid flight. The CAIB report also revealed findings regarding NASA's organizational culture, identifying a "...lack, over the past three decades, of any national mandate providing NASA a compelling mission requiring human presence in space...The result is the agency has found it necessary to gain the support of diverse constituencies. NASA has had to participate in the give and take of the normal political process in order to obtain the resources needed to carry out its programs. NASA has usually failed to receive budgetary support consistent with its ambitions. The result...is an organization straining to do too much with too little." (Gehman, Barry et al. 2003)

#### *What is the Goal of Human Spaceflight?*

Without a clear mandate, the future of the human spaceflight program was brought into serious question. A space policy report released by the Space Studies Board (SSB) in January 2004 highlighted this theme, stating that

*"...without such a long-range goal the human spaceflight program's reason for being is hard to articulate." (Bylerby, Leshner et al. 2004)*

The U.S. Congress, the body elected to represent the will of the American people, held hearings to address this issue. In October 2003 hearings on the future of human spaceflight, Rep. Ralph Hall's opening statements captured the essence of the dilemma facing human spaceflight:

*"Mr. Chairman, budgets are likely to be tight for the foreseeable future. That's the reality. As a result, it is even more important that Congress and the Administration need to work together to come up with a clear set of goals for the future of the human space flight program. Given goals, we can then determine how much we can afford to expend on an annual basis towards meeting those goals. I believe we have the means to start an exciting chapter in human exploration. We just need to decide where we want to go and then get started." (2003)*

### *The Vision for Space Exploration*

On January 14, 2004, President George W. Bush responded to the calls for direction in the human spaceflight program in announcing the Vision for Space Exploration (VSE). Stating that "This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart", Bush committed NASA and the nation to a multi-decade path that would ultimately return humans to the Moon, and then initiate the exploration of Mars and places beyond (Bush 2004).

The first step in implementing this plan called for the retirement of the Space Shuttle in 2010, followed by the construction of a Crew Exploration Vehicle (CEV), to be launched no later than 2014. NASA's human spaceflight program was now charged with the task of "Implement[ing] a sustained and affordable human and robotic program to explore the solar system and beyond", with the ultimate objective being the "exten[sion of] human presence across the solar system, starting with a human return to the Moon before the year 2020, in preparation for human exploration of Mars and other destinations" (Bush 2004).

### **Thesis Objective: Incorporating Policy Considerations into Design**

#### *The Need to Consider Policy*

In implementing this task, NASA is faced with a quandary. Development of a large space exploration system is a complex problem that spans many disciplines. Engineers designing any human-rated flight system for long-term space habitation must take into account many potentially-conflicting factors. System engineers must be concerned with the physical relation captured by Tsiolkovsky's rocket equation, which ensures that payload mass will always be an important driver of any system launched from Earth orbit (or any other appreciable gravity well). Medical concerns dominate the environment of long-duration spaceflight, where astronauts must be protected from the nocive effects of microgravity and from space radiation. The thermal environment of any space-ship must also be

closely monitored and regulated to ensure astronauts are protected from the extreme temperatures of the space environment. Telecommunications with ground control on Earth require construction and maintenance of an infrastructure that can simultaneously compensate for weather effects, the rotation of the globe, and the time-lags and power losses associated with transmission over large distances. Space systems must also be powered, a feat particularly difficult in the vacuum of space, where tradeoffs must be made between solar power sources, fuel-cells and other, less traditional techniques, such as nuclear fission reactors. Finally, any space vessel must be able to navigate its way across vast distances to its eventual destination, be it the Moon, Mars, or a space station on orbit. If the vessel is to enter through an atmosphere, it must survive harsh re-entry conditions imposed by aerodynamic friction, often at temperatures high enough to melt aluminum. All of these factors conspire to create a complex series of tradeoffs and constraints that must be satisfied if human spaceflight is to be achieved. It is therefore a testament to American, and indeed human, prowess in engineering and design that spaceflight is even possible at all. Nevertheless, this does not paint the complete picture. Whereas many of the above problems can be solved through traditional engineering methodologies, human spaceflight system architects have traditionally treated as exogenous the political environment. The interactions between the multiple political entities that influence the National Aeronautics and Space Administration (NASA), including the Executive Office of the President, industry lobbies, Congress and many others, are rarely taken explicitly into account. These are crucial in affecting the ability of the American space program to meet its goals.

(Wirin 1999) makes a compelling argument for the importance of policy analysis to space missions. In a manner typical of the traditional engineer, he characterizes the policy environment as a limit on mission design, arguing that “[e]ngineers accustomed to precise answers often find that legal and political issues intrude on the space mission design process just when everything is going smoothly...Why worry about law and policy? The simple answer is that a perfect engineering solution is useless until it can be implemented.” In other words, a system that is designed without explicit consideration of political concerns faces design irrelevance. Wirin argues that “space mission analysis and design must concern itself with the vagaries of policy and the multitude of concerns and interests that exist in the political arena”.

#### *Previous Work*

How can we identify the effects of the policy environment on the technical design? (Weigel and Hastings 2003; Weigel and Hastings 2004) provide the motivation and groundwork for this query, linking policy direction to architectural objectives, and finally to technical design parameters. A need for “policy robust” architectures, those that can survive specific policy changes, is

identified. The following generic “impact path diagram” captures the process used to analyze the effects of a political decision on technical choice.

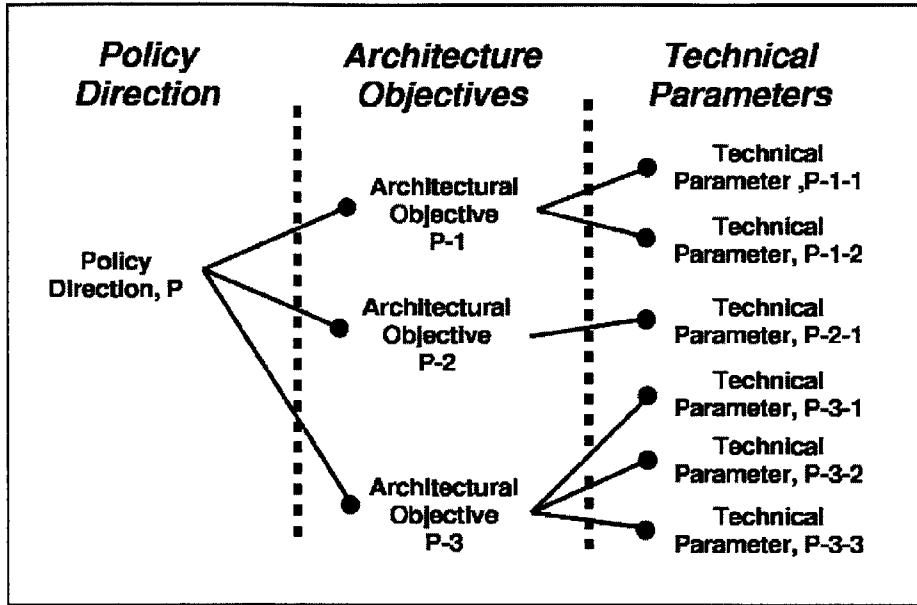


Figure 1: A generic influence diagram used to translate policy direction into technical parameters. Sourced from (Weigel and Hastings 2003).

Under this rubric, a policy robust architecture is one which minimizes the number of technical design parameters that are impacted by a given policy. If a design is insensitive to a given policy change, it is considered robust to that policy.

(Singleton and Weigel 2005) and (Wooster, Hofstetter et al. 2005) provide additional insight into interactions between the technical and political realms within the context of NASA’s Vision for Space Exploration, calling for a system architecture that can manage political risk. In effect, they articulate a need to understand how a technical choice might impact a political choice. The goal of this thesis is to advance a framework that might allow the system architect to trace such impacts.

*Thesis Contribution: Political Sustainability*

Today’s aerospace systems are becoming increasingly complex, with longer design lifecycles. In particular, many of NASA’s systems, such as the International Space Station, the Space Shuttle, and now, the Crew Exploration Vehicle, are to be

operated for decades at a time. These lifecycle times appear increasingly extended when contrasted with the American presidential term of four years, or a Congressional turnover rate of two years. Thus, if such engineering systems are to maintain the support required for continued operation, they must be able to deliver value under a constantly shifting political environment. These systems, and others, must therefore be designed with *political sustainability* in mind. The possibility of a change in stakeholders' support must be made an explicit part of the design. Once the system has been designed, political sustainability becomes an issue of maintaining the support that currently exists and potentially building the base for future support. In the case of NASA's systems, this support is generally manifested in the contest for budgetary resources. Therefore, this thesis examines the dynamics underlying *budgetary political sustainability*. Design for budgetary political sustainability requires that plans and designs that are made up-front do not undermine future goals. To the largest extent possible, a non-myopic, or long-term, perspective must be taken.

The primary purpose of this thesis is to illustrate a design methodology by which designers working within a federal agency might interact with the political process. In particular, the focus is on NASA's directive to accomplish the VSE announced by President Bush on January 14, 2004. This document is aimed at providing the system architect with a tool that may provide some measure of understanding and control of the interactions between a given technical choice and the political process. We focus on interactions between NASA, acting as an agent of the President, and Congress, the organization that reflects the will of the American people and provides funding. We explore how a system architect might affect policy outcomes. In doing so, we hope to explicitly integrate political sustainability into system design.

The concept of “Political Sustainability” is motivated by the 1987 Report on the World Commission on Environment and Development, the so-called “Brundtland Report”. This work asserts:

*“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”(Brundtland, Khalid et al. 1987)*

This thesis recognizes that politics requires a constant balance between fulfilling current needs and maintaining relationships for the future. Therefore, we define political sustainability as follows:

*An action is politically sustainable if it allows for the fulfillment of current political goals and resource needs without compromising future goals and needs.*

Politically sustainable actions simultaneously build support for, and advance, an item on the political agenda. Actions that are not politically sustainable advance a current agenda item at the expense of future support.

### **Framework: The Policy-Technology Feedback Cycle**

This thesis will focus specifically on the budgetary political sustainability of using legacy components in the design of the Crew Exploration Vehicle. The decision to separate CEV functionality into multiple “blocks” – one for Low Earth Orbit (LEO) capability and one for Lunar and Martian capability, will be explored, using the MIT Concept Exploration and Refinement (CER) Study and NASA’s Exploration Systems Architecture Study (ESAS) as baselines. The intent is to trace the effects of using legacy components through the design process, and therefore to provide a framework under which decisions to use legacy components can be evaluated.

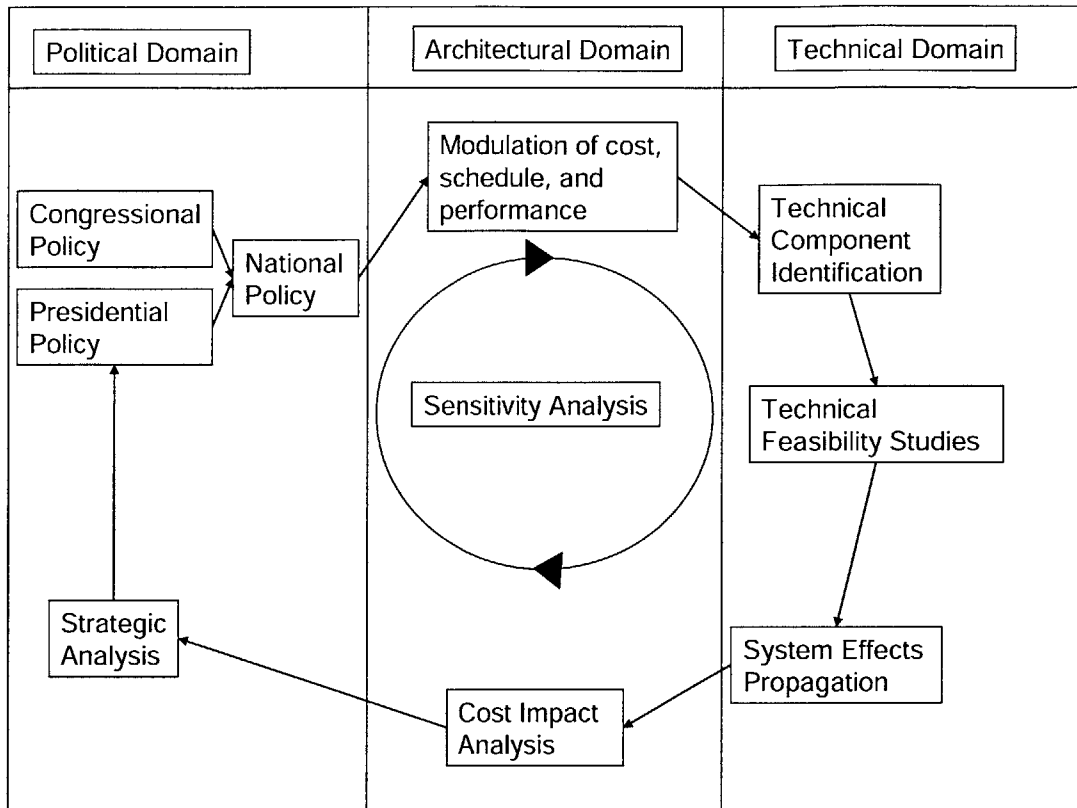


Figure 2: The Policy-Technology Feedback Cycle represents a framework that the system architect can use to trace the impacts of technical performance on national policy and vice versa.

The above diagram represents the notion that policy and technology constitute components of a *techno-political system*. Just as a policy change can impact technical parameters, changes to a technical system have the potential to propagate in such a way as to affect change in the political domain. The system architect, as the interlocutor between the political and technical domains, has the capability to trace these impacts through careful analysis. Each chapter in this thesis focuses on a specific set of components of this cycle, articulating how the implementation of the VSE is driven by Congressional and Presidential political concerns, and how technical choices, such as the decision to introduce certain kinds of legacy technology into the system design, can impact the political process. These impacts are traced across three domains, as follows:

*The Policy Domain: From Congressional and Presidential Policies to Law*

In order for any bill to become adopted as national policy within the United States of America, it must be passed by the Congress, the government's Legislative branch, and then signed into law by the President, leader of the Executive Branch. The structure of the government is such that each Branch (including the Legislative, Executive and Judicial branches) has a means to countermand an action taken by the others. For example, the President may veto any act of Congress, but the Congress can override that veto with a  $\frac{3}{4}$  majority. Similarly, the Judiciary can declare any act of Congress or the President unconstitutional. This system ensures that no one branch has unbridled power. Since the President and members of Congress are elected officials, this system ensures that few laws that are passed are inconsistent with the will of the electorate.

Each year, Congress passes the United States budget into law. The process by which this occurs is long and involved for both the Executive and Legislative branches. In order for an agency to successfully request funding, it must generally begin negotiations with the Office of Management and Budget (OMB) within the Executive Branch as many as two years prior to the time the funding is actually required. The interim time is used in negotiation.

Within NASA, individual project managers must submit funding requests for their projects to program managers. These program managers must then respond to the Director of their NASA center as well as to the specific Mission Directorate to which they report. The Center Directors and Mission Directorate Heads then report directly to the Office of the NASA Administrator, where the budget requests are aggregated. Furthermore, Center Directors require funds for institutional expenses, such as facility maintenance and utilities. Given that NASA Centers bring employment to local districts, members of Congress may choose to involve themselves in the budgetary process at this stage, sending signals to NASA that certain programs or facilities should receive additional funding. The

NASA Comptroller is simultaneously engaging in negotiations with representatives of the Office of Management and Budget to obtain an expected figure for how much funding might be available if a request is made. Eventually, an agency budget request is submitted to the OMB, who responds with a “passback” to NASA. This gives the agency the ability to appeal a specific budget request potentially allowing for negotiation that could go to the level of the President. In practice, such negotiations rarely move beyond the OMB, which is responsible for aggregating the President’s budget request for the entire nation. This request is then submitted to Congress on behalf of the President several months prior to the end of the fiscal year.

In Congress, a funding request must also undergo multiple stages. The Congress is divided into two Houses, the 435-member House of Representatives, and the 100-member Senate. Each of these Houses is divided into Committees that are further divided into Subcommittees. The first budgetary stage, referred to as “authorization”, is a statement of policy on the part of that House of Congress generally indicating that the nation should undertake a certain action. For example, one of these subcommittees can recommend that NASA engage in the VSE as proposed by the President. Authorizers may control the budget by imposing a spending cap for a given agency, or even a given program within that agency. Nevertheless, authorizers are unable to appropriate funding for an agency, as per rules imposed within each House of Congress. The subcommittee’s proposal must be approved by the parent committee, and then sent to the entire House of Congress for approval. At each stage, the authorization bill may be amended, aggregated with other bills, or traded against other priorities. Finally, the bill goes to a joint conference with the other House of Congress, resulting in a proposal that, once approved by both Houses, is sent to the President. The President may then choose to sign the bill into law or to veto it.

Once an agency has received authorization, it is up to the Congressional committees on appropriations (one in each house of Congress) to propose legislation that actually allocates funds. Subcommittees of the Committee on Appropriations must generally consider, and therefore aggregate, the requests of multiple agencies. An appropriations bill then goes through the same process as an authorization bill, requiring approval within each house, joint conference, and finally signature by the President. In the event that no authorization bill has been passed, the appropriations committee may pass a “continuing resolution” that allows for an agency to be funded at the same level as it has been in the past. Although theoretically possible, it is very rare that an agency will receive no funding. It is only after this process has been completed that an agency may receive funding for a project. More information about the appropriations process may be found in (Streeter 2004).

### *The Architectural Domain: From Law to Requirements*

Once a law is passed by Congress and signed by the President, it is the role of the systems architect to determine how an agency may best implement this directive. The architect is particularly concerned with such high-level parameters as system cost, performance and schedule. Generally a policy directive will place bounds on all three of these. For example, the VSE directs NASA to retire the Shuttle by 2010, construct a CEV before 2014, and return to the Moon before 2020. Furthermore, this must occur in a “sustained and affordable” manner (Bush 2004). The role of the system architect is to translate these policy directives into “0-level requirements”, or technical parameters that may eventually be used for conceptual design.

### *The Technical Domain: From Requirements to Hardware and Back Again*

Once 0-level requirements have been generated, it is the role of a team of systems engineers, working together with technical specialists, to generate a specific design concept. This team is then responsible for executing a “requirements flowdown”, creating low-level requirements from higher-level requirements. These are eventually intended to move beyond conceptual design into the detailed design phase. Nevertheless, system engineers must be wary of how the complex parts of a technical system interact. In particular, if a policy directive inspires change in a pre-existing design, the savvy system engineer must be aware of how that change will propagate through the system, the effects that such a change might have on the system’s ability to operate, and how performance, cost and schedule could be impacted. The system architect must be able to translate the results and assumptions underlying cost engineering results into a format that an agency’s legislative affairs specialists might understand. This, in turn, will affect how that agency approaches the OMB and Congress and how national policy is made in the future.

This thesis will trace the process described above; focusing at times on how the use of legacy components might affect the ability of NASA to carry out a potential Congressional directive to reduce the development time of the CEV so that lacks American access to space is minimized. The ultimate goal is to illustrate how such a policy change can propagate through the techno-political system, eventually affecting the policy that first called for CEV development, the President’s VSE. Throughout this entire process, modeling assumptions and limitations must be made explicit. Like any model, the results in this thesis are only as good as the assumptions that underlie it. It is therefore incumbent upon the author to examine the effects of varying these assumptions systematically, in a “sensitivity analysis” of sorts.

It must be stressed that the primary contribution of this thesis is not intended to be in the results of the model. Rather, the process by which these results are derived is intended to provide a methodology that system architects may use to evaluate how policies affect technologies and vice versa. The role of technical and political experts cannot be discounted, as they provide the crucial checks of the assumptions underlying this model, thereby grounding it in reality.

### **Thesis Structure**

This thesis is separated into seven chapters as follows:

This first chapter serves as an introduction to this thesis and outlines its structure and motivation.

The second chapter provides an overview of the existing literature linking technology and policy. In particular, it examines values that affect the budgetary process within the context of the American political system. This chapter also examines the other side of the equation – namely, Congressional valuations. In doing so, it explores the determinants behind Congress' budget in a qualitative manner.

The third chapter focuses on the specific technical implementation of a multi-block CEV architecture, outlining three ways in which legacy components might be used.

The fourth chapter examines how the cost of each of these components might change throughout the lifetime of the system and provides insight into how each of the different types of legacy component uses affect the cost of space system development.

The fifth chapter provides a strategic overview and a logic that NASA might use in deciding when, and when not to use certain types of legacy components.

The sixth chapter integrates all of the previous chapters to provide a description of how certain legacy component use might affect the eventual goal of return to the Moon.

Finally, the seventh chapter concludes this thesis and provides an overview of the analysis process. Areas for future research are also identified.

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LITERATURE REVIEW

This chapter explores the determinants of decision-making in the engineering and political realms, with the intention of demonstrating how these decisions translate to cost, schedule and performance parameters (see Figure 3).

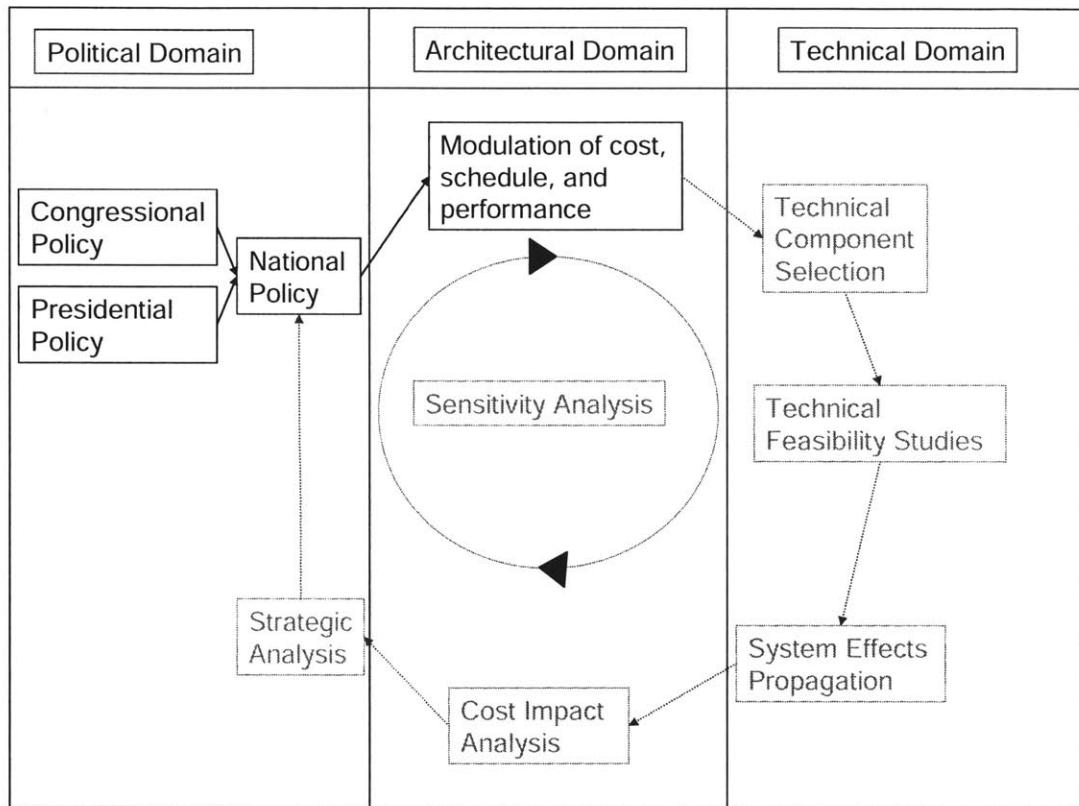


Figure 3: This chapter articulates the transition from the political domain to the architectural domain within the policy-technology feedback cycle.

**Decision-Making in the Political and Technical Environments**

In order to better understand how events may impact the political environment, we turn to the political science literature. In particular, studies of administrative, bureaucratic and Congressional decision-making are instructive in determining

how an engineering system interacts with the political realm. In order to best model behavior in each realm, we first examine how decisions are made.

### *Roots and Branches*

Perhaps the primary difference between an engineering decision and a political decision is the method by which conclusions are achieved. Whereas traditional engineering strives for rationality and optimal trades between clear objectives, political decisions are largely marked by compromise aimed at building supporting coalitions. Furthermore, the complexities of the political environment impose considerable limitations on rational choice. (Lindblom 1959) discusses these limitations in detail by identifying two paradigms for approaching a problem. The first, which he calls the “Rational-Comprehensive” or “root” method, is a description of a rational/positivist approach in which a decision maker will begin by clarifying values or objectives and then formulate comprehensive policy through means-end analysis. This method, representing the archetype of ideal engineering design, requires evaluating every alternative in a particular decision space and, although it is theoretically mathematically tractable, it requires a clear definition of goals and, perhaps more importantly, a well-defined utility function that can be used to distinguish between outcomes. When executed properly, a rational design yields a result that maximizes some performance metric within the basis of well-understood scientific theory. Thus, reliance on theory is the cornerstone of the root method.

Lindblom argues that genuine execution of the Rational-Comprehensive method for all but the simplest problems lies beyond the memory capacity of any human being. Engineers, generally possessing design goals, can circumvent these limitations using tools designed to identify an optimal design upon the basis of generalizable theory. The complexity of the political environment, on the other hand, is currently beyond the reach and understanding of any encompassing predictive theory. Furthermore, the existence of multiple independent intelligent actors suggests that any high-fidelity prediction is naturally intractable. In order to describe decision-making in this regime, Lindblom defines the method of “Successive Limited Comparisons”, or the “branch” method, which argues that the decision making process is one in which identification of values and goals are not separate from empirical analysis. Similarly, means and ends are not distinct, implying that a goal is generally not well-defined. Furthermore, since means-ends analysis is limited to those few alternatives that the decision maker can simultaneously consider, possible outcomes, policies and values are often not considered at all. Lindblom claims that, in the vast majority of cases, a decision maker will rely upon the branch method due to the fact that the computational power and data that are required to achieve the root method are generally not available. This represents the standard archetype of political decision-making. Resulting policies are therefore likely to be suboptimal from a purely rationalist

standpoint. Where engineering design is aimed at maximizing lifecycle performance, politics aims to maximize immediate desirability so that an item may be cleared from the policy-maker's agenda.

The method of Successive Limited Comparisons highlights the importance of providing a diversity of viewpoints to decision makers since they will only be able to choose between the arguments that are directly available and salient to them. This provides an implicit justification for a group to undertake advocacy activities since, without them, decision makers will naturally tend to forget about or ignore the viewpoints and goals that that particular group represents. Perhaps more importantly, it indicates that an actor who controls the flow of information concurrent with technical expertise possesses some degree of control over the final decision that is made. It is exactly this type of control that NASA, or any other administrative agency, can exercise in its interactions with Congress.

#### *Salience and Attention*

The stage is set for a description of the policy-making process as a battle between interest groups for salience within decision makers' limited attention resources. In the face of numerous pressing concerns from all sides, a policy maker will by necessity choose those alternatives that are directly within reach and most likely to simultaneously satisfy the largest number of stakeholders in the short-term. This suggests an environment of pure competition between interest groups wherein each group attempts to dominate the attention of the decision maker. Nonetheless, it is worth noting that the branch method also allows for agreement on policies without a necessary agreement on the goals that those policies might imply. Therefore, cooperation and coalition-building between groups that might both stand to gain from a particular policy occurs, even though these groups might have completely different viewpoints and opposing goals. A savvy politician builds consensus one step at a time, helping various groups achieve intermediate goals, to the extent that those goals are congruent with his/her ultimate goal.

The ability to agree on means when ends are in stark contrast is foreign to the traditional engineering mentality, which typically identifies a set of design goals and trades design parameters against this goal until exogenously-imposed requirements are fulfilled. Since political decision-makers often set, or must at least approve, the high-level goals of a publicly-funded endeavor, the above argument provides an explanation for why publicly-funded systems are subject to changing policy priorities. This, in turn, calls for an examination of how political goal-setting takes place.

### *Goals and Values*

(Van Dyke 1962) follows Lindblom's lead in suggesting that values may be defined as either "goal values", which are necessary in and of themselves and "instrumental values" that are necessary to the performance of another goal. He explains that a "goal value" is defined by the particular organization or individual in question, and that one organization's goal value might be another's instrumental value. This is particularly true for engineering systems, where the design goal of the system is likely to deliver instrumental value rather than directly serving a policy-maker's goal values. A case in point of this dynamic is the goal value of space exploration championed by NASA. Depending on the desires of the President and Congress of the time, this goal value was generally instrumental towards accomplishing some other goal. For example, the Apollo program was instrumental to defeating the Russians in a Cold War space race; the Shuttle program was instrumental as a high-tech re-election campaign; the International Space Station was instrumental first to demonstrate to the Soviet Union the resolve of the free world, and later, to employ Russian scientists who might otherwise contribute to nuclear proliferation. Thus, NASA's relevance to a political decision-maker increases or decreases to the extent that space exploration is instrumental to the goal values of the Presidency and Congress.

Stakeholders' goal values may be ranked using the *Hierarchy of Needs* proposed in (Maslow 1970).

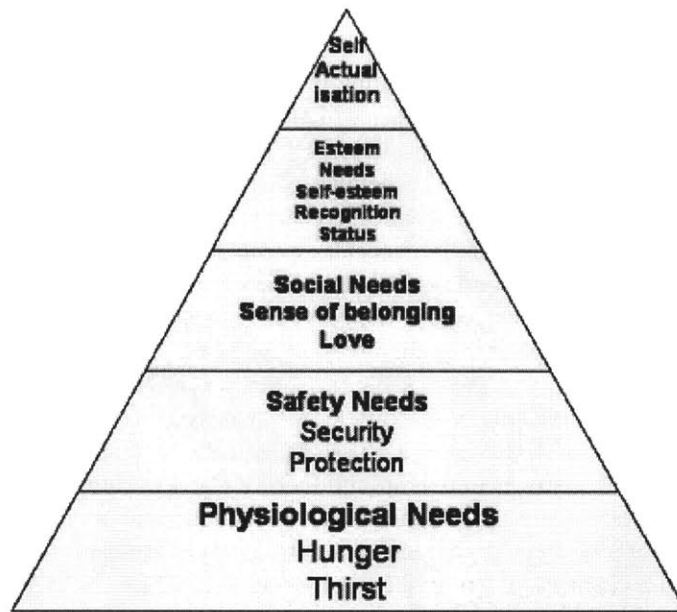


Figure 4: Maslow's "hierarchy of needs". An individual's attention is immediately diverted towards its most basic need when that need is endangered. Image sourced from (Maslow).

An instrumental goal is more likely to get support when it is linked to a goal value that is low on the pyramid, such as “security” or “safety”. This has implications for coalition building because an interest group might be willing to support a given policy even though that policy might not be directly related to that group’s “goal value”. If a case can be made that the policy, as executed, would serve as an instrumental goal for that interest group, then that interest group may provide support. Similarly, if a seemingly irrevocable conflict should arise between interest groups, a solution might be found by redirecting attention away from the value goals in conflict toward those instrumental goals that are held in common. To paraphrase Charles Dudley Warner, politics does indeed make strange bedfellows.

Van Dyke’s work has important implications for the designer, suggesting that technical expertise in administration is relied upon to promote politically selected values, an argument also suggested in (Jasanoff 1987). In the case of NASA, this suggests that any exploration architecture must actively seek relevance to current national policy. This further suggests that activities that are not directly relevant will not receive attention and will, at best, be left “idling” with incremental

funding and, at worst, be cut. At the same time, NASA has a unique role as the technical experts in all things related to their mandate in civil aerospace. As such, they are in a unique role to control the flow of information. Thus, once a congressional directive is issued, NASA has enormous power in determining the implementation for how that directive will be fulfilled and in what options are under consideration. Whereas Maslow's hierarchy suggests that salience may be achieved by putting a given value under threat, Van Dyke suggests that salience may be achieved through direct relevance to existing national priorities. This further suggests that the designer should explicitly consider the goal values that the system to be designed is intended to achieve. This is complicated by the fact that there are often many goal values – at least one for each stakeholder group – and that they may be in conflict. In this case, Van Dyke suggests that the best course of action is to alert the stakeholders of the potential conflicts and of the tradeoffs that will have to be made. This gives the stakeholders a sense of responsibility and ownership in the process, and allows for ease of negotiation. In the words of Otto von Bismarck, “politics is the art of the possible”. It is therefore the role of the technical expert to outline the space of possible options. At the same time, efforts must be undertaken by supporters of a given system design to illustrate to political decision-makers the consequences of changing resource allocations.

It is worth noting that linkage to a high-salience agenda item, such as a particular national security concern, is a double-edged sword. Whereas such a linkage is likely to ensure the program significant support in the short-term, eventual solution of the high-salience problem is likely to lead to the determination that so much support is no longer necessary. On the other hand, linkage to an item that is of lower salience, such as an ongoing mission of scientific discovery, is likely to receive less funding on an annual basis but is also likely to be more robust to large swings in support.

#### *Role-based Actions*

The above analysis illustrates some motivations behind the swiftly-changing nature of the political process. The political system is sufficiently complex that it likely lies beyond any current predictive capacity. Nonetheless, it is possible to outline certain patterns of behavior that seem to occur with regularity. (Simon 1964) notes that although individual members of an organization might be very different people, they must fulfill their organizational “roles”. For example, an OMB examiner will seek to reduce costs and increase efficiency regardless of the person holding that role. The role therefore defines, to some extent, the actions of the individuals holding that role. Although personal goals do play a part in organizations, Simon notes that actions on the basis of personal goals will be small compared to actions on the basis of role goals because of training and self-

selection. One can therefore infer an organization's goal simply from its behavior, since any action not taken is prevented by a constraint. As such, we may draw general conclusions about the behavior of specific types of political actors. Indeed, agencies often rely on this quasi-predictable type of behavior when generating budgetary strategy.

(Kingdon 2003) outlines the roles of several major players within the U.S. government. This book is a valuable source for any student of policy, providing quantitative and anecdotal evidence to support descriptions of policy actors and the types of power that they wield. A model of how policies are generated is then created, based upon the ethos of (Cohen, March et al. 1972), which essentially describes organizational choice as occurring in an almost unpredictable semi-chaotic fashion, driven by a complicated interplay of multiple streams. In particular, Kingdon characterizes three "streams" of policy-making – the Political Stream, the Policy Stream, and the Problems Stream. The Political Stream, composed of "such things as public mood, pressure group campaigns, election results, partisan or ideological distributions in Congress, and changes of administration", characterizes that element of the policy-making process that is colloquially identified as "politics". The author explains the events of the Political Stream in some detail, describing it as a promoter of agenda items. The Policy Stream, on the other hand, is largely dominated by specialists in a certain field, such as agency civil servants. Solutions are generated, often without specific problems to which these solutions might be attached, generating the phenomenon of "solutions looking for problems". The primary role of the members of the Policy Stream is to narrow the set of all possible policy proposals into a short list of those that are both technically feasible and may be seriously considered. Kingdon further classifies policy communities within this stream as either fragmented or non-fragmented, noting that fragmented communities, those that are composed of many diverse interests, are generally less successful because of their lack of coordination. This point is supported by the work of (Olson 1984). Kingdon draws parallels between the fragmentation of a policy community and the fragmentation of the associated political system, arguing that more fragmented systems require more overhead coordination. Finally, there is the Problems Stream, in which specific issues become taken up by the public and are brought to the attention of the electorate. This stream is largely influenced by leading indicators that policy makers can use to measure the efficacy of a problem's solution. Problems that are not initially salient are brought to policy makers' attentions through "focusing events", such as crises, accidents or symbolic actions. Kingdon describes the coming together of these three streams as the creation of a "policy window" through which a successful policy entrepreneur can achieve a lasting action. For a specific issue, these windows are generally short-lived and must be acted upon promptly when discovered, thus necessitating that a successful policy entrepreneur be constantly prepared to take

advantage of changing circumstances. For a given technical design, this suggests that policy advocates will attempt to justify the system as a potential solution to an existing problem for which the system might previously have had no requirement.

### **Budgetary Politics**

(Wildavsky 1964) is a detailed study of agency-Congress interactions and the attempts that agencies might use in order to assure and/or increase their yearly budget. Casting budget requests as well-thought-out strategies made by each agency, a budget request is generally aimed at getting the agency the maximum amount of money requested, but not so much that the request loses credibility. Arguing that “If politics is regarded in part as conflict over whose preferences shall prevail in the determination of national policy, then the budget records the outcome of this struggle”, Wildavsky characterizes executive branch agencies as organizational actors whose primary goal is to maximize their budget on a yearly basis. In his analysis, he identifies numerous strategies used by each agency in this endeavor, devoting an entire chapter to their description. Many of Wildavsky’s strategies are insightful and the savvy system architect may make use of them to incorporate design rules that can aid the political supporters of the program.

### *Budgetary Incrementalism*

Wildavsky argues that limited Congressional attention and budgetary resources, combined with each agency’s simultaneous attempt to defend or increase its budget will result in “incrementalism”, a state wherein each year, a budget may only increase or decrease slightly relative to the previous year’s baseline. This has significant implications for technical design in that one can not expect any sharp spikes in funding, even though such increases might be necessary to see a program transition from its development phase to its operations phase; rather the agency’s budgetary profile must be relatively constant over time. This suggests that as one project starts to consume more resources, the necessary funding will have to come from other projects. This funding will invariably come from those projects that do not have strong supporters defending them. This is particularly problematic within an agency like NASA where operations costs and sustainment have traditionally been high, stifling new development. Indeed, it is more likely that a political actor will defend a program that is already operating than one that is still in its conceptual or development phase, and therefore delivering no concrete results to a constituent base. Most importantly, Wildavsky’s empirically-derived observation links political events to budgetary salience, suggesting that without a clear goal established by political mandate, no agency, including NASA, can expect significant funding changes. On the one hand, this suggests that large development programs that do not fit within the current budget are unlikely to be funded. On the other hand, this observation reveals a sort of safety net,

essentially guaranteeing that, in the absence of extenuating circumstances, NASA is unlikely to lose its current funding level for the foreseeable future. As such, an agency's survival is a sort of existence proof that it provides a valuable contribution to society. It is only when an agency tries to increase its budget that it must justify its added value against that of its competitors.

(Davis, Dempster et al. 1966; Davis, Dempster et al. 1974) build off of Wildavsky's work by creating a mathematical description of budgetary agency allocations for each year, noting that Congress tends to follow an incremental strategy in allocating funding to agencies. In effect, they note that, in the absence of what they term "political shocks", agencies will receive approximately what they received in the previous year plus some fraction of what they requested. The motivation for this description is that Congress, lacking the attention resources to re-construct the budget from the ground up every year, must instead look at the previous budget for its guidelines and base the new budget on this data. Budgetary data from many agencies confirms the incremental hypothesis for some length of time, although incremental periods are often separated by short (one- or two-year-long) periods of non-incremental behavior. These sources provide no means of predicting these shocks, rendering their theory descriptive rather than predictive. Nonetheless, it is instructive to observe that, since the end of the Apollo program, NASA's budget and activities have become increasingly characterized as incremental in recent years, particularly as Congressional influence over NASA's budgetary process became stronger. (Jahnige 1968), written near the end of the Apollo program, describes this process in detail, observing that NASA, which had previously been impervious to Congressional oversight due to its strong presidential support and highly technical nature was now subject to an increasingly aware Congress that began to exert more control in curtailing NASA's spending activities largely through the employ of technically-capable staffers.

#### *The Politics of Space Exploration*

The effects of Congressional attention on American space policy is recounted in detail in (Johnson-Freese 2003). Noting that several members of Congress see NASA as "an entitlement or jobs program for its employees and contractors", the author concludes that costs tend to grow significantly when spent for political rather than technical purposes. This perception is strengthened by the fact that the scientific and technical nature of space activities is often viewed as arcane and beyond the grasp of the average Congress member. This, in turn, motivates a focus on other, more directly salient concerns, such as geographic distribution of jobs. Regardless of the Congress member's personal beliefs, each member is motivated to remain in his or her elected position, thus requiring that benefits be provided to constituents. (Roust 2002) elaborates on this hypothesis, demonstrating the role-based power of specific committee members on NASA

allocations. Thus, in order to be politically relevant, NASA must ensure that its money is spent in line with the political powers-that-be. As a multi-member legislature, Congress is often home to many differing and sometimes changing, opinions. In the absence of strong and sustained Presidential leadership, these opinions will come to dominate NASA's agenda, often resulting in changing requirements and redesigns, as NASA tries to adapt to serve all constituencies. Nonetheless, individual Congress-members need to maintain a reputation for responsibility, both to their constituents and to the nation. This means that, in the face of cost- and schedule- overruns, Congress members will demand accountability even if the lag in performance metrics is in part created by Congressional politics. Noting that "...incrementalism occurs when the decision-maker lacks the information and knowledge to put forward space policy goals", Johnson-Freese ties Congressional action to the work of Wildavsky, suggesting that incrementalism is a specific strategy employed by a non-technical Congress to ensure oversight of, and some measure of control over, NASA's programs. (Logsdon 1986; McCurdy 1990) both elaborate on the extent to which NASA has adopted an incremental, coalition-based strategy in its dealings with an increasingly powerful Congress. Specifically, they address the circumstances surrounding the creation of the Space Shuttle and the International Space Station, both of which resulted in designs that are suboptimal from a purely technical standpoint but are nonetheless strong sources of Congressional benefits. Nevertheless, a question remains as to their efficacy in accomplishing the goals of Presidential politics. (Johnson-Freese 2003) observes that "[a]s long as the status quo is maintained, Congress seems content to remain mostly a benign benefactor...[t]he result is that Congress is not generally able to force coherent long-term change, nor does it really want to. Instead, legislative solutions tend to be across the board budget percentage cuts or caps to which agencies adapt to as best as possible. This often means continual downsizing of programs, but not a pruning out or elimination of anyone's particular program. It also explains why NASA's programs, such as ISS today, are often over budget and behind schedule". Many of NASA's cost and schedule problems are exacerbated, if not caused, by the political environment in which it sits. Thus, it would seem that the CAIB's conclusions regarding the political environment in which NASA exists represent the norm rather than the deviation. We may therefore expect such behavior to continue for some time to come.

#### *Incrementalism in the Vision for Space Exploration*

The Vision for Space Exploration, presumably anticipating Congressional incrementalism, advances a relatively constant NASA budget proposal for the long-term, increasing only to adjust for expected inflation rates after FY09 (see Figure 5). Unlike the days of the Apollo program, when schedule, rather than cost, was the primary mission driver, one may expect NASA's budget to remain

largely constrained within this funding envelope. Furthermore, it is not inconceivable that funding might decrease in the face of shifting priorities.

### Exploration Strategy Based on Long-Term Affordability

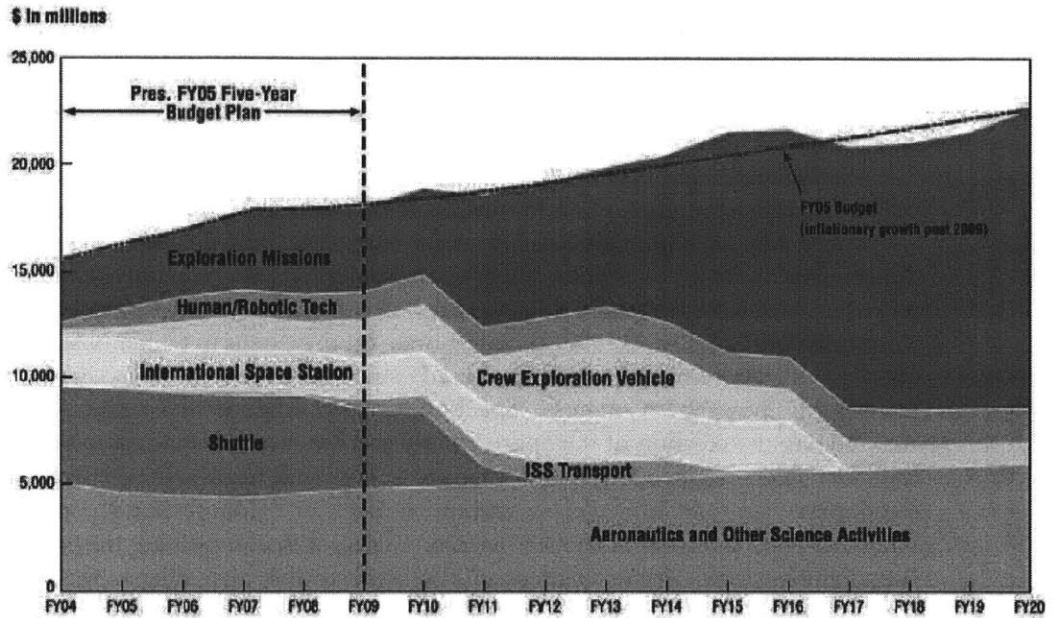


Figure 5. The following “sandchart”, representing NASA’s expected budget through time, shows a slight increase in NASA funding, after which the budget increases linearly in real dollars, in effect remaining constant with inflation. Source: (NASA 2004)

The linear budget predicted after FY07 is consistent with the incremental model of budgeting, which asserts that, for an agency, “models of the of the budgetary process are linear, stochastic, and strategic in character” (Davis, Dempster et al. 1966). An agency-level examination of recent NASA budgetary appropriations does indeed yield a roughly linear time-series, as shown in Figure 6. The stochastic nature of these appropriations characterizes the slight deviations from the linear approximation. Furthermore, NASA has previously been characterized as an incremental organization following the end of the Apollo era (McCurdy 1990).

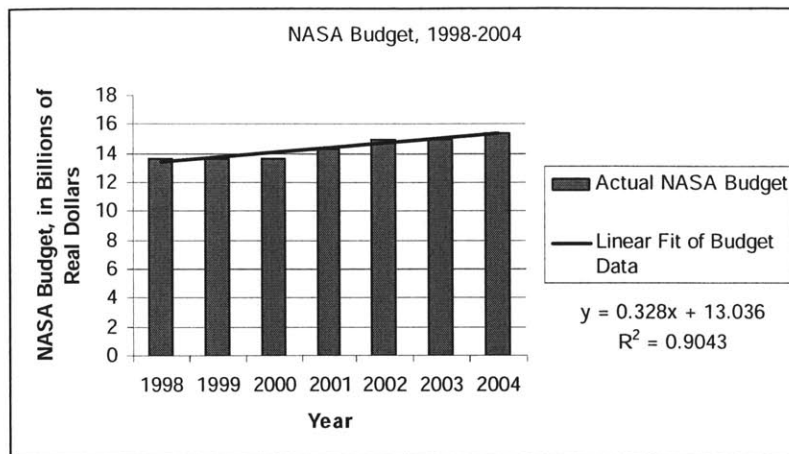


Figure 6. The above chart portrays NASA's total budget as granted by Congress, in real dollars. Note that it increases roughly linearly through time. A true incremental model would also incorporate data pertaining to the agency's budget request, perhaps providing a stronger correlation (NASA 2006).

Note that Figure 5 predicts very gradual growth through time for most of NASA's programs, with the exception that, as programs retire, their funds are folded into the Crew Exploration Vehicle and Exploration Missions. In general, this sandchart is devoid of sharp increases or decreases in funding on a yearly basis, that might belie the presence of conflict or changing priorities within the budgetary process. Nevertheless, incrementalism cannot be generalized to the programmatic level (Natchez and Bupp 1973).

Figure 7 shows the same data as in Figure 6, except that here, budget is broken down by program, rather than aggregated at the agency level.

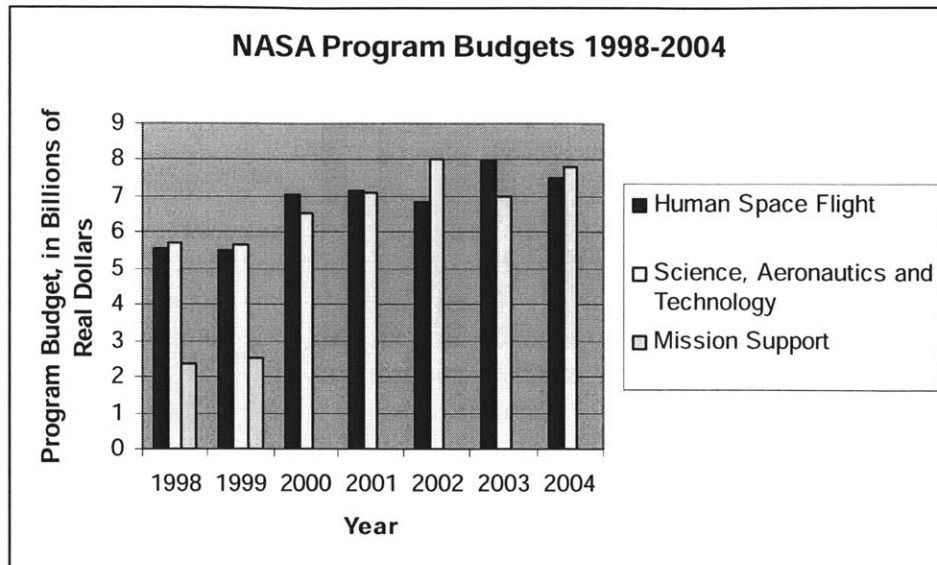


Figure 7: The above chart displays the same budgetary data as in Figure 6, broken down by program. The data are characterized by sharp, nonlinear changes associated with reorganizations (in FY2000) and shifting priorities (between FY2002 and FY2003) (NASA 2006).

Each program component historically underwent periods of non-incremental behavior. Comparing 2002 to 2003, for example, one notes a one-billion dollar shift from “Science, Aeronautics and Technology” toward “Human Space Flight”. In 2004, much of this funding is restored. In addition, the year 2000 saw the folding of “Mission Support” into the other two budgetary categories. This suggests that there are political forces at work beyond the traditional budgetary “satisficing” (Lindblom 1959). Indeed, previous work has faulted the incremental model for its inability to capture such program-level dynamics. An incremental analysis is therefore insufficient to be able to characterize the program-level budgetary environment through time. Since engineering systems are generally designed within the context of a program, rather than within the context of an entire agency, we must focus on determining the causes of these program-level dynamics.

#### *Program-Level Politics*

(Natchez and Bupp 1973) critiques the incremental model of budgeting; arguing that although the outcome of the budgetary process may indeed be incremental, the politics and the struggles leading to such an outcome are far from deterministic. Their examinations of the Atomic Energy Commission’s budget

reveal that, although the agency budget possessed a relatively linear incremental profile over time, individual programs were subject to wild swings in budgetary favor that correlated with executive branch policies. Figure 7 shows a similar outcome; whereas the overall agency profile is relatively constant, the disaggregated budgets are subject to changes of up to \$1 billion per year, an appreciable amount compared to the agency's overall budget of about \$15 billion. This suggests that although an agency's budget is likely to be stable over time, a specific program is much more subject to unpredictable political perturbations. This is especially true if such a program is "invisible" to Congress. Without congressional support, such a program is much more likely to be used as a political bargaining chip within the Executive Branch, potentially endangering its future survival. This is particularly true if the program has neither Congressional nor Presidential salience. Lacking a powerful constituency to support it, the program is likely to be cut so as to free funding for other priorities. This, in turn, raises the question of how a program might achieve Congressional or Presidential salience, thus guaranteeing at least some measure of stability of funding.

### **Congress-Agency Interactions**

(Cohen and Noll 1991) analyzes this problem as it relates to R&D projects within the context of the American federal system, drawing some general conclusions regarding the comparative roles of Congress and the President. Their conclusions are somewhat bleak, noting that "American political institutions introduce predictable, systematic biases into R&D programs so that, on balance, government programs will be susceptible to performance underruns and cost overruns". Nonetheless, the authors make important comments regarding how a program might achieve electoral salience, outlining three general types of circumstances. The first of these occurs when an R&D project is directly related to the state of the nation. Examples include the space race with the Soviet Union culminating in the Apollo program, the energy crisis of the 1970s leading to a brief increase in funding for alternative energy sources, and the Strategic Defense Initiative (Star Wars) missile defense system proposed during the Reagan administration. A second instance in which R&D programs become salient is the fallout resulting from a disaster or some event that exposes mismanagement or corruption within the program. Finally, the authors cite distributive effects; specifically the money and jobs created within the districts of individual members of Congress, and campaign contributions required for re-election. This particular circumstance becomes especially important when many individual constituents have a stake in the continuation of a program. The authors link political salience to contract size noting that positive spillover effects from increased employment increase salience for political representatives, eventually reaching beyond congressional districts and potentially into the attention of senators and possibly even presidential candidates. Nonetheless, as a program size continues to grow, it

will eventually reach a point of diminishing political returns. A notional diagram of this concept is shown in Figure 8.

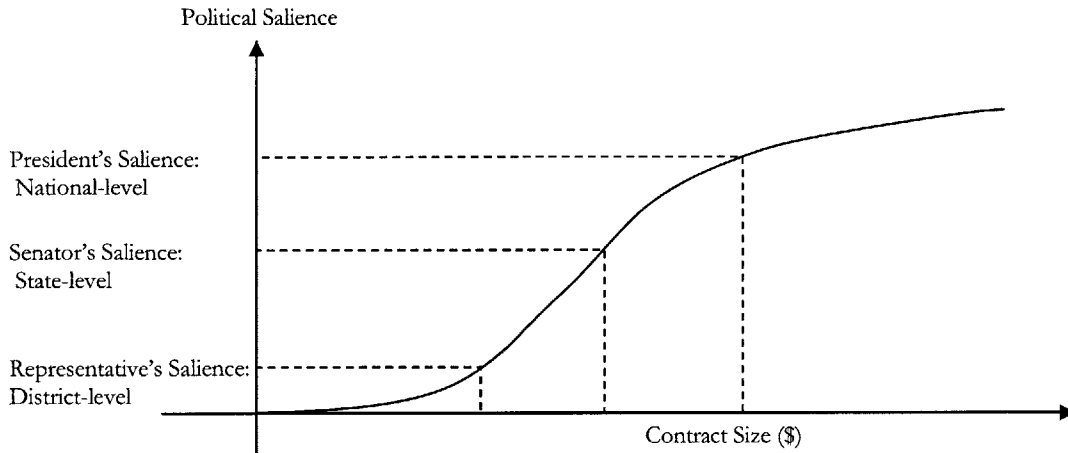


Figure 8: Notional representation of the effects of contract size on political salience

It is worth noting that a program that promises electoral advantages for the future is much less likely to receive support than a program that is currently delivering value. This is largely due to the uncertainty surrounding who will receive development contracts. Cohen and Noll note that “citizens who are unaware that they are destined to be employed in the new program are unlikely to engage in political behavior motivated by its enactment. Once contracts are awarded and workers are hired...identifiable and organized groups (firms, unions, local governments) have a clear stake.” This sort of behavior, in which potential losses loom larger than potential gains, is well-documented in the risk-aversion and psychology literature, and is especially consistent with the predictions of “Prospect Theory” (Kahneman and Tversky 1979). Furthermore, we may expect Congressional representatives to share this type of behavior with regards to distributive benefits within their district, largely because their prospects for re-election depend on the continued support of their constituencies. Thus, a program is likely to engender salience from Congress members if the distributive benefits that it provides are simultaneously put under threat and sufficiently large to warrant the attention. (Cohen and Noll 1991) further elaborate on this theme, characterizing politicians, and Congress-members in particular, as impatient and risk-averse with regards to R&D programs. Since R&D programs are naturally risky prospects with uncertain results and payoffs in the long-term, they tend to be systematically undervalued within the American political system. This suggests

that programs which can deliver politically-relevant benefits early on are more likely to be sustained by Congress. The President, on the other hand, has more latitude to propose large long-term programs. Cohen and Noll note that “A president must certainly be concerned that programs initiated in one term will not be carried to conclusion in the next; however, if a program is reasonably successful, and if expenditures are large enough to cross the threshold of political significance for a number of legislators, a president can be reasonably confident that a program will be difficult to kill in subsequent sessions of the legislature.” This argument casts the President in the role of proposing programs while leaving it to the Congress to sustain these programs, a statement supported by the game-theoretic analysis of (Kiewiet and McCubbins 1988). If, on the other hand, the President were to try to sustain a program unpopular with Congress, the program would likely not be successful. Therefore, the distributive goals of Congress members must be taken into account, even, and perhaps especially, with Congressional support.

The role of the agency is to ensure that the execution of a program’s agenda is both politically acceptable and technically feasible. This is often accomplished through agency-industry coalitions wherein much of the agency funding is allocated to industry contractors, many of whose firms represent large political constituencies. This phenomenon, often referred to as a “revolving door” or an “iron triangle”, can increase political support within Congress but has the potential to stifle innovation.

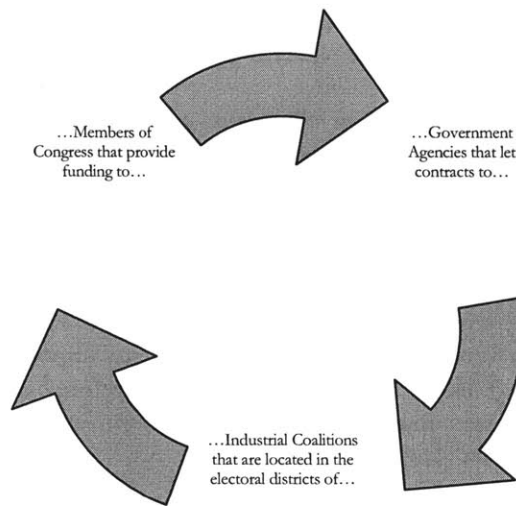


Figure 9: The "revolving door" or "iron triangle" -- a self-reinforcing feedback mechanism among members of Congress, Industrial Coalitions and Executive Branch Agencies (Cohen and Noll 1991).

Given the challenges inherent in generating a program that will gain and maintain Presidential and Congressional salience, (Cohen and Noll 1991) discusses many of these issues in significant detail, outlining a set of general characteristics that an R&D program might possess in order to make it more likely to survive in the political environment. These characteristics are as follows:

- 1) "First, the government is more likely to be willing to undertake programs oriented toward a concentrated industry than a competitive one." (Cohen and Noll 1991)

This particular characteristic speaks to the relative political ease of associating with a small, concentrated number of players rather than a larger, more diffuse interest (Olson 1984). For the purposes of determining the available NASA budget for the CEV development program, this characteristic speaks to the Congressional desire to avoid alienating a key constituency. Thus, the concerns of those groups that are heavily invested in aerospace must be taken into consideration. For example, this characteristic suggests an advantage to using

legacy components for the CEV design, if only to maintain the support of the producers of those components.

- 2) “Second, R&D projects will be more attractive if they address a broadly salient national political issue, so that they plausibly constitute an effective response to a concern of the citizenry at large.” (Cohen and Noll 1991)

This characteristic is driven by the Congressional requirement that a coalition be built in order to achieve action. Although each member of Congress serves a given fixed constituency, a program is much more likely to receive support from fellow members if it is viewed as a boon to the nation, rather than simply a “pork-barrel” for particular districts. It is within this context that the national pride and prestige elements of human spaceflight become the most important – if a majority in Congress perceives that the national interest is threatened, more support may be expected. The Apollo program was the archetype of this modality (Van Dyke 1964). Nevertheless, such threats are generally short-term in nature and cannot be expected to provide sustainable results. The drive to accelerate the CEV represents such a concern, ensuring that the US will not cede superiority in human spaceflight to other nations.

- 3) “Third, an R&D program will be more attractive if it has a short time horizon and does not entail a radical change in the technological base of an industry.” (Cohen and Noll 1991)

This characteristic speaks to the need for Congress members to show results to their constituents within an election cycle (as little as two years for a US representative). Furthermore, the industrial base requirement suggests that the costs of showing these results should be relatively small and should displace the smallest number of people and equipment possible. In the specific context of the CEV, this characteristic provides a direct justification for acceleration of the program while simultaneously maintaining the employment of the existing aerospace workforce. Once again, legacy technologies are useful in implementing this directive.

- 4) “Fourth, the net benefits of a program are likely to play an important role early in the history of a program, simply because there are only weak political reasons to undertake a program unless it is economically attractive.” (Cohen and Noll 1991)

The explanation for this characteristic is similar to that of the previous two. When a program is first proposed, it requires a broad national consensus in order for it to be approved and then funded. In order for it to avoid cancellation, it must deliver upon these commitments. Nevertheless, once the program has

become significantly entrenched, individual members of Congress will be willing to expend political capital to advocate for its continued existence. This is largely because it is in their interest to see to their constituents' continued well-being. There are also valid national reasons to maintain a skilled workforce that can be mobilized when necessary, but until such a mobilization is required, the benefits of this maintenance are conferred upon those particular regions of the nation where the workforce is located, whereas the costs are diffused upon the entire nation. Programs often take advantage of this characteristic, using what is referred to as the "camel's nose": An agency may "wedge" a program into the budget, initially requesting little and then overrunning as the program matures (Wildavsky 1964).

- 5) "Fifth, programs that can be fragmented into many, largely independent components are usually more attractive politically than programs that can be implemented only if they are centralized." (Cohen and Noll 1991)

The logic underlying this characteristic relates to the observation that support in Congress is roughly proportional to the number of Congress members willing to advocate for the program (exceptions to this rule involve the support or opposition of powerful figures such as chairs of relevant committees, and other leadership positions). If a significant number of people are employed by a given program within a given district, the representatives of that district will be willing to lend their political capital to the cause. A technical system that can be easily fragmented and spread around the country such that parts of it can be built in many districts will benefit from this support (Klein 2000). Distributed management brings similar benefits (Baldwin and Clark 1997). For example, the Space Shuttle program gained significant support from the Utah delegation in Congress when Morton Thiokol, a Utah-based company, was selected as the prime contractor for the Shuttle's Solid Rocket Motors, even though this required that special additional infrastructure be created to transport these often highly volatile components to Florida for launch (Hoff 1997). The Space Shuttle and International Space Station programs have been highly successful in maintaining Congressional support through distribution. Thus, this characteristic suggests that the distribution assigned during these programs not be changed, and that existing infrastructure be utilized to the greatest extent possible. It is generally considered politically prudent to locate these facilities (and the resulting jobs) in the districts of powerful members of Congress. Nevertheless, it is not advisable to spread the program too much. Given that NASA's budget is relatively fixed and incremental, over-spreading of the program will lead to less spending per district, engendering less support from each Congress-member. In all, the distributive benefits to be realized would be too small to cross the threshold of political salience (Kingdon 2003). Furthermore, members of Congress will usually not advocate to increase



replacement human-rated ablative TPS material (The Charles Stark Draper Laboratory Inc. 2005).

- 6) “Sixth...Proponents of unattractive ongoing projects...will often seek logrolls with advocates of new programs, thereby achieving majority support and presidential consent for the entire package.” (Cohen and Noll 1991)

This characteristic speaks to the practice of Congressional “logrolling”, wherein one member will support another’s agenda in return for a future vote of support. Linking new programs to old programs allows the implied continuation of one program by folding it into another. In other words, transitions between programs should be sufficiently smooth that the end of one program is indistinguishable from the start of the next (Wildavsky 1964). Use of legacy components on the CEV enables supporters of the Shuttle and ISS programs to claim a linkage to a popular Moon/Mars exploration endeavor. At the same time, proponents of this new exploration program can point to the Shuttle and ISS programs as stepping stones to their goals. This characteristic therefore acts to minimize technical change from year to year. Agencies take advantage of this characteristic through the “bundling” of programs: If an agency’s budget is to be cut, agencies may try to cut the most popular program using a deterrent threat as a political maneuver (Wildavsky 1964). On the other hand, if cuts are certain, losing the least popular programs will maintain a coalition (Wildavsky 1964). Thus, the political calculus of a program manager within an incremental agency depends strongly on how much support s/he expects the program to receive. It is for this reasons that agencies maintain strong ties to Congress through liaison offices (Murphy 1972).

One may conclude from the above characteristics that the average incremental Congress will base its decisions largely upon considerations of cost, schedule, performance, distributive benefits, and national utility. In particular, we may distinguish two modes of behavior under which a program might receive support. The first mode, characterizing the Space Shuttle and International Space Station programs, is best described as incremental. Under this regime, cost, and to a lesser extent, schedule, are the main architectural drivers of the program (Maier and Rehtin 2000). Without a clear national goal to adhere to, Congressional support for these programs focuses on the distributive benefits that they may deliver to individual districts (Kingdon 2003). Coalitions are built around maintaining these entrenched interests, sometimes at the expense of technical performance metrics (Cohen and Noll 1991). The second mode, characterizing the Apollo program and other pride and prestige items, is much more performance-driven (Van Dyke 1964). Although distributive interests do play a large role in the structuring of the program, the need to achieve high performance mitigates the resulting inefficiencies somewhat (McDougall 1985). The presence

of a national goal or national concern helps to focus efforts and can serve to draw resources to the program, mitigating the budgetary wrangling often associated with incremental programs. Nevertheless, the nature of national crises is that they must generally be solved quickly. Thus, this latter mode is likely not sustainable over a period of time sufficiently long to execute the entire Vision for Space Exploration or any other sustained directive. Furthermore, national goals are subject to rapid change and are motivated by such things as economic prosperity and foreign threats, most of which are rapidly changing and notoriously difficult to predict. The checks and balances system of the US federal government is configured to establish oversight by the Congress of large, Presidential expenditures. Therefore, even in the presence of a long-term goal, one may expect the eventual *modus operandi* of federal agency spending to be incremental and distributive. This pattern is confirmed by NASA history (Jahnige 1968). Thus, we may think of the budgeting process for NASA as consisting of an incremental steady-state with occasional transient peaks. As such, we may expect Congressional valuations of NASA's budgetary request to be different during these peaks as compared to the incremental steady-state. Table 1 summarizes the type of behavior that we might expect from Congress, given the environment in which a budgetary request is made:

Table 1: Expected Congressional budgeting behavior under periods of incrementalism and national salience

Incrementalism	National Salience
<ul style="list-style-type: none"> <li>• Slight changes in budgetary allocation from year-to-year</li> </ul>	<ul style="list-style-type: none"> <li>• Infrequent larger changes in budget are possible</li> </ul>
<ul style="list-style-type: none"> <li>• Program is cost-driven – budget-constraints drive design and outcome.</li> </ul>	<ul style="list-style-type: none"> <li>• Program is schedule- and performance-driven – budget is negotiable to meet objective.</li> </ul>
<ul style="list-style-type: none"> <li>• Coalition-building drives re-use of legacy components – sometimes at the cost of technical efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Drive toward technical optimality allows development of new components and facilities.</li> </ul>

The above analysis demonstrates that policy choices do not stand in a vacuum. Rather, they may be influenced by many factors, including technical choice. Space systems, and space system engineering, are complex by nature. That complexity is exacerbated by uncertainty within the political environment. Although some work has been performed enumerating the effects of policy choices on the technical architecture, there is no clear framework for how technology affects policy. This

thesis is aimed at providing such a framework within the context of NASA's space exploration plans.

## **Conclusion**

The political science literature provides us a sense for what motivates political change. Whereas technical choice is based upon tractable theory that can be pursued to a rational and often deterministic end, political choice is marked by an environment of information scarcity wherein many of the options available to a decision-maker are not clear. A political decision-maker is thus forced to choose between a limited number of generally sub-optimal options, often without the time or ability to investigate the full ramifications of these options in detail. As such, an entity that can exercise control over the information available to policy makers can exercise some element of control over the outcomes. In particular, NASA's technical expertise allows a powerful role in defining options that are to be presented as policy choices.

It is up to the policy maker to make decisions based upon what information and options are the most salient to his/her own values. To the policy-maker, agencies, such as NASA, are tools to be used in implementing a specific policy directive. Therefore, an agency will receive attention when its work can be used to satisfy a salient directive, or when its goals are instrumental towards achieving the policy-maker's goals. Since goals change, an agency cannot always fulfill a salient concern. During these periods, they are dominated by role-based activity. The budgeting process, in particular, is dominated by a particular type of role-based activity often referred to as "incrementalism". Furthermore, there is a considerable body of space policy literature characterizing NASA as incremental. As such we can expect NASA's budgeting behavior to be largely driven by the same forces that drive most incremental agencies. Generally, these act to maintain the status quo by creating an environment of budgetary scarcity for new projects. In technical terms, this drives the agency to reduce costs of new programs. Use of legacy components and technology is one widely-used means of reducing costs while simultaneously forging a political linkage between new and old programs. So as to enhance tractability, the remainder of this thesis will focus on the techno-political effects of legacy component use within the space exploration system architecture. The next chapter explores the choice to use legacy components to enable an accelerated deployment of the CEV to LEO. Nevertheless, the larger techno-political interaction effects of incrementalism remain a rich area for study and bears further research.

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TRANSLATING POLICY PREFERENCES TO TECHNICAL REQUIREMENTS

The previous chapter highlights the political attractiveness of programs that have short development lifecycles, minimize changes in the nation's industrial and technological base, and provide distributive benefits to members of Congress and their constituents. Use of legacy technological components in the design of new systems is a convenient way of simultaneously meeting all of these criteria. This chapter traces the effects of these preferences through the architectural domain, and into technical parameters (see Figure 11).

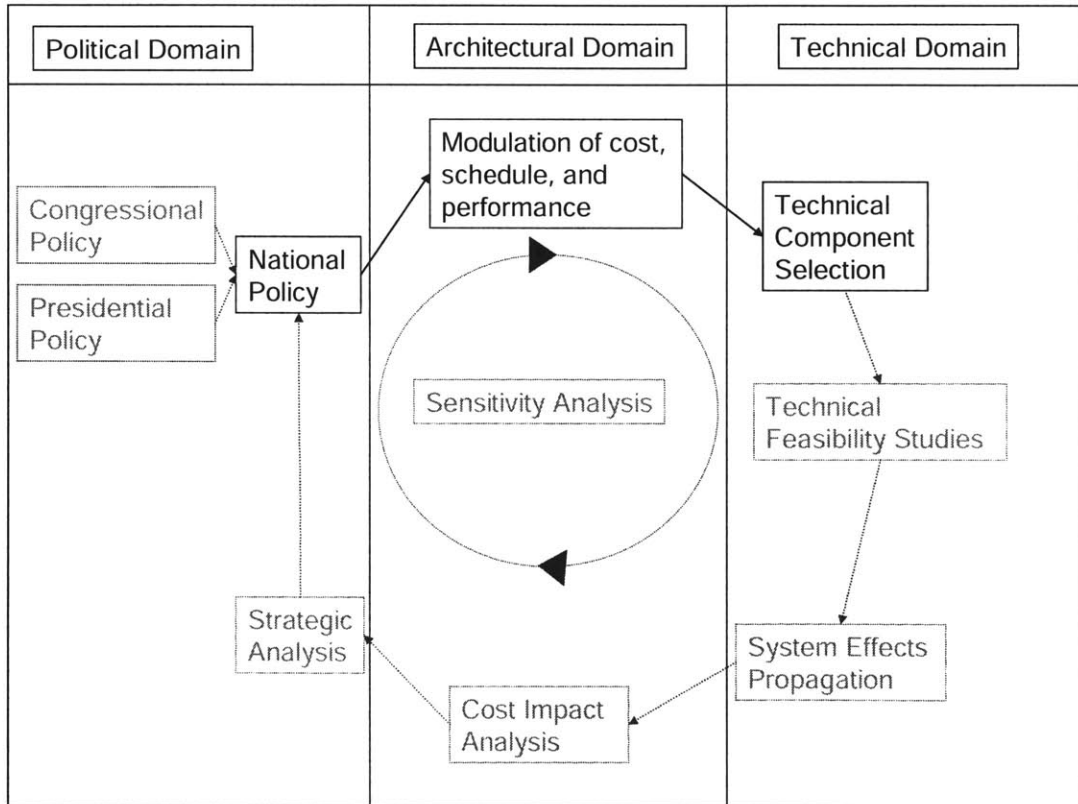


Figure 11: This chapter articulates the transition from the political and architectural domains to the technical domain within the policy-technology feedback cycle.

When designing for political sustainability, the architect must always be cognizant of the effects that decisions made today might have on the future political and technical environments. This chapter analyzes the effects of using legacy technology within the specific context of achieving an acceleration of the CEV so as to return American astronauts to LEO as soon as possible. The effect of this acceleration on the ability to achieve future lunar objectives is investigated. Three types of legacy components are identified, each with a specific effect on the cost of the system under development. Where appropriate, technical analysis is performed to analyze the feasibility and system effects of a specific legacy component choice.

### **CEV Acceleration**

On April 14, 2005, Dr. Michael D. Griffin became NASA Administrator. Responding to Congressional concern that the existing plans to retire the Space Shuttle by 2010 would leave a four year gap in American access to LEO, Griffin announced his intention to accelerate the CEV to the extent possible within the budget constraints imposed.

*"Griffin wants to fly the proposed new spacecraft as soon as possible once the space shuttle fleet is retired in 2010 -- avoiding a four-year gap in which the United States would have no way to launch astronauts ... Griffin said he finds that four-year launch gap unacceptable and hopes to have a plan for closing it ... "CEV needs to be safe, it needs to be simple, it needs to be soon," Griffin told reporters later in the afternoon..."The six-year gap between the 1975 Apollo-Soyuz mission and the 1981 debut of the shuttle damaged both the U.S. space program and the nation", Griffin said. "I don't want to do it again." (Technology News 2005)*

As part of the plan to accelerate the CEV, Griffin commenced the ESAS, aimed at identifying a candidate architecture that could implement the VSE while simultaneously satisfying the above directive. So as to enable the successful construction of a CEV as early as possible, ESAS recommended that CEV development be divided into "blocks", with Block 1 aimed at servicing the International Space Station (ISS) in LEO, Block 2 aimed at lunar operations and Block 3 intended for Mars. These blocks provide convenient benchmarks for analysis of each legacy component – the effects of using a particular type of legacy component to accelerate Block 1, for example, will propagate the Blocks 2 and 3. If the use of a given legacy component for Block 1, for example, does not erode support for the eventual deployment of future blocks, then use of such a component may be said to be politically sustainable.

*Legacy Components as a Means to Accelerate the CEV*

As described in Chapter 2, NASA’s budget constraints make use of legacy components an attractive option. From a performance standpoint, use of legacy components has the potential to reduce development cost, schedule and risk for the Block 1 vehicle. From the perspective of the political environment, this behavior will also reduce the pace of the changes in workforce and industrial-base distribution that can be dangerous to new R&D programs (Cohen and Noll 1991). The intended CEV acceleration makes this option almost indispensable. Figure 12 traces this decision calculus.

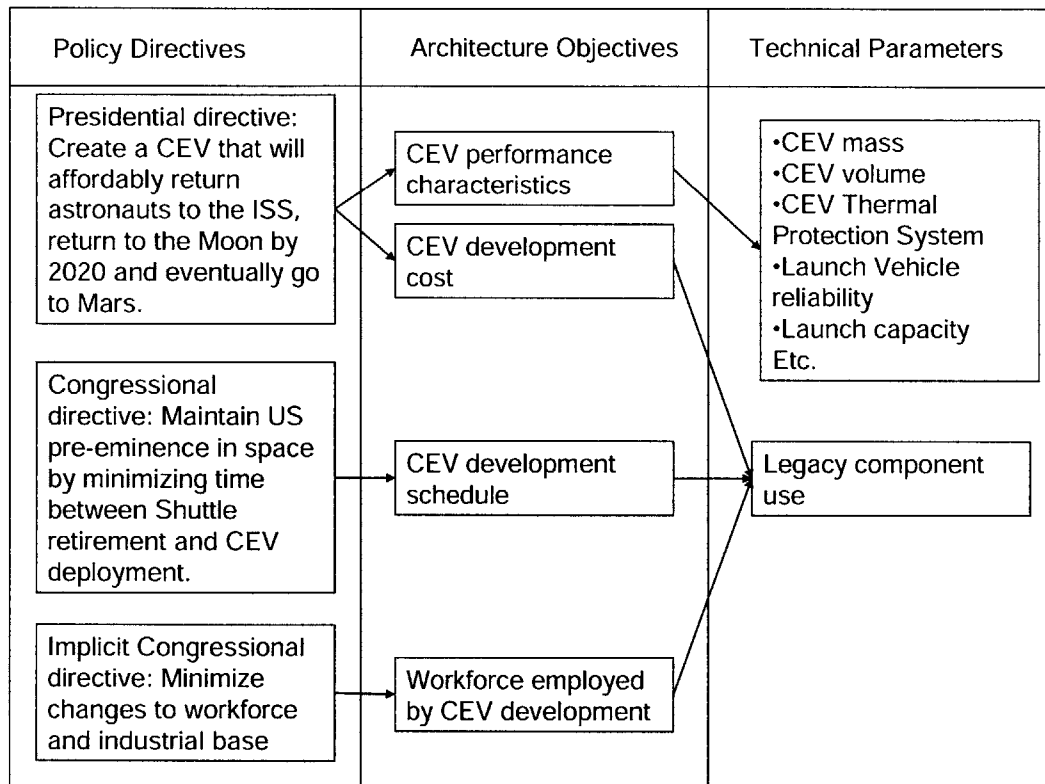
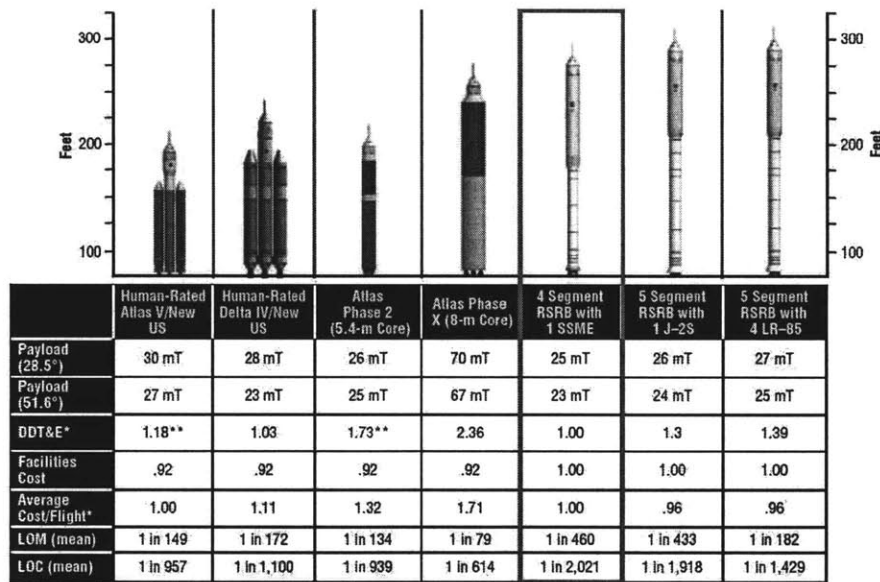


Figure 12: Impact-path diagram capturing the logic behind the use of legacy components to accelerate the CEV

The ESAS design relies heavily on legacy components to enable affordability within the incremental funding regime expected from Congress. In particular, many Space Shuttle-derived components, such as the Solid Rocket Boosters (SRBs), External Tank (ET) and Space Shuttle Main Engines (SSMEs) are to be incorporated into the design. The motivation for these choices is both technical

and economic. For example, Figure 13, sourced from ESAS, contrasts the SRB/SSME combination to other possible Crew Launch Vehicle (CLV) options. All of the options under consideration make use of existing systems – the option of designing a new system was discarded, most likely because of the expense involved in implementation. The selected option provides adequate lifting capability for minimal cost at the highest safety rate, the technical metric of the most interest when designing human launch systems. The choice of SRBs to loft the CEV will propagate through the system, placing requirements and constraints upon the design that must be explicitly recognized. For example, the loss of *Challenger* was largely due to attempts to launch an SRB under unfavorable environmental conditions. Nevertheless, the presence of emergent behavior is hardly restricted to this particular type of launch vehicle – indeed; the previous successful use of SRBs has built up a record of operation that is largely responsible for the reliability numbers shown below.



LOM: Loss of Mission LOC: Loss of Crew US: Upper Stage RSRB: Reusable Solid Rocket Booster

\* All cost estimates include reserves (20% for DDT&E, 10% for Operations), Government oversight/full cost; Average cost/flight based on 6 launches per year.

\*\* Assumes NASA has to fund the Americanization of the RD-180.

Lockheed Martin is currently required to provide a co-production capability by the USAF.

Figure 13: Comparison of Crew LEO Launch Systems -- sourced from (NASA 2005)

It is conceivable that a completely redesigned CLV could reduce future recurring costs (e.g., by obviating the need for transport of SRB segments from Utah to Cape Canvernal via barge from Michoud, Louisiana), although such a redesign would undoubtedly be more expensive than the legacy CLV choice, likely

exceeding the President's budget request. This is an example of compromising current resource constraints to accommodate future needs and it is therefore not politically sustainable. On the other hand, the CLV as described above is politically sustainable. A reduction in the CLV up-front development cost certainly reduces the costs of implementing Block 1 while simultaneously taking advantage of existing infrastructure that is already in place for the transport of SRB segments. At the same time, since the CLV will be used throughout the exploration campaign, the design of Blocks 2 and 3 will benefit from the reduced cost and increased experience gained from CLV use. The CLV represents a *common* component between all CEV blocks and development is therefore intended to be a one-time expenditure. Furthermore, the CLV requires minimal change to existing infrastructure, assuring current supporters in government that their constituents will be able to continue their tasks with minimal interruption. The continued use of the CLV throughout the multi-decade exploration campaign strengthens this attribute, allowing CEV supporters the opportunity to claim security for their constituents for the foreseeable future. Finally, as future blocks are deployed, the CLV's basic parameters can be expected not to change, solidifying the benefits described above.

The Lunar Cargo Launch Vehicle (CaLV), shown in Figure 14, also makes extensive use of legacy components, including SRBs, an ET and SSMEs. Again, all alternatives are selected from legacy designs. The selected design is chosen upon the basis of low cost and high reliability. Conveniently, each of the CLV and CaLV designs makes use of components that are manufactured in districts that have traditionally provided strong support for NASA's human spaceflight programs. This allows the workforce associated with these components to largely be maintained, preventing large changes that might engender Congressional opposition.

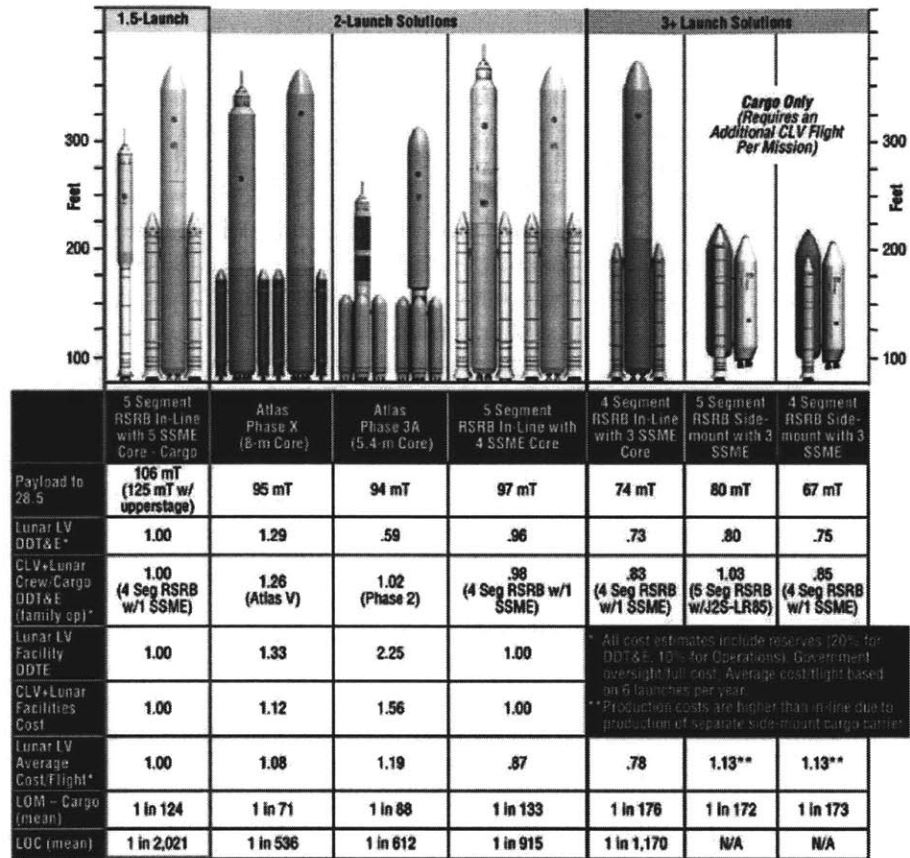


Figure 14: Lunar Cargo Launch Comparison -- sourced from (NASA 2005)

Unlike the CLV, the CaLV is intended to be used as part of Block 2 to enable cargo to be transported to the Moon. As such, some of the components that make up the CaLV (the ET in particular) will not be used immediately. Instead they must be stored and maintained until Block 2 is ready for deployment. In addition to the comparatively small development costs required to convert the legacy components from their initial form to the new design, a maintenance cost must be incurred until Block 2 is deployed so as to ensure that the facilities and workforce expertise making up the specific legacy components are not lost. From a purely economic perspective, this approach makes sense so long as the costs of maintenance are less than the costs of development of an entirely new system. Given the expense required to develop new launch systems, this is likely to hold. Recalling the definition of political sustainability as an action that allows for meeting current resource needs without compromising future resource needs, we

see that the CaLV represents a type of legacy component that is politically sustainable if its maintenance costs do not prohibit the successful deployment of Block 1 by overburdening the exploration program budget. As component maintenance costs increase, the political sustainability of their use decreases. Taken to an extreme, more money would be spent on maintenance than on the actual execution of the VSE. The CaLV represents a *delayed* legacy component – one that reduces future costs at the expense of present costs. Like the CLV, the CaLV requires minimal change to existing infrastructure and will be used throughout the exploration campaign once it is deployed. As such, the political benefits derived from using these components are considerable. The architect must therefore trade this political support against increased maintenance recurring costs, with the understanding that these recurring costs represent an investment in future capability.

Other opportunities for cost reduction through legacy component use are also available. For example, (Wooster, Hofstetter et al. 2005) note that a LEO-only CEV Thermal Protection System based upon reuse of Shuttle TPS components could enable a successful acceleration of Block 1 while simultaneously allowing more time for the development of a lunar-capable heat shield. This option is particularly salient given the fact that no human-rated heat-shield materials currently exist that can return astronauts safely from the Moon or Mars (Wooster, Hofstetter et al. 2005). Although NASA has released a Request for Information (RFI) soliciting non-Shuttle LEO-only TPS concepts, the Shuttle TPS is currently planned as a baseline (NASA Ames Research Center 2006). Unlike the two examples provided above, reuse of Shuttle TPS components does not provide a clear cost reduction for the VSE, since an upgrade to an ablative TPS must eventually be performed. Using a LEO-only TPS will likely increase total lifecycle cost since two TPS systems must be designed. Shuttle TPS elements are an example of a *temporary* legacy component – one that lowers immediate per annum cost at the expense of lifecycle cost. This can be achieved by delaying or stretching development costs for the lunar TPS over multiple years.

Analysis of these different legacy component types yields the following question: When is it appropriate to use legacy components for design within a technological environment? Solutions depend on the specific subsystem under study, and require an ability to analyze the political and technical drivers behind a given decision. This process must begin with a technical feasibility analysis to ensure that the proposed component may be used (see Figure 15).

### Technical Feasibility Analysis of Shuttle TPS Element Re-Use

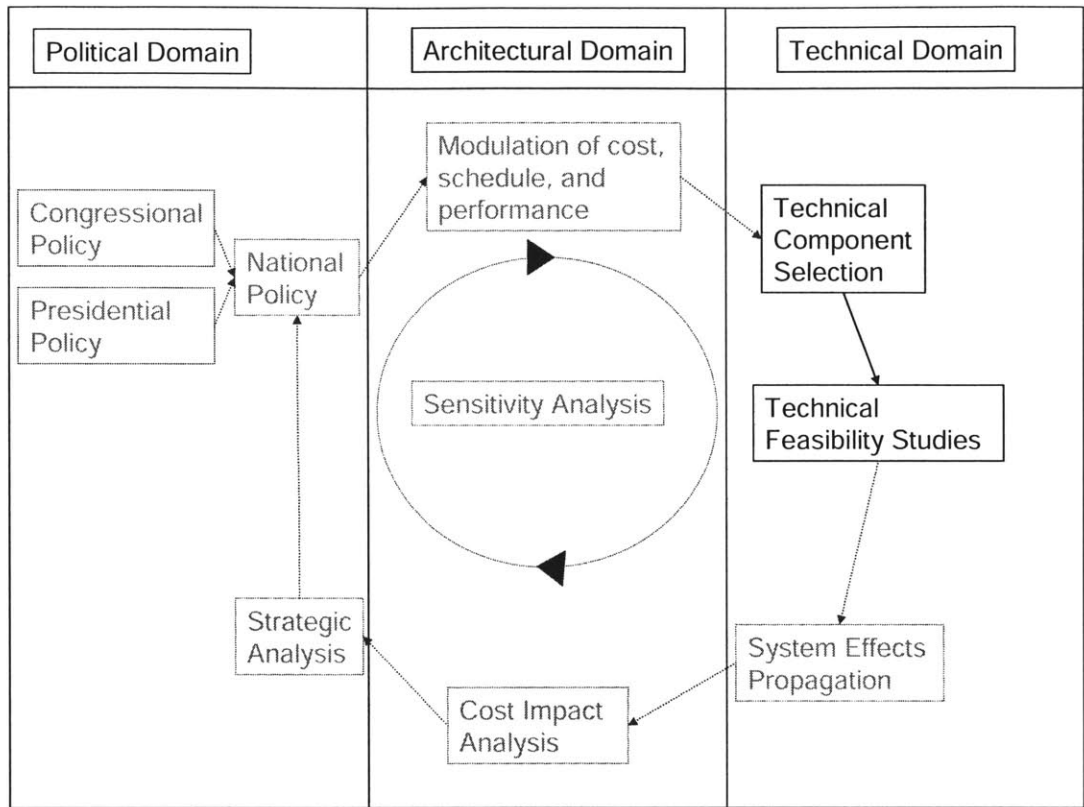


Figure 15: Within the technical domain, specific technical components must be evaluated to determine if their use is physically feasible.

This section examines the technical feasibility of using Space Shuttle TPS elements on the heat-shield forebody of a conic CEV, such as shown in Figure 16, for LEO return. In addition, any use of legacy components must take into account the effects that such a choice will have upon the rest of the space exploration architecture. Therefore, the technical analysis is supplemented by an articulation of the subsystems across which system effects might propagate. Political and organizational factors add to the richness of this analysis and are therefore also considered.

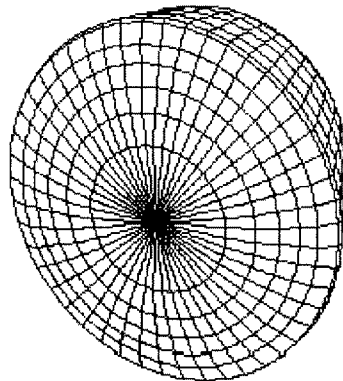


Figure 16: A candidate conic CEV shape, identified by the Draper/MIT CER team as providing a low maximum heat rate while not compromising volumetric efficiency. Sourced from (The Charles Stark Draper Laboratory Inc. 2005)

Any vehicle that is returning to Earth must survive the harsh environment of atmospheric re-entry. Crewed vehicles, in particular, are subject to a number of constraints imposed by the requirement to maintain the astronauts on board in good health while not interfering with the successful operation and return of the vehicle. The material composition of the TPS is driven, in particular, by the maximum heat rate that the vehicle will encounter during hypersonic re-entry.

In order to calculate the maximum heat rate encountered during re-entry, we must first define parameters for the vehicle and the planet to be studied. Table 2 outlines the values of the variables used.

Table 2: Parameters for initial CEV TPS analysis – CEV specific values were derived from (The Charles Stark Draper Laboratory Inc. 2005).

Variable Name	Value	Units	Notes
S	19.635	m <sup>2</sup>	TPS surface area
m	10000	kg	CEV mass – conservative overestimate
W	98000	N	CEV weight
$\rho_{sl}$	1.225	kg/m <sup>3</sup>	Atmospheric density at sea level
$\alpha$	0.000141	m <sup>-1</sup>	Atmospheric decay constant
V <sub>0</sub>	7000	m/s	Initial entry velocity from LEO
h <sub>0</sub>	200000	m	Initial altitude
g	9.8	m/s <sup>2</sup>	Acceleration due to gravity
R <sub>n</sub>	5.13	m	CEV nose radius of curvature for a 5-meter diameter CEV
V <sub>c</sub>	8029	m/s	Satellite circular velocity at initial altitude

In order to determine the technical feasibility of using Shuttle legacy TPS elements on the CEV, we must first determine the maximum heat rate [W/cm<sup>2</sup>] that the vehicle might face upon re-entry from the Earth's atmosphere. To provide a lower bound on the heating rates that we might expect the CEV to encounter, we assume a lifting entry trajectory. This regime is premised on the assumption that the entry angle into the Earth's atmosphere,  $\gamma$ , is negligible with respect to the horizontal. The following two equations govern the re-entry profile for the equilibrium glide path (the minimum velocity necessary to maintain lifting flight) (Hankey 1988):

$$\frac{L}{W} = \left[ 1 - \frac{V^2}{V_c^2} \right] = \left[ \frac{SC_L}{2W} \right] \rho V^2$$

$\rho$  is the instantaneous atmospheric density, L is the lift force acting upon the vehicle, and V is the instantaneous relative velocity measured with respect to the moving atmosphere.

$$\frac{D}{W} = \frac{D}{L} \left[ \frac{L}{W} \right] = \frac{D}{L} \left[ 1 - \frac{V^2}{V_c^2} \right] = -\frac{\dot{V}}{g}$$

D is the drag force acting upon the vehicle and  $\dot{V}$  is the time-derivative of velocity.

The trajectory outlined by these equations is called the “equilibrium glide path”, and constitutes the shallow border of the re-entry corridor (Condon, Tigges et al.). Attempts to reduce entry drag force, and thus heating rate, beneath the values derived from these equations would result in a skip out of Earth’s atmosphere.

An upper bound estimate may be placed on heating rate through the use of a ballistic entry profile. Under this regime, we assume that the entry angle,  $\gamma$ , is constant and sufficiently large in magnitude that any lift force acting upon the body may be neglected. The following equations govern the re-entry profile for ballistic entries (Hankey 1988):

$$\dot{h} = V \sin \gamma_0 = V_0 e^{-\frac{\rho}{\beta}} \sin \gamma_0$$

where  $\beta$ , the ballistic coefficient, is defined as  $\beta = \frac{-2W\alpha \sin \gamma_0}{gC_D S}$

$$-\frac{\dot{V}}{g} = \frac{D}{W} = \frac{C_D S}{2W} \rho V^2 = -\frac{\beta C_D S}{2W} V^2 \ln \frac{V}{V_0}$$

Ballistic re-entry heating is calculated for  $\gamma = -7^\circ$  (the largest target entry angle used during the Apollo missions) and  $\gamma = -5.46^\circ$  (congruent with the analysis performed by (Putnam, Braun et al. pending) in conjunction with the NASA CE&R study).

These equations, with the initial conditions outlined above, may be used to determine limiting cases for velocity profiles of a vehicle entering the Earth’s atmosphere. Based upon the results of these analyses, heat rate was calculated using a Detra-Kemp-Riddell equation for convective heating at the stagnation point, as follows (Condon, Tigges et al.):

$$\dot{q}_s = \dot{q}_{Const} * \left(\frac{1}{\sqrt{R_n}}\right) * \left(\sqrt{\frac{\rho}{\rho_{sl}}}\right) * \left(\frac{V}{V_c}\right)^{3.15}$$

where the stagnation-point heat rate,  $\dot{q}_s$ , is measured in  $W/cm^2$ , and  $\dot{q}_{Const}$  is a dimensionless value set equal to 11,030 (Condon, Tigges et al.). Radiative heating was considered negligible for Earth entry velocities under 9 km/s (Tauber and Sutton 1991). Using Euler’s method, implemented in Microsoft Excel with a time-step of 0.01 seconds, the maximum stagnation-point heat rate throughout the flight was determined.

Maximum heating rates were calculated for a number of L/D and  $C_D$  configurations, consistent with a capsule of a shape similar to that of the Apollo command module. The following figure outlines these values, which were used as inputs to the above equations.

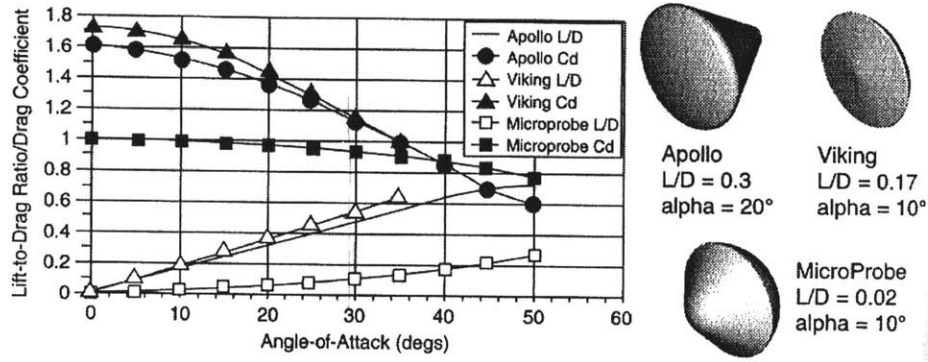


Figure 17: Input data for heating rate equations was sourced from (Condon, Tigges et al.)

The following Table 3 gives these values and their associated maximum heat rates for the range of conditions described above.

Table 3: Maximum heating rates as a function of angle of attack for an Apollo-style capsule with parameters listed above

Angle of Attack (degrees)	L/D	$C_D$	$q_{s, \max}$ [W/cm <sup>2</sup> ], $\gamma_0 = 0^\circ$ (Lifting Re-entry)	$q_{s, \max}$ [W/cm <sup>2</sup> ], $\gamma_0 = -7^\circ$ (Ballistic Re-entry)	$q_{s, \max}$ [W/cm <sup>2</sup> ], $\gamma_0 = -5.46^\circ$ (Ballistic Re-entry)
5	0.1	1.60	45	72	64
10	0.2	1.50	37	75	66
15	0.3	1.50	31	75	66
20	0.35	1.35	30	79	69
25	0.4	1.30	28	80	71
30	0.5	1.10	28	87	77
35	0.55	1.00	28	91	81
40	0.65	0.85	28	99	87
45	0.7	0.70	29	109	96
50	0.7	0.60	32	118	104

Table 4, sourced from (The Charles Stark Draper Laboratory Inc. 2005), outlines the maximum heating rate that the Block 1 CEV may be expected to endure:

Table 4: Listing of existing Thermal Protection System materials, courtesy of Bernie Laub, NASA Ames Research Center (The Charles Stark Draper Laboratory Inc. 2005).

**TPS Options: Ablative vs. Reusable**

	Material	Manufacturer	Density (kg/m <sup>3</sup> )	Highest Test (W/cm <sup>2</sup> )
Ablative	Carbon Phenolic (Galileo)	Fibercote, Hitco Inc.	1,440	25,000
	Carbon-Carbon (Genesis)	C-C Advanced Technologies, Inc.	1,800/180 (layer 1/2)	25,000
	PhenCarb (TRL = 5)	Applied Research Associates	320-448	~722
	PICA (Stardust)	Fiber Materials, Inc.	224 - 321	~3,000
	Avcoat 5026 (Apollo)	AVCO Corp (out of business, recipe found)	513	>2,500
Reusable	AETB-8,12 (Shuttle)	Boeing, Forrest Machining, United Space Alliance (USA)	128 - 192	~35
	FRCI-12,20 (Shuttle)	Boeing, Forrest Machining, United Space Alliance (USA)	192 - 320	~35

Table 5, sourced from (Ewert, Curry et al.), corroborates this data for Shuttle reusable surface insulation and provides values for the reinforced carbon-carbon (RCC) that is used on the Space Shuttle's nose, chin and wing leading edges (the areas of highest heating).

Table 5: Candidate TPS Materials. Sourced from (Ewert, Curry et al.)

	Service Limits		
	Density (g/cm <sup>3</sup> )	q <sub>max</sub> (W/cm <sup>2</sup> )	Temperature (K)
<b>Metallics</b>			
René 41	8.249	9	1145
L-605/Haynes-25	9.130	13	1256
Coated columbium	8.670	33	1589
Tantalum	16.723	69	1922
Titanium multiwall	0.192	3.4	922
<b>Ablators</b>			
Silicone elastomers	0.240-0.577	69	<1922
Avco 5026-39 (Apollo)	0.512	432	3033
Phenolic nylon	1.201	432-1109	3033-3839
Carbon phenolic	1.458	>1109	>3839
Carbon-carbon	1.568	69-108	1922-2061
<b>Reusable surface insulation</b>			
Rigid	0.144-0.352	28-45	1533-1744
Flexible	0.096-0.160	0.88-12	644-1256

Note that peak heating rates decrease with entry angle. This suggests that, as entry angle decreases, maximum heating rates will converge to the values predicted by the lifting-entry equations. For entry angles comparable to the upper limits of those used in Apollo missions, a ballistic re-entry exceeds the minimum tolerances of both Shuttle TPS tiles and Shuttle carbon-carbon. This implies that a shallower entry angle should be used.

For entry angles less than or equal to -5.46 degrees, use of Shuttle TPS elements is feasible if carbon-carbon is used to supplement the regions of highest heating. Since the CEV would be operating near the boundary of  $q_{s, \max}$  for carbon-carbon, and beyond the heat rate tolerances of the tiles, carbon-carbon should be used at the stagnation point, similar to the nose cap used on the Space Shuttle Orbiter. The absence of significant heat-rate margin suggests that a Block 1 CEV should use a shallow entry angle so as to reduce peak heat rate. This, in turn, will decrease entry corridor width as the vehicle is forced to fly closer to the equilibrium glide path and the skip-out boundary. This decrease in heat rate comes at the expense of an increase in total heat load (Condon, Tigges et al.), as

shown in Figure 18 and Figure 19, requiring an ECLSS system that can tolerate large heat inputs for longer periods of time during reentry. Alternatively, the requirement that the heat of atmospheric reentry be dissipated over a longer period of time requires a thicker, and thus more massive, TPS to insulate astronauts from the thermal environment.

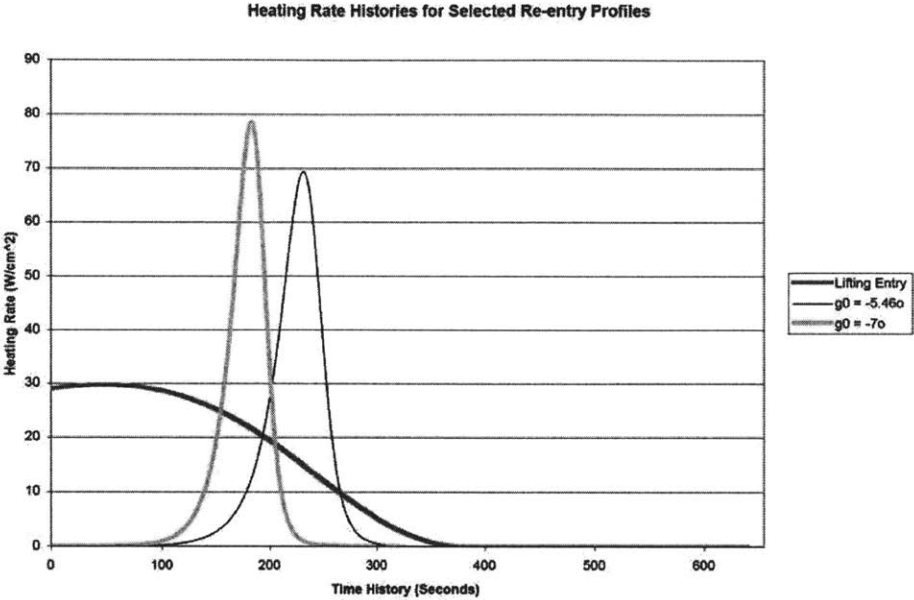


Figure 18: Heating-rate time history for a CEV with a 20-degree angle of attack

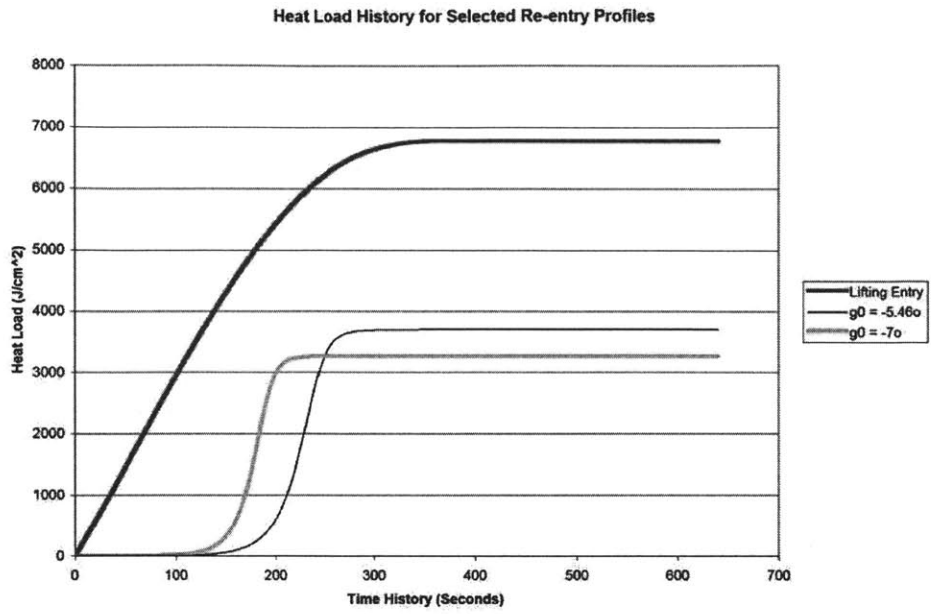


Figure 19: Heat load time history for a CEV with a 20-degree angle of attack

### System Effects Propagation Analysis for Shuttle TPS Element Re-Use

This section examines how a decision to use Shuttle TPS elements might propagate through the CEV system (see Figure 20).

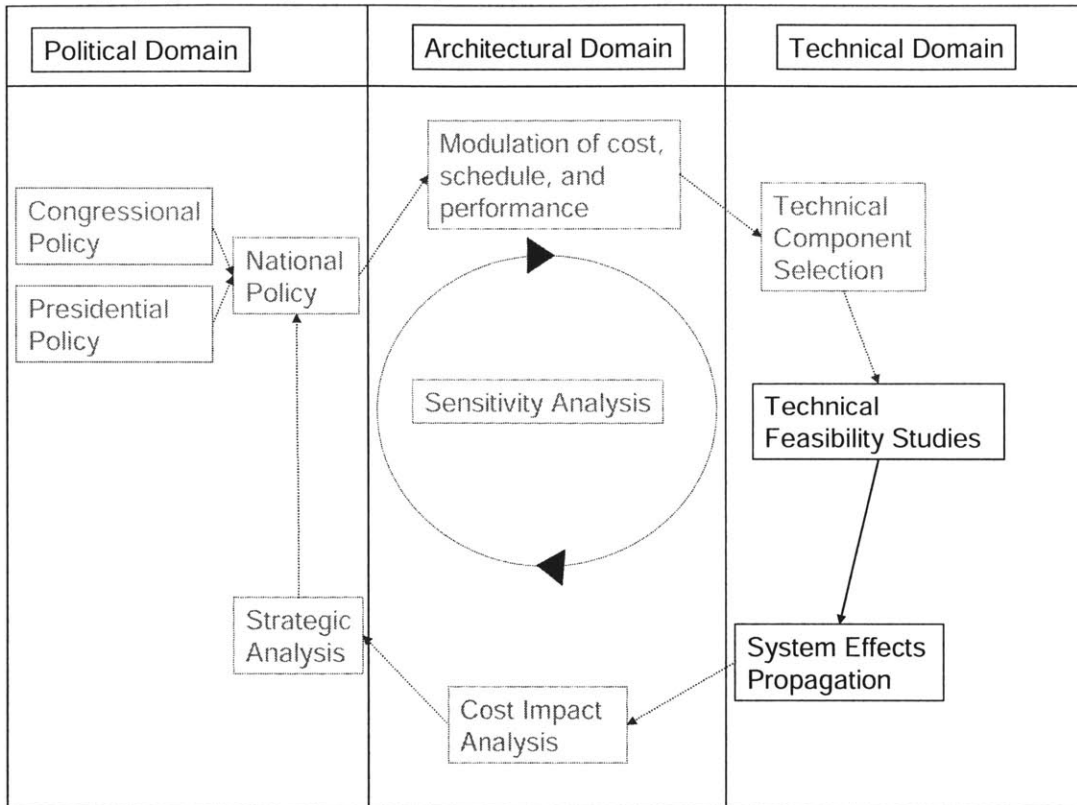


Figure 20: Once a component's use has been determined technically feasible, it must be examined for system effects and otherwise unexpected interactions with the rest of the system.

Given that LEO entries using Shuttle TPS elements are driven by the requirement to reduce heat rate, entry angles must be relatively shallow, driving trajectories closer to the equilibrium glide path. As a result, the vehicle must spend more time in atmospheric re-entry. Both of these effects cause a buildup of navigation error and a concomitant reduction in targeting accuracy (Col. Young 2006). This, in turn, negatively impacts landing site targeting accuracy. In the event of a Pacific Ocean landing, as planned by ESAS for return from ISS, this leads to a requirement for a larger dispersion of crew retrieval ships, ultimately increasing operations costs (NASA 2005).

ESAS lunar return utilizes ground landing techniques, taking advantage of the extra incoming velocity to execute a skip-out maneuver from the Earth's atmosphere to reduce targeting error. Since Shuttle TPS elements drive entry trajectories closer to the skip-out boundary, it is worth considering a similar skip-entry trajectory for LEO return. Compared to lunar return, the difficulty of return from LEO is increased by the smaller dynamic pressure during re-entry, an artifact of the smaller LEO re-entry velocity. In this case, a more powerful reaction control system (RCS) would be required to guide the CEV. This, in turn, requires that larger propellant and pressure tanks be included within the CEV structure, further driving up mass and reducing internal volume available for other items (Col. Young 2006). A trade study must be conducted to determine the relative costs of transitioning between operations plans for a sea-landing and a ground landing on one hand, and increasing the capability of the Block 1 CEV's GN&C and RCS subsystems on the other. In either case, a choice to use Shuttle TPS elements in the Block 1 CEV will have system effects that increase costs in other parts of the overall exploration architecture. Figure 21 illustrates the propagation of subsystem requirements resulting from the choice to use Shuttle TPS elements.

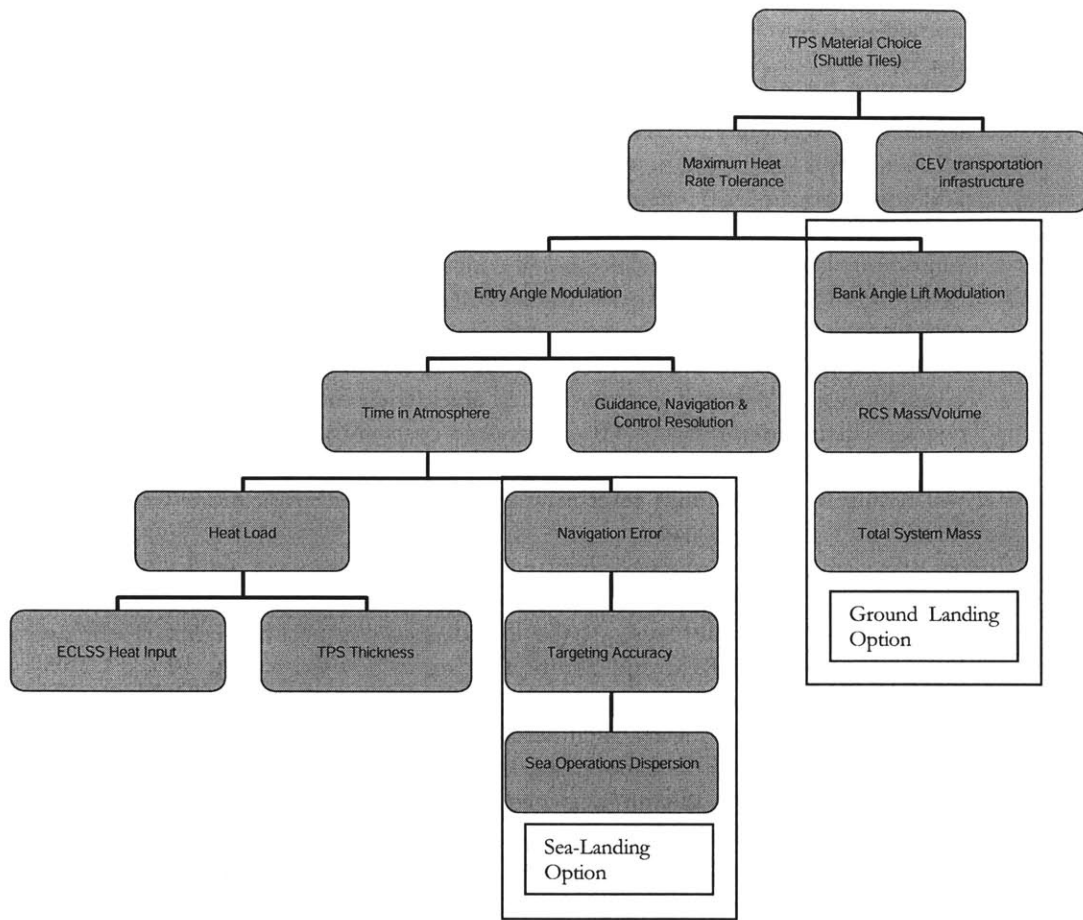


Figure 21: Tree diagram depicting the CEV subsystems that will be affected by a choice to use Shuttle TPS elements

Heat rate will be less of a driver for lunar and Mars returns, since human-rated versions of ablative materials with significantly more margin in heat-rate tolerance, such as Carbon Phenolic or PICA, will be used (The Charles Stark Draper Laboratory Inc. 2005) (PICA's tolerance of  $\sim 3000 \text{ W/cm}^2$  is twice the heat rate to be expected from an off-nominal Mars return at an entry angle of  $-5.46$  degrees (Putnam, Braun et al. pending)). Use of these materials on the Block 1 CEV would allow increased flexibility in the entry trajectory options available to ISS returns, since heat-rate would cease to be a large driver. On the other hand, this would delay CEV deployment until after development of human-rated ablative TPS materials. A system architect must therefore weigh the use of this particular legacy component, allowing for reductions in schedule, versus

immediately developing a new ablative TPS material, potentially delaying CEV deployment but allowing for more freedom in re-entry options and a reduced transition cost for going to the Moon. In addition, although it is within the range of technical feasibility to consider using Space Shuttle TPS elements to construct a LEO-only TPS for the new CEV, the system effects of this choice require that additional robustness be designed into certain subsystems up-front.

Numerous logistical and organizational concerns are also associated with the use of Shuttle TPS elements. These tiles and RCC panels are brittle, necessitating a review of each individual tile after each Shuttle's return (Cooper and Holloway 1981). Such reviews are expensive, partially driving the Shuttle's high workforce costs. Since the CEV will jettison the heat shield after each use, tile refurbishment checks will not drive legacy TPS workforce costs (NASA 2005). On the other hand those elements of the TPS that are to be reused, such as the upper TPS tiles, will require inspection and refurbishment steps for recertification (Col. Young 2006).

It was a breach in the RCC caused by an impact with a piece of insulating foam that was the proximate cause of the loss of *Columbia* upon re-entry (Gehman, Barry et al. 2003). If RCC and Shuttle tiles are to be used for the Block 1 TPS, extra care must be taken during transportation of the CEV to ensure that the TPS is not breached in any way. Such a requirement for added protection prior to launch is likely to increase the costs of transport and packaging for the CEV, potentially requiring a custom-designed sling or holder from which the vehicle could be suspended so as to prevent contact between the TPS and other hard surfaces (Col. Young 2006). An ablative TPS, on the other hand, is not as brittle and likely would not require that the CEV receive the same care in transport.

#### **Political & Workforce Implications of CEV TPS Element Re-Use**

A savvy system architect must also consider the political implications of using a particular legacy component. Table 6 lists the various parts that make up the Space Shuttle Orbiter TPS, and where these parts are made.

Table 6: Listing of distributive breakdown of Orbiter TPS Components. Data sourced from (Dumoulin 1988)

Orbiter TPS Component	Subsystem Contractor (as of 1988)	City	State
AFRSI quilted fabric	Rockwell International	Downey	CA
Quartz thread	J.P. Stevens Co.	Los Angeles	CA
Inconel 750 wire spring and fabric sleeving	Santa Fe Textiles	Santa Anna	CA
HRSI and LRSI tiles and HRSI FRCI-12 tiles	Lockheed Missiles and Space Co. Inc.	Sunnyvale	CA
Alumina mat	ICI United States Inc.	Washington	DE
Nomex felt	Albany International Research Co.	Dedham	MA
AB312 fibers	3M Company	St. Paul	MN
Macor machinable glass ceramic	Corning Glass Works	Corning	NY
Velcro hooks and loops	Velcro Corp.	New York	NY
Room-temperature vulcanizing adhesive	General Electric	Waterford	NY
High-purity silica glass	Johns Manville	Waterville	OH
Fibrous pile-S glass	Prodesco	Perkasie	PA
RCC	Vought Corporation	Dallas	TX

Unlike the SRB and the ET, a decision to cease using these TPS elements on the CEV would likely not deprive the nation of a core competency, nor would it leave a large number of people unemployed. This is particularly true given that NASA plans to use Shuttle TPS materials to shield the CEV upper-body – a part of the vehicle that is not in the stagnation path and will therefore not bear the brunt of the heat of re-entry – regardless of the material that is used for the forebody TPS (NASA 2005). As such, using new ablative TPS materials for the CEV forebody would only constitute a reduction in demand rather than a complete cessation of the product line. This is particularly true since the technology developed for the Orbiter TPS components has produced spin-offs that create a demand outside of the Space Shuttle program for high-performance thermal protection materials (e.g., some professional racing cars use Shuttle TPS-derived materials to insulate drivers from engine heat emissions) (Cooper and Holloway 1981; NASA 2006). Overall, this suggests that a decision not to use Shuttle TPS elements on the Block 1 CEV forebody would not meet with as much political resistance as a decision to stop using SRBs.

## Conclusion

NASA's directive to accelerate the Crew Exploration Vehicle drives the development of a system architecture that employs a multi-block deployment strategy and significant re-use of legacy components. The potential cost- and schedule-savings to be gained from such legacy component use makes their consideration attractive to the system designer. Nevertheless, care must be taken to ensure that the unintended system costs of such a choice do not outweigh the benefits to be gained. The Shuttle TPS trades outlined above provide a methodology that the system designer might use in approaching this decision. In particular, we find that use of Shuttle TPS elements is feasible, although it will require changes that propagate throughout the entire system. For example, use of these components would necessitate a trade between landing site targeting accuracy, maximum heat rate endured by the entry vehicle, and total system mass and volumetric efficiency. This example demonstrates that inclusion of legacy components come with a cost. Although we leave the task of characterizing this cost tradeoff to future research, we may apply the same type of thinking to establish a framework to classify types of legacy components.

The CLV is largely enabled by what we call a Common legacy component. Common components, such as the SSME and the SRB, may be incorporated directly into Block 1 of the CEV architecture, and will continue to be used throughout the product's lifecycle. Since the system was initially designed around these components, we assume negligible system effects for Common legacy components. We may therefore model this by a reduction in up-front development cost. The CaLV, on the other hand, is partially enabled by the ET, a Delayed legacy component. Delayed components are to be incorporated into Block 2 or later and therefore must incur some maintenance cost until they are utilized. We may model this by a recurring maintenance cost followed by a non-recurring implementation cost. In order for a Delayed legacy component to be economical, the implementation cost must be less than the cost of building a new vehicle. A system designer must decide whether the maintenance costs required for Delayed legacy component use are worth the future savings.

Finally, we identify Shuttle TPS elements as an example of a Temporary legacy component. These are parts that are to be used in Block One and then replaced in Block Two by new technologies. We model this by a reduced development cost for Block One followed by an upgrade cost for Block Two. Thus, Temporary legacy components are used as a means of reducing the costs of the current vehicle block by deferring these costs until the next block's development begins. Table 7 summarizes the three types of legacy components identified:

Table 7: Summary of the different legacy component types identified in this chapter.

Legacy Component Type	Effects on Block 1 Deployment Cost	Effects on Block 2 Upgrade Cost
Common	Reduced cost	No effect
Delayed	Added maintenance cost	Reduced cost
Temporary	Reduced cost	Added upgrade cost

The three types of legacy components displayed above all have different cost profiles that will affect the budgetary history, and therefore the political success, of the CEV acceleration. Thus, through judicious choice of legacy components a savvy system architect may modulate the per annum, and total lifecycle, costs of the system under development. This ability is limited by the range of legacy components available – more options allow increased controllability over the space of available cost profiles – and by the ability of the architect to understand how use of a particular component might affect the overall cost profile in an uncertain future.

The next chapter attempts to characterize the cost tradeoffs dominating each of the three types of legacy components identified. This information is used to determine how a decision to accelerate the CEV through the use of legacy components might affect the overall system and upgrade cost. This will allow for a comparison of the costs of upgrading to Block 2 at some point in the future vs. building in a lunar capability now.

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EVALUATING THE COSTS OF LEGACY COMPONENT USE

The previous chapter identified three separate types of legacy components differentiated by the architectural blocks in which they are deployed. Each of these three types may be expected to yield different cost profiles over the lifecycle of the system. Since design for political sustainability requires an understanding of how cost might change through time, an understanding of the determinants of these cost profiles is useful to the system designer. This chapter is aimed at characterizing these determinants. In so doing, a system architect can translate technical information into cost parameters more useful to political actors (see Figure 22).

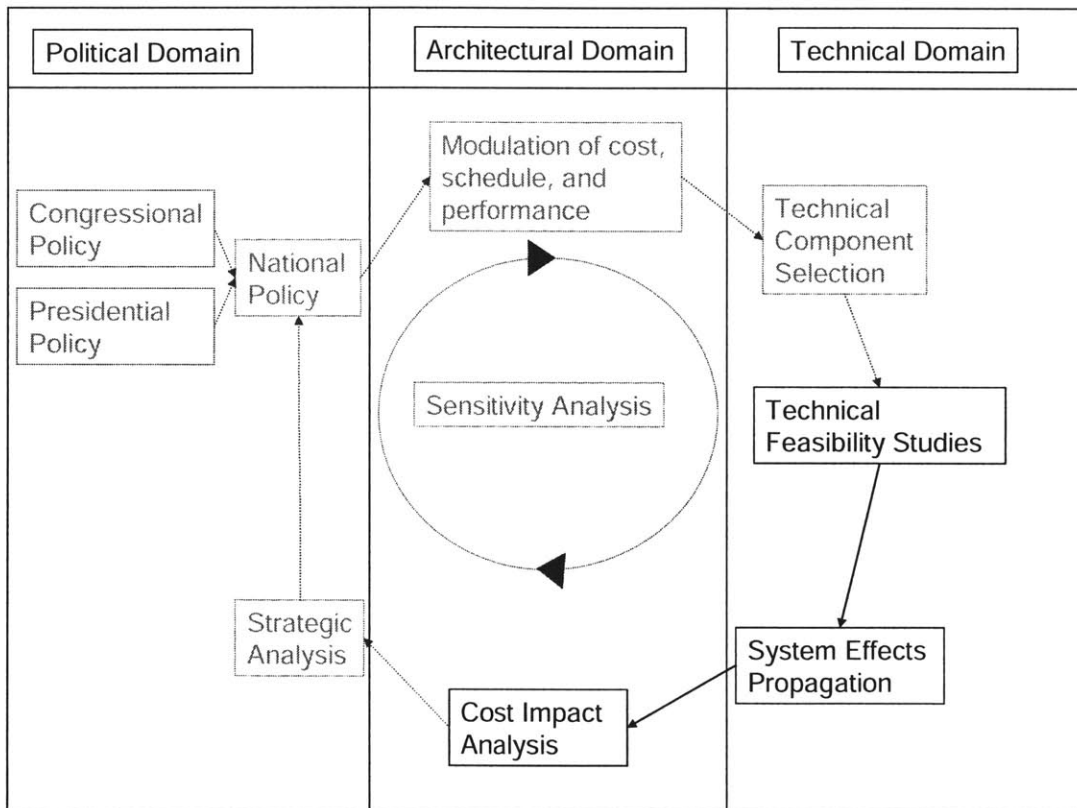


Figure 22: This chapter demonstrates one means of translation from the technical domain to the architectural domain.

At the early stages of design, there is very little detailed information that may be fed into a cost model. Nevertheless, we can make use of the best tools that we have available to provide rough order of magnitude cost estimates. The Advanced Missions Cost Model (AMCM), developed at Johnson Space Center, takes block versioning into account for system-level modules (in this case, the CEV). The AMCM uses the following equation to derive system cost upon the basis of past regression data (Guerra and Shishko):

$$C = \alpha * Q^\beta * M^\Xi * \delta^S * \varepsilon^{\frac{1}{IOC-1900}} * B^\phi * \gamma^D$$

where C is the total system cost, Q is the quantity of items to be produced (in the case of development, Q is the number of test articles, mockups, etc.), M is the system's dry mass, S is a dimensionless variable reflecting what type of mission is to be accomplished (for human reentry, S=2.27), IOC is the initial year of operation, B is the block number, and D is a qualitative assessment of difficulty ranging from -2.5 to 2.5 in increments of 0.5. In addition, the following dimensionless parameters take on the values listed below based upon historical data and regression analyses:

$$\begin{aligned}\alpha &= 5.64 * 10^{-4} \\ \beta &= 0.5941 \\ \Xi &= 0.6604 \\ \delta &= 80.599 \\ \varepsilon &= 3.8085 * 10^{-55} \\ \phi &= -0.3553 \\ \gamma &= 1.5691\end{aligned}$$

### **The Effects of Development Date on Cost**

Figure 23 displays the predicted cost of bringing a CEV online as a function of initial year of operation and block number. These costs have been normalized such that the cost of Block 1 CEV in 2012 is set equal to 1.

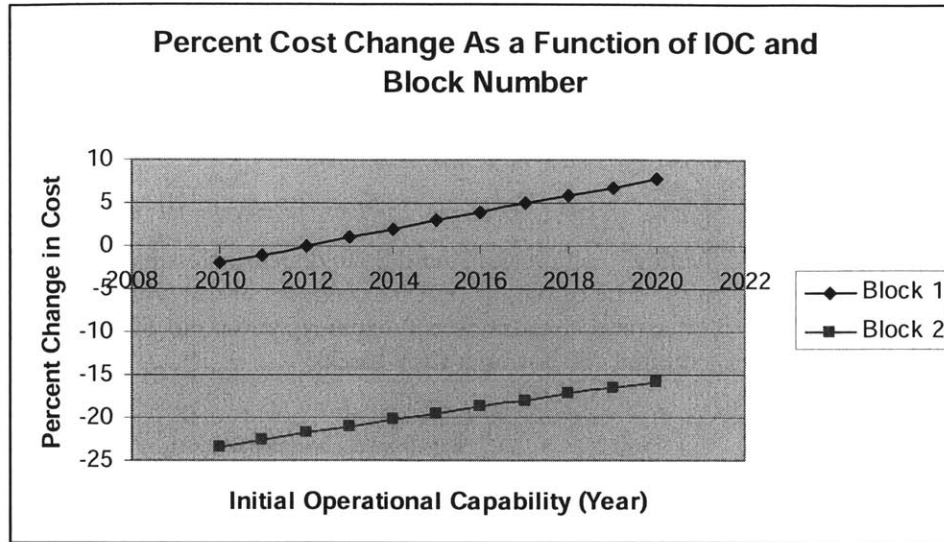


Figure 23: Holding all else equal, Block 2 will consistently cost less than Block 1, largely due to experience and learning benefits that are not directly quantified in this model.

Holding all else equal, the AMCM predicts that a Block 2 CEV will cost approximately 0.8 times the cost of a Block 1 CEV. Cost also increases slightly (~2%) for each year that the CEV is delayed.

The CER study performed at MIT put a dollar-figure on the overall CEV cost. The following cost estimation relationship (CER), based on the NASA Air Force Cost Model (NAFCOM), describes the total CEV development cost as a function of its dry mass (The Charles Stark Draper Laboratory Inc. 2005):

$$Cost = 2879.5 \ln M - 19120$$

Since the above CER is a function of mass only, we will assume that Block 1 cost remains constant regardless of the cost of the Block 2 CEV. Given that we are examining the relative costs of the two vehicles, this assumption allows us to place the associated numerical costs within the correct order of magnitude. Assuming an input dry mass of 6200 kg, we may predict a total CEV development cost on the order of \$6billion (The Charles Stark Draper Laboratory Inc. 2005). Assuming equal difficulty, and that the Block 1 CEV is to be launched in 2012 and the Block 2 CEV is launched in 2018, we can expect the Block 2 CEV to cost at most \$4.8billion to develop. We assume that the Block 1 CEV will be ready for launch by 2012, and the Block 2 CEV will be ready for launch by 2018. We also make a preliminary assumption that these blocks both begin

development in 2006. Given these assumptions and the above results, the cost per year of the CEV may be estimated through the application of cost-spreading beta curves. The generic form of such a curve is given by the following equation (Guerra and Shishko):

$$\text{Cumulative Cost Fraction} = A(10F^2 - 20F^3 + 10F^4) + B(10F^3 - 20F^4 + 10F^5) + 5F^4 - 4F^5$$

Where F is the time fraction and A and B are dimensionless parameters that vary depending on the type of project. For the purposes of this work, we assume that A=0 and B=1, typical for a crewed program (Guerra and Shishko). Figure 24 displays the expected cost for both CEV blocks:

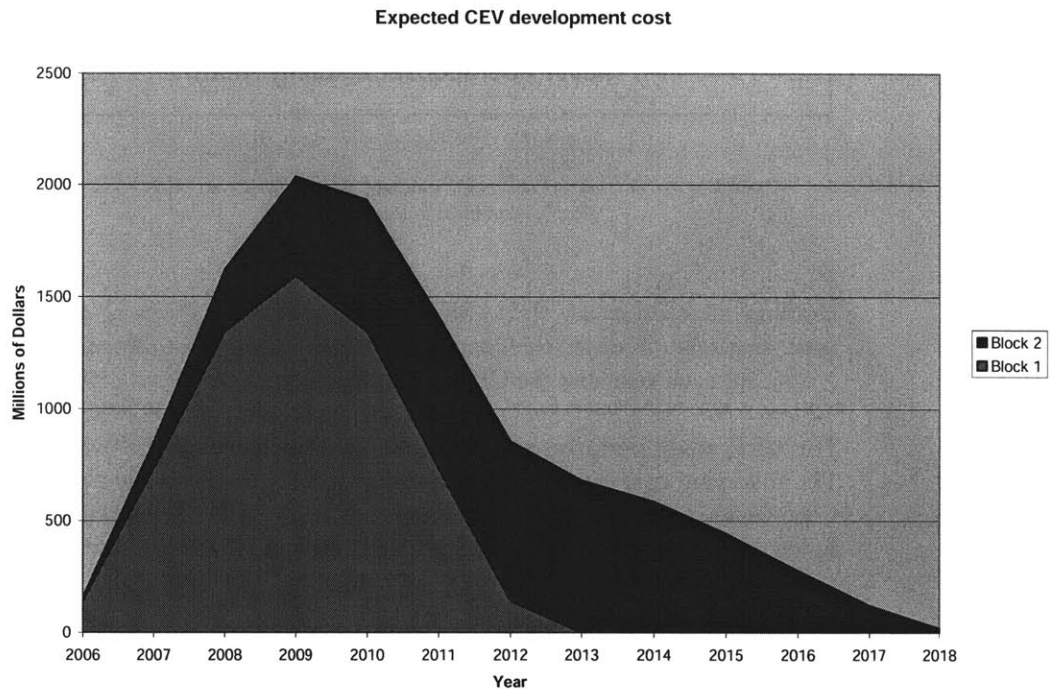


Figure 24: Notional budget sand-chart depicting expected CEV development cost assuming equal difficulty between CEV blocks and parallel development cycles.

The key take-away from this chart is that, for the development of two CEV blocks of relatively equal difficulty, beginning the development of Block 2 early can significantly reduce per annum cost in the out-years, even at slight increase to lifecycle cost. This is particularly relevant to Delayed legacy components – those

that must be maintained until they are to be used – since the lag time before deployment allows an amortization of the development cost. Beginning development of Block 2 as early as possible would also take advantage of Wildavsky’s strategy for incremental agencies that states that new programs and old programs should be linked so as to transfer support between the two (Wildavsky 1964). In the case of the CEV, this would link Congressional support for a return to LEO with Presidential support for a return to the Moon. Furthermore, early commencement of Block 2 development would allow the earlier development of a vested distributive workforce base which may be used to support the Block 2 CEV once the Block 1 has already been deployed. These benefits must nevertheless be weighed against the risk that the added annual cost of developing Block 2 would exceed the amount that Congress might be willing to provide funding for in a given year.

To illustrate the consequences of this trade, Figure 25 assumes that development of the Block 2 CEV is started in 2012, when the Block 1 CEV is first launched. In this case, the development costs of Block 2 are essentially compressed into half of the development time, decreasing present costs at the expense of the future. Delay of Block 2 until 2012 could erode Congressional support, particularly if the skilled workforce associated with a Delayed legacy component is lost in the interim. Furthermore, Block 2 would have to commence development at the same time that costs are increasing, potentially eroding political sustainability. Thus, beginning Block 2 development earlier may be said to enable political sustainability, presuming that Congressional funding limits are not exceeded. This particular constraint will be treated in more detail in the Chapter 5.

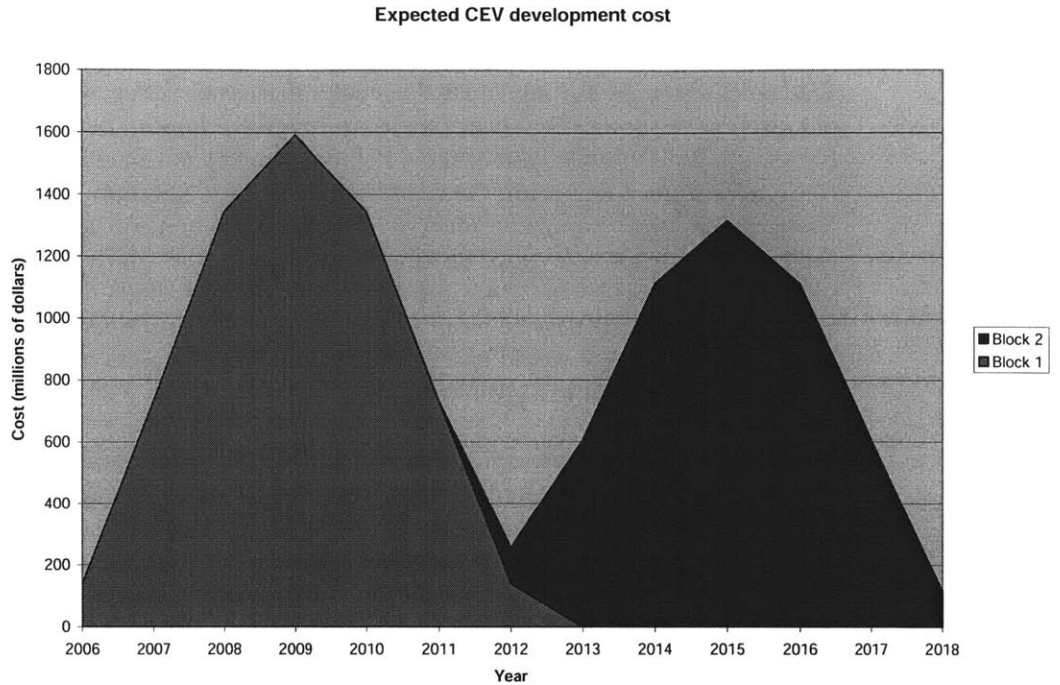


Figure 25: Notional budget sand-chart depicting expected CEV development cost assuming equal difficulty between CEV blocks and serial development cycles.

### The Effects of Development Difficulty on Cost

The above cases represent an example of what one might expect for the cost of the Block 2 CEV, varying only deployment date and holding all else equal. In practice, not all else is equal. For example, the Block 2 CEV could take advantage of commonality and existing synergies between the two vehicles so as to reduce the number of items to be produced, tending to reduce the difficulty, and hence the cost, of the upgrade. At the same time, the process of rushing a development schedule increases the difficulty of the development, tending to increase cost. The remainder of this analysis therefore examines difficulty as a parameter of interest. The AMCM cost estimation relationship (CER) described above includes a qualitative measure of “difficulty” that is related to new technology development. Although only an experienced program designer can evaluate this quantity within the context of AMCM, (Guerra and Shishko) provides some reference conditions for an analogous “complexity factor”, displayed in Table 8. The conditions attached to these complexity factors provide some insight into the drivers behind program difficulty.

Table 8: Reference Conditions and Values for Complexity Factors. Sourced from (Guerra and Shishko).

Condition	Complexity Factor
Off-the-shelf, minor modifications	0-0.2
Basic design exists, few technical issues, 20% new	0.3-0.5
Similar design exists, some technical issues, 80% new	0.6-0.9
Requires new design and qualification; needs some technology development	1.0
Requires new design and qualification; needs some technology development, multiple contractors	1.1-1.5
Requires new design and qualification, major technology development	1.6-1.9
Requires new design and qualification, major technology development, crash schedule	2.0+

### *Easy Upgrades*

Table 8 illustrates the primary benefit to be gained from using legacy components. Due to pre-existing design, development and qualification, legacy component use has the potential reduce complexity and therefore, cost, assuming negligible system effects. Common legacy components are particularly attractive since they will reduce the complexity of Block 1 without negatively affecting Block Two complexity. This can therefore reduce overall lifecycle cost. Delayed legacy components, on the other hand, can reduce Block 2 complexity without negatively affecting Block 1 complexity. This also has the potential to reduce lifecycle cost, assuming that the maintenance costs of these components do not outweigh the later cost savings. Thus, Delayed components are most effective when the time between Block 1 deployment and Block 2 upgrade is minimal. Finally, Temporary components have the potential to reduce the complexity of Block 1 while, in the best case, maintaining the complexity of Block 2. In the worst case, the complexity of Block 2 increases because of the added effort required to replace the legacy component. To better understand the effects of Temporary legacy component use, we must examine what drives complexity factors.

A decision to accelerate the CEV increases the vehicle’s complexity factor from within the 1.6-1.9 range to the 2.0+ range, largely because of the “crash schedule”. A decision to utilize legacy components on a Block 1 CEV would mitigate this complexity somewhat, particularly if the major technology development items are deferred through the use of Temporary legacy components. Depending on the extent to which legacy technology is used, this

could reduce the CEV Block 1's complexity significantly, perhaps to as low as the 1.1-1.5 range. We assume this as a lower bound given that political requirements would likely ensure the existence of multiple contractors. Nevertheless, if a lunar mission is to be achieved eventually, the technology required for Block 2 lunar missions must be developed. This suggests that the Block 2 CEV would have a complexity factor of at least 1.0, since, in the best case, Block 2 would need "some technology development" for the flight qualification and design of lunar systems after Block 1 has been flown. For example, a decision to use Shuttle TPS tiles on Block 1 would still require the development of a new ablative TPS for Block 2 lunar missions.

Alternatively, one may attempt as much technology development as possible early-on, thus reducing the complexity of Block 2 while increasing the complexity of Block 1. In this case, the Block 1 CEV would have a complexity factor of 2.0+, due to the rushed schedule, but the Block 2 upgrade would have an extremely low complexity factor, likely within the 0.3-0.5 range. This situation would be congruent with a choice to develop an ablative LEO-only TPS that allowed for an entry trajectory similar to that encountered by a lunar CEV. Since the Block 1 to Block 2 TPS upgrade would require minimal development (e.g., a thickening of a TPS to withstand higher heat loads) the transition from LEO missions to lunar missions would be relatively easy and low-cost. Taken to an extreme, this would suggest building a lunar-capable CEV initially and dispensing with the Block 1 to Block 2 transition. Therefore, there is a tradeoff between reducing the complexity, and thus the cost, of the CEV up-front and enabling an easier transition between Block 1 and Block 2 in the future.

The AMCM uses a difficulty metric analogous to complexity factors (Guerra and Shishko). We therefore apply the same type of logic in order to determine a cost differential. In particular, if we were to attempt to determine the CEV Block 2 cost, based upon relative difficulty, we could consider the *difficulty ratio* between the two systems, which is simply the ratio of the two difficulty factors. In the limiting case, we assume that the Block 1 CEV has the highest difficulty value available, 2.5, and that the Block 2 CEV has the lowest difficulty value available, -2.5. In this case, significant development work would have gone into designing Block One such that upgrade costs would be minimal. This allows for the smoothest possible transition between CEV Blocks since the vast majority of the development work has been performed in advance. Legacy components would largely be Types One and Two. In this case, the difficulty ratio would be equal to  $\gamma^{-5} = 0.11$ . In this case, and accounting for the AMCM block factor, the total cost of the Block 2 upgrade would be approximately 0.09 times the cost of the Block 1 CEV. For example, if we assume a \$6billion Block 1, this predicts a Block 2 cost lower bound of about \$500million (in practice, Block 1 would likely be more expensive due to the additional capability; nevertheless, the cost numbers

provided are rough order of magnitude, intended only for purposes of comparison). This cost number would be congruent with the situation described above in which the vast majority of LEO and lunar technology development occurs on the Block 1 CEV, with Block 2 incorporating relatively minor upgrades. For example, if the Block 1 CEV were to use an ablative TPS with material that could withstand lunar return, the costs of the Block 2 TPS upgrade would simply be those of testing and certifying a larger heat shield that could withstand lunar and Martian re-entry parameters. This cost comparison is captured in Figure 26 and Figure 27. On the other hand, if we were to assume that the Block 1 CEV and the Block 2 CEV were similar in difficulty, the situation would be similar to that displayed in Figure 24 and Figure 25.

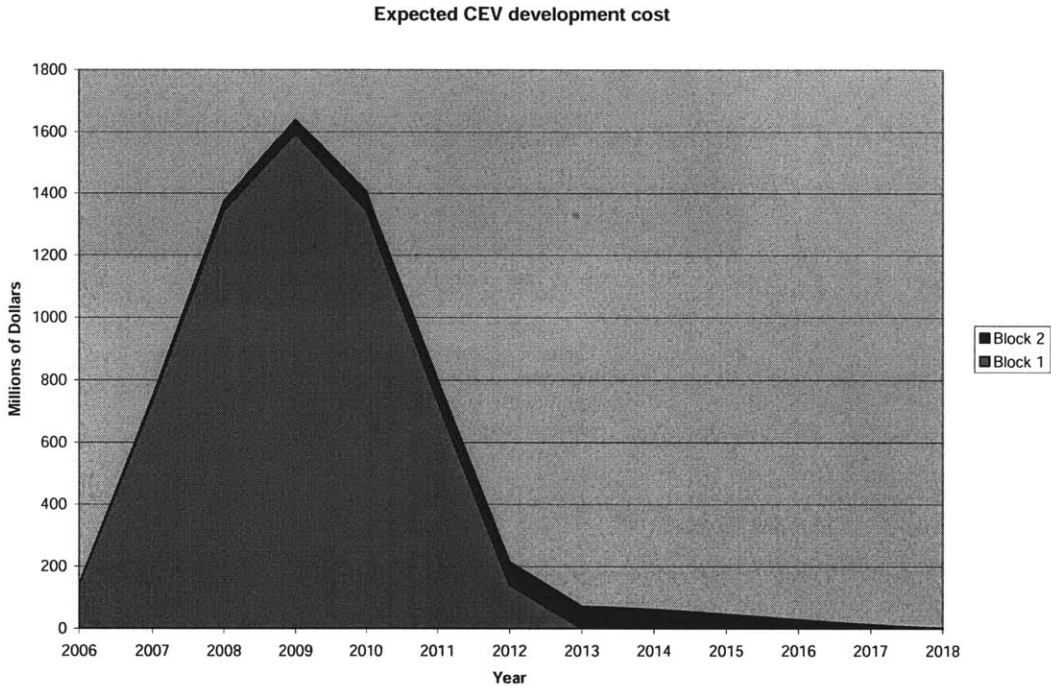


Figure 26: Notional budget sand-chart depicting expected CEV development cost assuming significantly less difficulty for CEV Block II and parallel development cycles.

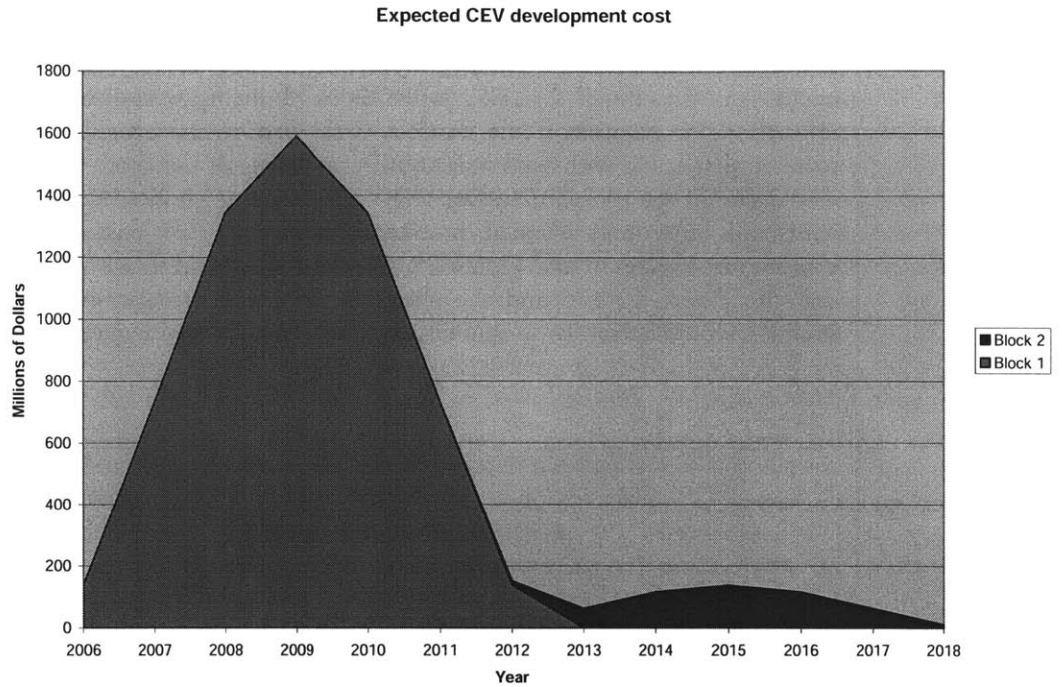


Figure 27: Notional budget sand-chart depicting expected CEV development cost assuming significantly less difficulty for CEV Block II and serial development cycles.

### *Difficult Upgrades*

The other extreme, in which the Block 1 CEV development has low difficulty and the Block 2 CEV development is very difficult, is illustrated below. This design would make significant use of Common and especially Temporary legacy components. The strategy in this case would be to reduce the cost of the Block 1 CEV, ignoring the future costs of the Block 2 CEV upgrade. In this case, we assume a Block 1 CEV development cost of \$500million, with a Block 2 upgrade cost of \$6billion (again, these numbers are rough order of magnitude estimates, intended only to provide extreme examples of how costs might be spread). Figure 28 displays the per annum cost assuming early commencement of the CEV Block 2 development.

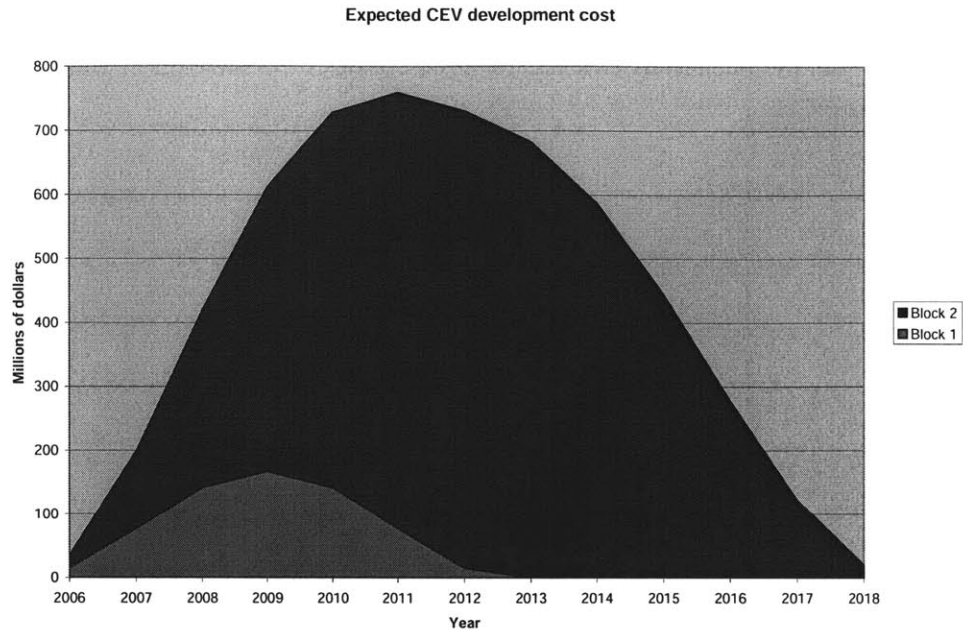


Figure 28: Notional budget sand-chart depicting expected CEV development cost assuming significantly more difficulty for CEV Block II and serial development cycles.

This scheme reduces per annum cost by spreading the majority of CEV development expenditure over 12 years, rather than six years. It is this type of thinking that motivates the deployment of a Block 1 CEV with reduced capability to accelerate the return of American astronauts to LEO. Given Congressional budget caps, this method might be used to reduce per annum cost to the point where NASA’s budget request resides below the incremental level; however, overuse of this strategy carries with it the risk that Congress might lose interest in funding the Block 2 CEV before it is deployed. Indeed, each additional year during which NASA is unable to show Congress a symbol of progress allows the program’s opponents to portray it as a waste of taxpayer resources. Furthermore, the above chart represents an extreme case that assumes large amounts legacy component use. It is at this point that limits on technology become important, since it might not be possible to use legacy components to this degree while still maintaining a viable vehicle design. Finally, this method stretches Wildavsky’s strategy to the limits of credibility – it might be difficult for NASA to justify expenditures for a LEO-only Block 1 CEV when the majority of those resources is in fact going to Block 2 development (Wildavsky 1964). In this case, NASA’s technical expertise and power over information exchange becomes critical.

Nevertheless, the message remains the same – there is an advantage to using legacy components to accelerate Block 1 of the CEV if the cost savings in doing so are diverted to Block 2. Figure 29 displays the situation in which those cost savings are not taken advantage of.

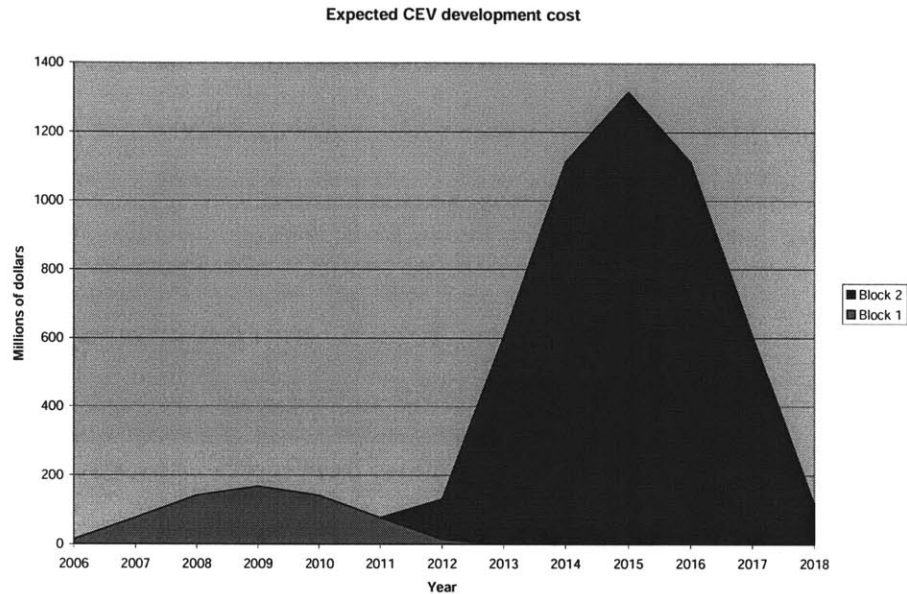


Figure 29: Notional budget sand-chart depicting expected CEV development cost assuming significantly more difficulty for CEV Block II and serial development cycles.

In this situation, Block 2 development begins following deployment of Block 1. As a result, Block 2 costs are compressed into a shorter time scale, creating a need for a large peak in funding, especially when compared with the costs of Block 1. This situation is inconsistent with the incremental expectations of Congress. Therefore, significant advocacy would have to occur in order to obtain the funding required for Block 2. Since we assume NASA’s budget is likely to remain relatively constant, this suggests that the funding required to carry out Block 2 development must be taken from another program, potentially alienating supporters and coalition members. This situation undermines political sustainability since deferral of costs today increases costs in the future, likely beyond the point where Congress would be willing to provide support.

**Conclusion**

Significant uncertainty surrounds the process of estimating the cost of complex space vehicles. Nevertheless, rough order of magnitude cost modeling techniques

can provide insight into how annual cost might be modulated by legacy component use and block deployment date. In particular, up-front development cost for Block 1 might be reduced by delaying Block 2 development, and by using legacy components aimed at reducing difficulty. Both of these methods will increase Block 2 per annum development costs, potentially undermining political sustainability if Block 2 costs become so high that Congress refuses to provide funding. This is particularly true if Temporary legacy components are used that reduce the difficulty of Block 1 development while maintaining, or increasing, the difficulty of the Block 2 upgrade. On the other hand, Block 2 per annum costs can be significantly reduced by commencing development earlier. By performing the most difficult development tasks early, the costs of upgrade can also be reduced. Thus, overall per annum cost may be modulated by decisions regarding which components to use and when to use them. The question remains as to how to best enable political sustainability through cost modulation. In order to answer this question, the next chapter returns to an analysis of the political environment in which NASA is situated. In particular, we examine how NASA and Congress may engage in strategic interactions in such a way as to enable simultaneous fulfillment of the Presidential Vision for Space Exploration goals and the Congressional desire to maintain American pre-eminence in human spaceflight.

## References

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- The Charles Stark Draper Laboratory Inc. (2005). CONCEPT EXPLORATION & REFINEMENT STUDY FINAL REPORT, NASA Exploration Systems Mission Directorate.
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STRATEGIC ANALYSIS

The previous chapter outlined some of the determinants of cost for the CEV. In particular, Temporary legacy components may be used to defer development expenses, thus reducing Block 1 costs at the expense of the Block 2 upgrade. Similarly, the Block 2 per annum cost may be reduced by beginning development earlier, thus increasing costs during the Block 1 development years. Thus, with careful planning, NASA can modulate its future cost to be consistent with spending limits. This chapter demonstrates how an agency, by understanding and modulating its costs, can interact with Congress to create a politically sustainable program (see Figure 30).

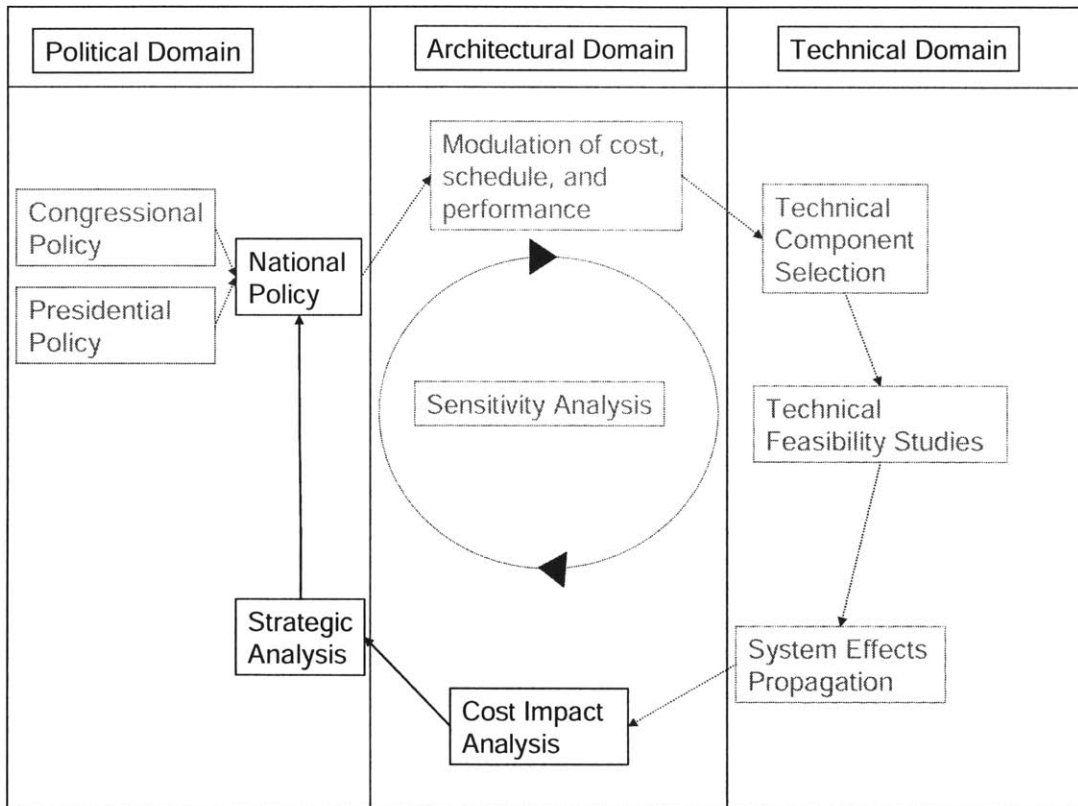


Figure 30: This chapter completes the policy-technology feedback cycle, demonstrating how architectural choices may impact policy decisions.

Since NASA, as a Presidential agency, is subject to political forces, particularly from the Executive Office of the President and from the U.S. Congress, we focus this chapter on the process by which NASA, acting as a proxy for the President, and the U.S. Congress interact to arrive at an affordable and politically sustainable funding level on a repeated yearly basis. Due to the fast-paced nature of events in the political environment, stakeholders must engage in myopic (short-term) strategies when defining the nature of their interactions. Nevertheless, long system lifecycles require that a system be sustained. Thus, non-myopic (long-term) strategies must also be employed. Similarly, NASA derives utility in both the myopic and non-myopic regimes. A successful balance between these two, often competing, needs is required for political sustainability. We construct a game-theoretic model to inform technical decision-making with regards to how costs may be spread to enable political sustainability. In order to capture non-myopic motivations, Brams' Theory of Moves is used to supplement traditional game theory (Brams 1994). We examine circumstances under which NASA and Congress may exercise "threat power" to motivate political decision making; yielding the counter-intuitive result that NASA's high valuation of its human spaceflight programs, and its concomitant unwillingness to put these under threat, creates an incentive for Congress to provide NASA less funding than requested. This dynamic, repeated over several years, is congruent with incremental funding.

### **Game Theoretic Analysis**

#### *Theory of Moves*

In order to examine the interplay of stakeholders using Theory of Moves (TOM), it is necessary to understand some of TOM's underlying concepts. *Threat power*, defined as "The ability to deter or compel an opponent to take action, at a loss to both players, given that the threatener will make a net profit in repeated play", figures prominently in our analysis (Brams 2003). It is worth noting that, using TOM, repeated play is differently defined than in standard game theory. In standard game theory, repeated play indicates that each player will literally re-play a stage game multiple consecutive times with the goal of maximizing total or average utility. In TOM, repeated play "...means that there is always later play that enables a threatener to recoup losses it may have incurred earlier in carrying out threats." (Brams 1994). In effect, a threatener may temporarily accept a loss so as to improve the final outcome. Practically speaking, this implies that a player may change position on a normal-form game matrix after the initial move has been made. Players then alternate, moving sequentially around the matrix, until one player decides to stop moving thereby ending the game.

In assessing the outcome of each of these models, we will examine two solution concepts – the Nash Equilibrium, defined as the "profile of strategies such that

each player's strategy is an optimal response to the other players' strategies", and the outcome induced by threat power (Fudenberg and Tirole 1991). In the specific context of the games mentioned below, the Nash Equilibrium can be identified by examining each player's best response to its opponent's strategy. The location where the best responses coincide is the Nash Equilibrium. For the purposes of this model and the situations that it describes, the Nash Equilibrium represents the myopic outcome – the result that would prevail if either player were to cease repeating the game in future rounds. This is also the outcome we could expect if each actor were to forego planning for future funding cycles, reacting only to the immediate situation at hand. As the name "myopic" suggests, the Nash Equilibrium represents an outcome taken without extensive foresight by the players involved. On the other hand, the outcome induced by threat power represents the non-myopic outcome – the result that would prevail if each player were to think ahead several steps in an attempt to anticipate and counter the other player's movements. In this case, the player with threat power is able to leverage the underlying structure-induced power-dynamics of the game to attain a favorable outcome. In the specific situations mentioned below, Congressional threat power represents the budgetary power guaranteed Congress by the checks and balances inherent in the framing of the constitution. NASA's threat power, when available, reflects the control that an agency possesses over the flow of technical/implementation information.

Myopic and non-myopic dynamics may interact in several interesting ways. Consider the case where the Nash Equilibrium is enforced by threat power. In this situation, myopic and non-myopic motivations overlap, suggesting that the structure of the interactions is such that actors perceive it within their long-term interests to observe their short-term interests. In other words, both players find the status quo satisfactory. On the other hand, when two outcomes do not coincide, we have a situation in which at least one player is willing to risk a possibly inferior outcome in the short-term in order to gain long-term advantage. In this situation, threat power indicates that one actor is being threatened with the Nash Equilibrium. The threatener must publicly announce an intention to default to the Nash Equilibrium if the threatened actor does not cooperate. A credible threat is therefore one in which the threatened actor concludes that it is in neither player's long-term interest to engage in myopic strategizing. As such, the threat-power-induced outcome must be Pareto-superior to the Nash Equilibrium outcome. In effect, there must be a strong incentive for each player to act in a non-myopic manner. Furthermore, the benefits of doing so must be common knowledge. This necessitates that the threatener make the consequences of not acquiescing common knowledge as well. To the extent that the threatened party perceives the threat as credible, the non-myopic outcome will result. Finally, we must consider the situation in which there is no threat power. In this case, myopic dynamics dominate and the Nash Equilibrium outcome may be expected.

*The Agency-Congress Game*

We model the Congressional budgeting process as a repeated game since it is an event that recurs every year at roughly the same time. To do so, we first consider the following simple game description: Every year, Congress must decide on how it will budget funds to each of the Executive Branch agencies within the Federal Government. This situation may be modeled as a game played between Congress, who makes the decision to *Save* or to *Spend* and the Agency, following the policy direction of the President, who must decide to *Deliver a Service* or *Not to Deliver a Service* to Congress, and by extension, the American public. Generally speaking, the situation may be described with by the normal-form game in Figure 31.

		Congress	
		Spend	Save
Agency	Deliver	(?,?)	(?,?)
	Not	(?,?)	(?,?)
	Deliver	(?,?)	(?,?)

Figure 31: A generic game matrix for the Agency-Congress game.

We may use a variant of this game to describe the funding process for an Executive Branch agency after submission of the President’s budget request. In this case, we define the agency in question as NASA providing the service of flying or not flying the vehicles capable of the next stage of human spaceflight (e.g., the three Space Shuttles, or the next Block of the CEV). In the case of CEV development, NASA is providing the service of preparing a new vehicle or new vehicle block by a predetermined scheduled launch date. For any given service to be delivered, we are interested in each player’s *valuation* of that service – which outcomes are preferred to NASA and to Congress? Four combinations of valuations, shown in Figure 32, are studied in this paper. These scenarios are linked to the drivers of Congressional valuation identified in Chapter 2. Our intent in creating these games is to illustrate where NASA can exercise influence over the budgetary process to enable political sustainability.

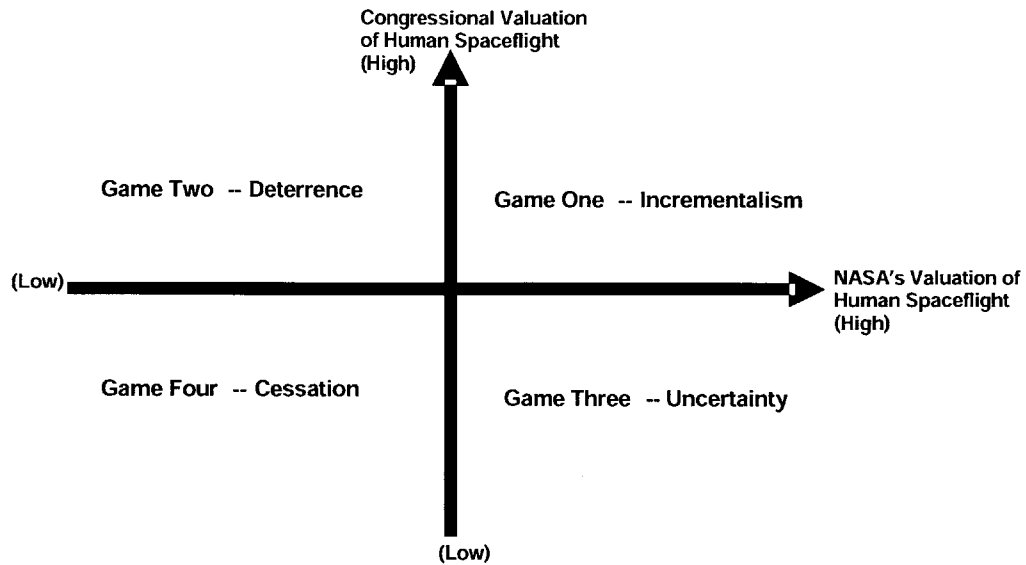


Figure 32: NASA's and Congress' relative valuations of human-spaceflight capability define the preference-ordering structure of each game. The four scenarios considered in this paper correspond to the four quadrants represented in this diagram.

We call the first scenario the Incrementalism Game because it describes a situation similar to that prevailing before the loss of the Shuttle *Columbia*: the agency's high valuation of the human spaceflight capability provided by the Shuttle and ISS programs combined with a Congressional incentive to keep costs low. This contributed to a budgetary environment marked by incremental budgeting and policy making (Davis, Dempster et al. 1966; McCurdy 1990). More generally, this game describes any situation wherein the agency or the President desires funding for something that Congress does not value as highly. In most years, NASA's activities do not address a salient Congressional concern (Wildavsky 1964). Thus, Incrementalism represents the typical situation faced by NASA (McCurdy 1990). As such, it will be the baseline from which the other games are assessed.

The second scenario, the Deterrence Game, describes a change in preferences brought about by exogenous events, such as the reorganization of the Congressional Appropriations Committees, which placed Congress members with civil space interests in positions of power, and the loss of *Columbia* – an event of national importance that raises the prospect that Americans might lose the dominant position in the human spaceflight arena. These events both

increased the salience of NASA's activities in Congress. In this situation, NASA may exercise threat power in order to achieve its desired outcome of obtaining funding from Congress for the purposes of maintaining human spaceflight capability. This is the situation in which NASA finds itself now, and it will likely continue until sustained American presence in LEO is regained, either via a return to flight for the Shuttle, or more likely via the launch of a CEV that has at least the capability of going to LEO.

The third scenario, the Uncertainty Game, explores the period of time in between the *Columbia* tragedy and the reorganization of the Appropriations Committees, when it was not clear if Congress would maintain its commitment to human spaceflight. More generally, this represents a situation in which the President values a capability that Congress does not. Other examples include President Reagan's directive to NASA to construct Space Station Freedom in 1985 without immediate Congressional support. Within the specific context of the CEV block upgrade, this game would represent the situation wherein NASA requests the funding for a new capability, such as an upgrade to Block 2, and Congress makes the determination that such an upgrade is not immediately necessary. In this situation, NASA's budget request would be sufficiently high that, compared to other priorities, the benefits delivered to Congress by maintaining human spaceflight capability do not offset the costs. Under these circumstances, NASA would be forced to continue to fly without receiving its full funding request.

Finally, the Cessation Game describes a situation wherein the President and Congress agree that a new capability does not provide value. In this situation, both parties agree to direct NASA to terminate the program. Such a situation occurred with the announcement by President George H.W. Bush of the Space Exploration Initiative (SEI) which, after a cost of over \$400 billion was announced, was dropped by Congress and by the President as too expensive to be politically sustainable (Ragsdale 1997).

These four games are represented using an instantiation of the Agency-Congress game mentioned above. In this "NASA-Congress" game, NASA may choose to Ground or Fly the vehicle providing human spaceflight capability (e.g., the Space Shuttle, or later, the CEV). In addition, the President makes a yearly budget request for NASA to Congress. The amount requested is designated BR. Congress then decides to grant NASA a certain level of funding, F, which may either be less than or greater than BR. A generic version of the NASA-Congress game is shown in the normal-form matrix in Figure 33.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	$(?, ?)$	$(?, ?)$
	Ground	$(?, ?)$	$(?, ?)$

Figure 33: A generic instantiation of the NASA-Congress game.  $F$  is the funding level granted by Congress and  $BR$  is the funding level requested by the President for NASA.

These games are used to define a framework for determining Congressional action in response to various NASA activities. In particular, we are interested in determining how astronaut launch capability to LEO might affect future available funding. We then examine this choice within the context of political sustainability.

#### *The Incrementalism Game*

##### *NASA's Preferences*

We examine the Incrementalism game first since this represents the baseline from which we measure increases or decreases in the NASA budget. The assumption underlying each player's preferences in this model dictate the outcomes. These assumptions are as follows:

- 1) NASA prefers flying its vehicle to grounding it.

We justify this assumption by noting that many of NASA's activities (such as the construction of the International Space Station and potential Hubble servicing missions) require a functional vehicle to be executed. NASA Administrator Dr. Michael Griffin adds that "...it takes about \$4.5 billion to keep the [Space Shuttle] going, whether you fly any flights or not" (2005), a significant portion of which goes to maintenance costs, workforce salaries, and refurbishment costs on the ground (Wertz 2000). This statement is reflective of the maintenance of any of the facilities involved in the human spaceflight enterprise, suggesting that NASA's budgetary expenditures would not be significantly reduced in the event that its vehicles become grounded. NASA would not ground its vehicles to save money.

- 2) NASA prefers receiving funding to having its funding cut.

This is largely justified by studies that conclude that an agency’s power and influence is largely related to the size of the budget under its control (Jackson 1983).

- 3) NASA prefers not to terminate a program or upgrade when sufficient funding is not present.

We justify this last assumption based upon historical observation, wherein NASA has displayed a “can-do” attitude, perhaps compelling the attempt of complex undertakings when the resources required to support them are not present. Indeed, following the Columbia tragedy, NASA was characterized as “an organization straining to do too much with too little.” (Gehman, Barry et al. 2003), indicating that NASA has harbored a preference for action, even in the absence of sufficient budgetary resources. These assumptions are sufficient to define a ranked set of preferences for NASA for each of the four possible outcomes (See Table 9).

Table 9: NASA's baseline preferences make up the Incrementalism Game, based upon the above assumptions.

Outcome	Preference Ranking
(Ground, Save)	1
(Ground, Spend)	2
(Fly, Save)	3
(Fly, Spend)	4

*Congressional Preferences*

We must next define the preference ordering structure for Congress, as follows:

- 1) All else equal, Congress prefers to see NASA’s vehicle fly.

Reasons for such a preference are manifold, including, but not limited to, the national pride and prestige associated with a national spaceflight program, as well as more locally-oriented interests, such as the revenues and employment

opportunities that a large federal program can bring to individual Congress members' districts (Van Dyke 1964). For example,

*"The Space Shuttle program occupies 640 facilities, utilizes over 900,000 equipment line items, and directly employs over 2,000 civil servants and more than 15,000 work-year-equivalent prime contractors, with an additional 3,000 people working indirectly on Space Shuttle activities at all NASA Centers. Thousands more are employed at the subcontractor level in 43 states across the country. The total equipment value held by the Program is over \$12 billion. The total facilities value held by the Program is approximately \$5.7 billion (approximately one-third of the value of NASA's entire facility inventory), mostly at the field centers. There are also approximately 1,500 active suppliers and 3,000 - 4,000 qualified suppliers that directly support the Space Shuttle program." (Griffin 2005)*

Those members of Congress with NASA employees in their district have a distinct electoral incentive to keep a vehicle flying, namely keeping their constituents employed and maintaining existing revenue streams in their state. This is also an incentive for the use of legacy components in a new program. Other incentives include the achievement of foreign and scientific policy objectives, as illustrated by the following statement by Senator Barbara Mikulski (D-MD), Ranking Member of the Senate Appropriations Committee, Subcommittee on Commerce, Justice, Science and Related Agencies, which includes NASA:

*"The United States of America should always have its own access to space. The space station, too, we need to be able to finish that, keep our commitment to our international partners, and keep it as a premier research facility. And, of course, then there is Hubble. Everyone knows my position on Hubble. And I believe it's been the greatest telescope invention since Galileo himself stood on that rooftop in Florence." (2005)*

It is worth noting that the International Space Station and the Hubble Space Telescope both require additional flights if they are to be completed and repaired, respectively. As such, Congress members that support these programs would prefer that the vehicle fly rather than that it be grounded.

- 2) Given a certain vehicle state (either flying or grounded), Congress strictly prefers saving its money for other priorities.

In game-theoretic terms, Congress' strategy of saving resources is strictly dominant. Thus, given that a domestic vehicle (such as the Space Shuttle or the upcoming CEV) is already flying, Congress will not provide additional funding for human spaceflight, since the need for human spaceflight is already fulfilled.

Thus, if NASA attempts a Block 2 CEV upgrade when Congress values a LEO, rather than a lunar, capability, additional funding is unlikely to be available. Maslow describes this phenomenon in psychological terms as follows: "...a want that is satisfied is no longer a want. The organism [in this case, Congress] is dominated and its behavior organized only by unsatisfied needs. If hunger is satisfied, it becomes unimportant in the current dynamics of the individual." (Maslow 1970) Van Dyke elaborates, "[Political figures] tend to speak of those values or interests that are threatened or that seem to be in need of attention, and they tend to forget about values and interests that seem to be assured. Sometimes there has seemed to be complete unawareness of certain values and interests and complete insensitivity to developing dangers." (Van Dyke 1962) Similarly, given that the vehicle is grounded, Congress will not expend extra resources if those resources will not generate human spaceflight capability. Therefore, Congress always prefers to save its resources if spending them will not alter the outcome.

- 3) Given a choice, Congress prefers to pay to keep the vehicle flying, rather than to have it grounded.

We justify this assumption by observing that, following the *Challenger* and *Columbia* tragedies, Congress has continued to provide funding to NASA for human spaceflight activities, under the assumption that the vehicle would return to flight. In fact, following the *Challenger* explosion, NASA requested, and was provided with, additional funding in order to build a new Shuttle, *Endeavour*, demonstrating a willingness on the part of Congress to provide supplemental funding when human spaceflight capability is endangered. These assumptions are sufficient to define a ranked set of preferences for Congress for each of the four possible outcomes (See Table 10).

Table 10: Congressional baseline preferences make up the Incrementalism Game, based upon the above assumptions.

Outcome	Preference Ranking
(Ground, Save)	1
(Ground, Spend)	2
(Fly, Spend)	3
(Fly, Save)	4

These preference orderings, taken together, result in the normal-form game matrix seen in Figure 34.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,3)	(3,4)
	Ground	(2,1)	(1,2)

Figure 34: The normal-form matrix representing the Incrementalism Game. The Nash Equilibrium is boxed. The shaded area represents Congress' compellent threat.

#### *Game Analysis*

A brief inspection of the normal-form matrix in Figure 34 yields that the Nash Equilibrium solution of this game is at (Fly, Save). This conclusion may also be attained by iterated strict dominance of strategies. In other words, NASA can always do better by flying than by not flying, and Congress can always do better by saving money than by spending money. In the short term, NASA will fly its vehicle and Congress will provide less funding than the President requests. This outcome is consistent with the situation described in the CAIB report (Gehman, Barry et al. 2003).

Having defined the game matrix, we now ask whether, given these conditions, NASA possesses any threat power. Given this payoff matrix, NASA would only attempt to enforce the (Fly, Spend) outcome, since that is the only outcome that is better than the Nash equilibrium-enforced status quo. If Congress were to decide to cut the vehicle's funding below the amount requested by the President, NASA could exercise this threat by providing a technical argument linking scarcity of resources to a need to ground its vehicle or otherwise discontinue service, e.g. for safety reasons. This is classified as a *deterrent* threat since NASA is attempting to prevent Congress from taking an action by threatening a retaliation (Brams 1994). We note that although this threat is real (Congress would suffer a loss in utility if NASA decided to ground the Shuttle), this threat is not rational, since NASA would also suffer a reduction in utility. Therefore, this threat is not credible and NASA does not possess any power to enforce this deterrence.

Next we explore whether Congress wields any threat power. We begin by noting that Congress would prefer to enforce the Nash-equilibrium outcome of (Fly, Save). Congress could employ a threat to prevent NASA from grounding its vehicle by refusing to move from its position of refusal regardless of NASA's actions. This type of threat is classified as *compellent* since Congress is trying to compel NASA to fly by refusing to move. Here we note that this threat is both real (since NASA stands to lose from grounding the vehicle) and rational (since Congress will only reduce its payoffs by deciding to increase funding). Thus Congress possesses sufficient power to enforce its desired outcome, namely the Nash Equilibrium outcome, in repeated play, suggesting that the funding shortage is chronic. We feel that this accurately describes the situation surrounding the Shuttle Program prior to the *Columbia* tragedy. Furthermore, this type of behavior may be said to be typical of any incremental agency politics. Congress, lacking any direct incentive to increase the budget for human spaceflight, would simply renew or, at best, incrementally increase the previous year's human spaceflight budget, effectively causing a reduction in constant-year dollars as inflation decreases buying power (Davis, Dempster et al. 1966). To make matters worse, as a reusable vehicle fleet gets older, one can expect its recovery and refurbishment costs to increase substantially, leading to a tighter budgetary environment (Wertz 2000). These factors, when combined with the chronic cost overruns and rushed schedule for completion of the International Space Station, contributed to the organizational difficulties that eventually led to the *Challenger* and *Columbia* tragedies (McCurdy 1990; Gehman, Barry et al. 2003).

This game captures the observation that incrementalism occurs partially because NASA's needs are not a salient interest to Congress. Possessing limited budgetary and attentional resources, Congress will focus on other, more salient concerns. The remaining budget is allocated to NASA and other non-salient agencies in an incremental fashion. This translates to an under-funding of the President's request for NASA, particularly in periods of budgetary scarcity. NASA's high valuation of its own programs ensures that Congress' compellent threat is credible.

#### *The Deterrence Game*

Now consider the case in which NASA no longer subscribes to the "can-do" attitude. Instead, if NASA is not receiving sufficient funding, it prefers to ground its vehicle citing technical justifications. For example, NASA may fear for astronauts' safety in the face of inadequate resources. This change in preferences could be brought about by a shock, such as the *Columbia* tragedy, wherein priorities within the agency and/or the White House are redefined. This may be justified as a precaution taken during a period of extreme sensitivity to the risks involved in flying astronauts in a vehicle that is perceived as unsafe. We model this change by reversing the last of NASA's preferences, stating that:

- NASA prefers to terminate a program or upgrade when sufficient funding is not present.

This last assumption works as something of a “wild-card”, essentially guaranteeing that NASA absolutely prefers not to fly its vehicle unless funding is present. The other assumptions remain. The change in NASA’s preferences is illustrated in Table 11.

Table 11: A change in NASA’s preferences from the baseline yields the Deterrence game. These new assumptions guarantee that NASA is unwilling to fly its vehicle unless funding is present.

Outcome	Preference Ranking
(Ground, Save)	1-2
(Ground, Spend)	2-3
(Fly, Save)	3-1
(Fly, Spend)	4

These preferences generate the game matrix seen in Figure 35.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,3)	(1,4)
	Ground	(3,1)	(2,2)

Figure 35: The normal-form matrix representing the Deterrence Game. The Nash Equilibrium is boxed. Arrows represent the deterrent threat that would be employed by NASA in the event Congress chooses not to fund.

### *Game Analysis*

Again, we begin by identifying the Nash Equilibrium of the game. We find that it is located at the “breakdown outcome” of (Ground, Save), so-called because it is the state resulting from a breakdown of negotiations between the Congress and NASA. This implies that, if each player were to act myopically, thinking only of their near term interests, the human spaceflight program’s future would be called into serious question. In this case, Congress would essentially give up on human spaceflight as an endeavor that does not deliver sufficient value to fully fund the President’s request, whereas NASA, fearing for astronauts’ safety in a scarce budget environment, would not maintain the vehicle in flight. This is the myopic, short term outcome. Analyzing this game for threat power yields a different result. As before, we examine the case where NASA tries to enforce the (Fly, Spend) outcome using a deterrent threat. Here we note that the threat is real, since Congress prefers to see the vehicle flying than to see the vehicle grounded, and the threat is rational, since NASA prefers to ground the vehicle in the case of no funding. NASA therefore possesses credible deterrent threat power. In addition, we note that Congress no longer has compellent threat power. Although Saving is still a dominant strategy for Congress in the traditional game-theoretic sense, Congress’ threat is no longer rational since it can do better by acquiescing to the President’s request for more NASA funding. Thus, while it might seem that the program is under danger in the short-term, Congress and NASA can cooperate to provide the funding necessary to ensure safe and successful operation.

These results highlight the effects that changing one player’s preference ordering may have on both players’ threat power, and hence the outcome of the game. In this case, NASA, in changing its preferences, affects Congress’ threat power, allowing for a funding increase. In other words, Congress’ threat in the Incrementalism Game is rational only because NASA prefers to fly the vehicle in spite of insufficient funding. This yields the counter-intuitive result that NASA’s high valuation of its own programs allows Congress to under-fund them. Cast differently, this implies that NASA, as the technical experts evaluating the feasibility and safety of human spaceflight, might be able to elicit increased funding for the program if it can be demonstrated that such funding is necessary to ensure crew safety and vehicle reliability. This highlights the power that NASA possesses as the sole source of information regarding human spaceflight. This conclusion is similar to that reached by (Kiewiet and McCubbins 1988) who note that the structure of the President’s veto power allows control over the outcome of the game to the player who values the program less. It will be noted later that there is a practical limit to how much money Congress might be willing to spend, even when faced with a deterrent threat.

We justify the results of this model historically. The following testimony demonstrates that the selection of NASA Administrator Michael D. Griffin has effectively acted to change NASA's preferences, whereas the *Columbia* tragedy and incipient Shuttle retirement threatens a potential hiatus in human spaceflight:

*"NASA's new boss made an impassioned case yesterday [May 2, 2005] for speeding up development of a new spacecraft so that the United States will not lose access to space when the shuttle is retired ... Griffin wants to fly the proposed new spacecraft as soon as possible once the space shuttle fleet is retired in 2010 -- avoiding a four-year gap in which the United States would have no way to launch astronauts ... Griffin said he finds that four-year launch gap unacceptable and hopes to have a plan for closing it by mid-July ... "CEV needs to be safe, it needs to be simple, it needs to be soon," Griffin told reporters later in the afternoon..."The six-year gap between the 1975 Apollo-Soyuz mission and the 1981 debut of the shuttle damaged both the U.S. space program and the nation", Griffin said. "I don't want to do it again." (Technology News 2005)*

*"The estimated cost of these new vehicles is from \$10 billion to \$15 billion through 2015...NASA hopes to pay the tab from its scheduled modest budget increases and saving from falling return to flight costs. But one official says that those return-to-flight costs will climb as high as \$7 billion over 5 years--\$2 billion more than previous estimated. That figure would leave little room for new ventures, the cost of which have traditionally been underestimated." (Lawler 2005)*

*"Testifying before the House Science Committee Today, Michael Griffin, [NASA] Administrator...said that NASA needs \$3-5 billion more than is currently budgeted to fund the Space Shuttle through 2010..."(House Science Committee 2005)*

In this situation, a signal is being sent advocating that Congress at least approve, if not improve upon, NASA's budget for the next years and threatening Congress with a lapse in human spaceflight capability that, if unchecked and under funded, could become debilitating or, at worst, permanent. Acceleration of CEV development, although eliminating this gap, compounds the budget issue, making the threat more real and more credible to Congress.

Many prominent members of Congress have expressed their support for NASA's human spaceflight activities, and seemed poised to approve NASA's budget request. As of June 17, 2005, the House of Representatives supported NASA's budget request:

*"House Majority Leader Tom DeLay (R-Texas) today said the Science, State, Justice and Commerce spending bill, which includes \$16.5 billion for NASA, will continue Congress' work to implement President Bush's bold new vision for space exploration. The House of Representatives passed the appropriation bill today by a bipartisan vote of 418- 7...The funding bill passed today sets aside \$16.5 billion for NASA - \$275 million more than last year's bill and \$15 million above the administration's request. In addition to providing the full request for the Space Shuttle program, this legislation funds the president's vision for space exploration at \$3.1 billion..."The president's vision will be fulfilled, NASA's mission will be accomplished, and mankind's ancient questions will be answered," DeLay said. "That's not overconfidence; that's a promise.""* (DeLay 2005)

Fulfillment of this promise began on July 22, 2005, with the passage of a NASA reauthorization.

*"By an overwhelming margin, the U.S. House of Representatives today passed legislation to reauthorize the National Aeronautics and Space Administration (NASA) that was sponsored by Space and Aeronautics Subcommittee Chairman Ken Calvert (R-CA) and Science Committee Chairman Sherwood Boehlert (R-NY). The bill, H.R. 3070, National Aeronautics and Space Administration Authorization Act of 2005, was adopted by of vote of 383 to 15. [H.R. 3070] allows NASA to proceed with its plan to retire the Space Shuttle fleet by the end of 2010; and encourages NASA to launch the Crew Exploration Vehicle (the Shuttle's replacement) as close to 2010 as possible...A manager's amendment offered by Chairman Boehlert was agreed to by voice vote. In addition to making technical and clarifying changes, the amendment...Increases the amount of funding authorized to be appropriated for NASA to support the President's budget request for exploration for fiscal years 2006 and 2007 [and] expresses the Sense of the Congress that NASA should return the Space Shuttle to flight as soon as the Administrator determines that it can be accomplished with an acceptable level of safety"*(House Science Committee 2005)

*"The Manager's Amendment increases funding for FY06 to \$16.9 billion and elevates FY07 funding to \$17.7 billion. This increase restores the full funding requested by the Administration for Human Exploration...I am pleased with the bipartisan strides that the House Science Committee has made to work together to achieve the best results for NASA. Such an inclusive compromise indicates that this country can truly achieve its vision of space exploration for generations to come," commented Rep. Sheila Jackson-Lee (D-TX)."*(House Science Committee Democratic Membership 2005)

*"This Congress recognizes and embraces the importance of NASA's technological innovation and research, and this reauthorization provides for it," DeLay said. "Ultimately, this bill does one thing: it gives the men and women of NASA – many of whom I am fortunate enough to represent – the resources they need to make their next giant leap" (DeLay 2005)*

In addition, prominent Senators from both political parties have voiced their support for NASA's human spaceflight activities. Senator Kay Bailey Hutchison (R-TX), a member of the Senate Committee on Appropriations; Subcommittee on Commerce, Justice and Science, as well as the Chair of the Senate Committee on Commerce, Science and Transportation; Subcommittee on Science and Space, stated the following in a May 12, 2005 hearing with NASA Administrator Griffin, effectively belying the reality of NASA's deterrent threat:

*"Where I have questions and concerns about NASA, they revolve around longer-term impacts to our current investments in human space flight capabilities. As you know, Mr. Administrator, I am concerned about the possibility of a gap between the planned retirement of the shuttle and the availability of the replacement crew return vehicle. I think a five-year gap is unacceptable. I think it is not only a risk to the important scientific research that we are doing, but it is a security risk to our country. And I am pleased that you have shared the same concerns. And I know both the chairman and the ranking member here have also expressed those concerns." (2005)*

In addition, coincident with the passage of H.R. 3070, mentioned above, Senator Hutchison and her Democratic counterpart, Ranking Member Sen. Bill Nelson of Florida, submitted an amendment to the Defense Authorization Bill "expressing the Sense of the Senate regarding the critical nature of human space flight to America's security" (Hutchison 2005). This amendment includes the following language:

*"(a) FINDINGS.--The Congress finds that--*

*(1) human spaceflight preeminence allows the United States to project leadership around the world and forms an important component of United States national security;*

*(2) continued development of human spaceflight in low-Earth orbit, on the Moon, and beyond adds to the overall national strategic posture;*

*(3) human spaceflight enables continued stewardship of the region between the earth and the Moon—an area that is critical and of growing national and international security relevance;*

*(4) human spaceflight provides unprecedented opportunities for the United States to lead peaceful and productive international relationships with the world community in support of United States security and geo-political objectives;*

*(5) a growing number of nations are pursuing human spaceflight and space-related capabilities, including China and India;*

*(6) past investments in human spaceflight capabilities represent a national resource that can be built upon and leveraged for a broad range of purposes, including national and economic security; and*

*(7) the industrial base and capabilities represented by the Space Transportation System provide a critical dissimilar launch capability for the nation.*

*(b) **SENSE OF THE SENATE.**--It is the sense of the Senate that it is in the national security interest of the United States to maintain uninterrupted preeminence in human spaceflight.” (United States Senate 2005)*

Senator Hutchison explained her reasoning as follows:

*“During our consideration of this bill and during hearings, it became clear that we must think of manned spaceflight in terms of national security, as well as science and exploration. For these reasons, I believe it is important that in the context of this Defense authorization bill, we express the sense of the Senate that we recognize the important and vital role of human spaceflight in the furtherance of our national security interests, and that we reaffirm our commitment to retaining our Nation's leadership role in the growing international human spaceflight community of nations... Let us stand united to recognize the inexorable link and importance of human spaceflight in our national security. I hope my colleagues will support this important statement that says keeping our dominance in space is a matter of national security for our country... The idea that we would consider a hiatus in our opportunities to put humans in space is one that is unacceptable to me and to my ranking member. We hope the sense-of-the-Senate amendment will be adopted to acknowledge and assure that space exploration is shown to be a part of our national security interests. It is essential that we not, in any way, ever let our eye get off that ball, that we must have dominance in space if we are going to keep our preeminence in national defense.” (United States Senate 2005)*

Senator Nelson added:

*"I join with my colleague, the distinguished Senator from Texas, who serves as the Chair of our Science and Space Subcommittee and of which I have the privilege of being the ranking member...What this amendment does--and I want to say a word about our two colleagues who lead our Armed Services Committee who I think will accept this amendment--it simply says: It is the sense of the Senate that it is in the national interest of the United States to maintain uninterrupted preeminence in human spaceflight. Why? Why are we saying that? Because we could be in a posture that if the space shuttle is shut down in 2010, which is the timeline, and if we did not soon thereafter come with a new vehicle to have human access to space...that if we don't watch out and we have a hiatus between when we shut down the space shuttle and when the new vehicle flies, one originally that was planned by NASA to be 4 years, which meant it was going to be 6, 7, or 8 years, then we don't have an American vehicle to get into space. If that is not bad enough, who knows what the geopolitics of planet Earth is going to be in the years 2011 to 2018. We may find that those vehicles we rely on to get today, for example, to the space station, when we are down with the American vehicle, may be aligned with somebody else. That is why we want to make sure we have that other vehicle ready about the time we shut down the space shuttle so we will have human access to this international space station and reap the benefits, once it is fully constructed, of all the experimentation and the processing of materials we can uniquely do in the microgravity of Earth's orbit. That is the importance, in this Senator's mind, of this resolution." (United States Senate 2005)*

The three above quotes above refer to space exploration in terms of national security, prestige and strategic posture. Returning to the analogy provided by Maslow's hierarchy of needs (see Figure 36), such security considerations take precedence over all but direct threats to the nation's safety. Although Maslow's hierarchy was intended to be used to describe individual needs, we feel an analogous application may be extended to Congress. Thus, the creation of a linkage between American presence in LEO and national security is a strong enabler of salience.

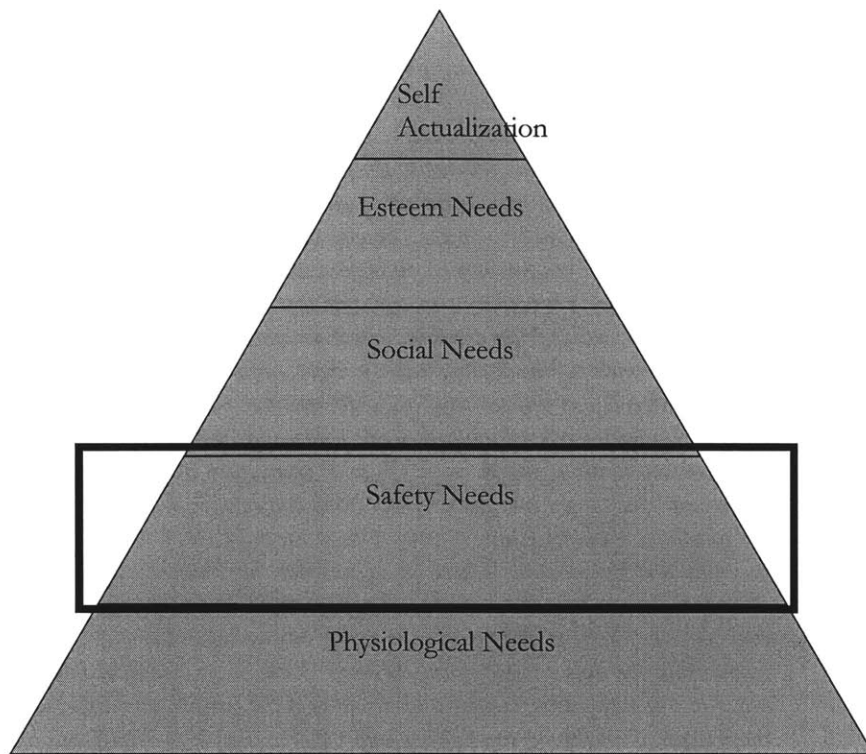


Figure 36: Maslow's Hierarchy of Needs -- Security Needs are among the most basic, and therefore command significant salience when threatened.

Such statements reflect the salience of American predominance in human spaceflight, and a high valuation of human spaceflight on the part of Congress. Nevertheless, these issues were not salient until the prospect of the loss of human spaceflight capability became real in the collective minds of Congress members. The prospect of the loss of human spaceflight capability, highlighted by the loss of *Columbia* and by Administrator Griffin's testimony, enables the credibility of the deterrent threat by focusing Congressional attention on the security implications of such a loss. This enables a real threat in the prospect of the loss of American human spaceflight capability. In addition, this threat is credible since current plans call for the retirement of the Shuttle by 2010. At the same time, note that there is little, if any, mention of lunar exploration in the above testimony – rather it is largely concerned with American pre-eminence. Given no

clear link between Congressional values and lunar capability, it is likely that once LEO capability is restored, NASA activities will lose salience in Congress.

That certain members of Congress support return to LEO as their primary goal is supported by the testimony of Senator Hutchison who, in a statement preceding a floor vote on S. 1281, the Senate version of the NASA reauthorization bill that “authorizes NASA appropriations in excess of the President’s budget request”, publicly recognized the link implied by the Deterrence game (2005). Referencing the recently-released NASA Exploration Systems Architecture Study, Senator Hutchison stated that

*“...the results track very closely to the provisions of S.1281. The CEV development would be accelerated to 2012, with the possibility of moving its operational date to 2011. The key to CEV acceleration is largely a question of resources, and sufficient funding could enable an even earlier operational date, possibly closing the potential gap in spaceflight capability altogether.”*  
(2005)

To reinforce this point, it is worth noting that the Senate has considered, but not passed, legislation that would require that the Shuttle fly until a CEV becomes available (2005). This language, which seems aimed at reducing the credibility of NASA’s threat, suggests that the Senate is aware of the vulnerability of their position. A later bill, S. 1281, somewhat diluted this requirement, stating that “there not be a hiatus between the retirement of the space shuttle orbiters and the availability of the next generation U.S. human-rated spacecraft”, omitting any specification of how this hiatus would be eliminated, potentially allowing for commercial or international solutions (2005). A requirement to keep the Shuttle flying until the CEV is developed could, in principle, allow Congress to continue behaving in an incremental fashion with regard to human spaceflight, since a delay in the CEV due to lack of funding would no longer be a present concern. Indeed, rather than fund the full development of a new vehicle, Congress could simply divert the funding required to keep the Shuttle flying from the CEV development funds. Given no mention of lunar capability, it is reasonable to assume that Congress could also allow funding for a LEO-only CEV, later behaving in an incremental fashion with regards to providing funding for the Block 2 upgrade. Either of these situations would be a return to the pre-Columbia funding paradigm. The testimony of Senator Hutchison acknowledges a Congressional preference for the use of legacy technology to maintain the status quo, stating that

*"NASA has begun several efforts in the past decade, to develop a replacement vehicle for human space flight, with a view to eventually retiring the space shuttle. Each of them has failed, after considerable expense, to find the technological breakthrough that was necessary for their success. They were focused on new technologies, new systems that were largely untested, and unproven. We are now out of time, and can no longer afford the luxury of attempting to develop a dramatically new and different human space flight capability." (2005)*

As such, NASA's deterrent threat has limitations. To the extent that Congress has information regarding technically feasible alternative methods to achieving the goal of returning American astronauts to LEO as soon as possible, NASA can be directed to implement alternative solutions that do not necessarily allow for an orderly or easy transition from LEO capability to lunar landing capability. As will be noted later, these additional dynamics seem to indicate the presence of a funding limit, beyond which NASA can not reasonably expect to receive funding, even if employing a deterrent threat. Nevertheless, this limit is influenced by exogenous factors. For example, the events surrounding the Shuttle *Discovery's* return to flight on July 26, 2005, have further served to increase the credibility of NASA's threat to ground the fleet for technical reasons:

*"NASA may never be able to prevent threatening chunks of insulation foam from breaking off the shuttle's fuel tank during launch, the agency's chief said Thursday, a day after future flights were ordered grounded because of the problem during Discovery's liftoff. "We are trying to get it down to the level that cannot damage the orbiter," NASA administrator Michael Griffin told NBC's "Today." "We will never be able to get the amount of debris shed by the tank down to zero," he said. With Discovery in orbit, NASA grounded all future flights because a large chunk of foam had broken off the external fuel tank in a hauntingly similar fashion to Columbia's doomed mission." (Dunn 2005)*

Griffin's statements in the above quote publicly reveal that flying the Shuttle indefinitely is simply not safe. Viewed in this light, a Congressional directive to keep the Shuttle flying until CEV deployment would appear irresponsible, particularly in light of another accident. These responses demonstrate the power a valid technical rationale may wield in strengthening a deterrent threat. Such events have an impact on Congressional decision-making, further suggesting that the spending cap representing Congress' maximum willingness to fund accelerated CEV development is not well-understood and may therefore be private information, uncovered only on Capitol Hill.

The above two games capture defining features that drive the interactions between NASA and Congress. In particular, they illustrate how the presence of a salient concern to Congress can drive NASA's deterrent threat capability, affecting a perturbation in the incremental baseline. In order for a concern to be salient it must be highly valued. At the same time, there must be a real possibility that might this capability could be lost. Given that NASA or the President also has a high valuation for this capability, the onus is upon them to implement and execute its maintenance. If the President has a very high valuation of a program, s/he may use a veto threat or a high budgetary request to affect change. NASA, on the other hand, is beholden to the President's request and the amount awarded by Congress – like any other agency, NASA's sole source of power is in the information surrounding the details of the technical implementation. If, Congress has a high valuation for a given program and the Executive Branch valuations are low, Congress must intervene in order to ensure that the capability is not lost. This occurs through mechanisms of legislation and resource allocation. In the specific context of the CEV, this salience is driven by the loss of *Columbia* and the concomitant possibility that American human spaceflight capability may also be lost permanently. In addition, this analysis illustrates the power of exogenous factors (i.e., those that are beyond players' control, such as factors that change player preferences) in determining the outcome of a game. As seen in the first example, the Nash-equilibrium outcome, reinforced by Congress' threat power, predicted that human spaceflight would be under funded. Furthermore, TOM predicts that this outcome would occur on a repeated (in this case, yearly) basis. Following the change in preferences, we note that a new paradigm has arisen whereby NASA, by acting proactively, may ensure additional funding for human spaceflight presuming an adequate rationale is presented. This outcome will be repeated for as long as NASA is willing and able to carry out its deterrent threat – until the nation's human spaceflight capability in LEO is restored. This suggests a new set of parameters governing the funding profile following the change in preferences. In the event that NASA's preferences were to return to those seen prior to the accident, the outcome would revert back as well. The Incrementalism game is consistent with McCurdy's identification of incrementalism as the modus operandi within NASA's internal political structure (McCurdy 1990). In addition, the presence of short, non-incremental time periods during which the parameters of the incremental model shift may be interpreted as "political shocks" or "policy punctuations" in between incremental periods (Goertz and Diehl 1995; Jones, Baumgartner et al. 1998). It is these non-incremental transients that allow NASA the ability to exercise deterrence until the emergence of a new incremental steady state.

From a psychological/informational perspective, NASA is not strictly carrying out a threat or asking for more funds; rather, the Administrator is providing testimony reminding Congress of the ill effects resulting from neglect of a highly-

valued capability. This dynamic is particularly important since the NASA Administrator is limited to formally requesting the amount put forward in the President's budget request. Any NASA desire for more funding outside of the President's request cannot be made through explicit formal channels without the NASA Administrator facing a situation potentially damaging to his career.

*The Uncertainty Game*

These two scenarios both assumed that Congress values the capability that NASA provides, even though it might be unwilling, in some cases, to pay for it. Next, we consider a different change to the set of preferences defining the Incrementalism game, this time by Congress. We examine the case wherein Congress prefers saving money for other endeavors, even at the expense of human spaceflight, to spending the money required to keep humans in space. We model this change by reversing the last of Congress' preferences, stating that:

- Given a choice, Congress prefers to ground the vehicle, rather than paying to keep it flying.

These assumptions are sufficient to define a ranked set of preferences for Congress for each of the four possible outcomes (See Table 12).

Table 12: A change in Congressional preferences from the baseline make up the Uncertainty Game. This guarantees that Congress will not pay to keep a vehicle flying.

Outcome	Preference Ranking
(Ground, Save)	1
(Ground, Spend)	2 3
(Fly, Spend)	3 2
(Fly, Save)	4

Such a situation might occur in the circumstance wherein a determination has been made by Congress that the value delivered in proceeding to the next stage of the human spaceflight program is simply not sufficiently high to warrant the funds requested by NASA. Alternatively, Congress might simply decide that additional human spaceflight activities are no longer within the nation's political interest. This game is also congruent with the stage of development of a large

program that has not yet obtained distributive benefits in Congress and requires sustained Presidential support and a promise of net national benefit to survive (Cohen and Noll 1991). This situation is described by the game matrix in Figure 37.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,2)	(3,4)
	Ground	(2,1)	(1,3)

Figure 37: The normal-form matrix representing the Uncertainty Game. The Nash Equilibrium is boxed. The shaded area represents Congress' compellent threat power. Note that this game has the same basic structure as the Incrementalism game.

### Game Analysis

This game assumes, as before, that NASA always has a higher valuation for providing a service than for terminating it. In this case, we note that Congress once again has compellent threat power. Note that Congressional compellence is independent of Congressional preferences. Rather, it is built into the nature of agency/Congress interactions, reflecting the checks and balances that are central to the American political system. NASA, lacking a threat that is neither real nor rational, has no credible threat available, and will simply default to flying its vehicle with insufficient funding. We also use the game to describe a situation wherein a LEO-only Block 1 CEV is flying and NASA is attempting to gain additional budgetary approval for the Block 2 CEV lunar capability upgrade. Although NASA might have the support of some members of Congress in this case, there would be no national crisis motivating large spending.

Outcomes here are indistinguishable from those in the Incrementalism game, suggesting that NASA may not be able to determine the preferences of Congress if they are receiving insufficient funding. In effect, by refusing to give NASA the requested funding, Congress sends an ambiguous signal. Figure 38 illustrates the uncertainty faced by NASA in this situation.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,?)	(3,4)
	Ground	(2,1)	(1,?)

Figure 38: NASA, lacking complete information about Congressional preferences, is unable to distinguish between the Incrementalism game and the Uncertainty game.

We find an historical analog for this game in the period immediately following the *Columbia* tragedy, but before the reorganization of the Congressional Appropriations Committees. It was only in 2005 that NASA, under the leadership of newly-appointed Administrator Michael D. Griffin, sent a signal indicating that long-term human spaceflight capability might be put under threat. The threat existed before this message was sent, but it was not salient to Congress in 2004. Indeed, a comparison of NASA's human spaceflight budget for FY2004 awarded by Congress with the President's request shows that the President's budget request was under funded by \$253 million for human spaceflight alone (2004; NASA 2005). FY2005 tells a different story; whereas the President requested \$16.2 billion in total for NASA, the Senate awarded \$16.4 billion, including \$800 million in emergency funds. In contrast, the House of Representatives only awarded \$15.1 billion in total; specifically awarding NASA \$959.6 million less than what had been requested for human spaceflight. This constituted a \$23.9 million reduction over the FY2004 appropriation (2004; Reinert 2004). Although NASA, and by extension, human spaceflight programs, eventually received full funding, this required extraordinary measures on the parts of President George W. Bush and House Majority Leader Tom DeLay (R-TX) (Weldon 2004). President Bush even went so far as to threaten to veto any budget that was not congruent with his funding request for NASA, an unprecedented move in space policy (Reinert 2004). At a time when the Shuttle was grounded and the future of American human spaceflight was uncertain, these moves by the House of Representatives called into question Congressional valuation of the human spaceflight program, suggesting that NASA simply did not have the threat power necessary to enforce its budget requests. The situation changed in February 2005, when Leader DeLay orchestrated the reorganization of the House Appropriations Committee. As a result, responsibility for NASA spending was shifted from what had been the Veterans' Affairs & Housing and Urban Development (VA-HUD) subcommittee to the Science, State, Justice and Commerce Committee (2005). These events are rarities in Congressional

relations, and may be considered enough of a political shock to have raised the salience of human spaceflight, just changing Congressional priorities. This, in turn, yielded Administrator Griffin the opportunity to take advantage of the newly available threat power coincident with his arrival. It remains to be seen whether shifting priorities may have caused another re-evaluation of the value of human spaceflight in the long-term. Although NASA's 2005 budget has been approved under trying Congressional circumstances, including the increased expense and damage associated with national disasters such as Hurricane Katrina, newer developments might have caused a return to a lower Congressional valuation (Hulse 2005; Spires 2005). For example, the resignation of Leader DeLay was widely viewed as a blow to the space advocacy community's power in Congress, and might have served to reduce Congressional valuation for human spaceflight (Berger 2006). Furthermore, there are disagreements within Congress regarding the utility of providing more funding directly for space exploration. For example, House Science Committee Chairman Sherwood Boehlert (R-NY) indicated a strong preference for not providing the funding required to accelerate the CEV, as follows:

*"...let me make clear that I do not think it is a priority to add funding above the request to the Crew Exploration Vehicle (CEV) program at NASA. I support the President's Vision for Space Exploration, but I do not see any great advantage to be gained from launching the CEV in 2012 rather than 2014. Too many other items are of greater concern.*

*"No one has described any actual threat posed by the additional two-year gap – even taking into account Chinese space efforts – and the U.S. should be able to maintain an adequate aerospace workforce as long as it is clear that work on the CEV is proceeding according to schedule. Our priorities should not be skewed by emotional appeals"(House Science Committee 2006).*

These statements demonstrate that Congress' valuations, and hence NASA's threat power, are highly volatile and subject to change. In the absence of a clear leadership figure, such as DeLay, who could guarantee a given outcome, determining Congressional valuations requires weighing the preferences of the House of Representatives, as represented by Chairman Boehlert, against that of his Senate counterpart, Chairman Ted Stevens (R-AK), of the Senate Commerce, Science and Transportation Committee. In addition, it remains to be seen whether or not the new House leadership will take an active stance on space exploration.

#### *The Cessation Game*

Finally, for completeness, we consider the case wherein Congress possesses a low valuation for the Space Shuttle program and NASA prefers to ground its vehicle

in the absence of sufficient funding. Preferences for this game are the superposition of the deviations from the Incrementalism baseline found in the Deterrence and Uncertainty games. This game is represented by the normal-form matrix in Figure 39.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,2)	(1,4)
	Ground	(3,1)	(2,3)

Figure 39: The normal-form matrix representing, the Cessation Game. The Nash Equilibrium is boxed. The lack of long-term dynamics is suggestive of the terminal nature of these interactions.

### *Game Analysis*

We note that, in this case, neither player possesses threat power of any kind. As a result, neither player is able to enforce a desired outcome. In addition, the Nash Equilibrium of this game is also the breakdown state of (Ground, Save). The intuition for this result is that if neither NASA nor Congress is interested in maintaining human spaceflight, it will be put on hold. For repeated games, this implies cancellation or stagnation in the human spaceflight program. An historical analog of this game is the SEI announced by President George H.W. Bush on the 20<sup>th</sup> anniversary of the in 1969 Apollo 11 landings. Bush directed NASA to undertake a program of exploration of the Moon and Mars, similar in many ways to today's VSE. Nevertheless, the SEI failed to materialize because it swiftly lost both Congressional and Presidential support (Ragsdale 1997).

### **Applying the Game-Theoretic Model**

Although we have been examining the application of a game-theoretic framework to the events following the *Columbia* tragedy, we may expect the same incremental, structure-induced dynamics to apply to Congress for future funding cycles. This has implications for the effects of how cost is spread throughout the program's lifetime. Thus, the following analysis will proceed in two steps. We begin by analyzing the dynamics surrounding the development of the CEV Block 1. The minimum capability of this CEV is the ability to travel to and from LEO so that astronauts may service the ISS. On the other extreme, this Block 1 might be capable of lunar and Mars return. In this latter case, a Block 2 CEV is

unnecessary. Chapter 4 demonstrated that cost will vary directly with difficulty, and we assume that a LEO-only CEV is less difficult than a lunar or Mars CEV to build, and therefore less expensive to implement. Holding all else equal, we can expect a less-expensive CEV to be more likely to see approval during a given funding cycle than a more expensive CEV. This is true regardless of Congressional and NASA valuations for human spaceflight. A lower-cost CEV will reduce BR, the funding request. This, in turn, increases the likelihood that  $BR < P$  in any given year, suggesting that NASA is more likely to be able to obtain funding for the CEV Block 1. At the same time, the previous analysis indicated that NASA is currently playing the Deterrence game, and is likely to be able to do so until the national crisis that makes it possible has abated. The Congressional testimony shown above indicates that this crisis is largely driven by the lack of American access to humans in space. Indeed, until a vehicle is available that can routinely return American astronauts to LEO, the effects of this crisis are likely to intensify rather than decrease. This is particularly true if other nations, such as the China and Russia execute plans to up-scale their activities in LEO, and potentially on the Moon (2004; 2005; spacedaily 2006). This threatens the American perception of leadership in human spaceflight (United States Senate 2005). NASA could therefore provide a technical rationale that serves as a deterrent threat, justifying a funding request to build a Block 1 CEV that is more than minimally capable.

Now, consider the situation in which the Block 1, LEO-only CEV has been launched, human spaceflight capability has been regained, and the President directs NASA to undertake the construction of Block 2 to proceed to the Moon. Assuming no change in the general state of space geopolitics by the time of this occurrence, we may expect that Congress will not perceive a return to the Moon as a national imperative. We support this conclusion by noting that, up until now, a return to the Moon has not been a priority within Congress despite previous Presidential directives (Ragsdale 1997). In addition, we have already noted that Congressional arguments justifying NASA's salience focus on the LEO capability provided, rather than the lunar capability. Lacking a national impetus, we may expect Congressional valuation of lunar capability to be relatively low, particularly if there are no immediate distributive benefits associated with this part of the architecture. It is worth noting that if any of the other nations' lunar exploration plans do get underway, acceleration of Block 2 is likely to become a salient consideration. This is reflected by the statements of Rep. Ken Calvert, chairman of the House Science subcommittee on space and aeronautics:

*"Right now, we're saying we can't do for 13 years something we've already done...if the Chinese beat us [to the Moon], that's embarrassing. I don't want to see that happen as an American. I think we ought to maintain our pre-eminence in outer space."(Morris 2005)*

Nevertheless, Congress has not taken substantive action on Rep. Calvert's statements, largely because the tentative human lunar exploration plans of several nations, including Russia and China, have not materialized in any concrete form (2004; 2005; spacedaily 2006). This, in turn, suggests that NASA will be unable to carry out a deterrent threat after the launch of Block 1. If NASA is to successfully obtain the support of Congress in executing the lunar exploration plans of the President, the transition costs of moving from Block 1 to Block 2 must be sufficiently low that they may be supported by incremental funding. This, in turn, suggests that a Block 1 CEV must be designed so as to minimize the costs of future transition while not spending so much that Congress is unwilling to pay up-front. In effect, NASA may take advantage of the current deterrent environment to design a lunar-capable CEV while the funds are available. Such a decision would exhibit budgetary political sustainability since it would take advantage of current resources in such a way as to enable future resource use without exceeding the amount that Congress has mandated by law in a given year. It is unclear exactly how much extra Congress might be willing to spend under a condition of deterrence in any given year. This amount is largely a function of the quality of negotiations between the Executive and Legislative branches of government, and of other national directives.

#### *Incomplete Information in Congressional Valuations*

Congressional valuations are private information. It is therefore a risky proposition as to how much additional funding NASA might be able to extract through a deterrent threat. Suppose that NASA does indeed value human spaceflight highly. In this case, Congress possesses the threat power to restrict NASA funding regardless of the Congressional valuation. As Figure 40 demonstrates, without complete information, NASA would be unaware of Congress' valuation of human spaceflight. NASA takes the risk of attempting to carry out a non-credible threat that might result in the loss or under-funding of human spaceflight capability. If, on the other hand, NASA makes a deterrent threat and fails to enforce it, this may negatively impact NASA's ability to make future credible threats. This is a structure-induced effect that gives NASA an incentive to act in accordance with its valuations, reflecting the compellent power of Congress. NASA's actions send Congress a signal indicating NASA's valuation of the human spaceflight program – it is very difficult for NASA to keep secrets.

		Congress	
		Spend $F > BR$	Save $F < BR$
Agency	Fly	(4,3)	(1,4)
	Ground	(3,1)	(2,2)

Figure 40: NASA, lacking complete information about Congressional preferences, risks terminating human spaceflight capability if a non-credible deterrent threat is exercised. Here, NASA must distinguish between the Deterrence game and the Cessation game.

NASA's power in this scenario stems from its ability to control which technical options are presented to Congress (Kingdon 2003). In the event of a Deterrence situation, wherein Congress is concerned with the future of the human spaceflight program, NASA has the ability to present the CEV solution to this problem as a multi-block or a single-block architecture. A single-block architecture may be too expensive, even in a deterrence situation, necessitating a multi-block architecture. On the other hand, a multi-block architecture will likely end the deterrence situation, enabling Congress the ability to indefinitely defer the Block 2 upgrade – unless Block 1 is sufficiently advanced so as to minimize the upgrade costs. On the other hand, in the absence of a threat from NASA (or exogenous forces, such as a Presidential veto threat), Congress will seek to reduce funding, regardless of its valuation of the Shuttle program. Therefore, any signal sent by Congress is ambiguous, relegating NASA to a position wherein they do not immediately possess sufficient information to determine whether a deterrent threat might be successful. Although a methodology for weighing such risks is left to future research, informal negotiations between agents of the President and Congress allow for experts in the field to make decisions on the basis of the best information available to them.

#### *Political Sustainability*

These results may be used to define a politically sustainable funding level in terms of the parameters of the game. As we have seen previously, the requested funding level,  $BR$ , serves as the threshold point around which Congress makes its decision. This value of  $BR$  is critical in defining Congress' preferences, assuming that Congress has a certain private valuation,  $P$ , of human spaceflight capability. As in auction theory, one may think of  $P$  as Congress' *reservation price*, the

maximum amount that Congress would be willing to pay in order to maintain the human spaceflight program. If  $BR < P$ , that is equivalent to saying that Congress possesses a high enough valuation of the human spaceflight program to provide that level of funding under threat. In this case, if NASA knows that Congress' valuation of the human spaceflight program is high, NASA could reasonably request more funding (presumably until the funding request exceeds  $P$ ) by employing a deterrent threat. NASA, in the role of technical expert, could make a case for the need for more resources (Kingdon 2003). Conversely, if  $BR > P$ , then Congress' valuation of the Shuttle program is lower than what NASA requests. In this case, challenging Congress for more funding would, at best, be ineffective and at worst would lead to the Cessation of the program. Therefore,  $P$  is an upper bound on the amount of funding that NASA might expect to receive in any given year. In effect,  $P$  is the maximum value at which funding may be sustained, or the *politically sustainable funding level*. As mentioned previously, NASA has imperfect information regarding Congress' valuation. If NASA were able to correctly elicit the value of  $P$  from Congress, this would effectively turn the game into one of perfect information. Chapter 2 gives us some insight into what might drive  $P$ . As these factors, including geographic distribution and the national mood surrounding the decision under consideration, increase, so does  $P$ . Congress is not likely to consider NASA's budget alone, but will generally weigh it against other programs, further complicating matters (Johnson-Freese 2003). Any calculation of  $P$  must take these complicating factors into account. Therefore, future work in this area should focus upon a method for correctly determining  $P$  on a yearly basis.

The above model demonstrates that a program is unlikely to receive its requested level of funding if it is perceived that the program can maintain a consistent pattern of operation without it. In particular, this model examines the situation in which NASA provides Congress (and by extension, the American people) with human spaceflight capability. Until that capability is put under threat by exogenous events, Congress is unlikely to fully support a funding request for additional human spaceflight capability, and may reallocate funding in the face of more pressing concerns. The intuition for this conclusion is that Congress, already receiving LEO human spaceflight capability at a lower funding level, receives very little added marginal value from the added capability. The lunar capability requested in a Block 2 upgrade is a Presidential, rather than a Congressional, directive and may be viewed as extraneous, particularly since the LEO capability that Congress values is already present in Block 1. In other words, Congress will not pay more to receive what it is already getting. If, however, there is a perception that the capability is under threat, Congress will be willing to provide support up to the point where a determination is made that the benefits no longer outweigh the costs. Thus, a Block 1 CEV that incorporates lunar return capability or minimizes upgrade costs in the future might receive

Congressional support since it simultaneously fulfills Presidential and Congressional goals. This has implications for an agency's advocacy to Congress: in order to maintain political sustainability, a successful case must be made on a yearly basis for why funding is necessary not only to achieve certain objectives, but to maintain existing capability at a level where they deliver value. If the objectives of NASA, and hence, the President, do not coincide with those of Congress, a dearth of funding will result. To the extent that the goals of the two branches of government coincide, cooperation may occur in such a way as to allow sufficient funding to solve the problems of both actors.

Just as the previous chapter outlined NASA's ability to modulate its annual budget through the use of legacy components, this chapter demonstrates how NASA, or any incremental agency, may take advantage of current events in formulating its budget request. In particular, when the agency's agenda is salient to Congress, a deterrent threat might be employed in order to receive more resources. It is imperative that this threat be backed up by a valid technical rationale, so as to make the threat credible. This is particularly true since Congress has become increasingly technically savvy, and thus more able to evaluate the veracity of NASA's claims (Jahnige 1968). Nevertheless, agencies still hold primary power over the implementation of any directive set forth by Congress or by the President. It is this power that is the source of the deterrence capability. Utilizing such a threat is a risky measure that depends on Congressional willingness to see a capability through to implementation. If Congress does not highly value the capability being provided, the threat could backfire resulting in the loss of the capability.

If political sustainability is to be attained, NASA must be able to anticipate and plan for future budgetary incrementalism. Current testimony indicates that NASA's recent budgetary increases are driven by Congressional concern over the American geo-political posture as regards human spaceflight. Barring future events that might increase the value to Congress of sending Americans to the Moon, we can expect that NASA funding will return to an incremental steady-state after NASA has satisfied the current Congressional concern. The primary way in which this would be accomplished would be the return of astronauts to LEO by a Block 1 CEV. NASA could mitigate the difficulty of spending large sums of money during an incremental regime by taking advantage of increased expenditures during non-incremental periods to increase the CEV's *upgradeability* – by reducing future costs, even at increased costs at present. In effect, NASA would be reducing the difficulty ratio, as identified in Chapter 4, of the Block 2 upgrade. Nevertheless, deterrent threats are risky and should only be used when deemed absolutely necessary. Congress members are politically savvy, almost by definition, and will generally not reward a threat that is non-credible. Thus, this course of action is only politically sustainable if NASA's per annum costs remain

within the realm of what Congress is willing to pay, and if the capability that is being provided is something that is truly valued. The art of politics is truly essential at this stage, since the agency must convincingly craft an argument to Congress advocating both the technical and political needs for increased funding – and how future upgradeability is in line with priorities today.

### **Conclusion**

Political sustainability is intimately tied with goals, values and interests. In particular, a program will be sustained if it is delivering value to the stakeholders who are contributing the resources necessary to keep it going. Value delivery is a necessary condition, but it is not a sufficient condition. This is particularly true in situations in which there are limited budgetary resources and many worthy goals to address with those resources. Such a situation is encountered on a regular basis by any number of government programs attempting to obtain federal funding from a Congress that has several options to choose from with regards to where to allocate funding. An agency or program, on the other hand, has only one source of funding, namely Congress. Future work should therefore focus upon determining the goals and interests of Congress, and indeed, of all stakeholders involved in the resource allocations process, in order to determine their crucial needs and how best to fulfill these such that they are willing to contribute sustained support.

The next chapter examines the conditions under which the parameters outlined in the above sections may be used to predict outcomes. Changing the values of these parameters will yield differing strategies that NASA may use in order to achieve political sustainability.

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SENSITIVITY ANALYSIS

In illustrating ways in which a technical choice affects a political decision, this thesis makes a number of assumptions. The purpose of this chapter is to identify and then challenge the assumptions that are made in each of the previous chapters. The intention of doing so is to test the sensitivity of the results to these assumptions, creating a “sensitivity analysis”.

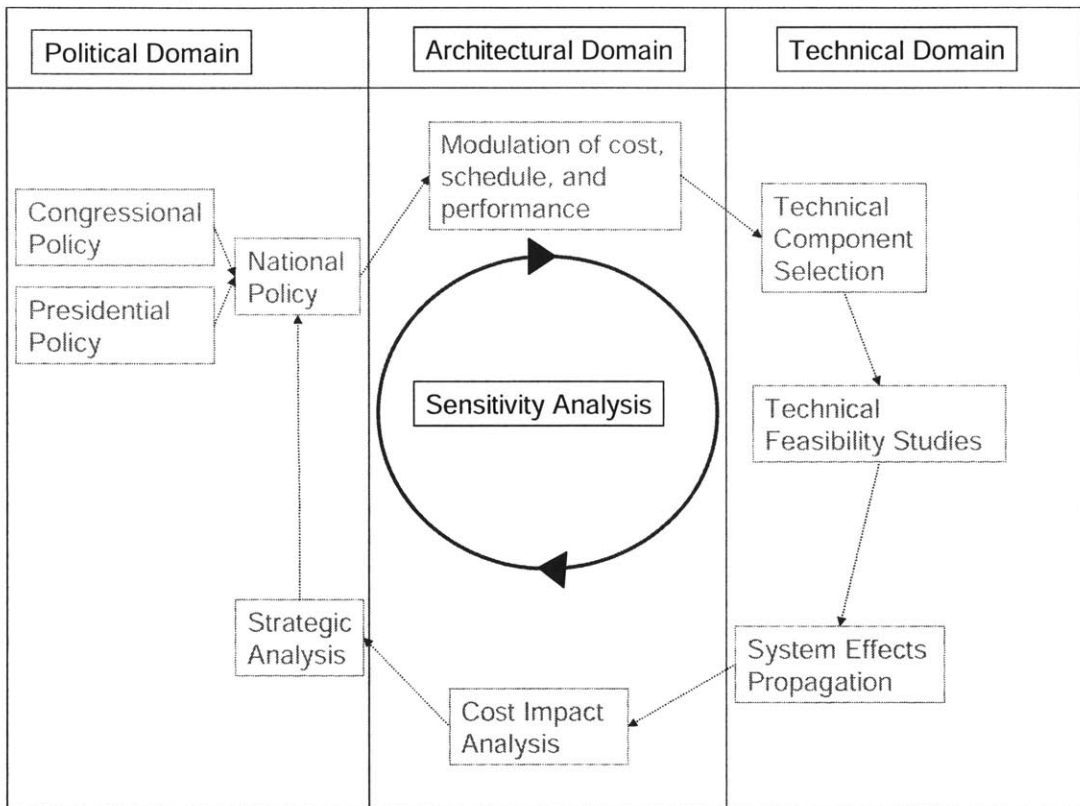


Figure 41: This chapter examines the assumptions underlying each step made in the previous chapter, exposing areas for future research.

As seen in Chapter 2 and Chapter 5, a Congressional drive to ensure the continuity of American presence in LEO has led to a directive that the CEV be accelerated, reducing the gap between Shuttle retirement and CEV deployment as much as possible. An analysis of the strategic drivers underlying Congressional budgeting reveals NASA's ability to execute a deterrent threat in situations where Congress has a high valuation of a program that NASA is willing to forego for technical reasons. Based upon the literature in Chapter 2 and the testimony in Chapter 5, this thesis assumes that NASA's threat power is currently enabled by the absence of an American capability to send astronauts to LEO. One may therefore conclude that Congress' willingness to provide funding above the incremental level is likely to decrease after the Block 1 CEV has been actively deployed. In other words, Congress will revert to incremental funding for NASA after the return of American astronauts to LEO. These conclusions are premised on the following assumptions:

**Assumption #1:** Lunar activity does not engender Congressional salience.

In other words, Congress does not consider a return to the Moon enough of a national priority to spend more than incremental funding for it. For the purposes of the sensitivity analysis, this thesis examines the consequences of reversing assumption #1. In this case, some external event would dictate that Congress consider a return to the Moon a national priority. Such an event would allow NASA to execute future deterrent threats after the launch of the Block 1 CEV, and would obviate the need for a return to incremental funding. This would benefit the exploration architecture in the sense that carrying out the President's vision of implementing a return to the Moon would now also be a goal fully shared by Congress. This could occur if another nation credibly stated an intention to land on the Moon, an outcome that is not entirely unlikely given the stated goals of China, India, Russia, Japan and the European Union to engage in more aggressive lunar exploration activity (Briggs 2005; Johnson 2006). A Chinese landing on the Moon, in particular, would likely draw attention in Congress, potentially raising lunar return to a salient national issue (People's Daily Online 2006; Wheeler 2006). Nevertheless, none of these nations have advertised concrete, actionable plans that involve sending humans to the lunar surface (Reuters 2006). Such an event, were it to occur, would simply replace one crisis (lack of LEO capability) with another (competition for lunar access). Any crisis must eventually be solved and is therefore not sustainable. As such, it can be expected that funding will eventually return to the incremental level. If NASA is to engage in a sustained and affordable exploration of the solar system, operation under conditions of budgetary incrementalism must become the accepted norm. Assumption #1 is therefore necessary to illustrate how NASA could take

advantage of current salience to better fulfill the President's directive during incremental periods.

**Assumption #2:** National priorities with regards to space exploration are static.

Assumption #2 asserts that there will be no change in national priorities that divert attention from NASA's exploration objectives. Reversing this assumption could entail a major national crisis that requires that the resources consumed by NASA be diverted to other needs. In such a situation, NASA would not be the only agency targeted. As with any other crisis, such a diversion is difficult to predict and likely cannot be anticipated. In the wake of requirements for large expenditures such as caused by national disasters (e.g., Hurricane Katrina) or military conflicts, NASA's budget has persevered. It is not inconceivable that a sufficiently large crisis could require that NASA, and other agencies, lose funding. Generating robustness to this eventuality is likely beyond the control of any individual government actor and beyond the scope of this thesis.

The presence of a President or set of powerful members of Congress who oppose the Vision for Space Exploration could also undermine Assumption #2. It is difficult to predict the outcome of future elections, and how individual preferences might change. At the same time, nothing succeeds like success. If NASA is carrying out the VSE in such a way that it is providing tangible signs of success to the public, future cancellation will be more difficult. Examination of this assumption therefore reveals an important component to political sustainability – NASA, like any other political actor, must maintain the support of its constituency. Chapter 2 illustrated the distributive nature of NASA politics. Given the embedded infrastructure that already exists for space exploration, cancellation of the VSE is likely to be inherently difficult, simply because several members of Congress, and their associated advocacy groups, would create a vibrant opposition. Any move to cancel the VSE would incur significant political capital on the part of the executor. In effect, canceling the VSE would be more trouble than it's worth. At the same time, a specific project manager must be concerned that their specific project would not be targeted. The strategies outlined in Chapter 5 are aimed at providing insight into how projects might be protected. Building a coalition of supporters is necessary to protect a program from cancellation. It is exactly this sort of behavior that eventually leads to incrementalism. In a Darwinian analogy, the most successful programs are those that are able to generate support. Those that do not will be cut, whereas those that do will eventually find their way to the incremental equilibrium. Any program that is currently subject to incrementalism has at least enough support to maintain its current budget at approximately those levels. Even if a new President or some new members of Congress do not highly value the capability provided by the agency, there is likely to be continuity of the incremental outcome. This is the

situation captured by the Uncertainty game in Chapter 5. It is exactly during non-incremental periods that an agency might risk a large change in budget. This case, captured by the Cessation game in Chapter 5 is the time when a program may come under the most scrutiny. If the program fails under scrutiny, as determined by the powers that be, it risks cancellation. Nevertheless, the dynamics of Congressional politics are such that if a program is providing some minimal amount of value, its advocates will ensure that cancellation of that program is difficult. Given the current distributive benefits associated with human space exploration, it is unlikely that cancellation of the VSE and associated programs will be easy. Furthermore, the logic driving political sustainability holds in this situation. If a program is currently highly valued and able to attain more funding by means of a deterrent threat, some of that funding must be diverted towards building the base for future support. In the case of the CEV, this suggests that an upgrade to lunar capability be easy to attain, thus expanding the base of advocates who might support future lunar missions. In effect, allowing the Block 2 CEV to be easily built will provide a reason for those in Congress who support the CEV's constituents to simultaneously support a lunar exploration program. Assumption #2 is therefore a sort of self-fulfilling prophecy. Barring a major crisis of the sort that would necessitate a large redirection of the entire government's resources, NASA's activities may expect to be supported, at least at the incremental level, by advocates who derive benefits from these activities. As such, a sudden, large loss of support is unlikely, although once it does occur it can be debilitating. Therefore, a program's activities in this regard must be to ensure the satisfaction of current constituents while always searching for new supporters. A program manager must be a "policy entrepreneur" (Kingdon 2003).

**Assumption #3:** NASA does not require more money than the President requests, and the President requests the amount of money required by NASA.

The game-theoretic model in Chapter 5 does not explicitly include the role of the Executive Office of the President in generating budgetary policy. Interactions within the Executive Branch, for example between the Office of Management and Budget and NASA, are outside of the scope of this thesis, largely because the results of these negotiations are embargoed to the public. Nevertheless, they represent an important determinant of NASA's funding situation, and any work towards characterizing these interactions would constitute an important research contribution. This thesis assumes that NASA and the President are acting in concert, largely because NASA is carrying out a Presidential directive. As world events change and other Presidents are elected, it is certain that the standing of NASA within the Executive Branch will change. This provides added justification for engaging in politically sustainable strategies that reduce risks now. Given that there will be a new president in 2008, and that the new president might not support the VSE as fully, any actions that could be taken now to reduce the costs

to future Administrations would help ensure the future survivability of the program. In the event that NASA attempts to execute a deterrent threat that is aimed at generating more funding than the president requests, the president might threaten a veto as a political gesture (e.g., to send a message of fiscal conservatism). Indeed, it is not uncommon for advocate members of Congress to question the president's request, inquiring why a certain agency is not receiving more funding. It is for this reason that the threshold point, BR, is set at the president's budget request and not higher. Although NASA could, in principle, ask for more money than the president requested, there is no formal channel for doing so. The NASA Administrator, as a political appointee of the president, is expected to support the president's request, even if it comes at the expense of the agency's well-being. From the perspective of the Executive Branch, the president is concerned with the well-being of the nation. Agencies are tools to execute the president's agenda rather than constituencies that must be appeased. As such, the president's request represents an upper-bound on what an agency may expect to receive in any given year.

Given the three assumptions outlined above, NASA has the option of exercising threat power from now until the launch of the Block 1 CEV. After this point, Congressional compellence will return and NASA will likely revert to an incrementally-funded agency. The above discussion suggests that NASA could best implement the president's directive to sustainably and affordably return to the Moon by utilizing the currently available threat power to obtain funding for a Block 1 CEV that is more easily upgradeable. Similarly, Block 2 CEV development should begin as soon as possible, concurrent with Block 1 development, so as to reduce the costs of the upgrade in the future. The aim of both of these measures is to ensure that the switching costs between the Block 1 and Block 2 CEVs are minimal. This will prevent a peak in funding that would occur at exactly the time when Congress would be looking to assert more control over the NASA budget by returning to incrementalism.

**Assumption #4:** NASA's funding profile will largely be driven by exploration throughout the VSE.

The above assumption ensures that Congressional preferences regarding NASA will largely be driven by exploration activities. Given President Bush's articulation of the Vision for Space Exploration as NASA's primary mission and the budgetary sand-chart shown in Chapter 2, it is unlikely that NASA's other programs (namely science and aeronautics), would dominate the budget.

Chapter 4 provides insight into how NASA could modulate its funding profile. Reasons for doing so include concentrating costs during years where Congress might be expected to provide more funding. NASA's Advanced Mission Cost

Model (AMCM) is applied to obtain a rough order of magnitude estimate of how varying difficulty in component development can affect overall price. In particular, mission complexity metrics are used to derive an estimate of the AMCM difficulty ratio. Feeding this into the AMCM provides a rough order of magnitude cost estimate that can be used for demonstration purposes. The results provided by the AMCM are normalized to a value provided for the CEV cost by the NASA Air Force Cost Model (NAFCOM). Finally, the development cost is spread over several years using standard cost-spreading “beta curves” to obtain estimates of per annum cost. The AMCM also yields important insight into the effects of development start date on per annum cost. In particular, commencement of Block 2 development concurrent with Block 1 can reduce per annum costs by stretching development out over a longer time period.

The results of this model are subject to the assumptions and limitations that underlie the AMCM and other regressive cost models. For example, the AMCM assumes an exponential fit for future missions, based upon previous missions. NAFCOM assumes similar future costs based on past data. Since these cost models are intended to span multiple mission types, they may capture only gross cost differences and cannot be used for fine measurements. Furthermore, the AMCM relies on the system engineer’s subjective evaluation of the difficulty of constructing a given vehicle. Since difficulty metrics are inherently subjective, the repeatability of the results of the AMCM cannot be guaranteed. Indeed, most predictions of this cost model may be debated upon these grounds. To illustrate this point, one only needs to examine the order of magnitude cost difference between the extreme cases of difficulty upgrades shown in Chapter 4. It is for this reason that a range of difficulty ratios are examined, leaving the determination of this parameter to the mission architect. Despite all of the shortcomings of this, and other, cost modeling techniques, they are instructive for the initial stages of comparative conceptual design and thus suited to our purposes. Furthermore, given that Congress is largely concerned with oversight of NASA at the agency and program levels (as opposed to the subsystem or component levels), the rough costing provided by the AMCM is congruent with the fidelity Congress might expect to encounter.

Application of the AMCM allows us to categorize the cost-spreading allowed through the modulation of difficulty ratio and Block 2 development start date. The analysis performed in Chapter 4 identifies the launch of the Block 1 CEV as the critical date after which this thesis assumes a Congressional return to incrementalism. Table 13 outlines the effects of variation of these two parameters on the cost before and after the launch of the Block 1 CEV.

Table 13: This table shows CEV cost as a function of difficulty ratio and the commencement of development. Graphical representations of these relationships may be found in Chapter 4

		Cost before Block 1	Cost after Block 1
Easy upgrade (difficulty ratio = $\gamma^{-5}$ )	Block 2 Development commences in 2006	Very High	Very Low
	Block 2 Development commences in 2006	High	Low
Moderate upgrade (difficulty ratio = 1)	Block 2 Development commences in 2006	Moderately High	Moderately Low
	Block 2 Development commences in 2006	Moderately Low	Moderately High
Difficult upgrade (difficulty ratio = $\gamma^5$ )	Block 2 Development commences in 2006	Low	High
	Block 2 Development commences in 2006	Very Low	Very High

These cost models should not be used for high-fidelity calculations. If at all possible, costing experts using appropriate modeling techniques should evaluate the cost differentials of different architectures. The purpose of applying the AMCM is to illustrate areas where NASA might apply specialized technical knowledge to exert control over its cost profile. This, in turn, can be used by experts in the specifics of the political process to evaluate how Congress may react to changes in per annum cost. As such, the goal of this thesis is to outline a process rather than a specific methodology.

Thinking of cost as a controllable variable, rather than as a constraint placed by Congress, is admittedly foreign to the traditional engineering mentality, although

the field of cost-engineering has begun pioneering efforts in this area. Nevertheless, it is through the language of funding that agencies and Congress fundamentally interact (Wildavsky 1964). There are, of course, hard technical limits on the extent to which costs may be modulated. These limits are dictated by the particulars of the mission under development. Nevertheless, within these limits, NASA can influence the per annum and lifecycle costs of its projects. These considerations drive the next assumption:

**Assumption #5:** Legacy component use primarily acts to reduce the difficulty factor of CEV Block construction.

Chapter 3 and Chapter 4 identify two ways through which NASA can exert some control over the per annum cost of its projects: modulation of development start date and use of legacy components. Development start date is restricted by organizational and logistic factors, such as availability of skilled workforce and materials to execute a given conceptual design – indeed; generation of a design concept is itself a major undertaking that, despite its low cost, has a major effect on the eventual mission architecture. Nevertheless, the earlier a design can be initiated and its execution can begin, the more opportunity exists for spreading the cost of the program over multiple years, driving down per annum cost. In particular, multi-block designs are well-suited to take advantage of this cost-spreading property since they may show a tangible result in the deployment of Block 1 while simultaneously improving upon that design for Block 2. The disadvantages of beginning development and conceptual design early include lock-in of older technologies and design concepts that might inhibit innovation on later versions; nevertheless, in the specific case of the CEV's TPS, ablative materials, which have been available technically feasible since the 1960s, do not require a major technological breakthrough. Although the trade between innovation and cost is not explicitly addressed in this thesis, it remains a salient concern for future designers and likely requires consideration on a case-by-case basis – some designs will be more given to early commencement while others, that might entail a high degree of technological uncertainty, should likely be delayed.

**Assumption #6:** System effects of legacy component use are negligible.

Chapter 3 and Chapter 4 explored how technological choice can drive mission per annum cost. They examined legacy components and how their judicious choice could be used to shape NASA's cost profile through time. Nevertheless, significant uncertainty surrounds the system effects of incorporating legacy components into design. For example, some of the aerospace industry's major disasters have been caused by indiscriminate component re-use (Leveson 2004). Such experiences illustrate the need for technical experts with a systems

perspective who are able to determine which legacy components are appropriate to use under which circumstances. A generalized framework for performing this type of analysis is outside of the scope of this thesis, but would constitute a valuable research contribution. Nevertheless, the savings from appropriate legacy component re-use cannot be discounted. This analysis assumes that the specific legacy components used are well-researched and characterized, such that their use is beneficial. To this end, three types of legacy components may be classified as follows:

Table 14: Three types of legacy components identified in Chapter 3.

Legacy Component Type	Effects on Block 1 Deployment Cost	Effects on Block 2 Upgrade Cost
Common	Reduced cost	No effect
Delayed	Added maintenance cost	Reduced cost
Temporary	Reduced cost	Added upgrade cost

The selective incorporation of these components allows NASA some measure of control over its present and future costs, as the situation demands. When available, Common legacy components are ideal for the purposes of cost reduction. It is this principle, identified in (Taylor, Broniatowski et al. 2005) and elaborated upon in (The Charles Stark Draper Laboratory Inc. 2005) that is at the heart of design for commonality – today’s state-of-the-art designs become tomorrow’s legacy components – therefore, design for sustainability requires that commonality be planned into design. Nevertheless, not all legacy component use can be anticipated. Some components will not be immediately required for incorporation, and others will not be useful throughout the entire system’s design lifecycle. Thus, the effects of Delayed and Temporary component use must also be considered. An analysis of the propagation of system effects of a legacy component can be instructive in determining how a choice to reuse certain components might affect overall cost and technical performance.

This thesis explicitly recognizes the linkage between legacy components and political constituencies. The presence of these advocacy coalitions creates political, as well as technical, advantages to the use of certain legacy components. At the same time, it is not always technically advantageous to appease given constituencies. Conversely, there are often political costs to implementing the technically optimal solution. Determining a method to trade political costs against technical costs would constitute an important research contribution to the design of techno-political systems, such as those constructed by NASA. It is the intention of this thesis to take the first steps in this direction.

### **Conclusion: Tying It All Together**

Whereas a program's costs are driven largely by technical and organizational parameters, Congressional budgeting behavior is driven largely by salience and political compromise. In the absence of a salient interest, NASA can expect to receive an incremental funding baseline – approximately equal between years but for minor stochastic perturbations. On the other hand, periods of non-incremental behavior arise when outside factors conspire to divert funding to or from NASA's budget. This upset in the status quo can occur for many, often unpredictable reasons. Chapter 2 and Chapter 5 link salience of NASA's agenda to national security in the specific context of returning astronauts to LEO after the loss of the Space Shuttle *Columbia*. In addition to the motivations of national pride and prestige associated with having an American presence in LEO, many members of Congress derive distributive benefits from NASA's human spaceflight programs. The threat inherent in the prospect of the loss of these values and associated distributive benefits is sufficient to gain Congressional attention and, if the testimony of certain members of Congress serves as any indication, additional funding. Nevertheless, the conditions of Congressional salience cannot be expected to last forever. If history is any indication, NASA's budget can be expected to return to an incremental steady-state following the fulfillment of Congress' desire to return humans to LEO. If NASA is to fulfill the President's directive to affordably and sustainably explore beyond LEO, funding must be present to enable a successful CEV upgrade from Block 1 to Block 2. Given this environmental context, design for ease of upgradeability becomes a salient concern for NASA. Political sustainability within this context suggests that NASA should take advantage of the threat power awarded by Congress' increased salience to build a CEV that may be easily upgraded later in the future. In the specific example provided by the TPS, NASA should begin development of the Block 2 TPS now while there is funding available. For example, if it is at all possible to minimize future funding by including a lunar-capable TPS in a Block 1 CEV, it should be done.

Delaying Block 2 expenditures until Block 1 deployment is not politically sustainable from a lifecycle perspective. Indeed, if the costs of upgrade from Block 1 to Block 2 are too high, the deployment of a lunar-capable CEV will be delayed, and possibly cancelled, in the face of more pressing national priorities. Thus, acceleration of the CEV should be undertaken with utmost care to ensure that the means by which this acceleration is implemented do not undermine the Vision for Space Exploration. This dynamic illustrates the differing preferences of Congress and the President. To the extent that Presidential and Congressional goals are in alignment, one may expect definite action accompanied by the funding required to carry it out. It is therefore unlikely that the Block 1 CEV will be cancelled or significantly delayed. Nevertheless, if the Presidential goal of lunar

exploration is to be carried out, NASA must take advantage of the current political environment to design a CEV that does not inspire Congressional ambivalence by exceeding future funding expectations. This will more easily enable a sustainable lunar exploration by helping to keep future development costs for the CEV under the incremental level enforced by Congress-NASA power dynamics.

The conclusions of this thesis are based upon many assumptions regarding cost-spreading, Congressional valuations and the feasibility of using legacy components to reduce cost. The purpose of this chapter in explicitly recognizing these assumptions is to examine how the results of this analysis might change in response to perturbations. This analysis was conducted in reverse, exploring first the effects of varying assumptions about NASA/Congress interactions. Varying our costing assumptions might propagate in such a way as to cause changes in these interactions. Finally, the costing assumptions might be affected by changes in the assumptions underlying our technical parameters, such as system effects. In so doing, a set of possible scenarios that NASA and Congress might face in the coming years was outlined.

Political sustainability on the part of NASA requires a constant attention to the details of technical design and political choice. Although it might also seem to require a prescience that extends over several years, general principles can apply to how systems are developed in a politically sustainable fashion. In particular, the presence of events that raise an agency's national salience allows that agency an opportunity to increase expenditures for the purposes of reducing future costs. So as to maintain credibility, these expenditures must be associated with the goals of Congress. Nevertheless, NASA's ability to control design implementation allows for the selection of a design that can simultaneously satisfy Congressional directives while enabling ease of future execution of the President's VSE.

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THESIS CONTRIBUTIONS

This thesis outlines a methodology by which a system architect can model interactions between the political and technical realms within a techno-political system. In particular, we focused on the Congressional directive to accelerate the CEV, and how implementation of this directive might interact with the Presidential goals of returning to the Moon before 2020. In so doing, this thesis proposes a definition for political sustainability, arguing that NASA, when designing systems to fulfill the directives of the President, must take into account future funding cycles, how the cost of these systems might evolve through time, and how NASA's budgetary profile might change in response to fulfillment of Presidential directives. Figure 42 captures these dynamics graphically.

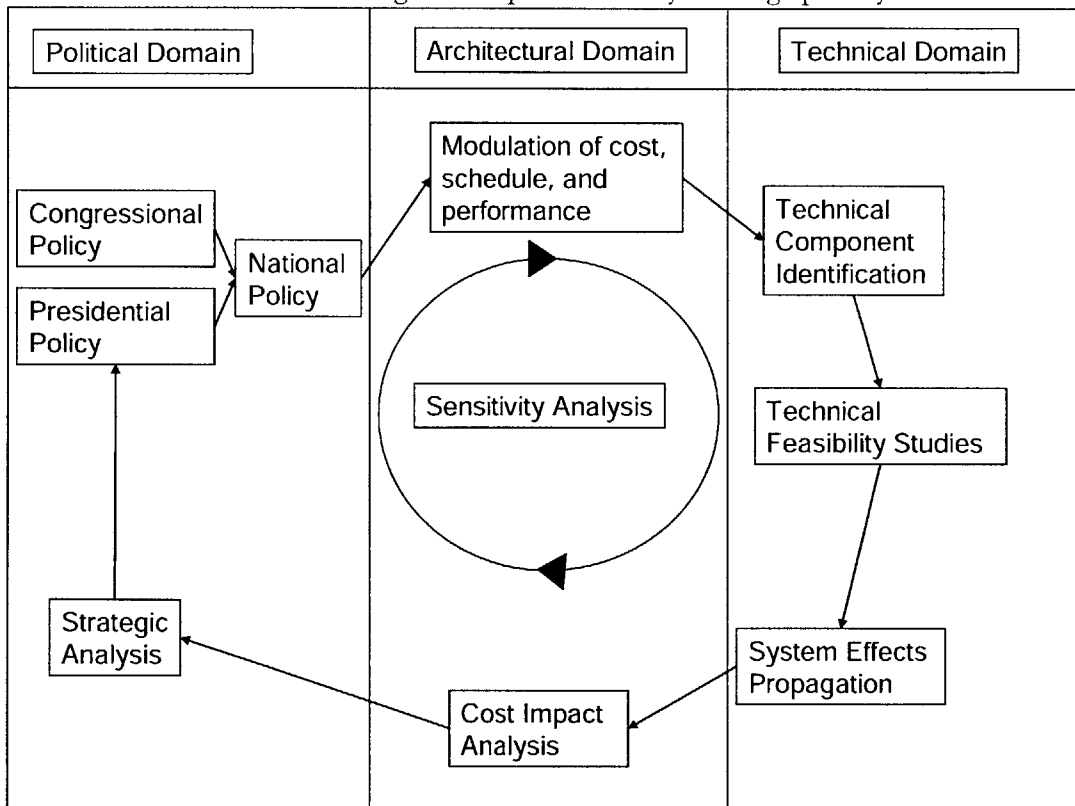


Figure 42: The full Policy-Technology Feedback Cycle for Executive Branch Agencies.

Chapter 1, the introduction, provides a historical motivation and context for this work, introduces and defines political sustainability, and provides a brief overview of the literature linking political directives to technical choice.

Chapter 2 extends this literature review into the political sciences, approaching the problem from the other direction. Specific attributes and characteristics of agency-Congress relations are identified, with the intention of illustrating what drives budgetary policymaking. The space policy literature is then drawn upon to link this theoretical work to NASA's specific case. In particular, NASA is identified as an incremental agency, undergoing incremental changes in funding. Strategies used by incremental agencies are identified, yielding insight into what drives Congressional valuations of an agency's agenda. Finally, two funding regimes are identified for an agency – namely, the incremental regime wherein programs must compete with one another for barely sufficient funding in a zero-sum environment, and the national salience regime wherein specific programs are identified as fulfilling an important or salient value to the nation and are therefore accelerated and grown. This lasts until the salient problem is solved, after which point the program is either discontinued or returned to an incremental funding level.

Chapter 3 serves as the technical analysis of this report, identifying three types of legacy components and how they might impact overall cost. In particular, Common components reduce total cost, Delayed components reduce future costs at the expense of up-front maintenance, and Temporary components reduce current costs, pushing the costs of component upgrades into the future. This chapter focuses specifically on Shuttle TPS elements as an example of a Temporary legacy component, first probing the technical feasibility of their use, and then exploring the possible system effects that might arise from component reuse.

Chapter 4 uses standard cost-estimation techniques to illustrate how per annum costs might be spread across the development lifecycle of the first two CEV Blocks. NASA may modulate these costs by varying development start date and development "difficulty", which is linked in part to the amount of new technology to be developed and tested. As such, the judicious use of legacy components may modulate difficulty, allowing NASA to trace impacts on cost. Given the three types of components identified in the Chapter 3, this model may be used to determine when it may or may not be appropriate to design new components as opposed to re-using old ones. The results of this chapter are intended to be notional; illustrating that cost is subject to some measure of control through the variation of schedule and legacy component use. As such, NASA might modulate its funding profile so as to be congruent with Congressional valuations.

Chapter 5 presents a game-theoretic framework, based upon the Theory of Moves, which is aimed at outlining the interactions between agencies and Congress. In particular, this thesis identifies four generic types of interactions based upon the valuations held by the Executive and Legislative Branches of a particular program. We see that the structure-induced “threat power” of each Branch is affected by the preferences of both actor. The four situations identified are represented by four games. The Incrementalism game reflects the standard situation found in agency-Congress relations in which an agency’s high valuation of a program allows Congress the ability to provide incremental funding – the agency will see to it that that program continues to exist, cutting less important programs if necessary. This situation is duplicated when Congress does not have a high valuation of that program, a situation reflected by the Uncertainty game. When an agency possesses a low valuation of a program that Congress values highly, the agency can successfully execute larger funding requests through the use of a “deterrent threat” – a situation wherein the agency explicitly states that without the funding, the program cannot be executed. The agency can do this credibly because of the technical implementation expertise that is held within that organization. This game is therefore called the Deterrence game. If both branches of government have a low valuation of a specific program, that program will be cancelled, a situation reflected by the Cessation game. This final situation also serves as an example of what might happen if an agency loses its credibility by overstating its budget request. The framework provided by these games illustrates how NASA might want to structure its funding profile in any given year. In the event that NASA encounters a period of national salience, the Deterrence game predicts that more funding could be available if it can be justified. On the other hand, in incremental periods, the Incrementalism game suggests that NASA should keep a low profile. Given that national salience is driven by exogenous political events, if one can identify the source of that event, one can anticipate a return to incremental funding. As such, the politically sustainable strategy suggests that the agency should design for upgradeability during periods of national salience – when funding is available – so that when funding is less prevalent, execution of the President’s goals can continue with minimal intervention necessary from Congress. This represents a win-win situation for all parties, since, during periods of incrementalism, the President is accomplishing a stated goal, and Congress-members can show national and distributive results to their constituents without breaking the bank. During periods of national salience, Congress has less need to justify expenditures, since these are in line with national priorities, and therefore constitute both a solution to an existing problem and an investment in the nation’s future.

Finally, Chapter 6 provides an overview of each of the preceding chapters, systematically identifying and challenging the assumptions in these chapters. In so

doing, areas for future work that might ameliorate the limitations of this framework are suggested. Furthermore, this chapter highlights the role of experts in the design and political processes, including lawyers who must interpret Congressional legislation, political appointees who receive direction for the agency from the President, systems engineers who oversee conceptual design, technical experts, who oversee detailed design, cost engineers and economists who are responsible for performing cost analyses and estimation, and legislative affairs personnel, who are responsible for representing the agency to Congress. The role of system architect is to serve as interlocutor between these experts, and to pool their expertise in such a way as to forge a coherent strategy that will enable the long-term political sustainability of the President's directive.

There are four major contributions of this thesis:

1. The framework provided by the policy-technology feedback loop, which illustrates that a techno-political system is engaged in constant give and take between the political and technical realms. This framework may be used by a system architect to trace the effects of a given political choice on a technical decision, and vice versa. Ultimately, the goal is to aid in communication between engineers and policy-makers, so as to avoid situations that might lead to disastrous outcomes.
2. The literature review and references collected in this body of work are synthesized to provide a comparison and contrast of political and engineering decision-making. These are related to literature on incremental policy making, with the aim of enabling the system architect to better understand and anticipate the nature of interactions between the political and technical environments.
3. The application of game theory, and particularly the Theory of Moves, as a descriptive tool to understand interactions between the US Congress and federal agencies. Observations and assertions regarding the validity of the application of this particular tool are supported by testimony given by members of Congress and NASA, and news sources. The four general classes of agency-Congress interactions identified can also serve as proscriptive guideposts for NASA and other agencies as they prepare their interactions with Congress in response to current events that drive Congressional opinion.
4. The four areas for future work identified in this thesis suggest several possible lines of inquiry that can enrich our collective understanding of techno-political systems. These areas are as follows:
  - a. Techno-political interactions under incrementalism: Many agencies besides NASA are subject to incremental funding. Creation and oversight of engineering systems within the bureaucratic and political environments of these agencies is difficult, largely due to shifting political priorities and the frequent

lack of a clear national direction. A generalized body of research characterizing these interactions would allow decision-makers the ability to discover solutions to these problems when possible, and to determine under which conditions the government should engage in techno-political system design and operation.

- b. Articulating the costs of legacy component use: It is conventional wisdom that legacy components have the potential to reduce costs in engineering system design by obviating the need for redesign of certain components. Nevertheless, some legacy components used in some situations may adversely affect system operation, for example through the presence of unanticipated, or emergent, behavior. In addition, the costs of incorporating legacy components may be high, carrying requirements that extend beyond the engineering domain, such as the need to maintain a certain workforce or a given facility. The formulation of a rigorous and inclusive framework for the valuation of legacy components could help system designers make better decisions regarding legacy component use, and would therefore be an important contribution to the engineering systems literature.
- c. Determining and incorporating multi-stakeholder valuations into the design of techno-political systems: Engineering systems designed within the political environment must often be built to serve several constituencies. Many stakeholders may agree on the need for a certain system, although they may have different ideas in mind for the actual functionality that the system is to deliver. As such, valuations of a given system are unclear. Future research into methodologies for determining the needs and values of stakeholders in engineering systems design can help to determine how a specific architecture might better serve various constituencies. Furthermore, such research could facilitate negotiations between stakeholders, allowing for informed determinations regarding whether or not a particular stakeholder should participate in the design process or levy requirements on the engineering system.
- d. Articulating informal negotiations within the government: Negotiations between agencies and the OMB, or between the OMB and Congress, or between members of Congress and individual agencies, are generally not captured in the process of submitting a formal budget request. Nevertheless, these interactions have an important effect on the ultimate budgetary and design outcomes. Capturing these dynamics is difficult since they are private by design. Nevertheless, an understanding of how these negotiations occur and are carried out can inform decision-

making and would provide an important contribution to both the political science and engineering systems bodies of literature.

### **Conclusion**

This thesis is largely concerned with political sustainability. In the broadest sense, political sustainability requires an active process of cooperation and coordination between system architects, political experts and technically-trained engineers. Most importantly, the interdependence of those in the technical and political realms must be realized. This requires that the concerns of Congress and other stakeholders in the political process be explicitly taken into account during the technical design process. Likewise, political actors must be informed of the consequences of their decisions upon the technical architectures. Although this process of information transmission is represented by a “deterrent threat” in the language of game theory, it does not necessarily have to entail the overt hostility implied by this term. Rather, communications between representatives of the President and members of Congress must be structured so as to explicitly reflect the core values of our elected representatives. These communications must focus on enabling non-myopic thinking both among agencies and Congress. The role of the system architect in this regard is therefore one of translator – the architect must be able link the technical parameters of the engineering system under consideration to the salient values of the policy-makers who are supporting it. For this support to be sustained, the architect must be able to translate the long-term considerations of system design into short-term, frequently-delivered benefits for the system’s stakeholders. To paraphrase (Brundtland, Khalid et al. 1987), the concept of political sustainability does imply limits – not absolute limits but limits imposed by existing technological capabilities and political organization on budgetary resources and by the ability of the taxpayer, through Congress, to fund the human expansion into space. But technology and political organization can be both managed and improved to make way for a new era of space exploration. This thesis takes the first tentative steps in this direction.

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