Developing Structural Improvements for the Military Spacecraft Acquisition and Development Process

by

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ABSTRACT

Because of continued defense downsizing and the increased prominence that national security space programs have taken in recent defense budgets, government and industry leaders have a renewed and more fervent interest than ever in reducing the cost and time it takes to acquire military space systems. Presently and throughout the history of military space those close to acquisition have proposed organizational, technical, and managerial solutions for increasing acquisition efficiency. These solutions, if implemented in a largely uncoordinated manner, are likely, however, to work at cross purposes potentially having a detrimental effect on the present acquisition process.

This thesis attempts to identify a holistic approach to assessing the affects of new military acquisition initiatives on the present system. First, it documents the unique technical challenges of building a space system and the different organizations in government and industry that work together to accomplish a system's construction. Using this knowledge, this thesis presents the common process used up into recent times for acquiring unclassified military spacecraft and documents it in a design structure matrix (DSM). This documentation provides a basis for analyzing the government space acquisition process and identifying some potential areas for improvement - namely reducing technical uncertainty and increasing a shared acquisition vision. This thesis takes into consideration these observations and conclusions and presents an alternative process for spacecraft acquisition and development which uses existing military acquisition agents.

This thesis recognizes that many initiatives are ongoing in government and industry to address issues of acquisition efficiency. The military space acquisition process is changing. By documenting the common acquisition process - prior to any of these recent changes - this thesis attempts to provide a framework so that policymakers can think holistically about the effects of the solutions they have developed recently and will develop in the future.

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Abbreviations

ACAT	Acquisition Category
ADACS	Attitude Determination and Control System
ADM	Acquisition Decision Memorandum
AEDC	Arnold Engineering Development Center
AFFTC	Air Force Flight Test Center
AFSCN	Air Force Satellite Control Network
AIAA	American Institute of Aeronautics and Astonautics
ARPA	Advanced Research Projects Agency
ASD	Aeronautical System Division
ATB	Advanced Technology Bomber
ATR	Automatic Target Recognizer
BMDO	Ballistic Missile Defense Organization
BOL	Beginning of Life
C&DH	Command and Data Handling System
C3I	Command, Control, Communications, and Intelligence
CDR	Critical Design Review
CEM	Cost Engineering Model
CO2	Carbon Dioxide
D.C.	District of Columbia
DARPA	Defense Advanced Research Projects Agency
dem/val	Demonstration and Validation
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DoD	Department of Defense
DODI	Department of Defense Instruction
DOI	Department of Interior
DOT	Department of Transportation
DSM	Design Structure Matrix
DSP	Defense Satellite Program
DTC	Design-To-Cost
EMD	Engineering and Manufacturing Development
ENG	Engineering
ENSIP	Engine Structural Improvement Program
EOL	End of Life
FLTSATCOM	Fleet Satellite Communications System
FOV	Field of View
GEO	Geosynchronous Earth Orbit
GHz	Giga Hertz
GOES	Geostationary Operational Environmental Satellite
GORD	Ground Operation Requirements Document
GPS	Global Positioning System
HEAO	High Energy Astronomy Observatory
ICD	Interface Control Document
IDEFO	Integrated Computer-Aided Manufacturing Definition Method
IOC	Initial Operational Capability
IRN	Interface Review Notice

JCS	Joint Chiefs of Staff
JROC	Joint Requirements Oversight Council
LANTIRN	Low-Altitude Navigation Targeting Infrared for Night System
LEO	Low Earth Orbit
MCC	Mission Control Center
MEO	Middle Earth Orbit
MFG	Manufacturing
MilSpec	Military Specification
MilStd	Military Standard
MMS	Multimission Modular Spacecraft
MNS	Mission Need Statement
MSFC	Marshall Space Flight Center
NASA	National Atmospheric and Space Administration
NNSS	Navy Navigation Satellite System
NOAA	National Oceanic and Atmospheric Administration
NRO	National Reconnaissance Office
OSD	Office of the Secretary of Defense
OTA	Office of Technology Assessment
PDR	Preliminary Design Review
POCC	Payload Operations Control Center
RF	Radio Frequency
RFP	Request for Proposals
SDR	System Design Review
SMC	Space and Missile System Center
SMM	Solar Maximum Mission
SOCC	Spacecraft Operations Control Center
SPO	System Project Office
SRR	System Requirements Review
SSAO	Space System Acquisition Office
TAC	Tactical Air Command
TDRSS	Telemetry and Data Tracking Relay Satellite System
TRD	Technical Requirements Document
TRW	Thompson Ramo Williams
TT&C	Telemetry Tracking and Control System
U.S.	The United States of America
USAF	The United States Air Force
USDAQ	Undersecretary of Defense for Acquisition
USSR	Union of Soviet Socialist Republics
WBS	Work Breakdown Structure

Chapter 1: Introduction

1. The Need for Controlling Cost and Schedule in Spacecraft Development

In Fiscal Year 1995 the defense and intelligence communities are spending $13.5 billion on space programs. This amount represents 5.4% of the $252.2 billion requested by the Department of Defense (DoD) for the 1995 fiscal year. Combined with a NASA operating budget of $14.3 billion, the United States government is spending over $27 billion on space this year alone (*The Congressional Record*, 1994). Furthermore, forecasts indicate that despite a reduction in national security spending as a whole, funding for national security space programs will remain level or slightly increase over the next several years. In fact, over the next 5 years, the defense and intelligence communities plan to spend $70.7 billion on space (*The Congressional Record*, 1994).

As spending on space programs becomes a larger percentage of the entire defense budget, controlling the costs of developing, building, launching, and operating spacecraft will become increasingly important. There are two reasons for this. First, each percentage point that a particular program goes over budget will represent a larger strain on the defense budget than ever before. Second, because it will have a larger share of the defense budget, military space will receive a larger share of political scrutiny. Thus, each program mishap will garner more Congressional attention and create bigger barriers to that program's completion.

Military space is not prepared, however, for this added exposure to budgetary and political pressures. In general, high level government and industry officials as well as the rank-in-file developers and managers involved with space system development have not found a way to reduce the cost or schedule for developing and launching space systems. Conversely, government space programs, military and civilian, typically run vastly over budget on cost and schedule. One GAO report finds that a set of 25 projects under development or recently completed by NASA were, on average, 99% over budget. More disturbingly, only *three* of those projects were under budget (GAO, 1992). Although similar numbers for DoD space are not readily available, there is little debate in the space community that military space acquisition also greatly suffers from cost and schedule difficulties (*The Congressional Record*, 1994).

Policymakers and program managers, alike, have made many attempts to improve this persistent condition. Over the past thirty years at least twelve major studies have analyzed the defense weapons acquisition process noting its strengths, deficiencies, and needed reforms (Fox, 1988). Reforms suggested by these reports focused mostly on managerial and organizational solutions. Other reports written during this period have called for a national space vision to: (1) define the military, intelligence, civil, and commercial space sector objectives; (2) direct a clear course of action for addressing each sector's mission needs and operational requirements; (3)

establish a mechanism for converging each sector's approach to satisfying its technical and funding requirements; and (4) identify potential financial, technological, and societal benefits to be achieved (*The Congressional Record*, 1994). Still other reports developed technical strategies including small satellites, cheap satellites, light satellites, modularity, standardization, and prototyping to reduce the cost of spacecraft acquisition.

Only now, however, has finding solutions to cost and schedule overruns become an issue of survival for the defense aerospace community. The fall of the Eastern Block has resulted in reduced budgets throughout the defense industry and, specifically, the elimination or severe reduction in several space programs such as The Strategic Defense Initiative, also known as "Star Wars." Added to this, the rapidly changing threats that still exist, for example those evidenced by the Persian Gulf War at the beginning of this decade, indicate that the Armed Forces need swift responses to the military space needs developing in the future. Development programs, such as Milstar, which took more than 15 years and $10 billion to orbit its first demonstration and validation satellite, are not acceptable in a new environment of constrained funding and constantly changing threat environments.

The choice is a clear one. Either develop a reduced number of systems and possess a lower level of capability under the status quo acquisition system, or modify the military's space system acquisition and development processes to produce cheaper and more efficient development programs. Otherwise, the military might not be able to support all the programs that already exist, such as the Global Positioning System (GPS), Milstar, the Defense Meteorological Satellite Program (DMSP), and several infrared surveillance systems. Accepting the first of these two choices and the associated consequences is tantamount to admitting defeat - admitting that government and industry cannot improve the way they do business. Government and industry leaders therefore have a renewed and more fervent interest than ever in understanding the solutions suggested in the past for alleviating budget and schedule woes. These leaders also wish to identify new solutions to existing acquisition problems and judge whether any of these solutions, past or present, are effective.

Reorganization may help the military and intelligence communities to alleviate some of the existing inefficiencies within defense space acquisition. Certain technologies may help to improve the performance of, control the costs of, or speed the completion of spacecraft under development. These solutions, if implemented in a largely uncoordinated manner, are likely, however, to work at cross-purposes making matters worse than before. For example, uncoordinated technology development efforts might spend money on devising multiple solutions to the same problem while neglecting the solution of other problems altogether. Another example might be if DoD reduces reporting requirements during the development of spacecraft to streamline the acquisition process. If, however, Congress reinstates these reporting requirements through budget legislation, then any extra efficiency possible under the DoD plan is offset by the extra Congressional oversight. As a result, a new way of thinking about problems in the spacecraft acquisition and development process and developing solutions and strategies to implement them must be found. This thesis attempts to define this new way of thinking and establish some of the strategies important to improving the process for acquiring military spacecraft.

1.2 Thesis Focus and Organization

1.2.1 Focus

This thesis identifies problems with and potential solutions to the process for acquiring defense space systems. Two characteristics of this thesis' approach, however, make it different and more effective than other works before it. First, while many of the existing works cited in Fox (1988) and other literature focuses on military acquisition as a whole, this thesis focuses specifically on the acquisition and development of military space systems. Space systems have several unique challenges and attributes that significantly set their acquisition apart from the acquisition of other types of defense systems. As a result, this thesis provides less general, not necessarily applicable to the acquisition of all kinds of defense systems, but more applicable observations about and solutions to the problems faced by the defense aerospace community. Second, this thesis does not focus singularly on technical, managerial, or organizational issues. Instead, it takes a holistic approach, considering a wide variety of technical, managerial, and organizational problems and their solutions.

A holistic approach is so critical because the structural causes of spacecraft acquisition and development difficulties are of managerial, technical, and organizational natures. Only by looking at the whole system can these causes be identified. Furthermore, a holistic, or systems, approach provides the perspective from which policymakers can develop a coherent road map of technical, managerial, and organizational solutions for implementation into the acquisition process. Therefore, this thesis uses a systems approach to identify the structural changes to the acquisition and development processes that are necessary for controlling acquisition costs and schedules. In-control costs and efficient schedules are two program attributes that are critical to the future of the defense aerospace industry.

The intent of this thesis then is to identify the fundamental, or structural, causes of the problems witnessed in spacecraft development and acquisition. Budget and schedule overruns, this thesis maintains, are merely the result of conditions within a program that exist because of structural flaws in the process for the acquisition and development of all spacecraft. These structural, or systemic, flaws are the real causes of budget and schedule difficulties seen across most spacecraft programs. By understanding these causes, policymakers can make changes that will positively affect all future programs.

In particular, this thesis argues that there are two main structural faults in the spacecraft acquisition system. First, the current DoD acquisition process, as applied to spacecraft, does not adequately reduce uncertainty before system development begins. Second, the players in the acquisition process often work at cross purposes creating a set of dynamic, conflicting goals which are unattainable. This thesis shows that problems with incomplete or poorly written requirements, the concurrency of innovative design with repeat design work, and technical shortfalls are results of this first fault. This thesis, likewise, shows that the second structural fault leads to troubled lines of communications among the players, a lack of intermediate process feedback, and unreasonable performance, cost, and schedule goals. Furthermore, a lack of common goals continues to prevent the effective resolution of these structural faults. Finally, this thesis takes into consideration these observations and conclusions when presenting an alternate process for spacecraft acquisition and development.

1.2.2 Organization

Chapter 2 describes the basic technology and major components found in a space system design, some of the special design constraints that exist when designing for the space environment, and the major players in the space system acquisition and development processes. Knowledge of these issues is important for understanding the discussion of the spacecraft acquisition and development processes that follows in Chapters 3 and 4. Chapter 3 documents the activities that occur before the official establishment of a new space system development program. Chapter 4 reports the process by which elements of DoD and the aerospace industry work together to design and launch a new spacecraft into orbit.

These three chapters set the stage for the second part of the thesis, which is contained in Chapters 5 and 6. Chapter 5 uses a Design Structure Matrix (DSM) to represent the spacecraft development process and the information flows that take place within it. From the DSM several observations are made about the process. They include the symptoms that indicate structural causes for acquisition difficulties. Chapter 6 explicitly discusses these structural deficiencies and proposes solutions where appropriate. Chapter 7 establishes an alternative acquisition process based upon the conclusions of Chapters 5 and 6. Chapter 8 concludes the thesis with a summary of the major issues discussed in the thesis as well as potential solutions to them.

Chapter 2: The Design Space

1. Space Mission Architecture

A space mission is comprised of a set of elements or components that are arranged and selected in such a way as to optimize the mission concept which they accomplish. These elements form the space mission architecture. They are the mission subject, orbit, communications architecture, payload, spacecraft bus, launch system, ground system, and mission operations. The discussion that follows describes the operation of a spacecraft as well as the other components of the space mission.

1.1 The Mission Subject

Simply put, the mission subject is the raison d'être for the mission. The space system interacts with and/or uses its sensors to study the mission subject. Some examples of a mission subject include measuring atmospheric moisture content and temperature, tracking intercontinental ballistic missiles (ICBMs), and supporting a set of equipment on earth or on another spacecraft (as in the case of communications or navigation missions).

1.2 The Orbit

The orbit is the spacecraft's trajectory or path. Typically, a spacecraft goes through several different types of orbits in its lifetime including several intermediate orbits which are used to achieve the spacecraft's final mission orbit in the most fuel efficient manner. Intermediate orbit types include a parking orbit which provides a safe and convenient location to check for proper operation of the spacecraft and a transfer orbit which is used to move the spacecraft from one intermediate orbit to another intermediate orbit or a final orbit.

The final orbit can typically be categorized in one of two ways. Space-referenced orbits refer to those spacecraft missions where space (not Earth) is the primary mission subject. Examples of missions using space-referenced orbits are the Voyager interplanetary probes or the Hubble Space Telescope. Earth-referenced orbits are for spacecraft providing the necessary coverage of Earth or near Earth space. Communications satellites are in Earth-referenced orbits since their primary mission is sending and receiving signals to and from different locations all over the earth.

Final orbits, for spacecraft in orbit around the earth, can also be categorized by their height above the earth. Low-Earth orbits (LEO) are those that are less than 600 miles above the earth's surface. Spacecraft such as Hubble or the Space Shuttle use LEO orbits to carry out their missions. Mid-range altitudes (several thousand miles above the earth's surface) offer some missions valuable coverage characteristics. For instance, the Global Positioning System uses a set, or constellation, of 24 satellites to provide location information to over 95% of the earth's surface. Typically, however, mission designers try to avoid mid-range orbits because clouds of charged ions, referred to as the Van Allen belts, create difficult radiation environments for spacecraft. Geosynchronous orbits (GEO) are those orbits approximately 22,300 miles above the earth. Spacecraft in this type of orbit remain relatively stationary over one point on the earth and can observe almost half of the earth's surface at any one time, making GEO orbits popular for communications and some types of surveillance satellites. (Approximately 80 percent of all satellites are in a GEO orbit (Martens, 1990).) Despite their ability to observe half of the earth's surface at a time, space system designers will usually use three or more geostationary satellites to accomplish full coverage of the earth. For example, the GOES/NOAA constellation of weather satellites uses two GEO spacecraft (the GOES spacecraft) to focus on equatorial regions of the earth and two other GEO spacecraft (the NOAA spacecraft) to cover the earth's polar regions.

Sometimes a spacecraft is moved to another parking, or disposal, orbit after its mission is finished. This way another satellite can take over the other's orbital slot. The orbit chosen for a spacecraft affects a great many mission parameters like the number of spacecraft needed to cover a specified viewing area, the launch vehicle needed to get a spacecraft to its required orbit, the timing of the spacecraft launch, the size of ground and spacecraft communication antennas, the power required by a spacecraft, the radiation hardening needed for a spacecraft's components, and the spacecraft payload's accuracy on orbit. In reality, however, the design of the spacecraft, the orbit, and other parts of the mission architecture is an iterative process where designers trade off various combinations of these parameters against one another.

1.3 The Spacecraft

Spacecraft and satellite are used interchangeably in much of the literature written, but spacecraft is the more technically correct term. Whereas a satellite refers to any natural or man-made object orbiting a celestial body (e.g., the Moon around Earth, Earth around the Sun, or a Global Positioning System satellite around the earth), spacecraft denotes only the machines built by humans expressly for the purpose of entering space and performing a certain set of functions there.

Together, the spacecraft bus, payload, and the launch vehicle adapter, which mechanically and electrically connects the spacecraft with the launch vehicle, are known as the spacecraft. The categorization of the spacecraft's functions into subsystems and the physical arrangement of these subsystem components on the spacecraft is what is referred to as the spacecraft architecture. This is not to be confused with the space mission architecture.

1.3.1 The Payload

The payload is the set of hardware and software on the spacecraft that performs the mission for which the spacecraft is designed, fabricated, and launched. The payload is the part of the space system which senses or interacts with the mission subject. For a communications satellite it is a set of antennas and the related electronics necessary to receive, send, and route data through the spacecraft. On a surveillance spacecraft, it might be an array of sensors imaging an object, such as a weapons test range or space vehicle launch site, in different electromagnetic spectrum bands. Yet another type of payload is an experimental payload designed to perform and take data from experiments that require a space environment.

The payload largely determines the mission's cost, complexity, and effectiveness. It's parameters (e.g., imaging accuracy, scan rate, data rate, and required pointing accuracy) affect the design of the spacecraft, its respective subsystems, and the spacecraft orbit. The payload's parameters, on the other hand, are affected strongly by the mission subject, orbit, communications architecture, and ground system capabilities.

1.3.2 The Spacecraft Bus

The spacecraft bus contains the subsystems necessary for proper operation of the payload. Reeves (Larson and Wertz, 1992) notes that the spacecraft bus functions to "support the payload mass; point the payload at the subject it is studying correctly; keep the payload at the correct temperature; provide electric power, commands and telemetry; put the payload in the right orbit and keep it there; provide data storage and communications, if required." To aid the designer, both conceptually and organizationally, the spacecraft bus is broken up into a set of subsystems, which are equipment groups associated together by a certain set of functions. This categorization is known as the spacecraft architecture. The following are subsystems in the spacecraft architecture: attitude determination and control (ADACS), communication, command and data handling, power, propulsion, structures and mechanisms, and thermal.

These groupings are somewhat arbitrary and vary slightly depending on the designer listing them. Nevertheless, use of this particular functional breakdown is fairly standard throughout the unmanned spacecraft community. Furthermore, these groupings in no way imply that the equipment for each subsystem is separate into its own section of the spacecraft. In fact, this, often, is not the case. It is also sometimes true that the payload equipment is entirely integrated with the spacecraft bus equipment, thereby leaving no clear physical distinction even between the payload and the spacecraft bus. A brief discussion of each subsystem's function follows.

Attitude Determination and Control Subsystem (ADACS)

The attitude determination and control subsystem (ADACS) measures and controls the spacecraft's orientation. In short, it makes sure that the payload is pointing in the correct direction to within a design specified tolerance at all the times. Sometimes, spacecraft requiring no or very coarse (e.g., ± several degrees) orientation control will have no ADACS subsystem or maintain pointing requirements by passive methods such as spinning or interacting with the Earth's magnetic gravity field.

Active systems provide more accurate control using actuators, torquers, or propulsion subsystem thrusters to change spacecraft attitude, velocity, or angular momentum. Primary determiners of the ADACS' design, complexity, and cost are the number of independent appendages for which it must maintain accurate pointing (e.g., keeping the solar array pointed at the sun while keeping the payload's scanners pointed at the earth), the pointing accuracy it must provide, the required speed of adjustment to pointing disturbances like atmospheric drag or solar winds, and the bandwidth of disturbances requiring the ADACS to respond.

Communications

The communications subsystem allows the spacecraft to pass information back and forth with the ground and other spacecraft of the same or different missions. Information flowing to the spacecraft from the ground is referred to as the uplink. This usually consists of commands telling the spacecraft to perform certain functions. Information flowing from the spacecraft to the ground, the downlink, consists of telemetry, reporting the "health" of the satellite and payload data. Communication between spacecraft is done via crosslinks through which spacecraft exchange health, payload and positional data.

The basic communication subsystem has a receiver, transmitter, and wide-angle (hemispherical or omnidirectional antenna). Depending on the demands placed on the subsystem, other antennas of different types might be integrated onto the spacecraft. Also, some systems are presently developing optical crosslinks which use lasers, instead of antennas, to transmit information. Laser radiation increases the communication bandwidth over methods presently available, but the use of lasers requires much more stringent spacecraft pointing and stability requirements. Primary parameters influencing the design of the communications system are data rate, the allowable rate of errors during transmission, the distance the signals must travel, and the frequency at which signals are received and transmitted.

Command and Data Handling (C&DH)

The command and data handling (C&DH) subsystem distributes commands instructing the spacecraft bus and the payload how to operate. Equipment in C&DH also accumulates, stores and formats data from the spacecraft bus, known as the spacecraft's telemetry data, as well as the payload telemetry and mission data. In less complex systems, C&DH and communications are sometimes combined into a telemetry, tracking and control (TT&C) subsystem. More often, however, command and data handling is a separate subsystem that includes a central processor, data storage units, and the interfaces necessary to send and receive the bus and payload data stored in the data storage units.

There is an interesting spacecraft system design question that arises when designing the C&DH subsystem. The decision is that of distributed processing versus central processing. Distributed processing exists when each subsystem handles all or some of their own functions using microprocessors, or more likely, microcontrollers that are imbedded into that particular subsystem's design. Central processing employs one, central microprocessor for handling the data processing needs of the entire spacecraft. In trading off between these two processing architectures, the designer must consider the amount of data and the rate at which that data must be processed. The designer must then consider how these data characteristics affect the complexity and risks associated with a distributed or centralized system. Medium to high data rates certainly require some sort of central processor, but one can imagine that on the high performance end, there could be so much data that a central data handling subsystem would need the help of some distributed processing or risk the effort of a lengthy, costly, and difficult new processor development program. Distributed systems, however, require more interface work and may, as a result, also increase system complexity, inefficiencies, and probability of failure.

Power

The power subsystem provides electrical power to the entire spacecraft for operation on orbit. Power has always been direct current (DC), although some concepts for the future are considering using alternating current (AC). The power source, usually solar cells which harness the energy of the Sun's radiation, provides energy to the subsystems and also stores energy to batteries, so that, when the spacecraft is in eclipse (e.g., the earth blocks the spacecraft from the sun), it has electric power to operate.

When designing the power system, the designer must look at five things in particular, the duty cycle, time of eclipse, the spacecraft design life, and beginning-of-life (BOL), and end-of-life (EOL) requirements. The duty cycle maps out how much power is used by the spacecraft during each orbit of its lifetime. The longer an eclipse is the more storage capacity is needed in the batteries. Battery storage capacity might also be used to store up energy for the spacecraft's peak power usage as predicted by the duty cycle. Over the life of a spacecraft, the solar cells' ability to capture power and the batteries' ability to store power diminish. At the same time the spacecraft's duty cycle might also shift (typically to reduced power demands). Therefore, it is important to compare how the power subsystem operation will degrade with the power requirements at the beginning and end of the spacecraft life.

Propulsion

Although some spacecraft do not have one, the propulsion subsystem has two main functions. First, it provides the energy needed to achieve and maintain the spacecraft's final orbit. Next, it applies torques to the spacecraft to change the spacecraft's angular momentum. This is sometimes called metered propulsion since, in order to control the spacecraft's angular momentum, thrusters must be turned on and off in a pattern, or metered. Pressurized gasses or bipropellant systems, where two substances when mixed create a thrust producing reaction, are used to fuel these thrusters. Also, at a more developmental stage are electric and ion propulsion systems. The advantages of these systems over chemical propulsion are they possess less mass, last longer, and reduce the hazardous materials that must be handled by spacecraft fabricators. On the other hand, they require much more power from the spacecraft and can cause an electrical bias of the spacecraft and its equipment.

A series of system level design decisions play an important role in determining the propulsion subsystem's design. The biggest decisions are the final orbit and launch vehicle. The launch vehicle, spacecraft mass, and final orbit, determine the amount of energy the propulsion subsystem must provide for the spacecraft to reach final orbit. Spacecraft in LEO must also overcome atmospheric drag. Even though there is very little, there is still some of the earth's atmosphere present in LEO around the earth. The atmosphere creates aerodynamic drag on the spacecraft traveling through it, thus reducing the spacecraft's speed and making it fall into a lower orbit. Propellant must, therefore, be present to periodically make up the energy lost due to drag. Pointing accuracy and other ADACS parameters also affect the propulsion subsystem and the amount of propellant and size of the thrusters used to keep the spacecraft's proper orientation while in orbit.

Structure and Mechanisms

The structural subsystem carries, supports, and mechanically aligns the spacecraft equipment. It also protects folded components, often referred to as deployables, during launch and deploys them upon reaching orbit. Launch accelerations, vibration, and spacecraft mass determine the required strength and stiffness of the main load-carrying structure, or primary load structure. Transient events and launch vibration are the key parameters for sizing the secondary structure which consists of deployables, brackets, and fasteners.

Thermal

The thermal subsystem controls the spacecraft equipment's temperature. Passive systems use equipment position on the spacecraft structure, insulative materials, and reflective coatings to moderate the effects of energy absorption from the earth and Sun and the equipment's power dissipation and radiation to space. Sometimes, however, active means of temperature control are necessary. Active thermal subsystems use electrical heaters or high-capacity heat conductors, heat pipes, to control equipment temperature. The amount of heat dissipation along with required equipment operating temperatures determine the size and complexity of this subsystem.

Table 1 lists all the subsystems, their function, and typical percentage mass and cost of the spacecraft.

Subsystem	Function	% Mass [1]	% Cost [2]
Payload	• The hardware and software on the spacecraft that senses or interacts with the mission subject • Key driver of satellite cost, complexity, and performance	28.06	25
Spacecraft Bus	• The group of subsystems necessary for the proper operation of the payload	------	75[3]
-Attitude Determination and Control System (ADACS)	• Assures the proper pointing direction, accuracy, and navigational stability for the payload	5.99	10
-Communications	• Allows the spacecraft to pass payload data and other information back and forth with the ground and other spacecraft	4.41	10[4]
-Command and Data Handling (C&DH)	• Distributes commands instructing the spacecraft bus and payload how to operate	-------	-------
-Power	• Provides electrical power to the entire spacecraft on orbit	29.90	20
-Propulsion (optional)	• Provides the energy needed to achieve and maintain the spacecraft's final orbit • Applies torques to the spacecraft to modify the spacecraft's angular momentum	4.31	25
-Structure and Mechanisms	• Carries, supports, and mechanically aligns the spacecraft equipment • Protects folded components (deployables) during launch and deploys them upon reaching orbit	21.06	20[5]
-Thermal	• Sets and maintains the desired temperatures for the spacecraft subsystem	4.45	------

Notes
[1] Average percentage values of dry mass (mass without including propellant mass) for selected satellites (Larson and Wertz, 1992)
[2] Martens, 1990.
[3] The average costs for these subsystems add to this 75% number.
[4] Includes command and data handling.
[5] Includes cost of thermal.

Table 1 Spacecraft Subsystems and Their Functions (Martens, 1990; Larson and Wertz, 1992)

1.4 The Launch Segment

The launch segment includes the launch facility, service interfaces, and the launch vehicle which is the means by which a spacecraft is lifted into orbit. Most launch vehicles are unmanned and possess a booster portion and a fairing. The boosters provide the propulsion necessary for achieving the velocity and altitude required to attain a specified orbit. The fairing is the part of the launch vehicle that contains and protects the spacecraft during launch. Sometimes, the final orbital objective requires the addition of an extra propulsion stage, referred to as an upper stage, to be assembled between the fairing and the rest of the launch vehicle. Upon reaching the required orbit, the fairing releases the spacecraft which then assumes its operational orbit. Examples of launch vehicles include the Titan, Atlas, and Ariane rockets. Some of their attributes and typical launch vehicle/upper stage combinations are shown in Table 2.

Launch System	Upper Stage	Payload Mass to LEO (kg)	Payload Mass to GEO (kg)	Launch Site	Fairing Envelopes	
					Diameter (m)	Length (m)
ATLAS I ATLAS II ATLAS IIAS	Centaur-1 Centaur-2 Centaur-2A	5580 6395 8390	450 570 1050	Air Force Eastern Test Range	2.9 4.2	7.7 9.7
ARIANE 40	H-10	4900	------	Kourou Launch Center	3.6	8.6 - 12.4
42P	H-10	6100	------			
42L	H-10	7400	------			
44P	H-10	6900	------			
44LP	H-10	8300	------			
44L	H-10	9600	------			
	EPS	18,000 at 550 km	------			
DELTA II 6920/25 7920/25	 PAM-D PAM-D	 3990 5045	 730 910	Air Force Western Test Range or Air Force Eastern Test Range	 2.5 2.8	 4.8, 6.8 4.2, 5.7
PEGASUS	NONE	455	------	Aircraft Launch	1.2	1.9
SHUTTLE	 IUS	24400 -----	------ 2360	Air Force Eastern Test Range	4.6	18.3
TITAN II	NUS	2150		Air Force Western Test Range (except TITAN II) or Air Force Eastern Test Range	2.8	6.0,7.6,9.0
TITAN III	NUS PAM-D2	14,400 ------	------ 1360		3.6	12.4 15.5
TITAN IV	NUS Centaur IUS NUS	17,700 ------ ------ 21,645	------ 4540 2380 ------		4.5	17.0 20.0 23.0, 26.0

Table 2 Attributes of Common Launch Vehicles (Larson and Wertz, 1992)

1.5 The Communications Architecture

The communications architecture is the set of components necessary for satisfying the mission's communication, command and control requirements. It is heavily dependent upon data handling requirements as well as payload pointing requirements. The ability of other space and ground assets to transmit data is also a factor in configuring the communications architecture.

1.6 The Ground System

The ground system consists of fixed and, sometimes, mobile ground stations allowing operators to command, track, and communicate with the spacecraft and the command centers responsible for budgeting time among the basic monitoring and controlling of spacecraft functions, the collecting of payload data, and the commanding of payload operations. In more detail, the ground stations acquire information from the spacecraft on spacecraft health and position, as well as payload, or mission, data. The ground station also sends specific commands to the spacecraft requesting that the payload or spacecraft as a whole perform certain operations.[1]

The control centers balance the amount of time that is spent meeting and monitoring basic spacecraft needs versus user data needs. There are three types of control centers, mission, spacecraft operations and payload operations. The mission control center (MCC) plans and operates the entire space mission, including the configuration and scheduling of resources for both space and ground systems. MCC is in charge of computing critical information such as data on the spacecraft's orbit, the schedule of times when the spacecraft will fly over the different ground stations that are part of its ground system, and spacecraft and ground station antenna pointing angles so that the ground segment and spacecraft can communicate. MCC also passes this information on to other ground system elements and users. The spacecraft operations control center (SOCC) monitors and commands the spacecraft bus and systems common to the bus and payload. SOCC's job is to monitor spacecraft telemetry and telemetry from payload instruments that might affect the spacecraft's attitude or dynamics. SOCC is the only ground system element that writes the commands that are transmitted to the spacecraft through the use of ground station equipment. The payload operations control center (POCC) monitors payload instrument data and telemetry. It coordinates with SOCC to provide and write commands telling these instruments how to operate. The commands are transmitted to the spacecraft upon MCC approval.

Ground station size, quantity, and data handling equipment are determined by spacecraft orbit and mission and the user's needs which may change from time to time during a spacecraft's life. The decision whether or not to develop and build a dedicated ground system for a particular space system depends upon the amount of payload data required by the users; the amount of access to the payload part of the spacecraft the users need; and the level of security surrounding the users' data. A ground system dedicated to one satellite constellation provides much greater security and access to the spacecraft but at the cost of increased development and life cycle budget, schedule, and technical risks.

For users who either cannot afford or do not require a dedicated system, certain ground station networks are available. These include the Navy Navigation Satellite System (NNSS) and the Air Force Satellite Control Network (AFSCN). A more creative approach is NASA's Tracking and Data Relay Satellite System (TDRSS) which uses a network of satellites to relay information to the system's only two ground stations which are located in the continental United States. Choosing to become part of one of these networks and being accepted by the network influences the design of the spacecraft's communications and command and data handling

[1]For instance, during Operation Desert Storm, certain weather, surveillance, and communications satellites were commanded to modify their orbits so that the military could have better coverage of the Persian Gulf region.

subsystems. This choice also means that this space mission must share time on the network with other mission.

2. The Uniqueness of Space

The space and launch environments that a spacecraft must survive present its designers with tremendous challenges. On launch, despite the protection of the fairing, the spacecraft is subjected to considerable accelerations, vibrations, dynamic pressures and shock. The accelerations and vibrations are due to the burning of highly explosive fuel which provides the massive propulsive power used to overcome the earth's gravity and bring the spacecraft up to the speed and altitude necessary for inserting the spacecraft into its required orbit. A harsh dynamic pressure environment is the result of rapid altitude changes as the spacecraft enters the vacuum of space from the approximately sea level atmosphere at the launch site. Finally, the spacecraft experiences shocks from the firing of explosive bolts which are used to separate the spacecraft from the fairing when final orbit or the intended parking orbit is reached and to separate launch vehicle segments that have expended all of their fuel during launch. For example in a Titan-Centaur configuration, where the Titan is the primary launch vehicle and the Centaur is an added upper stage, the two main engines of the Titan are jettisoned after they have burned all of their fuel. This allows for the activation of the Centaur upper stage to continue the spacecraft's journey to orbit.

The environmental factors that must be overcome in space are different. They include hazards due to radiation, thermal cycling, vacuum, orbital debris, and shock. Radiation hazards come in many forms. Galactic cosmic rays may cause momentary dysfunction or, potentially, service life threatening malfunctions to electronic equipment through which they are passing. Prolonged exposure of electronics to cosmic radiation causes voltage leakage and biasing in semiconductors, impairing their ability to perform their mission functions. Solar arrays tend to lose power generating capability over a lifetime of exposure to solar particle events, which are rapid increases in the flux, usually associated with solar flares, of energetic particles emanating from the sun. Finally, trapped radiation in plasmas and the Van Allen Belt can cause electrostatic discharges that result in sensor noise or other phenomena that adversely affect spacecraft operation. Radiation from nuclear explosions and laser attacks can potentially cause temporary or permanent damage to the spacecraft.

The sun, however, produces more than radiation effects on the spacecraft. As a spacecraft orbits the earth, it goes through periods of exposure to the sun as well as periods of eclipse. The cycle time for sun exposures and eclipses depends upon the height of the orbit. For example, the Space Shuttle, which flies in LEO, orbits the earth approximately every 90 or 100 minutes. A GEO communications satellite will orbit with the earth, thus being thermally cycled once a day. The mean value of solar heating on the spacecraft during these cycles ranges from

1358 W/m^2, during direct sun exposure to 0 W/m^2, when in full eclipse (Larson and Wertz, 1992). This corresponds to temperatures from several hundred to nearly zero Kelvin.

Much of the hardware flown in space, however, only operate properly within a narrow range of temperature variation (e.g., 60-70 ^{o}C). Furthermore, different pieces of hardware require different temperature ranges. For instance, an infrared sensor requires a near 0 K operating temperature, whereas, most electronics require a room temperature environment. Finally, launch vehicle constraints require that the volume of the spacecraft be minimized. This constraint causes designers, therefore, to place all of this equipment in close proximity to one another. As a result, spacecraft designers are forced to develop a system of reflective paints, heat pipes, heaters, and coolers to maintain nominal spacecraft operation.

Microgravity and the vacuum of space, although it offers many exciting possibilities for pharmaceuticals and materials processing and manufacturing, has many negative effects on spacecraft hardware. Parts of a spacecraft, for example most computer chips and switches, must be pressurized and hermetically sealed in order to avoid electrical arcing, shorts, or other abnormal behavior. Certain metallic materials, like tin-lead solder, are not used during spacecraft manufacture because "whisker" growth, when a metal forms unintended metallic outcroppings, in the material may cause electrical shorts when one of these outcroppings connects two nearby circuit paths. Finally, outgassing by some materials, the breakdown of a material into its chemical constituents due to the microgravity environment, may cause corrosive or other undesirable compounds to form on spacecraft surfaces.

Both natural and man-made orbital debris exist and pose a serious threat to spacecraft operation. McKnight states that "about 20,000 tons of natural material consisting of interplanetary dust, meteoroids, and asteroid/comet fragments filters down to the Earth's surface every year .... At any one time, there are several hundred kilograms in [orbit] around the earth" (Larson and Wertz, 1992). Added to this natural debris are empty rocket fuel tanks, out-of-service spacecraft, and spacecraft debris from exploded or disintegrated spacecraft, as well as tiny pieces of paint and solid rocket propellant that are orbiting the earth at velocities of several kilometers per second. A collision between anyone of these objects and a spacecraft, because of the high velocity of impact, could result in severe damage to or total destruction of the spacecraft. On one occasion, what was later identified as a piece of paint collided with a space shuttle creating a deep crack in one of the space shuttle's cockpit windows. The design of anti-satellite weapons which use the phenomena of hypervelocity impact to destroy a spacecraft is, in fact, a proposed area of research which focuses on using the destructive power of orbital collisions between spacecraft and debris as a weapon.

3. Organizational Roles in Defense Space Acquisition

The spacecraft design space is very complicated. Not only are there great technological challenges requiring creative design solutions, but there are great organizational challenges in coordinating the resources necessary for space system development. It is the project manager's task to handle these technical and organizational demands in such a way as to keep their immediate commanders, the Secretary of Defense, Congress, and their contractors happy (or more realistically, at bay). Prior to describing the roles of organizations that play a major part in the acquisition of defense space systems, it is helpful and interesting to learn how this basic organizational structure arose.

Sputnik and the National Aeronautics and Space Act of 1958

The launch of Sputnik 1, the first artificial satellite ever placed in orbit around the earth, by the Soviet Union in 1957 was a call to arms for the United States government and public alike. In the previous ten years, the USSR had solidified control over Eastern Europe, allied itself with China, and held American forces to a standstill in Korea. Americans, especially their leaders, felt they had to respond to the launch of Sputnik, thereby, preventing the rising tide of Communism from gaining another "victory" over America. By the end of 1958 the U.S. had launched its first satellite, Explorer, and enacted the National Aeronautics and Space Act of 1958. (The bill was passed July 29, 1958.) It mandated that the United States become "a leader in space", and, as part of that mandate, established a civilian space program and a military space program which was to be coordinated by a White House National Aeronautics and Space Council chaired by the President of the United States (Wilkening, 1992).

President Dwight D. Eisenhower initially favored centralized control of all space endeavors, civilian and military, within the Department of Defense (DoD) feeling that the most pressing space needs were of a military nature. He also felt that one centralized organization would avoid needless duplication of activities and capabilities. His advisors, however, persuaded him that having a separate civilian space agency was better from a political and propaganda standpoint. An open, unclassified space program which other countries could participate in, they argued, greatly contrasted the secretive, entirely military program of the Soviets. Eventually, the argument for a separate civilian program won. As a result, the National Aeronautics and Space Act of 1958 created the National Aeronautics and Space Agency (NASA) (Wilkening 1992). Ironically, Congress also worried about a lack of coordination between the two agencies. They therefore formed the presidentially chaired space council as a part of the space act. (In 1961, the act was amended to make the Vice President the chair of the committee.).

Concurrently, in 1958, the Secretary of Defense created DARPA (the Defense Advanced Research Projects Agency) as a central organization for defense space applications. DoD saw this as a temporary measure to minimize interservice rivalry for the new space mission (Wilkening 1992). From 1958 to 1961, planned space projects, facilities, and personnel were allocated to

NASA if they were predominantly civil in character or to DoD if their primary application was of a national security nature. Leaders within DoD, assigned most of the military programs to the individual services (i.e., Air Force, Army, and Navy). DARPA quickly lost its role as the central DoD space organization.

The Soviets Orbit the First Human

In April 1961, the Soviets struck a second major blow to America's prowess through the use of space. Yuri Gegarin, launched into orbit from the USSR, gave the Soviets the distinction of having the first human in space. Gegarin's, albeit short, voyage served as a giant propaganda defeat. The presence of a new, younger, and more visionary administration in the White House and increasing Cold War tensions, combined with the ignominious defeat of Gegarin's flight, helped to create a national drive to be the *undisputed* leader in space (Wilkening, 1992). In a memorandum to Vice President Lyndon B. Johnson, the new head of the National Aeronautics and Space Council, James Webb, NASA Administrator, and Secretary of Defense Robert McNamara argued (McNamara and Webb, 1961):

> Dramatic achievements in space, therefore, symbolize the technological power and organizing capacity of a nation ...
>
> It is for reasons such as these that major achievements in space contribute to national prestige. Major successes, such as orbiting a man as the Soviets have just done, lend national prestige even though, scientific, commercial, or military value of the undertaking may by ordinary standards be marginal or economically unjustified.
>
> [The United States] needs to make a positive decision to pursue space projects aimed at enhancing national prestige. Our attainments are a major element in international competition between the Soviet system and our own. The non-military, non-commercial, non-scientific but "civilian" projects such as lunar and planetary exploration are, in this sense, part of the battle along the fluid front of the cold war. Such undertakings may affect our military strength only indirectly if at all, but they have an increasing effect upon our national posture.

Two weeks after Johnson received the memorandum, President John F. Kennedy created the Apollo program and assigned NASA the task of "getting America to the Moon by the end of the decade." This commitment to besting the Soviets in high profile manned and unmanned space exploration missions led NASA to be first and only country to land men on the Moon in the 1960s and 1970s as well land robotic expeditions on Mars in the 1970s. Missions to Venus, Mercury, and Jupiter during the 1970s were also a result of this policy. NASA was the first to Saturn, Uranus, and Neptune in the 1980s. Finally, America was the first to have a reusable, manned spacecraft when the Space Shuttle Columbia made its first flight in 1981.

The Cold War drove developments in military space as well. In the early 1960s, tensions continued to increase with the Soviets. Events including the failed Bay of Pigs Invasion in 1961 and the Cuban Missile Crisis of 1962 increased America's need for more concrete information on the location and strength of Soviet troops, nuclear test sites and other military science centers.

Surveillance satellites were a logical solution to the problem. Flying with impunity high above military air defenses, these spacecraft could monitor Soviet activities without the threat of being shot down. Also, DoD could configure the orbits of these satellites to provide considerably more continuous coverage of important regions behind the Iron Curtain and in Cuba than reconnaissance aircraft ever had. Consequently DoD, along with the government's intelligence agencies, created a number of reconnaissance space programs. Because of the tremendous amount of security surrounding such projects, a secret agency, the National Reconnaissance Office (NRO), was created to separately and secretly handle the acquisition and operation of reconnaissance satellites, while the Air Force continued to fulfill its role as executive agent for the majority of DoD space programs. (The NRO's existence was declassified in 1992 at which time it became officially a part of the Department of the Air Force.).

The resulting NASA, Air Force and NRO organizations, all individually equipped to acquire spacecraft, created a powerful, force on the military and civilian space fronts of the Cold War. These programs, however, became increasingly expensive possessing overlapping programs and duplicate facilities. Wilkening, *et al.* (1992) maintain that this duplication was tolerated because (1) as stated earlier, an open space exploration system was an effective aid in winning the world to America's side during the Cold War; (2) a multi-organization system protected against Soviets gaining knowledge of the entire span of U.S. military and intelligence space efforts through high levels of program compartmentalization and security classification; (3) for the first decade or so of the space program, America's accomplishments were limited more by available technology than by funding constraints.

Organizational "Stovepipes"

In short, the Cold War pressures of direct competition with the Soviet Union not only escalated the space race, but the nature of these pressures dictated that U.S. space policymakers establish different organizations for handling civil, military, and highly secret space applications. Each organization, in turn, was equipped with all of the capabilities necessary to design and build space systems in house. As a result, several separately capable organizations with overlapping capabilities and missions, referred to as "stovepipe" organizations, evolved.

Within military and civilian sectors multiple agencies propagated, each developing space-related activities. For instance, for civil space, in addition to NASA, the Department of Transportation (DOT), the Department of Commerce (DOC) (including NOAA), the Department of Interior (DOI), and, most recently, the Department of Energy (DOE) have all evolved space-related functions. Within the national security community the story has been the same with the Air Force, Army, Navy, NRO, the Ballistic Missile Defense Organization (BMDO), and the Advanced Research Projects Agency (ARPA), formerly DARPA, all actively involved in the development and operation of space systems. Furthermore still the Air Force has divided itself into separate launch, acquisition, operations, and user elements. Each satellite program and each launch vehicle operated by DoD, in turn, has developed into its own system project office (SPO), specifically dedicated to the development of that one program's spacecraft or launch vehicle. Even from SPO to SPO organizational and cultural differences have been found.[2] Therefore, in certain cases, stovepipes within stovepipes within stovepipes have evolved. Tabl e 3 shows the agencies from the executive branch of government presently involved with space policy.

	NASA	DOE	DOC	DOT	AF	Army	Navy	NRO	BMDO	ARPA
R&D	X	X	X		X	X	X	X	X	X
Acquisition	X		X		X		X	X	X	X
Launch[1]	X			X	X		X		X	X
Operations	X		X		X	X	X	X	X	X

Table 3 Agency Functions and Responsibilities (Wilkening, 1992)
[1] Launch includes regulation or acquisition of commercial launch services.

Many disadvantages to this vertically organized system developed over time: excess bureaucracy, organizational proliferation, increased layers of policy oversight and review, institutional overlap and inefficiencies, and institutional rivalries which discourage synergism. Since each sector has handled its own research and development (R&D), acquisition, launch, and on-orbit operations, it has developed its own methods for carrying out these functions. Staffs have been hired to set and administer these policies. Thus, bureaucracy, too, has proliferated. Extensive efforts have been undertaken to establish some sort of policy cohesion, creating countless levels of oversight and policy planning. As the division of labor and oversight increased so did institutional rivalries. This is because more programs were competing for the same funds. This fragmentation of duties spread to the legislative branch of government as well. Oversight of space has expanded to as many as ten different Congressional committees, each protecting its own priorities (Fox, 1988).

In summary, each space sector possesses its own stovepipe organization to handle technology development, acquisition, launch, command and control, and operations needs, not as the result of efforts to achieve organizational efficiency, but for political purposes instead. Typically, within each organization there are further levels of divisional stovepipes, for example the existence of an individual program office for each large space system. Each stovepipe has optimized its organization to carry out its mission needs without consideration for the needs of other space fairing organizations. This division of labor has become so inefficient and redundant,

[2] This statement comes more from personal experience and discussions with industry experts rather than any particular literature citation.

that complex interfaces among several organizations are required to accomplish even a single mission. More is said about this in Chapters 5 and 6. The following subsections describe the *major* players in the military acquisition process. Many of the smaller programs such as DARPA and BMDO are not discussed here because they are responsible for the acquisition of relatively few systems.

3.1 Congress

Congress plays two major roles in the defense acquisition process. Its first role is to approve the expenditure of government money for defense system acquisition. Having budgeted the money, Congress also participates in managing the acquisition process. Congress' funding role is unique, since no other part of the government, but the legislative branch, can approve the expenditure of public funds. Funding a program is a multi-step process requiring the approval of two separate pieces of legislation. The annual *defense authorization bill* determines which newly proposed and already ongoing DoD programs are funded in the new fiscal year. Congress then uses the annual *defense appropriations bill* to allocate the exact amount of funds for the DOD to use in supporting particular programs (Fox, 1988).

Often times, however, DoD needs to change its funding profile from the one approved prior to the start of the new fiscal year. Congress, if it decides to, has three options for meeting these DoD requests. First, Congress can appropriate new money for a program through a bill for supplementary funding. Second, under reprogramming Congress allows money to be shifted from one item within an appropriations account to another (e.g., to shift funds from the Defense Meteorological Satellite Program to the Defense Communications Satellite Program within Space System Procurement, Air Force, account). A third method of shifting funds, requiring Congressional authorization, is between appropriations accounts (e.g., transferring funds from Aircraft Procurement, Army to Missile Procurement, Army). Usually, the annual defense appropriations bill stipulates a certain cumulative amount for this type of budget reallocation so that DoD officials have some latitude in planning budgets as the fiscal year unfolds. When transfers over the course of a fiscal year add to exceed this limit, Congress must approve any further transfers of funds (Fox, 1988).

Interestingly enough, many of these budget reappropriations are due to the fact that Congress, typically, authorizes far more programs than it can pay for. In 1982, for instance, it was estimated that 2.3 times the current defense spending levels were required to move all of the authorized programs from development to production, and that 3 times these levels were needed to complete all programs in production (Fox, 1988). It is no wonder, then, that budget crunches and overexpenditures are part of daily life in the acquisition system. Yet, Congress, under intense pressure from the electorate and media, feels the need to act to bring down costs. Consequently, Congress plays a strong, third role in acquisition, program management.

Over the last fifteen to twenty years, Congress has often involved itself in the management of day to day program activities. Congress' tools to carry out these managerial tasks (often referred to as *micromanagement*), however, are limited to regulating and earmarking funding to and imposing reporting requirements on the DoD element handling a system's acquisition (Fox 1988). This micromanagement of activities often results in committee hearings, burdensome reporting requirements, and, even, defense systems unwanted by DoD (Fox, 1988; *Aerospace Daily*, 1994). All of these oversight activities impose extra cost and development delays to the acquisition programs. Therefore, Congress typically increases costs in its attempt to decrease costs.

3.2 The Department of Defense (DoD)

The Department of Defense (DoD) is a cabinet level department in the executive branch of the United States Government. Its head, the Secretary of Defense, reports directly to the President of the United States and must receive confirmation by Congress before taking office. DoD, created in the late 1940s to coordinate defense activities, includes the Departments of the Air Force, Army, and Navy, which comprise the Armed Services, as well as centralized management activities for the coordination of the separate services. DoD's headquarters are at the Pentagon in Washington, D.C.

Centralized DoD management, separate of the Armed Services (i.e., separate of the Air Force, Army, and Navy), is involved throughout the acquisition life cycle. Early in a program's development, DoD validates mission needs and searches for non-materiel solutions to these needs. DoD makes the decision to start a new program, validates system requirements, and determines which service of the Armed Services develops the new system. DoD also plans and manages all acquisition budgets for defense systems, setting the dollar amounts listed in the president's budget and debated by Congress.

3.2.1 The Defense Acquisition Board (DAB)

The Defense Acquisition Board (DAB) monitors and reviews the approximately 100 major defense systems programs (Jones, 1989). Senior members of the Office of Secretary of Defense (OSD) and appropriate service and defense agency officials comprise this board. The Undersecretary of Defense for Acquisition (USDAQ) is its chairperson with the Vice Chairman of the Joint Chiefs of Staff (JCS) acting as the vice chairperson.

The DAB holds formal program reviews, evaluating programmatic and budgetary details along with technical progress. It assesses the acquisition agent's (i.e., the Army, Navy, or Air Force) execution of the program to that point and its readiness to proceed with upcoming parts of the program. It then advises the Deputy Secretary of Defense whether or not the program should proceed any further. It is up to the deputy secretary to make the final decision to proceed.

Ten review committees made up of OSD officials organized around certain disciplines support the DAB in its decision process. These committees also conduct periodic reviews of the ongoing programs analyzing potential program difficulties, measuring progress, and making recommendations to the DAB. The committees are Science and Technology, Nuclear weapons, Strategic Systems, Conventional Systems, C3I Systems, Test and Evaluation, Production and Logistics, Installations Support and Military Construction, International Programs, and Policy and Initiatives (Jones, 1989).

The DAB does not provide or recommend funds or vote on matters before it. Instead, it attempts to reach consensus for recommendations on a program it is reviewing. For example, during early program research and development, the DAB "assesses the possible tradeoffs among costs, schedule, performance and logistics support to obtain maximum benefit for the dollars spent. It then evaluates how this new system enhances .... [the] military forces' deterrent or warfighting capability" (Jones, 1989). As a result, typical issues that the DAB deals with include: cost growth, control, and effectiveness, joint-service squabbles, acquisition strategy, competition, production rates, test results, and interoperability (Jones 1989).

3.2.2 The Air Force (USAF)

Although there are several different organizations responsible for space acquisition, Table 4 shows that, by far, the Air Force plays the largest role in defense space acquisition.

	Number of Personnel		
Organization	Military	Civilian	Total
U.S. Space Command	443	128	571
AF Space Command	22.737	17,371	40.108
Navy Space Command	249	245	494
Army Space Command	401	89	490

Table 4 Space Acquisition Personnel (Congressional Record, 1994)

The Air Force is responsible for day to day management of nearly all space acquisition programs for the Armed Services. Separate System Project Offices (SPO), each one headed by a project manager (typically of the rank of Colonel or General), are organized for each operational or developmental program. All of these SPOs are part of Air Force Space Command and are located at the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base. Along with The Aerospace Corporation, a non-profit corporation aiding the Air Force in technical matters relating to space system acquisition and development, SMC deals with daily programmatic and technical issues of the contractors for all of the SPOs under its command.

3.3 The Prime Contractors

The prime contractors are the private, for profit companies responsible for the design, development, fabrication, test, and integration of the spacecraft and space system as a whole. Whereas, typically, prime contractors, or primes, do not perform all of the work involved with producing a space system, they are responsible for contracting and managing any subcontractor work necessary to develop parts of the payload and spacecraft bus. They are also responsible for contracting the launch vehicle providers, launch pad and support, ground systems, etc. They make sure that all of the elements of the mission architecture are properly developed and integrated to make the space system perform its mission flawlessly. The prime is held responsible for all work performed in the completion of the spacecraft whether or not their company is actually building the particular component in question. They communicate with the Air Force through SMC and act as SMC's connection to subcontractors that might be of concern to the Air Force management.

The Spacecraft Development Team

The spacecraft development team is an assemblage of technical and managerial specialists and generalists responsible for all facets of a spacecraft's design and fabrication. The team's composition changes with time as the program matures and requires different expertise. Each program team has three main elements: technical specialists, systems engineering, and program management.

Technical Specialists

Technical specialists is a broad term used to categorize all of the subsystem, fabrication, and test engineers, as well as the skilled technicians. The engineers usually include subsystem specialists (i.e., engineers experienced in the design and operation of one or a couple of the spacecraft subsystems described earlier), fabrication and test specialists (i.e., those engineers with experience in the manufacturing and test processes used to produce and assure the proper operation of spacecraft), and technology specialists (i.e., engineers or scientists who offer experience in a technology critical to the space mission's success, for instance, xenon ion propulsion or compact optics). The technicians carry out many of the activities needed to design, fabricate, and test the spacecraft. These include producing CAD drawings, finite element models, fabricating and assembling structural members, laying wires and assuring their continuity, and performing component, subsystem, and system test regimens.

Systems Engineering

Earlier sections of this chapter provide an overview of the many complex thermal, physical, electronic, and informational interactions that must be regulated within any spacecraft design. Controlling these interactions is complicated by the close proximity that is required of all of the spacecraft equipment by the limiting size and weight constraints of launch vehicles.

Furthermore, Smith and Reinertsen agree that being able to understand and properly trade off system interactions is critical to successful completion of a design activity (1991). Yet, the level of complexity in these interrelationships between various spacecraft subsystems are far more than the various spacecraft subsystem designers can handle while trying to perform detailed design activities for their own subsystem. Therefore, there is a need for a strong systems engineering component as a part of every program team. Systems engineering's job is to identify and regulate these complex interactions.

There are two types of interactions to be controlled: intentional and unintentional. For example, keeping the equipment on the spacecraft that produces the most heat away from a very sensitive infrared sensor can be thought of as the management of an intentional interaction. More specifically, this design decision intentionally *prevents* an interaction that might impair the spacecraft's ability to perform its mission. Unintentional interactions are ones that are not specifically planned for, but affect the spacecraft's performance. For example, a rotating hemispherical antenna may cause structural vibrations in the spacecraft. These vibrations can cause the blurring of optical images taken by one of the payload sensors. This example demonstrates the meaning of unintentional interactions spacecraft subsystems. Understanding these behaviors is necessary for mitigating their negative effects on the spacecraft's subsystem interactions. A systems engineering group, focuses on matters of this type, discovering these interactions and analyzing their effects on the proposed design. Systems engineering then acts as an impartial body for mediating the resolution of conflicts arising from designs that interact ineffectively with one another. They coordinate and verify the solutions to these problems and then moderate the process for creating the necessary design changes.

Finally, systems engineering plays the role as the glue that holds the system together. They do this by performing the engineering that does not fall to any of the subsystem disciplines. Examples are electromagnetic interference (EMI) mitigation, system reliability assessments, mass properties, and payload and launch vehicle integration. It is apparent then that strong systems engineers as well as strong subsystems engineers are critical to successfully handling the high levels of technical complexity characteristic of the spacecraft development process.

Program management

Every program team has several management activities that it must perform. It must set, monitor, and manage budgets and schedules. It must communicate with the customer. In addition, it must handle relationships with subcontractors who are performing work for it. Most importantly, the team must have leadership, guidance, and commitment to its goals. The program manager (PM) functions as the coordinator of these management activities and as the leader of the program. The PM usually has a small group of cost estimators and schedulers keeping track of program progress. The PM appoints a chief engineer, head of systems engineering, and subsystem design leaders to handle the detailed management of technical issues. The PM works to establish and set the program goals which designers work to during the proposal and design phases. During the design, fabrication and test phases, the PM aids in the resolution of major design conflicts and failures while monitoring schedules and shuffling resources as necessary. Finally, the program manager is the one who represents the program to high-level contractor management and Air Force program management, handling the complex and often cantankerous interactions that take place between these different elements.

4. Conclusions

One important conclusion to take from this chapter is that there are many mission components which are highly coupled. Together they form a complex space mission architecture for meeting the users' needs. Along with these technical challenges, a complex maze of organizational relationships must be negotiated before a program can be completed. Figure 1 summarizes this organizational interplay.

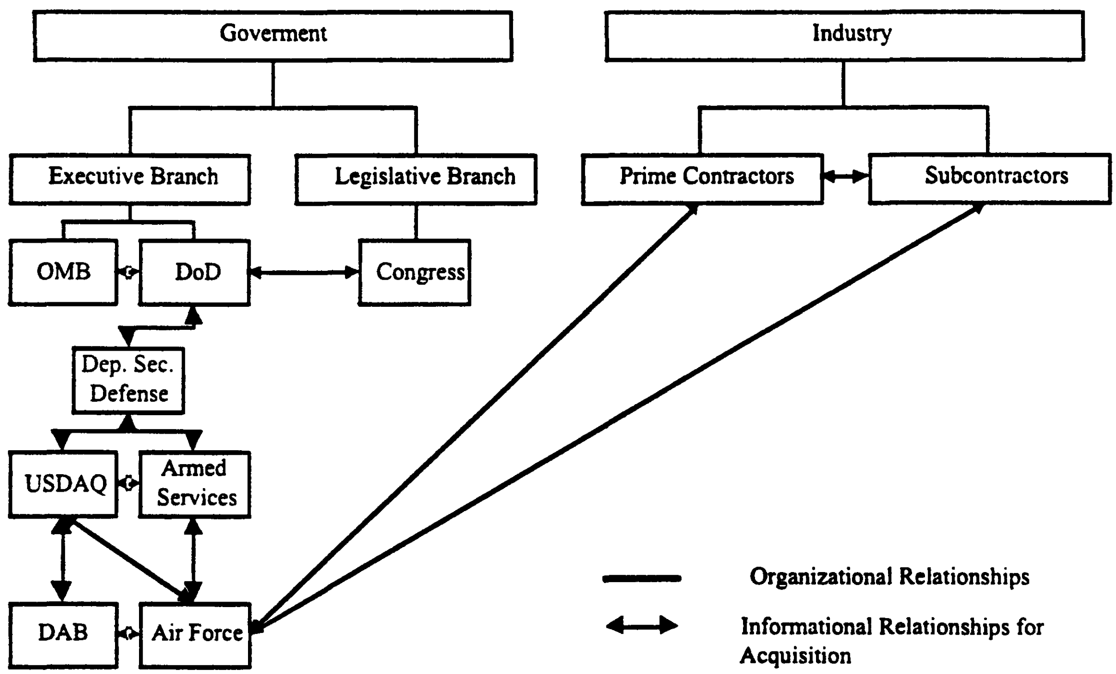

Figure 1 Organizational Relationships in the Military Space Acquisition Process

Fox (1988) points out that, because of this organizational structure, the normal rules of capitalism do not apply to defense system acquisition. First, the classical concepts of the industrial firm do not apply (Fox, 1988):

> "Price is not an overriding factor, product and quantity are determined, not by the management of the firm, but by governmental authority, and competition normally focuses on proposed design rather than the physical product, and on promises of performance rather than the performance itself. The supplier often holds a monopoly and the purchaser a monopsony (i.e., one buyer only).

Furthermore, the traditional functions of buyer and supplier are mixed under this arrangement with the buyer often specifying methods and rates of product production. Therefore, the contractor, under pressure to minimize costs while meeting some level of performance, is not able to utilize control over design and production parameters to accomplish this goal. Finally, there is extreme division of labor combined with heavily overlapping functions but differing goals within the customer's organization. This creates indecision and vacillations in goals and initiatives that the contractor must react to when dealing with its single customer. Inconsistent and incomplete requirements, schedule delays, cost overruns, and performance shortfalls are a common result of this arrangement. The rest of this thesis shows why this is the case.

In conclusion, an unstable mission subject or changing requirements, due to technical or political instability, can create a chain reaction of requirements and design changes within many or all of the other mission elements. Therefore, studying the design process for one of these mission elements, the spacecraft, illustrates how a deficient process adversely affects the accomplishment of an entire space mission. Despite all of these risks, technical and political, the use of space to carry out missions offers a rich set of opportunities. With a constellation of only a few spacecraft users can track the world's weather patterns, create global communications networks, detect and track missile launches, or instantaneously find their location any place in the world. The ability that a small constellation of space-based platforms offers to view large areas of the earth or the solar system allows users to accomplish many, otherwise, technically or financially infeasible goals.

Chapter 3: The Spacecraft Acquisition Process - Defining Mission Need and Exploring System Options

1. Introduction

The primary objective of the military acquisition process is for the Department of Defense (DoD) to acquire a combination of hardware and software systems. These systems enable DoD through the Armed Services to accomplish their mission objectives. DoD procures these systems through development and production contracts with industry. First, DoD solicits industry interest through a request for proposals (RFP). The RFP contains the scope of work, the technical requirements, and regulations that DoD expects the system's builder to follow. By responding to the RFP with a proposal, a contractor enters into competition with other responding contractors for the opportunity to develop the new system. The winning contractor completes the detailed design of system components during the development phase. A production phase, in which multiple copies of the system are manufactured, follows a successful system development phase by the winning contractor.

Throughout this entire acquisition process, DoD, as well as the members of private industry involved in the acquisition, must follow a strict set of laws and regulations. These laws and regulations have three goals: to prevent waste, fraud, and abuse; to establish and monitor the acquisition process; to enforce other desired conditions (e.g., require the hiring of minority contractors or disqualify the use of components made in certain countries). This thesis does not discuss he enforcement of working conditions. Later chapters discuss the effects that waste, fraud, and abuse legislation has on acquisition. The next two chapters, instead, focus on the laws and regulations, in particular the DoD 5000 series, that create the framework for the acquisition process. These chapters relate the goals of the intended process and compare them to their implementation during military satellite acquisition.

2. The DoD 5000 series

A mandatory, standard acquisition process aids DoD, Congress and the Office of Management and Budget (OMB) in acquisition management. The standardized format is an attempt by officials to effectively monitor a particular program's progress and compare it to similar past programs or to other ongoing programs. By having each program fulfill the same reporting requirements at standard timeline points, or milestones, in the acquisition process, DoD, Congress, and OMB can monitor any program using the same set of budgets, status reports, and timelines. For the program manager, a standardized process provides a template to which they can match their particular program's development plan. These laws and procedures, in short, attempt to establish a method for logically, effectively, and repeatably completing the acquisition of military systems.

The DoD 5000 series is the specific set of instructions, published by the Department of Defense, which govern all acquisitions made by DoD and the Armed Services. Along with the Office of Management and Budget (OMB) Circular A-109, "Major System Acquisitions" (1976) and applicable Congressional Laws, DoD Directive 5000.1, "Defense Acquisition," "establishes a disciplined management approach for acquiring systems and materiel that satisfy the operational user's needs" (1991). DoD Instruction 5000.2 "Defense Acquisition Management Policies and Procedures" sets "an integrated framework for translating broadly stated mission needs into ... acquisition programs ... [through] a rigorous event-oriented management process" (1991). DoD Manual 5000.2-M "Defense Acquisition Management Documentation and Reports," "contains the procedures and formats to be used to prepare various milestone documentation, periodic in-phase status reports, and statutory certifications" (1991). These documents establish the whys, whats, and hows of the present DoD acquisition system.

More specifically, the DoD 5000 series states that every defense acquisition program starts with a mission need as identified through continuing assessments of current and projected capabilities in the context of changing military threats and national defense policy. Upon the decision that a new or greatly improved system is essential to meet some of these needs, the acquisition process begins. The first step is *Phase 0, Concept Definition and Exploration,* in which a team from within DoD develops as many solutions to the mission needs as possible. After selecting several potentially viable solutions and gaining approval to proceed with their study, the managing unit moves the acquisition program into *Phase I, Concept Demonstration and Validation*.. During this program phase the investigatory team works with industry to perform more research in order to prove the technical, logistical, and financial feasibility of the most promising system concepts. The investigating team, now a project office, selects a single concept and, after gaining approval, moves into *Phase II, Engineering and Manufacturing Development* , where detailed designs are completed and initial test and operational units are manufactured. DoD and Congress decide whether or not to proceed with further production of the system, and, finally deployment of that system in *Phase III, Production and Deployment.* Figure 2 shows the process described by the DoD 5000 series. Each of these steps is described in more detail in this or the next chapter.

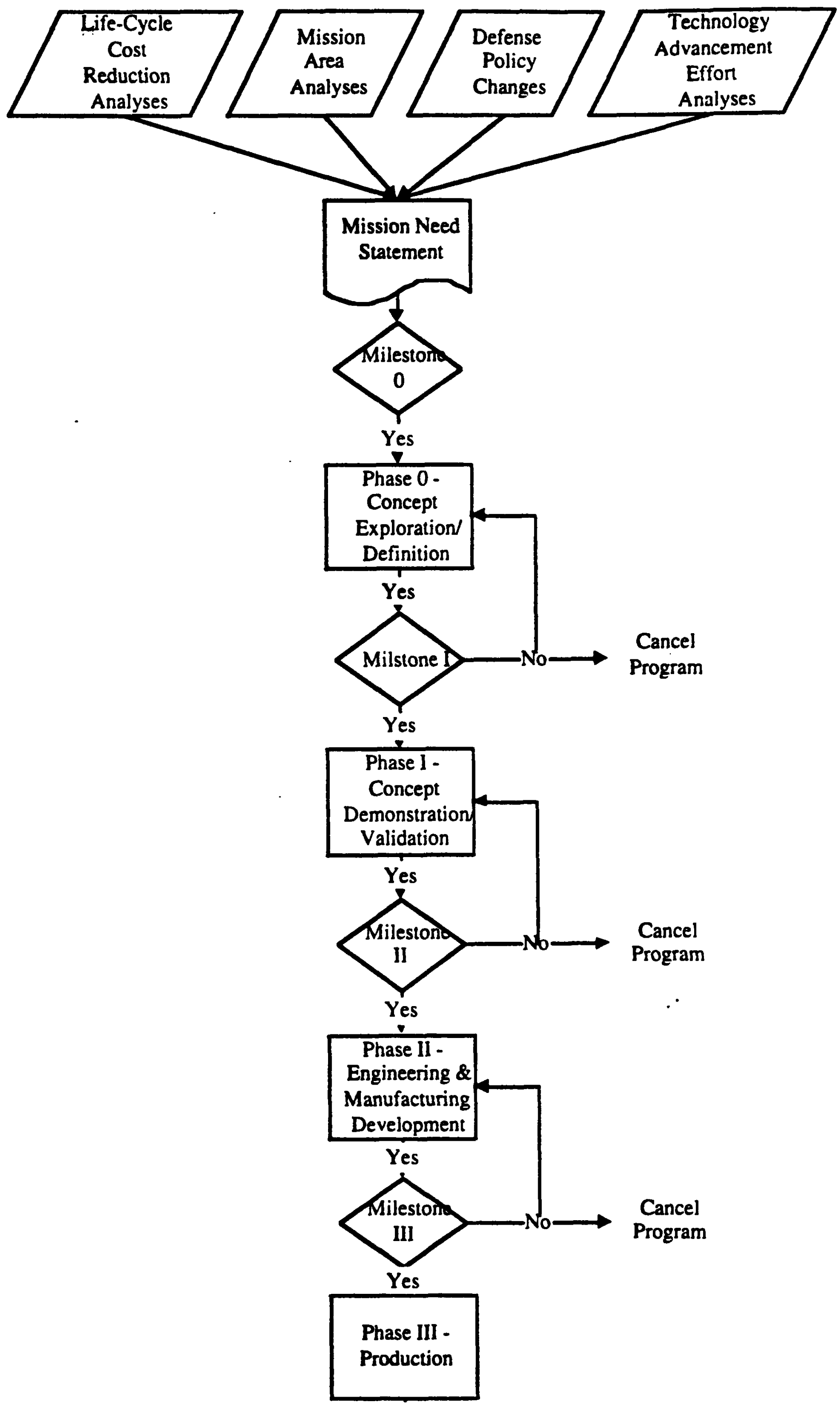

Figure 2 The DoD 5000 series Military Acquisition Process.

Although the DoD 5000 series provides a regimented procedure for military system acquisition, there is a large amount of flexibility as to how each program accomplishes a particular phase of the process. Flexibility is both a strength and a weakness of the DoD 5000 series. Later chapters describe how bad decisions in the up front phases can result in cost and time overruns. Basic flaws also exist within the DoD 5000 series, as it relates to governing spacecraft acquisition. This thesis discusses later their effect in amplifying such bad decisions. It should also be noted that the process described in the DoD 5000 series is for the acquisition of non-classified systems. Although there are a number of satellite programs that are of a classified nature, many large and important systems acquired by DoD, including the Global Positioning System (GPS) follow-on, Defense Meteorological Satellite Program (DMSP) follow-on, and Defense Satellite Program (DSP) follow-on, are *unclassified.*

3. Determining Mission Need

The defense acquisition process begins with the definition of a mission need from assessments of potential threats and advances in technology made at government laboratories, during research efforts contracted with private industry, or during independent research and development that is ongoing continually in private industry. Acquisition decisionmakers are also cogniscent of the need to replace already existing, but aging, systems. Mission needs become apparent during this continuous review process. Mission needs can be identified by the Unified or Specified Commands within the Armed Services, the military departments, the Office of the Secretary of Defense (OSD), or the Joint Chiefs of Staff. Mission needs may speak directly of a threat (e.g., to prevent contamination from chemical weapons) or of other defense related needs (e.g., to possess current weather information on all areas of the world in which the Armed Forces are or are likely to be located). Figure 3 depicts the process for determining a mission need.

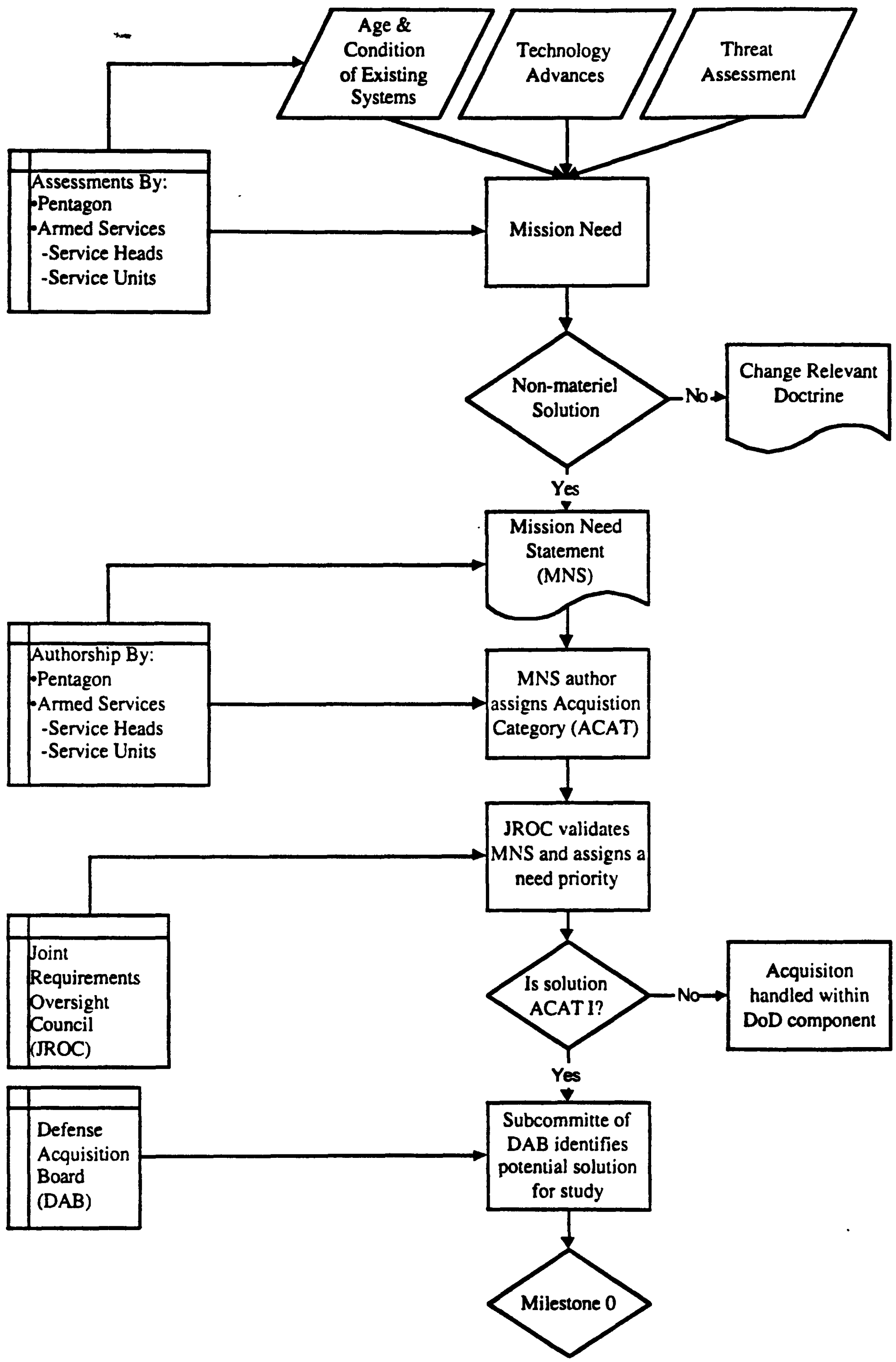

Figure 3 Establishing New Program Need

The organization that defines the mission need must also attempt to establish a non-materiel solution to meet this need. A non-materiel solution might include a change in doctrine, operational concepts, tactics, training, or organization. If a solution of this nature cannot be found, the organization authors a mission need statement (MNS) requesting a new or greatly upgraded system to meet that need.

DoD 5000 requires the mission need statement to be broad in nature. The MNS identifies a threat to be countered as well as the projected threat environment in which the need might occur. (In the case of GPS, the *threat* was the inability of Armed Services' components to accurately navigate themselves in three dimensions -- altitude as well as longitude and latitude -- during missions. The *environment* might include attempts by hostile forces to jam or spoof[1] the navigation signals used to determine position.) The materiel solution to the need is to be outlined in non-specific terms, i.e., in terms of operational capabilities not system specific solutions. The author of the MNS also assesses whether or not the MNS could result in initiation of a new category I (major defense acquisition) program or a category II, III, or IV program. DoD uses acquisition categories to specify the level of oversight a program receives. The more important the program is, the lower the ACAT number and the higher the level of oversight. Figure 4 shows the decision process for choosing a program's acquisition category (ACAT).

[1] *Spoofing* is the sending of false signals in an attempt to confuse or mislead the enemy. Spoofing navigation signals means sending false position signals to one's enemy.

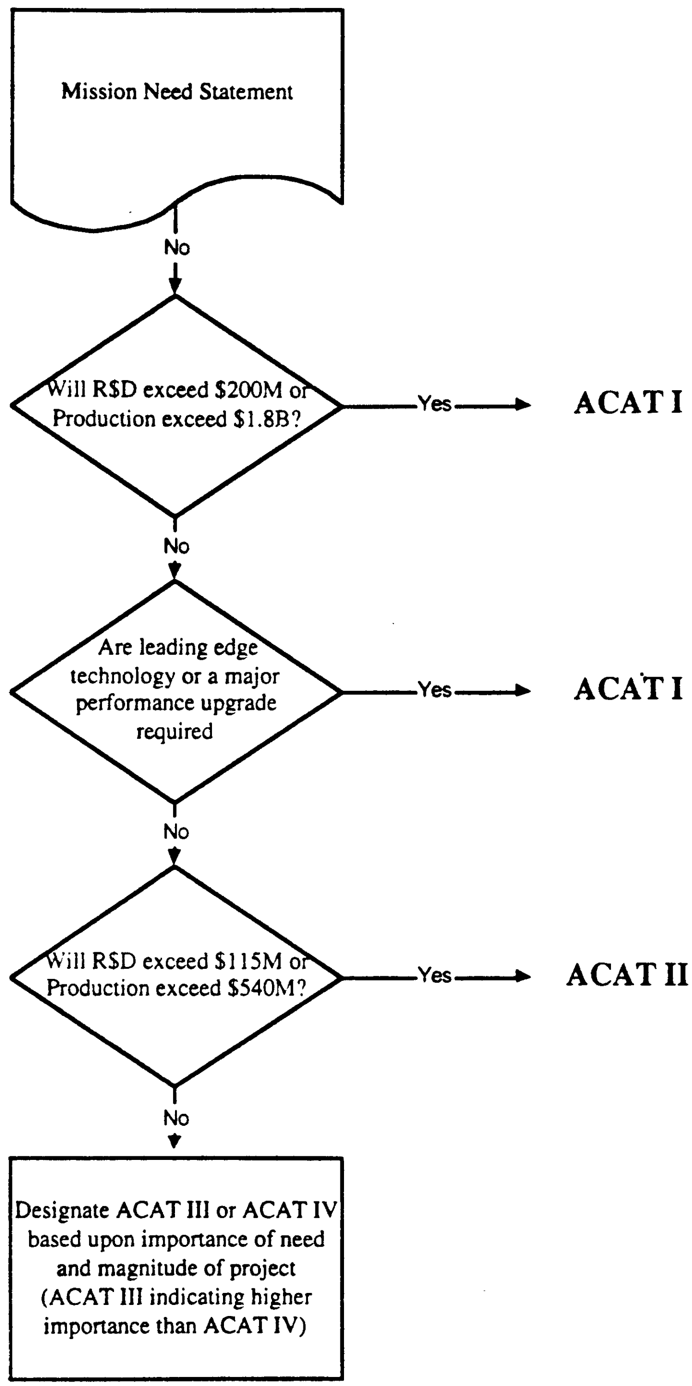

Figure 4 Method for Determining the Most Appropriate New Program Acquisition Category (All Dollar Figures are 1990 Constant Dollars) (DoD, 1991)

Presently, all unclassified major spacecraft acquisition programs have the ACAT I rating. An ACAT I designation means a high level of prominence in both DoD and Congress. Whereas, the high level of prominence might speed up the establishment of a program, it also raises the level of scrutiny given by Congress and DoD to managing the program. As a result, every technical problem becomes a political battle with the program's enemies. The scrutiny is often so intense that many programs seek the protection of a classified rating in order to avoid Congressional scrutiny (Forman, 1993). The relaxation of classification standards after the end of the Cold War and a recognition by Congress of attempts by DoD programs to circumvent its management control effectively nullify this strategy, which many programs in the mid to late 1980s enjoyed. Chapter 6 discusses the challenge of managing the risk that outside scrutiny adds to a large program.

After receiving an ACAT classification from its author, the Mission Need Statement is transmitted to the Joint Requirements Oversight Council (JROC). They verify the MNS does not have a non-materiel solution. The JROC then determines the validity of the identified needs, and assigns a joint priority as appropriate. They rank the importance of the need in relation to other, as yet, unmet needs and forward the MNS to the Undersecretary of Defense for Acquisition (USDAQ)[2] as approved or disapproved. Upon approval by the JROC, or as deemed appropriate by the USDAQ, the MNS is recommended to a subordinate committee of the Defense Acquisition Board (DAB) for review. The subordinate committee identifies and studies materiel alternatives that could potentially satisfy the identified need. They then identify and recommend a more detailed study of a subset of the concepts to the DAB, as a whole.

4. Milestone 0 - Concept Studies Approval

DoDI 5000.2 states that Milestone 0 marks the first formal interface between the requirements generation and acquisition management systems (1991). Up until this point only the need and the requirement for a new system are known; no formal acquisition program exists at this time. The DAB considers the recommendations of its subcommittee's study of certain materiel solutions and decides what action should be taken on the MNS. The DAB then defines a minimum set of alternative concept studies, to be performed either in house or by contracted efforts. The DAB also designates service organizations to lead the study effort and sets the dollar amounts and sources of funding for the approved set of studies. The decisions of the DAB in regards to study focus, funding sources, and supervising agencies are summarized into an Acquisition Decision Memorandum (ADM) signed by the USDAQ. Approval to proceed by the Deputy Secretary of Defense at Milestone 0 initiates Phase 0, Concept Exploration and Definition. *A decision to proceed at this time does not establish a new acquisition program.*

5. Phase 0 - Concept Exploration and Definition

Concept exploration, on average, takes anywhere from one to two years depending upon the size of the program, the methods of concept exploration chosen by the exploration team, and the level of detail desired by the exploration team and the DAB for the study results. Figure 5

[2]During the writing of this thesis, a separate position, Undersecretary of Defense for Space Acquisition was created. This decision by DoD to create a separate position shows an awakening realization by DoD that space acquisition differs significantly from other types of defense system acquisitions. The significance of these differences is discussed in later portion of this thesis.

shows the Phase 0 process steps Table 5 displays the technical objectives for Phase 0 stated in the DoD 5000 series

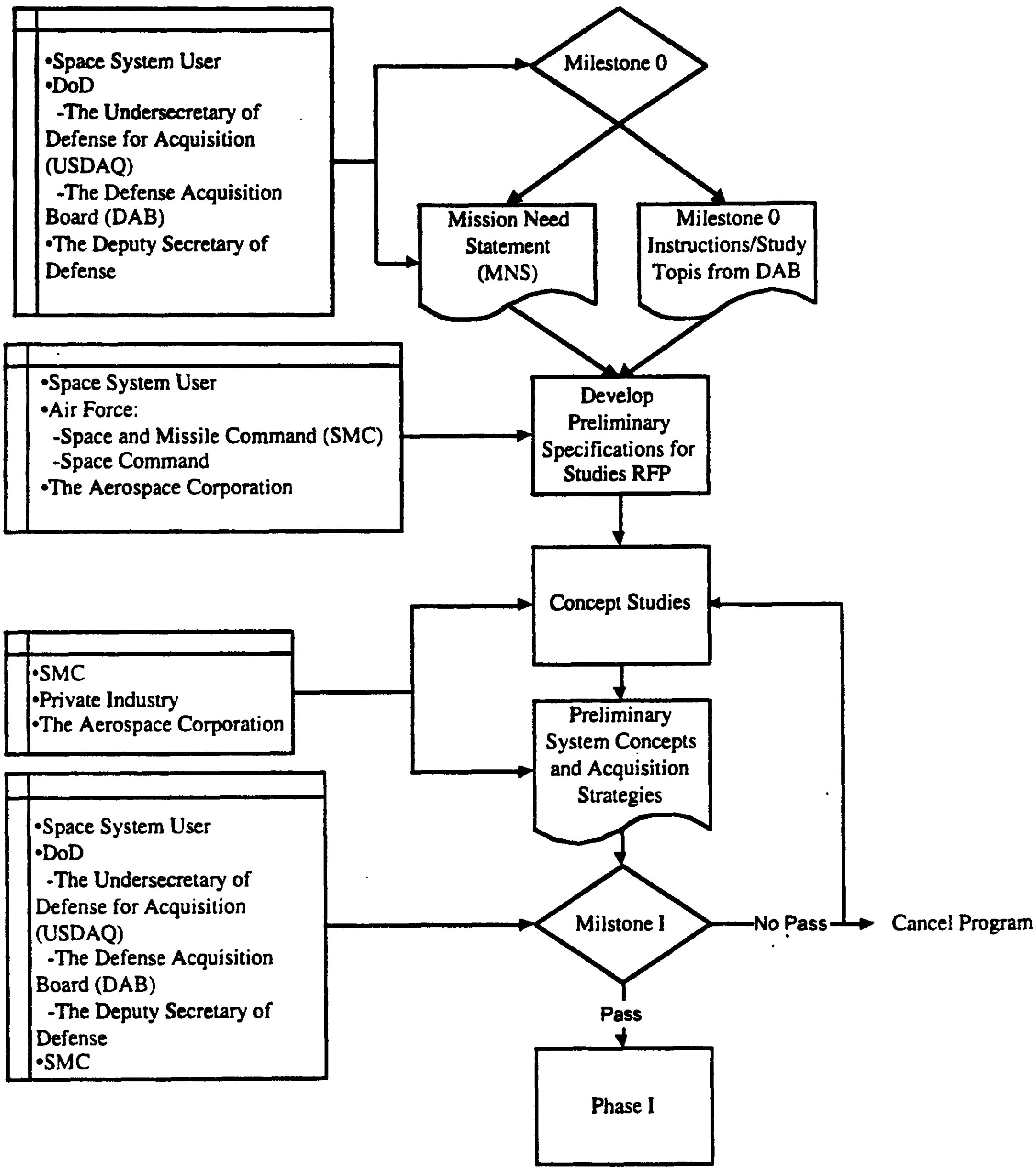

Figure 5 The Concept Exploration and Definition Process

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives
Phase 0 - Concept Exploration & Definition	• Explore material alternatives to satisfy mission need • Define the most promising concept(s) • Identify high risk areas and risk management approaches • Develop initial program strategy, cost, schedule, performance

Table 5 DoD 5000 Series Goals for the Concept Exploration and Definition Process

In practice, however, DoD decides whether the system will be a space system, a missile system, a ship, etc. before Concept Exploration and Definition begins. *Therefore, studies focus on what is required of a specific kind of system to meet the mission need.* The Air Force oversees the completion of these studies for space systems. Historically, when the DoD requires a space system, they establish an exploration group within the Air Force's Space and Missile Command (SMC) to coordinate the concept studies. SMC, with the help of The Aerospace Corporation[3], works with Air Force Space Command and other user elements, to develop the basic user requirements.

The exploration group then translates these requirements into a draft specification. The draft specification includes many topics, such as the area of the earth to be covered; whether or not the coverage must be continuous or take place only a certain fraction of the time; the potential level of data throughput; and sensor resolution. The focus of this specification is the payload since the payload is the part of the spacecraft that meets the users' needs and drives the rest of the spacecraft design. The Air Force uses this initial set of performance specifications to initiate several conceptual studies of space systems. These analyses provide data, such as early life cycle cost estimates, for comparing alternatives on the basis of cost, schedule, and performance; they form the basis for assessing the relative merits of the concepts during the next decision milestone, Milestone I, Concept Demonstration Approval.

There are three methods used for analyzing and comparing alternative system concepts in the defense aerospace industry: *design studies, cost engineering models* (CEM), and *design conferences*.[4] All three are similar in that they develop a set of competing conceptual mission architectures, costs, and development schedules from the draft specifications. The three methodologies, however, vary greatly in the number of concepts they generate and the amount of information that they feed back to the Air Force. The next three sections describe these methodologies.

5.1 Design Studies

The Air Force, with rare exceptions, explores new mission concepts using design studies. To accomplish these studies, the SMC study group awards competitive contracts to several (approximately 5) contractors. They sometimes ask groups such as The Aerospace Corporation, ARPA, Philips Laboratories and other knowledgeable service related organizations to carry out

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[3]The Aerospace Corporation possesses a large historical body of knowledge pertaining to past military contracts. It also has a large body of engineers experienced in many critical satellite technologies. The Air Force borrows on this knowledge heavily in creating the new system's technical requirements and studying potential system tradeoffs.

[4]This list of methods derives from interviews with members of The Aerospace Corporation, the Air Force, and aerospace contractors.

studies as well as or in place of contractors, especially when the study budgets are limited or the mission needs are highly undeveloped. The logic for having industry perform the bulk of these studies is that, since industry actually develops and fabricates the spacecraft, they have better information than the Air Force or its affiliated organizations for producing realistic conceptual designs and accurate estimates of potential development cost and schedule. In reality, this reasoning may be only partly true. In particular, The Aerospace Corporation has information on most DoD space development programs, including cost and technical data, dating from the early 1960s. As a result, they may have as much or more information than the individual prime contractors. Furthermore, its employees are a mixture of former employees of system prime contractors as well as engineers who have not worked with any these contractors. Therefore, their concepts are less likely to represent or be constrained by any one way of doing business. Many of the other DoD components as well possess important information on new space system technologies and fabrication techniques.

Those organizations performing a study receive a statement of work (SOW) describing the scope and deliverables of the study along with the draft specifications describing the proposed mission. SMC usually requires that each contractor produce one or, sometimes, a few potential designs. Usually, the level of detail a study yields is a rough satellite configuration with size, mass, data, and power requirements for each subsystem including the payload. Some effort may also spent defining manufacturing and test techniques as well as technologies important to the successful fabricate and operation of the conceptual systems. Early estimates of cost and schedule for each concept and, sometimes, potential acquisition strategies are also deliverables of these studies. Sometimes the outcome of these studies closely resemble the product. Often times they do not because of changes forced by, as yet, undiscovered technical difficulties or other operational infeasibilities that become apparent during the implementation of the winning concept.

SMC uses the information from these designs as data points when deriving relationships between cost and performance for the new system. The Air Force uses these relationships to determine which requirements to amend prior to entrance into Phase I, Concept Demonstration and Validation. A more detailed design study phase can cost \$10 - \$20 million and take 12 - 18 months to complete. The cost only represents 5% or less of the entire amount spent on creating the operational system. Nevertheless, the results of these studies greatly affect the outcome of the system development process.

5.2 Cost Engineering Model (CEM)[5]

[5]The Cost Engineering Model (CEM) methodology described in this sections was developed at The Aerospace Corporation of El Segundo, California.

An alternative to using design studies for Concept Exploration and Definition is the development of a cost engineering model by each of the contractors. A cost engineering model (CEM) is a spreadsheet based concurrent engineering tool used to bring together spacecraft payload and subsystem design experience with spacecraft cost estimating knowledge in order to develop conceptual designs from mission technical requirements. Specifically, the CEM uses algorithms that convert technical requirements into hardware and software parameters. The model simultaneously estimates a cost for the modeled equipment employing a set of cost algorithms .

Two key characteristics differentiate the CEM from the more common design studies methodology. The first feature is the interconnectivity of the CEM. The CEM links each subsystem's model with those of the other subsystems through the use of a spreadsheet. So, when one parameter of a particular subsystem's design changes, all of the other subsystems modify themselves for this change automatically. In contrast, during design studies the design changes to one part of a design must be "rippled through" the whole design manually to see how they affect the final design. This is because all of the subsystem models reside with the specialists who produced them. Therefore, each specialist must be consulted for each design change. Second, the CEM uses the spreadsheet to directly link technical models with cost models. Thus, unlike design studies in which a design is created and then a cost is established serially, the CEM automatically produces a new cost and design for each change in requirements.

When constructing a CEM, the developers first work with spacecraft payload technical experts to develop a set of equations used to determine the payload size, mass, power, and data throughput required to meet the technical requirements received from the user. Subsystem experts then develop the algorithms that derive the hardware size, mass, power, and data parameters of their subsystem. Finally, cost estimators generate a set of equations that use the payload and subsystem hardware parameters to generate costs for developing the system. The developers of the CEM integrate these models into a spreadsheet or another similar computer-based tool. This provides the interconnectivity missing when performing design studies. A fairly detailed model usually takes 3 - 6 months to develop at a cost of $300,000-$500,000. This model allows its users to convert many combinations of performance requirements, "real time", into hardware and cost estimates. Each contractor's study team can configure a subset of the more promising hardware designs into black box level solid models of the spacecraft. The combination of rapid computation power and integrated knowledge also allows CEM users to determine the sensitivity of system performance and cost to different technical requirements. The requirements to which the mission is most sensitive can then be identified and carefully reconsidered prior to entering the Phase I, Concept Demonstration and Validation .

5.3 Design Conferences

The design conferences methodology for exploring concepts, like design studies and the CEM, requires an initial set of mission requirements. To start the process, the Air Force invites all of the contractors interested in participating in the studies to a publicly announced *bidders conference*. There the Air Force disseminate these requirements and request that the contractors generate designs and present them to the investigating Air Force personnel in private meetings. During a private meeting, the Air Force asks the contractor questions about certain design decisions and requests further exploration of other design issues for the next meeting. Occasionally, another bidders conference takes place at which the Air Force discusses its latest thinking on the project and any changes it wants to make to its draft specification. Several cycles of a bidders conference followed by private meetings take place prior to entering the Demonstration and Validation phase. The design conferences method also lasts approximately 12-18 months at a cost of $5-10 million. Design conferences usually require the contractors to bear the burden of cost. The Air Force reimburses the contractor that wins the Concept Demonstration and Validation contract[6].

5.4 A Comparison of the Concept Exploration Methods

The CEM methodology has definite advantages over the design studies technique. The *design studies* technique is very rigid in structure because it does not effectively accommodate requirements iterations during the Concept Definition and Exploration phase. This is because manual iteration of designs is cumbersome, time consuming, and subject to errors in capturing the differences between several sets of requirements. Therefore, the Air Force derives a mission's cost v. performance relationships from a small set of data points developed from, at most, a couple sets of performance requirements. The CEM, in theory, can provide information on an infinite number of performance level combinations. In practice, tens or hundreds of concepts can be investigated by varying performance characteristics. This flexibility allows the Air Force to explicitly consider more options. It also enables the Air Force to study the sensitivity of the conceptual system to changes in different mission requirements. From these results, the Air Force can identify key technical and cost drivers in the new system. In short, the integrated, computerized nature of the CEM provides a powerful level of information generating capability to decisionmakers that does not exist within the design studies methodology.

Although design conferences do not provide as many iterations as the CEM, they may have an advantage in that they are more intuitive. That is with each new design comes a new visual configuration of the system. This configuration helps to illustrate the unique features of each concept. Not only does this kind of conceptual configuration provide more of a look and feel to the system for less technically inclined policymakers, it may also be more sensitive to

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[6]This process has been used for studying concepts for one-of-a-kind experimental spacecraft. No record of using such a strategy for an operational satellite system was found for this thesis.

integration and configuration issues that might arise in the design than either the CEM or the design studies methods. The design conferences approach also facilitates uncommonly open discussion between the customer and contractor because it allows contractors to represent their designs in person to the Air Force rather than in written form only.

Design conferences also have some significant shortcomings. First, these conferences might run into difficulties with competitive fairness, since the government might be able to "play" members of industry off one other, giving the government unfair negotiating power. Also, situations of favoritism might arise in which some contractors get more access to and more hints from the investigating Air Force team. The design conferences methodology also is not as adept at modeling less physical parts of the space mission architecture, such as the communications architecture, or capturing the interaction among these parts when requirements iterations occur. A final caveat is that the design conferences method may be cost prohibitive because it requires contractors to invest too much of their own money without any guarantee of a return on such an investment. This is especially true in the case of larger systems which require greater study efforts.

The method used to explore design concepts can greatly affect the level of conceptual maturity and knowledge taken into the next phase of a spacecraft's development. Also, adhering to a single set of requirements early on limits the number of design tradeoffs performed. Exploring these tradeoffs is critical to achieving an effective design solution. This observation indicates that the historically popular method of concept exploration, design studies, is deficient in providing the information needed for detailed concept exploration. Furthermore, another method better suited for performing concept exploration, namely the cost engineering model (CEM), currently exists.

6. Milestone I - Concept Demonstration Approval

After completing its concept exploration, the Air Force develops acquisition strategies for the system concepts they identify as the most promising. Upon completion of these strategies, the exploration team proceeds to a Milestone I review. Milestone I's purpose is to assess the affordability of a proposed new acquisition program and marks the first direct interaction between the planning, programming, and budgetary and acquisition management systems. Up until this point discretionary research and development accounts within DoD fund the development of the concept studies.

The DAB reviews the results of the Phase 0 studies as well as defense planning guidance, long-range modernization and investment plans, and other internal planning documents which help to frame a go-or-no-go decision for the new system under consideration. The DAB records the highlights of this review in a Major New Start issue paper, approved by the Undersecretary of Defense for Acquisition (USDAQ) and passed on to the Defense Planning and Resources Board.

This board reviews the issue paper and delivers it with recommendations in terms of available budgets and potential funding profiles to the Deputy Secretary of Defense, who then decides whether to pursue the program. In deciding that a program will not be pursued, the deputy secretary cancels activities altogether or recommends that Phase 0 be reentered in an attempt to gather more information.

When a program gets the go ahead, the Deputy Secretary of Defense establishes affordability constraints for the program and communicates these to the USDAQ. The USDAQ, in turn, prepares an Acquisition Decision Memorandum reflecting the decisions and direction established by the Deputy Secretary of Defense. Any additional direction and program specific exit criteria for Phase I, Demonstration and Validation, are also included in the memorandum. *For the first time, a new program officially exists.*

Approval at Milestone I also involves Congress for the first time in the acquisition process. During Phase 0, discretionary DoD funds support the concept studies taking place. As chapter 2 describes, law requires that an acquisition program must receive *authorization* from Congress each year it exists, and only Congress can *appropriate* government money to fund the project. Congressional involvement can stay as unintrusive as yearly reauthorization and appropriation. If the project is a major budget item and encounters technical or other difficulties or is perceived as high risk, Congress may establish extra reporting requirements and added checkpoints to the acquisition process. For example, Congress might withhold program reauthorization or additional funding until certain technical issues are proven under control by the program.[7]

Depending on the acquisition program, Congress' role in day to day management varies greatly. As a result, the rest of the acquisition process does not mention Congress explicitly. Therefore, remember these things about Congress while reading the next chapter. Each year they must reauthorize the program and establish funding for a program to exist. Depending on the level of funding they can restrict or accelerate a program's growth and progress. Also, Congress can involve itself in the acquisition process by demanding hearings and including language in legislation making a program's funding contingent upon the accomplishment of *Congressionally established* goals. Therefore, Congress can greatly affect a program's outcome, controlling its budget, influencing its goals, and possessing the ability to impose copious amounts of extra work on the program in the form of hearings and reporting requirements

7. Summary and Conclusions

This chapter relates the process by which DoD starts a new acquisition program. This part of the process has two major steps, determining mission need and Concept Exploration and

[7]The B1-B Bomber story in Chapter 6 offers a perfect example of extra Congressional involvement in managing an acquisition program.

Definition. Table 6 relays the objectives of these initiatives as stated by the DoD 5000 series and compares them to their actual implementation.

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives	In-practice Implementation of the DoD 5000 Series
Determining Mission Need	• Monitor threats, technological developments, and the performance of aging systems • Identify mission need • Attempt to define a non-materiel alternative • If in need of a new system, broadly state the mission need in terms of operational capability, not system specific solutions	• Mission needs often defined as a specific system type (e.g., space system, missile system, or aeronautical system)
Phase 0 - Concept Exploration & Definition	• Explore material alternatives to satisfy mission need • Define the most promising concept(s) • Identify high risk areas and risk management approaches • Develop initial program strategy, cost, schedule, performance	• Design studies are weak at identifying high risk areas and are not effective in developing initial program strategies due to a lack of iteration on system requirements

Table 6 DoD 5000 series goals for determining mission need and concept exploration

The chapter shows that the actual process and the theoretical process correspond closely in goals during the determination of mission need and concept exploration. Practice differs slightly from theory during the determination of mission need because a specific type of system is often defined as the part of the system need. Such definition, however, is acceptable in terms of DoD 5000 when the need is to replace an already existing, but aging system (DoD, 1991). In the context of a new system, the DAB, realistically, has to limit system choices during the Milestone I decision exercise if concept exploration is to have some focus. So, in the end, the mission need would probably be constrained to a specific system type by the initial DAB subcommittee studies prior to Milestone 0.

The more interesting differences between the *supposed-to-be* and *as-is* processes comes during concept exploration. The goals are the same, but the commonly used method for accomplishing them, the design studies method, fails to adequately assess high risk areas. Section 5.1 shows that design studies make analysis of system sensitivity to requirements changes very difficult to perform, especially when compared to the cost engineering model (CEM) method described in Section 5.2. As a result, investigators cannot define satisfactorily areas of risk in the system's development. This deficiency in risk assessment then makes it difficult to develop suitable program strategies and estimates for development cost, schedule, and performance. The next chapter shows that the *actual* process continues to increase developmental uncertainty when compared to the process stated in the DoD 5000 series.

Chapter 4: The Spacecraft Acquisition Process - Spacecraft Development

1. Phase I - Demonstration and Validation (dem/val)

The dem/val process established in DoDI 5000.2 specifies that competitive prototyping or paper studies (if prototyping has been waived) of multiple design approaches should take place during Phase I. According to DoDI 5000.2, the system project office (SPO) should pursue parallel technologies within the system concept(s) developed during this phase. DoDI 5000.2 also requests that heavy emphasis be placed on the consideration of manufacturing processes when developing system concepts (1991): "Supportability and manufacturing process design considerations must be integrated into the system design effort early. This is essential to preclude costly redesign efforts downstream in the process." Similarly, according to DoDI 5000.2, risk identification and reduction should become cornerstones of Phase I (1991):

> Prototyping, testing, and early operational assessment of critical systems, subsystems, and components will be emphasized .... This is essential to: (1) Identifying and reducing risk, and (2) Assessing if the most promising design approach(es) will operate in the intended operational environment including people and conditions."

Table 7 shows the technical objectives stated by the DoD 5000 series for Phase I, Demonstration and Validation.

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives
Phase I - Demonstration & Validation	• Better define critical design characteristics and expected capabilities of the system concept(s) • Demonstrate critical technologies can be incorporated into system design(s) with confidence • Prove that the processes critical to the most promising system concept(s) are understood and attainable • Revise strategy, cost, schedule, performance objectives for most promising approach

Table 7 DoD 5000 Series Goals for the Demonstration and Validation Process

The rest of Section 1 documents the spacecraft development activities that presently take place in dem/val. The summary and conclusions of Section 1.7 compare the *as-is* to the *should-be* process described by DoDI 5000.2.

1.1 Competition for Dem/Val Funding[1]

In reality, the Air Force uses the Demonstration and Validation (dem/val) phase to fully develop one or, in exceptionally rare cases, two of the most promising concepts generated during

[1]Much of this information comes from interviews with personnel from a defense aerospace contractor, the Air Force, and The Aerospace Corporation.

the Concept Exploration and Definition phase into flight articles. The Air Force selects the one or two contractors who further develop their Phase 0 concepts through another RFP and source selection. With the company(ies) "on contract" dem/val commences. Dem/val has two major parts, design and fabrication and verification. Several smaller parts compose both of these processes . Figures 6a and 6b illustrate the Phase I process.

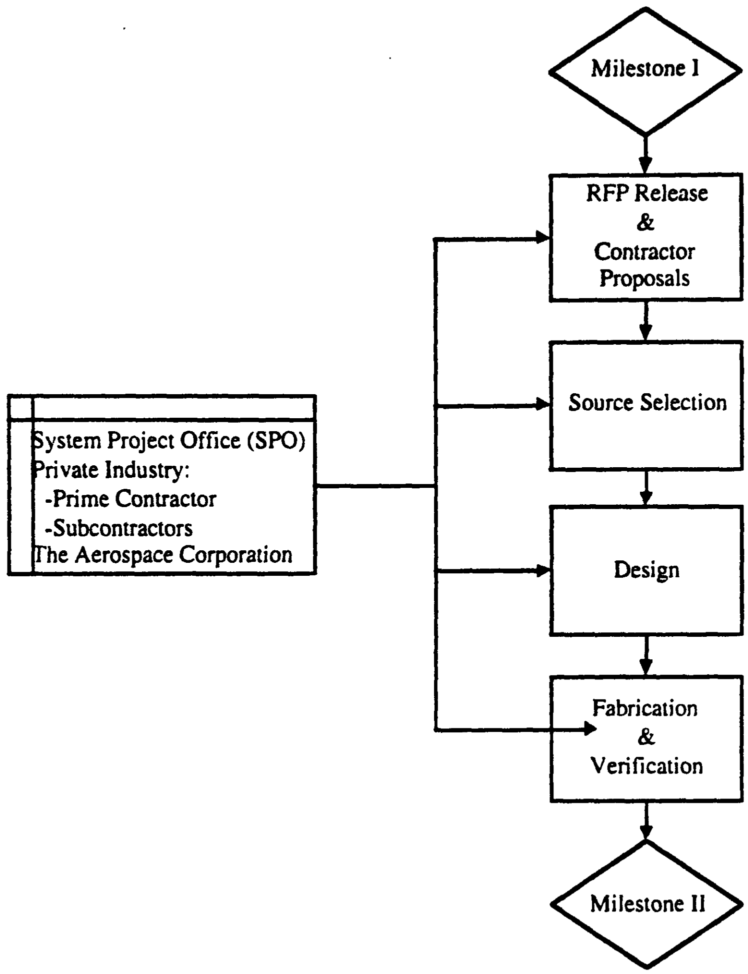

Figure 6a Phase I , Concept Demonstration and Validation

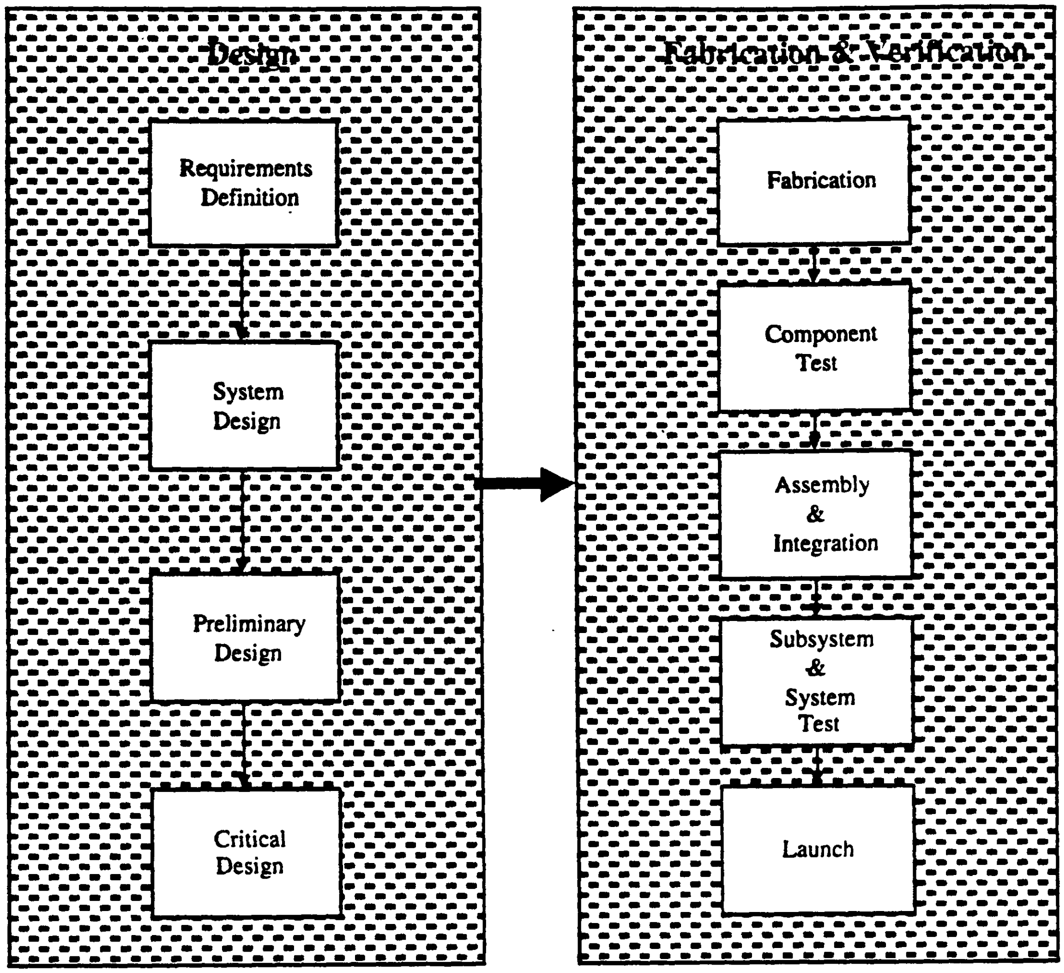

Figure 6b Phase I, Concept Demonstration and Validation - Two Major Subprocesses

1.1.1 Pre-RFP Activities Within the Air Force

By the beginning of Phase I, there is an Air Force or joint system project office (SPO) in charge of managing the acquisition of the new space system. Phase I begins with the SPO's revision of the existing set of system requirements, using inputs from Phase 0 and suggestions obtained from the Defense Acquisition Board (DAB) at the Milestone I review. The revised requirements become part of a draft request for proposal (RFP). The draft RFP consists of a statement of work (SOW) and a revised set of mission specifications, contained in the Technical Requirements Document (TRD).

The Air Force circulates for comment the draft RFP to interested members in industry. The SPO takes responses and modifies its RFP accordingly. Once the RFP is finalized, the Air Force announces, in *Commerce Business Daily*, an introductory briefing at which they release the RFP to all interested and qualified contractors. The contractors are given a period of 45 to 60 days, depending on the specific RFP, to develop a proposal. Their response must include a preliminary space system design and manufacturing and test plan, as well as estimates for development cost and schedule.

1.1.2 Contractor Response to the RFP

Each interested contractor establishes a bid team prior to the release of the RFP. This bid team consists of all of the engineering disciplines needed to fulfill the work required in the statement of work (SOW) portion of the RFP. Upon receiving the official RFP the bid team's systems engineering group along with structural engineering and subsystems and payload integration takes the lead in managing the creation of a design for the proposal. In the first days after the release of the RFP, systems engineering develops a more detailed set of design requirements for the spacecraft design engineering team from the RFP's Technical Requirements Document (TRD). The design engineering team consists of subsystem and payload engineers as well as manufacturing and test engineers. Figure 7 reviews the steps taken by contractors in responding to the RFP.

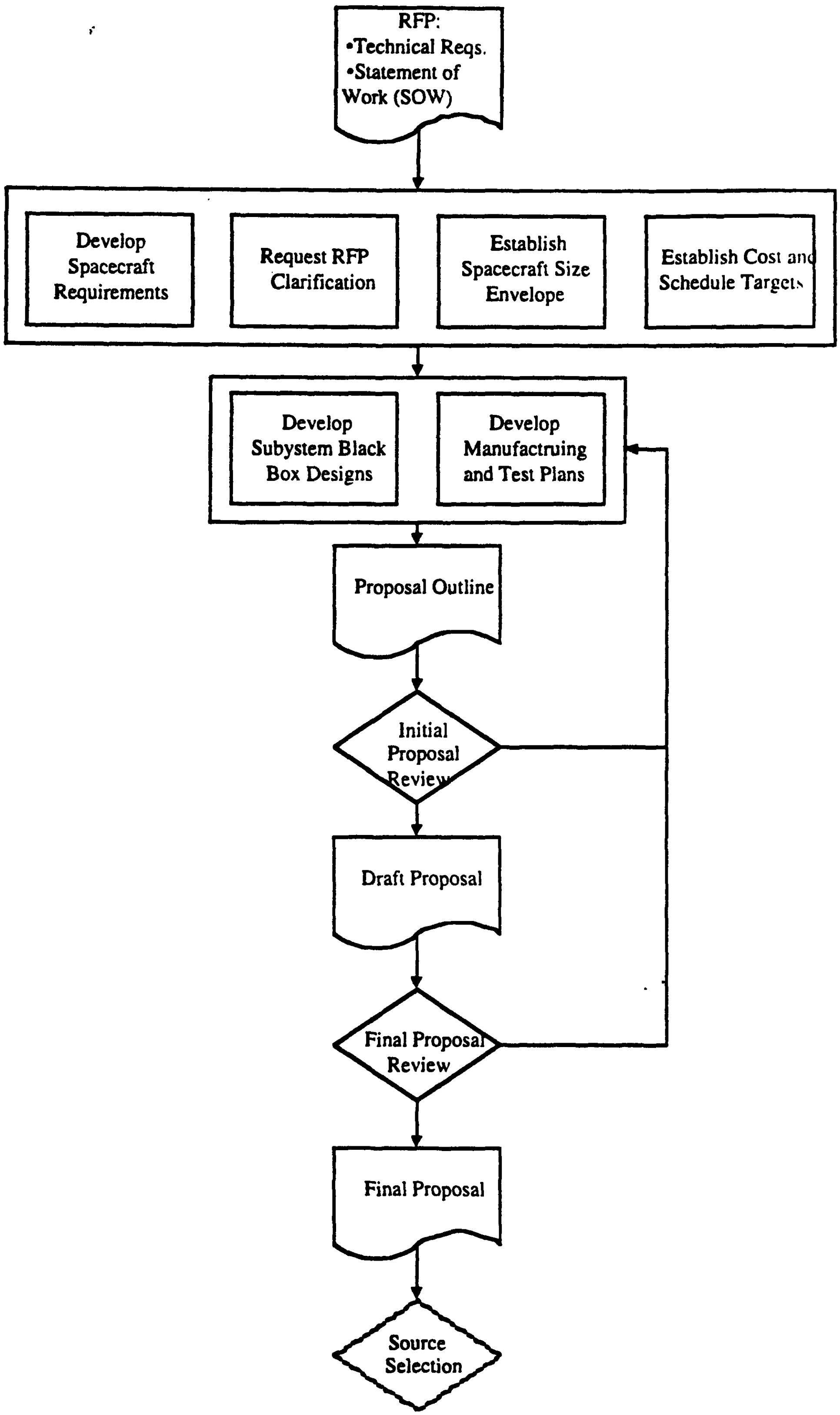

Figure 7 Contractor's response to RFP

Clarifying the Requirements

The first five days after the RFP release is a time for clarification of requirements with the Air Force. All requests for clarification must be made in writing to the Air Force. When the Air Force receives a question, it sends a copy of that question to all of the other contractors bidding on the contract. The Air Force then sends a response, also in writing, back to the origin of the question and a copy of the answer to all the other competing contractors. With this procedure the Air Force attempts to maintain fairness in the contract competition. After the five days , the Air Force refuses any further points for clarification.

Establishing the Spacecraft Black Box Design

Meanwhile, structural engineering and subsystems and payload integration establish a size envelope into which all parts of the spacecraft must fit at launch. The size envelope takes into account the fairing size of the launch vehicle that most likely will be used by the program. They pass along the size envelope to the rest of the program team. Using the set of requirements from systems engineering, the design envelope from structures and integration, and development cost and schedule targets set by the program manager, each subsystem's designers furnish the design integrator with black box designs for their subsystem. Each box comes with dimensions, a mass, thermal characteristics, vibration environment requirements, power requirements and duty cycles, and, in the case of the payload, field of view (FOV) requirements. Systems engineering and the appropriate subsystems engineers account for these parameters in the design work they perform.

Managing the Information Flow

Systems engineering and structures and integration manage the information that returns from the subsystem and payload designers. Structures also receives cost and schedule targets for their structural subsystem. They use the target cost and schedule and information about the subsystem black boxes to create a three dimensional computer solid model of the spacecraft. In developing the spacecraft configuration, the designers consider mass properties, accessibility of components, the reliability of the structure on which the components sit, testability of the structure and the components, strength of the structure, proximities of boxes in the same subsystem (sometimes this is requested by the subsystems designers, sometimes not), and contingencies for mass and size changes to the boxes which are inevitable over time due to the naissance of the designs. The structural designers rely heavily on experience and input from test and manufacturing specialists when developing their model.

Systems engineering manages the technical information transfer among designers. The following are examples of how they carry out this function. Periodically (e.g., biweekly) during the proposal phase, all of the program personnel attend a technical briefing. Each subsystem presents schematics of components and performance characteristics on overhead slides.

Everyone in the program receives an entire set of slides from the meeting. Systems engineering and program management co-host these meetings with the systems group keeping track of mass, power, and data budgets for the spacecraft and the program manager and chief engineer keeping track of schedule and cost issues. During the project team meetings, structures and integration also keeps track of the component characteristics like mass and center of gravity which affect the solid model they are developing.

Program management also plays the role of devil's advocate, challenging the designers to explain their decisions; any meeting participant, however, may raise an issue. These issues are commonly referred to as "action items." Systems engineering notes any action items raised during these meetings and tracks the items' subsequent follow-up. A method for tracking day to day progress and changes in the spacecraft's design is the creation and maintenance of a collection of evolutionary story boards detailing each of the subsystem designs. These story boards hang together on a wall within the program group. Daily program participants review and update these boards. They make comments about the work of others and receive comments about their own designs. Systems engineering aids in keeping track of the comments being made.

Developing Manufacturing and Test Plans

Manufacturing and test engineering have their own assignments during this period. The Air Force specifies certain tests and specific procedures to accomplish those tests in the RFP.[2] Typically test engineering analyzes these requirements and, using past program experience, makes suggestions about tailoring or substituting tests to save development time, or cost, or both. For example, the RFP might require the fully assembled spacecraft to survive thirty cycles within a thermal-vacuum chamber[3]. A contractor's experience might be that it has never had a failure beyond the fifteenth test cycle. As a result, they would suggest a smaller number of cycles, say fifteen, or maybe twenty as a compromise. These alternate test approaches appear in the proposal submitted to the Air Force which either approves or disapproves them on signing the dem/val contract. Manufacturing puts together a plan for how the spacecraft will be built. Their plan

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[2]Secretary of Defense Perry's 1994 memorandum abolishing the use of military specifications and standards might affect the amount of tests that are specified in the future. But as, Smith, et al. (1985) note, the more experienced commercial buyers of satellites have moved toward specifying the performance of certain tests in the contracts they establish with satellite vendors. Therefore, it seems highly unlikely that the practice of specifying tests in the RFP will be abolished completely.

[3]Thermal vacuum tests verify the workmanship of the spacecraft and provide a means of checking the operation of the spacecraft components in a simulated space environment. The chamber is a vacuum chamber equipped with nitrogen-cooled walls that simulate deep space and electric heaters or infrared lamps to simulate exposure to the sun or other higher temperature situations. Using these sources of heat and cool, testers can create temperature environments which force the spacecraft to maintain its own temperature for nominal operation (Larson and Wertz, 1992).

includes costs, schedules, facilities, and processes. Manufacturing processes that the Air Force requests[4] in the TRD may also require negotiation between the contractor and the Air Force.

Turning the Design Into a Proposal

Early in the proposal phase, the program manager can select a proposal administrator to oversee the preparation of the company's response to the RFP. The administrator, sometimes hired from outside the company, helps the program manager to establish the important themes of the proposal and a strategy for presenting them. These themes usually focus on what the management team thinks are the unique and beneficial solutions of their design to the Air Force's requirements. The administrator, with the approval of the program manager, prepares a proposal outline, specifying the size and contents of different parts of the proposal to different people on the program bid team.

Program management uses tools, such as story boards, to outline key proposal issues like the winning factors of a particular subsystem's design. Company personnel from outside the program team review these outlines playing the part of Air Force reviewers. Specifically, they concern themselves with the consistency of the spacecraft's overall design and how the different subsystem designs interact in an attempt to identify and eliminate conflicting design parameters that might exist. They also critique the manufacturing and test plans as well as the proposal's cost and schedule projections. After this review the program begins to write the proposal. In reality, only enough time exists for one or two iterations on the original text. Two to three weeks prior to the proposal deadline, the group of independent reviewers from within the contractor critiques the most recent draft of the proposal. Again the group plays the role of the Air Force and acts as if the draft they receive is the final proposal from the contractor. Although it is difficult, the review provides useful suggestions on how to improve the proposal. Afterwards, the program freezes the design and prepares a final version of the proposal which the contractor submits to the Air Force for review. The contractor spends approximately the last five days of the response period on publishing the proposal.

1.1.3 Summary - Competing for Dem/val Funding

After spending time up front on requirements definition and time at the end publishing the proposal, the program bid team has approximately 30 to 50 days, depending upon the specific program's proposal period, for the development of a conceptual spacecraft design. Because there is such limited time to produce a design during the actual contract response period, the maturity of the designs proposed by each of the contractors depends greatly upon the type and amount of

[4]One very common request is for the use of Class B or Class S military specification and standard (Mil Spec and Mil Standard) parts. All parts designated as either Class B or Class S have gone through several processes and quality assurance checks specified in designated military specifications, standards, and handbooks listed in the project's contract. Class S is the highest grade, Class B the middle grade; commercial grade parts are considered lower than Class B in this classification system. As alluded to earlier, DoD is reconsidering the use of Class B and Class S standards in program contracts.

work carried out during the *Concept Definition and Exploration* period preceding the proposal phase.

1.2 Source Selection

Upon receiving the contractors' responses, the Air Force enters into source selection. Two groups, one of management and logistics experts and the other of technical experts assemble off-site to review the contractor proposals which usually number from four to eight. The team reviews each proposal in turn with each individual scoring how a proposal meets the requirements as stated in the RFP. Most members of the review group possess a certain specialty (e.g., expertise in propulsion).They usually focus on the parts of the proposal that include that specialty when giving their score Once finished scoring a proposal, the reviewer must put that proposal away as well as their scoring sheet for it. They then review and rank the next proposal in a similar manner. Source selection rules prevent the reviewers form comparing two proposals, rating one proposal in terms of the others, or changing their scoring after moving to another proposal. *All grading is done in direct comparison to the requirements contained in the RFP only*. Following a complete review of all of the proposals, the source selection group gives each proposal a technical and programmatic score based upon the aggregate of all the reviewers' ratings and the weightings assigned to each category of the score prior to the commencement of source selection .

Following source selection, the Air Force can choose to seek clarification from each contractor on their respective proposals. After reviewing contractor responses to these questions, the Air Force usually asks each contractor to make a *best and final offer* on their development costs and schedule. In all but very rare cases, the Air Force is looking for the contractors to reduce their program cost, or schedule, or both. Some point after the contractors make their best and final offers, a decision is made on which and how many contractors will receive contracts. The period of time the Air Force takes for a decision is usually, at least, two to six months, but the period may be even longer depending upon concerns that arise about the quality of the proposals or the Air Force's ability to fund them. Figure 8 reviews the source selection process.

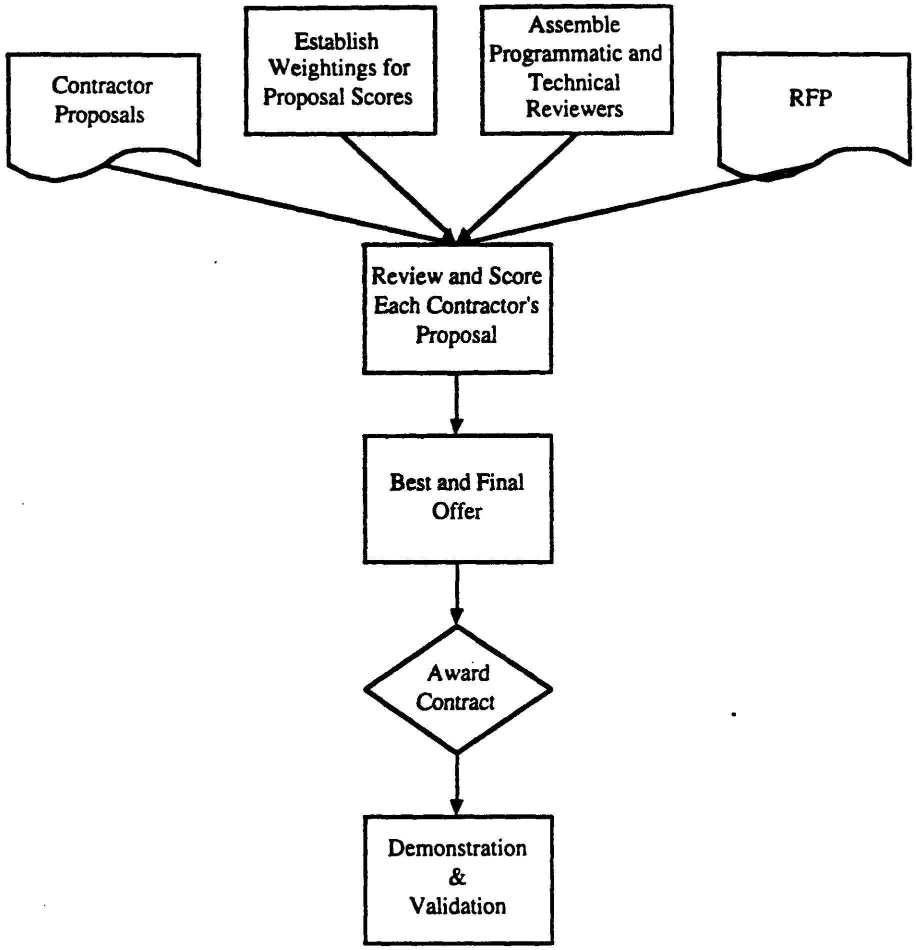

Figure 8 Source Selection

1.3 System Definition

Following source selection, the winning contractor continues to develop its conceptual design by undertaking a series of system definition activities. This system definition process consists of a system requirements phase and a system design phase. During the system requirements phase, the Air Force works with the contractor to clarify and amend the technical requirements as necessary. As the system requirements phase progresses, more detailed levels of requirements develop. Following a system requirements review (SRR), system definition enters into the system design phase where the creation of the spacecraft architecture and detailed black box component designs take place. The Air Force then holds a system design review (SDR).

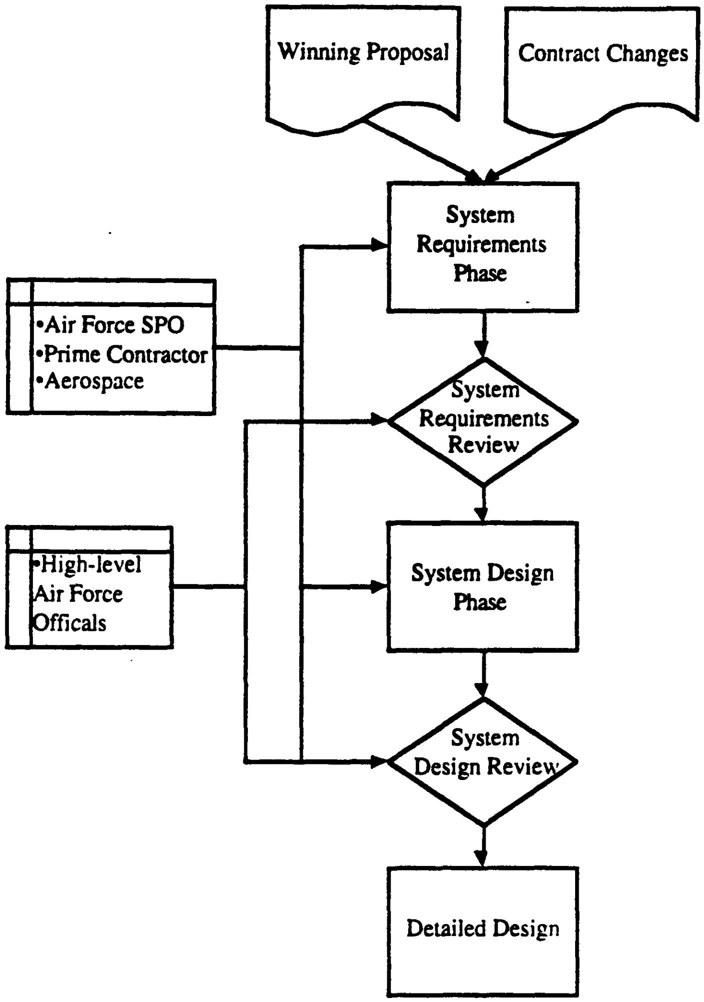

Figure 9 The System Definition Process

1.3.1 System Requirements

The Air Force and the contractor spend much of their time between source selection and the system requirements review (SRR) establishing more detailed requirements for the spacecraft based upon the technical requirements in the RFP. Some of these requirements take the form of *figures of merit*, what might be referred to in the consumer products world as a detailed set of specifications (e.g., pointing accuracy, orbit, mass, and power). At the contractor site work also begins on identifying potential subcontractor suppliers for major spacecraft components. The contents of the discussions between the contractor and subcontractors depend greatly on the maturity of the spacecraft design. The greater the level of maturity is, the more sophisticated the conversations are. Typically, the consultations center on improving black box mass, power, size, and data throughput estimates for the existing spacecraft model.

After a period of approximately eight to eighteen months of work with the contractor on the requirements, the Air Force holds a system requirements review (SRR) (Larson and Wertz, 1992). The SRR focuses on verifying that the contractor and the Air Force possess the same understanding of the mission requirements and figures of merit. The SRR also considers the plan for implementing these technical requirements into the spacecraft design. Any unresolved issues that arise become action items. Both parties attempt to close action items during the SRR. Any action items not handled at SRR become part of the SRR's record and must be brought to a close as quickly as possible. Upon completion of the SRR the system design phase begins.

1.3.2 System Design

The system design phase is a block of time roughly equal to that of the system requirements phase. Work on further developing the spacecraft's requirements continues during this phase. Systems engineering tracks the requirements flow down through the use of specification trees which record the filial relations of subsequent layers of design requirements for the spacecraft. The contractor spends an equal amount of time developing detailed subsystem designs . The study of system trades continues as well. For example, trades may be made between when and where the spacecraft is launched and the orbits into which it is launches; or various configurations of component box locations may undergo evaluation based upon thermal constraints or mass properties. The prime contractor may also begin to develop statements of work for subcontractor development of different spacecraft components.

Armed with a more detailed set of requirements and designs, the contractor enters into a system design review (SDR) with the Air Force. At this time the prime contractor attempts to prove that they have studied all of the major technical hurdles for the spacecraft and can deal with them. During this time, the design team presents concepts for deployables (e.g., to unfurl solar arrays or communication antennas on orbit), basic layouts of components, and preliminary outlines of their operation (e.g., reaction wheel placement along with the attitude control system's preliminary control laws).

1.4 Design Reviews

Design reviews are the periodic program reviews which take place to make sure that the program is technically sound and on target with cost and schedule projections. These reviews take place more often and delve to a more detailed level into both technical and programmatic issues than do the Defense Acquisition Board milestone reviews. The players are also different from the Milestone reviews. Experts from the Air Force and The Aerospace Corporation who are not associated with the program conduct technical reviews at these reviews, verifying the feasibility of the contractor's solutions. High-level members of the Air Force attend in order to monitor program progress and lend guidance if problems should occur. Members of the contractor team, the Air Force SPO, and associated members of The Aerospace Corporation (Aerospace) try to work together to set the review's agenda and represent the design effort. Sometimes, however, these reviews help to sort out differences in opinions among those closest to the project, i.e., the contractor, the Air Force, and program affiliated members of Aerospace.

Several months prior to the next design reviews, the contractor's systems engineering team issues a plan of action for that design review in order to coordinate the design team. These plans designate each of the briefers for, the amount of time for, and the content of each briefing. These plans also set the format for charts that are common among the different review segments (e.g., requirements flow down charts showing how the technical requirements documents were converted into system and subsystem specs). Well-organized design teams invite the Air Force SPO and affiliated members of Aerospace to review their briefings prior to a design review. This strategy helps to create a coordinated design review effort which, in turn, usually helps to produce a smoother design review.

The design review itself is a multi-day affair, often 2-3 days for a system requirements or system design review and 4-5 days for a preliminary design or critical design review. An executive summary of progress and future challenges takes place on the first day . For a system requirements or system design review, day 2 and much of day 3 are spent on each of the spacecraft bus subsystems, the payload, manufacturing, and testing. The review ends with a session summarizing the results of the review. Preliminary design and critical design reviews (PDR and CDR) also have an executive summary on Day 1. In these reviews, however, splinter groups meet over the next 2-3 days discussing in detail a particular part of the spacecraft development effort. This allows the reviewers to cover much more detail in roughly the same amount of time as an SRR or SDR. PDR and CDR also finish with a summary session. Each session within a design review has an Air Force and an Aerospace member keeping minutes. Answers to questions and action items are contractually binding; therefore, it is of utmost importance that a set of detailed, indisputable minutes is kept.

1.5 Detailed Design

Upon completion of the system design phase and a successful system design review, the satellite design process enters into the preliminary design phase. The critical design phase follows. Figure 10 shows the two phases.

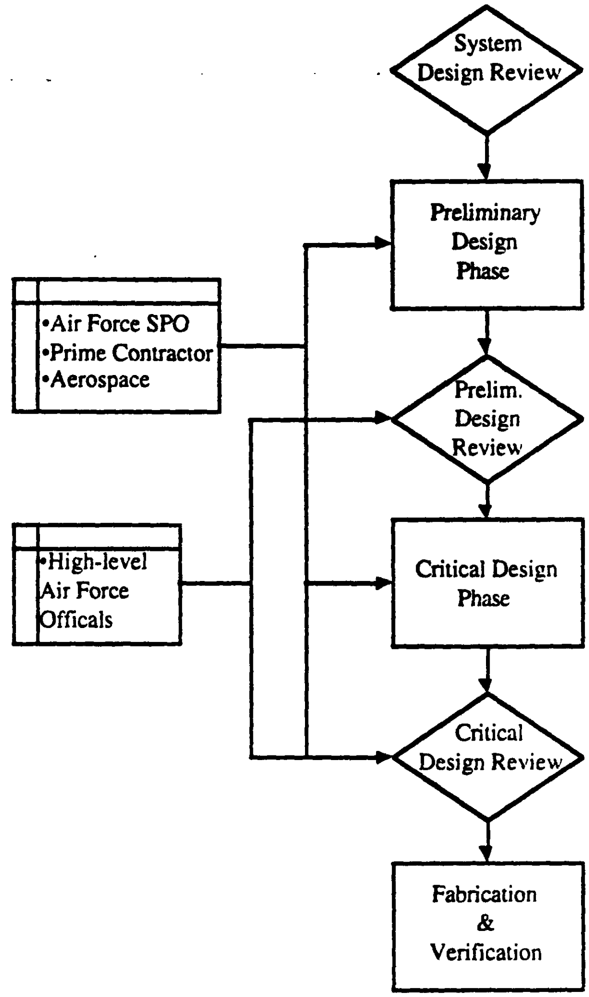

Figure 10 The Detailed Design Subprocess

1.5.1 Preliminary Design

In the preliminary design phase, the spacecraft design team takes the performance and design requirements derived in the system requirements phase and the system architecture and black box designs developed during the system design phase and creates detailed designs for all of the equipment, structures, mechanisms, and software that comprise the spacecraft. The team employs computer models to size and to assess the performance of the various subsystems. The designers iterate these models several times. Their revisions account for new, relevant information about other subsystems as well as requirements changes. The team derives hardware and software specifications from the information gained through these models. Table 8 lists several examples of types of computer models used by the design team and the kinds of decisions supported by the information in the models.

Subsystem	Example Computer Models	Decisions Supported
Structures	• 3-D solid model to establish a spacecraft size envelope for the different subsystem designs and to assess equipment accessibility as the subsystem designs become more detailed. • Finite element software for sizing structural members and specifying structural load paths	• Size and materials for structural members • Optimal equipment configuration on the spacecraft
Mechanisms	• Analysis of the kinematics of a deployment mechanism and the forces it must withstand during operation.	• Sizes and reliability of motors, microswitches, springs, etc.
Attitude Determination and Control	• Simulate various control system configurations and developing appropriate control laws.	• Types and sizes of attitude control sensors, reaction wheels, and position measurement units

Table 8 Examples of Computer Models Used to Aid Spacecraft Design Decisions

For those components that the prime contractor does not plan to fabricate, the hardware and software requirements for these components flow into draft statements of work and technical requirements documents which are forwarded to interested vendors for bidding. Typically, the prime contractor selects two subcontractors for each major spacecraft component that they are outsourcing. The subsystem designers use these bids to estimate the development cost and schedule of their system. This in turn initiates prime contractor and the subcontractor work on issues related to interfacing each of the specific components with the rest of the spacecraft.

Test also plays a role in the detailed design phases. During the preliminary and the subsequent critical design phases, they write test requirements documents. The test requirements documents specify not only the types of tests to be performed, but the quantity, the order, and the hardware and software involved in accomplishing them. The testing group coordinates who will produce the hardware and software necessary to carry out the tests to assure that the test series go smoothly (e.g., who will develop the software simulating the rest of the spacecraft during ADACS subsystem testing). Their planning also guards against repetitive preparation efforts. The test engineers then evaluate each of the tests to identify which tests they can run in parallel to save time, or money, or both. The test engineers also look for ways to minimize the level of system testing required for the spacecraft in order to save on cost and schedule, especially in disassembly for trouble shooting.

Also during the design phases, test contributes design input by raising issues of manufacturability, testability, and accessibility. For example, an accessibility issue might be ensuring that the lowest reliability equipment is the easiest to access when the spacecraft is fully assembled. An example of how testability issues affect spacecraft design is in the area of component design. During subsystem design, testing looks for several things. They verify the accuracy of subsystem outputs.[5] They assure that each subsystem design provides a defined answer and correlateable data as output. A good subsystem design not only indicates that the subsystem is receiving power, but indicates the level of power it is receiving and the variations in the power supply experienced by the subsystem's power inputs. Finally, test insures that designs possess more than one way of measuring a given parameter. This gives test technicians and engineers the ability to double check results.

The preliminary design phase lasts one to two years, depending upon the level of system complexity and technical challenges. It ends with a preliminary design review (PDR) by the Air Force. The Air Force uses the PDR, like the other design reviews, to assess program progress and to obtain impartial, outside review of the prime contractor's design decisions.

1.5.2 Critical Design

After PDR, the critical design phase begins. Design iterations continue to produce more and more detail. New or revised details become a part of the performance models; interfaces are finalized; action items are answered. As the critical design process continues, the prime contractor selects a single subcontractor to provide each spacecraft component. Design efforts then shift their focus to interface specifications such as bolt hole patterns for mating components to the spacecraft equipment panels. Interface control documents[6] (ICDs) record these details and must receive the approval of the prime contractor and subcontractors along with that of the Air Force SPO. The design team finalizes parts drawings, and the fabrication of some long lead time items begins. Test finalizes its requirements for the spacecraft; manufacturing establishes a plan for spacecraft fabrication and assembly.

At the critical design review (CDR), the Air Force approves the interface control documents (ICDs) and detailed design drawings. They specify any revisions that might be required. Also, the CDR participants finalize the parts of the ground operations requirements document[7] (GORDs) and the flight operations requirements document (FORD) that affect the

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[5]An example from the world of manufacturing process control illustrates this point. On a CNC milling machine under feedback control, the position of the part being machined is often determined from measurements by encoders placed on the ball screws used to translate the machine stage. As a result alignment errors between the machine axes and backlash in the screw will not be measured. Thus, the position measurement is only an approximation and not the true position of the part. Depending upon the grossness of approximation, measurement approximations like these might not be acceptable representations of the true system state.

[6]Interface Control Documents establish what the *structural, electrical, and thermal* interfaces are supposed to be for all of the different components being added to the spacecraft structure. ICDs formalize the interfaces to prevent mistakes from being made during integration. Once the ICDs are signed, changes to them must be agreed on and recorded in Interface Review Notices (IRNs) which must go through the same approval process as ICDs.

[7] The ground operations requirements document (GORD) and flight operations requirements document (FORD) specify how the spacecraft is to operated and maintained on the ground (i.e., in storage or at the launch site) and on flight, respectively. One might think of these documents as instruction manuals for the satellite operators. The Air Force and the prime contractor sign off on these documents some time during either the fabrication or test period.

spacecraft design, although the final version of these documents do not yet exist. At CDR the Air Force also releases the contract for the launch vehicle(s). Following CDR, the spacecraft design process concludes and fabrication and verification begins.

1.6 Fabrication and Verification

Fabrication and verification comes on the heals of the critical design review. The cutting of material, laying of wire, and building of components starts literally the day after the Air Force SPO approves part drawings and assembly and test plans. (Of course, fabrication of long lead items begins in the critical design phase.) Although this phase has very simple goals - build, test, and launch the spacecraft - it takes as long or longer than the entirety of the design activities which precede it. This phase is also the first time that the program tests their designs in the form of real hardware and software. Therefore this is the part of the spacecraft development process where mishaps and delays are most likely to occur. As a result, quality assurance of components, test and diagnosis of subsystem and system operation, component repair and rework, and system readiness are the focus of this part of the spacecraft development process.

1.6.1 Fabrication

People from the prime contractor's quality assurance group are on the scene at both the prime contractor and the subcontractors to minimize production difficulties and to report those that do arise to the prime and to the Air Force. There are two types of production errors: *errors in design,* either in the drawings or fundamental to the design, and *errors in fabrication*, e.g., the part gets dropped or is machined to the wrong dimensions. For each error a discrepancy report is filed by these quality assurance people. The discrepancy report goes to the subsystem engineer responsible for the component. There are typically two solutions: *scrap* or *fix/rework* the part.

Depending on the size and type of error it is, prime contractor personnel anywhere from the subsystem engineer in charge of the design to the highest levels of company management may decide a particular component's fate. The subsystem engineers usually has a limit of several thousands of dollars on the value of a component on which they can approve a scrap order. Above that level, the chief engineer or other high level program officials must approve a scrap order. Finally, if the value of the component being considered for scrap is on the order of hundreds of thousands of dollars then a scrap order often requires the approval of corporate executives from the prime contractor.

If fixing the part is the course of action chosen the contractor forms a *material review board*. The board usually has the subsystem engineer as well as manufacturing, reliability, and test engineers on it in order to identify all of the performance, process, test, and reliability issues associated with executing and verifying the effectiveness of a fabrication fix. The material review boards frequently forward all discrepancy reports and the solutions they approve to the Air

Force SPO. The prime contractor notifies the Air Force of any major problems requiring scrapping or reworking components as soon as possible.

Typically, the prime contractor arranges fabrication in an order that builds and assembles the spacecraft structure in time to accept components and other equipment as they arrive. Also during this period, the prime contractor and subcontractors produce interface review notices (IRNs) specifying necessary changes to equipment interfaces discovered during fabrication and assembly of that equipment. Some of the IRNs result from the increasing level of data which affects designs in a previously unclear way.

1.6.2 Verification

Because almost all spacecraft are irretrievable once on orbit, the Air Force requires its prime contractors to extensively test flight hardware and software before launching it. Testing is carried out at varying levels of spacecraft integration to verify that individual equipment boxes work correctly by themselves and together as subsystems and systems.

Any completely new design must be qualified before it can fly. Qualification testing stresses the design beyond operational requirements in order to assure design robustness. Each and every piece of equipment must be qualified separately before the new design can fly. The spacecraft, once integrated, must also pass qualification testing. A particular program may decide to dedicate one set of equipment exclusively to qualification testing (qual testing), or it may decide to qual test the first set of flight hardware.[8] Upon passing qual testing, all subsequent equipment and spacecraft are accepted following a regimen of acceptance testing which verifies nominal operation of the equipment within the mission specified limits.

The prime contractor reports anomalies that arise during test via discrepancy reports. Typically, a dedicated staff of engineers and technicians run the tests, take the data, and hand the data off to the relevant subsystem's engineers who analyze the data. determines the presence of any anomalies, and sends back a trouble shooting plan, as necessary, where either the box is removed or the errant data blamed on test procedures and the tests are rerun. A more streamlined approach employed by some programs has the test group analyze the data and call in the affiliated subsystem engineers only if they discover an anomaly. In the case of an anomaly, discussions ensue between the test group and subsystem engineering in which they develop a trouble shooting strategy.

Due to the small quantity of spacecraft produced, extra parts often do not exist to replace faulty equipment boxes. Therefore the program keeps a faulty box on the spacecraft as long as possible in an attempt to determine as many of the anomalies as possible at the same time. This helps to economize the testing time. In the production part of a larger program, like GPS, the

[8] At the component level, a design might be qualified by demonstrating that the component and its operation environment are identical to previously qualified material. This is referred to as qualification by similarity.

same box might be pulled off of a spacecraft, not as far along in assembly, and replace the defective box on the other spacecraft. Testing continues while the other box is reworked.

As in fabrication, the satellite development team files discrepancy reports with the Air Force . This time discrepancy reports involve components built to design specs that do not live up to performance requirements. A deficient design marks a significant setback to the program. Fixes are proposed, but if all else fails, performance requirements are relaxed. Design changes this late can impact cost and schedule dramatically.

Once a spacecraft is fully tested it is sent to the launch site where its is mated to the launch vehicle. Once mated, a series of tests are run to assure proper interface with the launch vehicle and that the spacecraft was not damaged in transit to the launch site. Troubleshooting any anomalies can require unstacking the spacecraft from the launch vehicle, creating cost increases and schedule delays. Once the spacecraft fully checks out at the launch site, it is ready for launch which takes place as soon as possible.

1.7 Summary and Conclusions - Demonstration and Validation

The space acquisition community interprets the words of DoDI 5000.2 to mean that they must develop a fully functional spacecraft, one that can serve as an operational system once it reaches orbit, in order to prove a new program's feasibility. Table 9 shows how the actual Phase I process compares with that stated by the DoD 5000 series.

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives	In-practice Implementation of the DoD 5000 Series
Phase I - Demonstration and Validation	• Better define critical design characteristics and expected capabilities of the system concept(s) • Demonstrate critical technologies can be incorporated into system design(s) with confidence • Prove that the processes critical to the most promising system concept(s) are understood and attainable • Revise strategy, cost, schedule, performance objectives for most promising approach	• Conquer all technical challenges to spacecraft development • Fully develop and implement spacecraft design • Achieve, at least, partial operational capability with the launch of dem/val spacecraft

Table 9 DoD 5000 series goals for determining mission need and concept exploration

This approach to spacecraft development contrasts, for example, fighter and missile development in which the project office develops a basic airframe and guidance control prototype to demonstrate a system's technical feasibility prior to producing actual final design aircraft (Drezner, 1992; Lorell, 1989; Larson, 1990; Mayer, 1993).

Research for this thesis did not find an explicitly stated reason why the space community chooses to develop entirely the space system during Phase I. The literature does present at least two conditions that, when considered together, might explain the existence of such a process.

First is the surviving Nixon administration policy of "fly before buy." Fly before buy requires the contractor or contractors who vi to produce a new system to fabricate a limited number of actual flight articles by the end of Engineering and Manufacturing Development, Phase II. A decision is made, after extensive testing of the flight articles, as to which of the two designs is the winner of the head-to head competition and how many of that design should be produced. The second issue that arises is that spacecraft are, typically, low volume acquisitions. Policymakers find that the low volume of spacecraft produced makes justifying the development of two different system concepts (i.e., using two contractors) as well as the development of two separate iterations of a system concept (i.e., the development of a technology demonstrator in Phase I and actual flight articles during Phase II) financially infeasible. Trying to gain the benefits of fly before buy while unable to defray the costs of such a policy over a large production run, spacecraft acquisition personnel probably justify that a strategy of total space system development in dem/val is the most financially and time efficient policy.

The interesting consequence of such a strategy is that successful launch and operation of a dem/val spacecraft means that the mission concept goes directly from design plans to an operational system without iteration through operational use. Therefore DoD commits itself, at the beginning of Phase I, to getting system development "done right" the first time. As shown above, the objectives of such a strategy reach far beyond what DoDI 5000.2 requires for Phase I. In fact, this decision helps to short circuit the multi-decision development process offered by the DoD 5000 series. This spacecraft development strategy, instead. combines technology demonstration with detailed system development, i.e., it combines Phases I and II. Thus, a well-informed decision as to whether the technical risks are low enough is not possible prior to commencing system development. This is an important result and relates to an observation made at the conclusion of Chapter 3 - each successive phase of military spacecraft acquisition contributes to developmental uncertainty as compared to the process offered by the DoD 5000 series. Later chapters discuss the effects of this conclusion. They also discuss why reasons why it is difficult for the defense aerospace community to follow the DoD 5000 series as written.

2. Milestone II - Developmental Approval

DoDI 5000.2 specifies Milestone II as the time when the Undersecretary of Defense for Acquisition (USDAQ), with the assistance of the Defense Acquisition Board, decides whether to proceed with Phase II, Engineering and Manufacturing Development (EMD). The decision is to be based upon Defense Planning Guidance, long range modernization and investment plans, internal documents of DoD components, and rigorous assessment of program risks and risk management plans. DoDI 5000.2 states that "program risks and risk management plans must also be rigorously assessed. This is critical because of the significant resource commitment that is associated with this decision" (1991).

At this time the USDAQ normally establishes a development baseline. DoDI 5000.2 notes that this requires effective interaction among the requirements generation, acquisition management and planning, and programming and budgeting systems. Within this plan, the low-rate initial production plan for material to be procured before the operational test and evaluation milestone should be re-evaluated and changes approved by the Milestone I decision authority in consultation with the Director, Operational Test and Evaluation based upon: (1) Fabrication complexity of the system, (2) Relatively small number to be procured and high unit cost, (3) length of the production period, (4) Need to preserve the mobilization production base for the system, (5) Acquisition strategy most advantageous to the government. Also, a test program leading up to full-operational test and evaluation should be structured to generate the maximum level of confidence deemed practicable in assessing the ultimate operational suitability and effectiveness of the systems (1991). This is what should happen. In reality, with the spacecraft already designed and built, the USDAQ and the DAB are left to identify specific more study for certain production concerns, such as components that might be difficult to fabricate and caused delays during Phase I.

2. Phase II - Engineering and Manufacturing Development

This phase has little significance for the spacecraft development process, except maybe to develop new equipment or make modifications to some already existing designs which are to be flown on any production spacecraft produced following dem/val. In theory, Phase II is a time, according to DoDI 5000.2, to alleviate program risk. "Effective risk management is especially critical during this phase" (1991). Therefore development and test activities should: (1) focus on high risk areas, (2) address the operational environment, and (3) be phased to support decision making at Milestone III, Production Approval. As a result, resources should only be committed commensurate with risk reduction and closure of risk. Risk assessments and planning for Phase III should address design stability, production, industrial base capacity, configuration control, deployment, and support.

The operational test activity should be supported by developmental testing that provides data for operational assessment prior to the beginning of formal initial operational test. Also, system specific performance requirements are being developed for contract specifications in coordination with the user or the user's representative. During this phase both the planning, programming and budgeting, and acquisition management systems periodically review the budget execution status. Any changes to the program resulting in an actual or projected breach of a program baseline parameter must be identified and formally communicated to the milestone decision authority. Again, this is the ***supposed-to -be***, not the *as is* process. Table 10 compares the two processes.

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives	In-practice Implementation of the DoD 5000 Series
Phase II - Engineering & Manufacturing Development	• Translate the most promising design approach into a stable, producible, and cost effective system design • Validate the manufacturing or production process • Demonstrate through testing that the system capabilities meet contract specification requirements and mission need	• Produce potential design modifications and upgrades • Scale-up for production (*if necessary*)

Table 10 DoD 5000 series Phase II Goals Compared to Military Space Acquisition's Implementation of Them.

3. Milestone III - Production Approval

DoDI 5000.2 states that the milestone decision authority, the USDAQ, is charged with: (1) confirming program affordability, (2) determining that the system is approved for service use as part of the production approval process, (3) ensuring design stability and producibility, (4) establishing the Production Baseline after having, first, proofed the production process. Establishing the Production Baseline requires the effective interaction of *all three major decision support systems*. In particular they must pay attention when: (1) assessing developmental and operational test and evaluation results, (2) establishing the most economic production rate that can be sustained, given affordability constraints, (3) identifying the criteria for determining operational capability, (4) ensuring that planning for deployment and support is complete and adequate, (5) planning for a possible transition to surge or mobilization production rates.

At this time, regulations not only require a revision of the design to average unit procurement cost objective, but they also require an independent cost estimate. A man power estimate report must be submitted to Congress 30 days prior to approval to enter the production and deployment phase. Proceeding beyond initial low rate production shall not be approved until: (1) initial operational test and evaluation of the program is completed, and (2) the DoD Director of Operational Test and Evaluation prepares and submits a Beyond Low-Rate Initial Production Report to the Secretary of Defense, USDAQ, and Congressional defense committees and the Congressional defense committees have received this report.

DoDI 5000.2 states that "a favorable decision at this point represents a commitment to build, deploy, and support the system" (1991). *In terms of spacecraft development*, this decision is of importance only in large production run (tens of satellites) systems like GPS or Brilliant Eyes, where all the spacecraft have not been built to complete the constellation. On smaller programs, this is more a decision to stay with the current contractor and design to build replenishment spacecraft for the ones already on orbit. Data from the operation of demonstration and validation spacecraft is used when making production decisions such as schedules and budgets. Changes to a spacecraft's design that will improve its producibility may also be identified at this time. The decision at Milestone III, however, is usually to plan when and how many spacecraft to acquire not whether or not to produce the spacecraft.

4. Phase III - Production and Deployment

DoDI 5000.2 says that Phase III requires the monitoring of field experience to include operational readiness rates. The data gathered is used to assess the ability of the system to perform as intended and identify and incorporate minor engineering change proposals to meet required capabilities. Any major upgrades or modifications that require a Milestone IV, Major Modification Approval should be identified during this time. As with phase III program budget execution status is being monitored by both the planning, programming, and budgeting and acquisition management systems.

Phase III, Production and Deployment affects the true spacecraft acquisition process in the following ways. The actual production of spacecraft can last a decade or longer. For example, production of the Defense Support Program's (DSP) spacecraft has been going on for over twenty years. GPS' production run was closer to a decade. One interesting production decision that must be made is whether to build spacecraft faster than they are needed and place them in storage or to build spacecraft to meet demand. An advantage of the prior strategy is that a gap in coverage (a satellite missing in the constellation because of a satellite or launch failure and no substitute satellite for it) is much less likely to occur from production delays. There are many issues about how spacecraft age in storage, especially as aging relates to mechanisms and their lubricants. Notetaking for system improvements to be made in a next generation system is also part of the production period. Usually, prior to the end of production, work begins on the design of a new version, or *block upgrade*, of the system. Table 11 relates compares the Phase III goals of the DoD 5000 series and space acquisition's interpretation of them

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives	In-practice Implementation of the DoD 5000 Series
Phase III - Production & Deployment	• Establish a stable, efficient production and support base • Achieve an operational capability that satisfies mission need • Follow-on operational and production verification testing to confirm and monitor performance, quality, and verify correction of deficiencies	• Finish fabrication and verification of remaining units planned for the operational system (including spares) • Identify improvements needed in system *block upgrade*

Table 11 DoD 5000 series Phase III Goals Compared to Military Space Acquisition's Implementation off Them.

5. Chapter 4 Summary and Conclusions

Present practice in the military spacecraft community fully develops a space system within Phase I, Demonstration and Validation, of the acquisition process established by DoDI 5000.2. Therefore a decision to proceed at Milestone I means approval for a new operational space system. One can only surmise that the institution of a "fly before policy" by the Nixon administration combined with the low production volume of most spacecraft create the root causes for the full development of spacecraft in the dem/val phase. It is clear, however, that this practice reduces the number of chances for policymakers to curtail a program prior to disbursing hundreds of millions or even billions of dollars. It is also clear that this *go/no-go* decision at the end of Phase 0 requires that a tremendous amount of information be gathered and analyzed in *Phase 0, Concept Exploration and Definition*. Finally, this dem/val development practice makes the reduction of design risks of new technology concurrent with system design and manufacturing decisions - something the DoD 5000 series explicitly tries to avoid, Table 12. More is said in the next two chapters about the detrimental effects full spacecraft development has in dem/val.

Acquisition Phase	DoD 5000 Series Acquisition Phase Objectives	In-practice Implementation of the DoD 5000 Series
Determining Mission Need	• Monitor threats, technological developments, and the performance of aging systems • Identify mission need • Attempt to define a non-materiel alternative • If in need of a new system, broadly state the mission need in terms of operational capability, not system specific solutions	• Mission needs often defined as a specific system type (e.g., space system, missile system, or aeronautical system)
Phase 0 - Concept Exploration & Definition	• Explore material alternatives to satisfy mission need • Define the most promising concept(s) • Identify high risk areas and risk management approaches • Develop initial program strategy, cost, schedule, performance	• *Design studies* are weak at identifying high risk areas and are not effective in developing initial program strategies due to a lack of iteration on system requirements
Phase I - Demonstration & Validation	• Better define critical design characteristics and expected capabilities of the system concept(s) • Demonstrate critical technologies can be incorporated into system design(s) with confidence • Prove that the processes critical to the most promising system concept(s) are understood and attainable • Revise strategy, cost, schedule, performance objectives for most promising approach	• Conquer all technical challenges to spacecraft development • Fully develop and implement spacecraft design • Achieve, at least, partial operational capability with the launch of dem/val spacecraft
Phase II - Engineering & Manufacturing Development	• Translate the most promising design approach into a stable, producible, and cost effective system design • Validate the manufacturing or production process • Demonstrate through testing that the system capabilities meet contract specification requirements and mission need	• Produce potential design modifications and upgrades • Scale-up for production (*if necessary*)
Phase III - Production & Deployment	• Establish a stable, efficient production and support base • Achieve an operational capability that satisfies mission need • Follow-on operational and production verification testing to confirm and monitor performance, quality, and verify correction of deficiencies	• Finish fabrication and verification of remaining units planned for the operational system (including spares) • Identify improvements needed in system *block upgrade*

Table 12 DoD 5000 Series Goals and Spacecraft Acquisition's Implementation of Them

Chapter 5: Observations of the Spacecraft Development Process

1. Introduction

Chapter 2 discussed the technical challenges faced by designers when creating a space system and showed the different organizations that must interact in order to establish requirements for, manage, and pay for the new system. Chapters 3 and 4 described the process through which these different organizations interact to create the new system. Chapter 5 uses a map of this spacecraft development process to synthesize the spacecraft development process into a single representation. Using the map it identifies problems with and potential solutions to the acquisition of defense space systems. In particular, Chapter 5 utilizes a Design Structure Matrix (DSM) to document the tasks and their order, the information flows among them, and the organizational relationships taking place in spacecraft development process The information content of this map also helps to identify symptoms of structural failures within the development process, for example cost and schedule overruns. Chapter 5 then attempts to observe which conditions in the process cause these symptoms to occur. Chapter 6 attributes the existence of these conditions to their structural causes in the military space acquisition process.

2. A Brief Primer on Reading the Design Structure Matrix (DSM)

Figure 11 shows a design structure matrix (DSM) representation of the *Phase I, Demonstration and Validation*, process for spacecraft. The DSM provides an effective means for mapping information flows within a complex process, determining which of the tasks are concurrent, serial, and parallel, and identifying important subprocesses. Its ability to compactly and concisely present a plethora of information about large, complex processes, makes the DSM a logical choice for mapping the spacecraft development process.

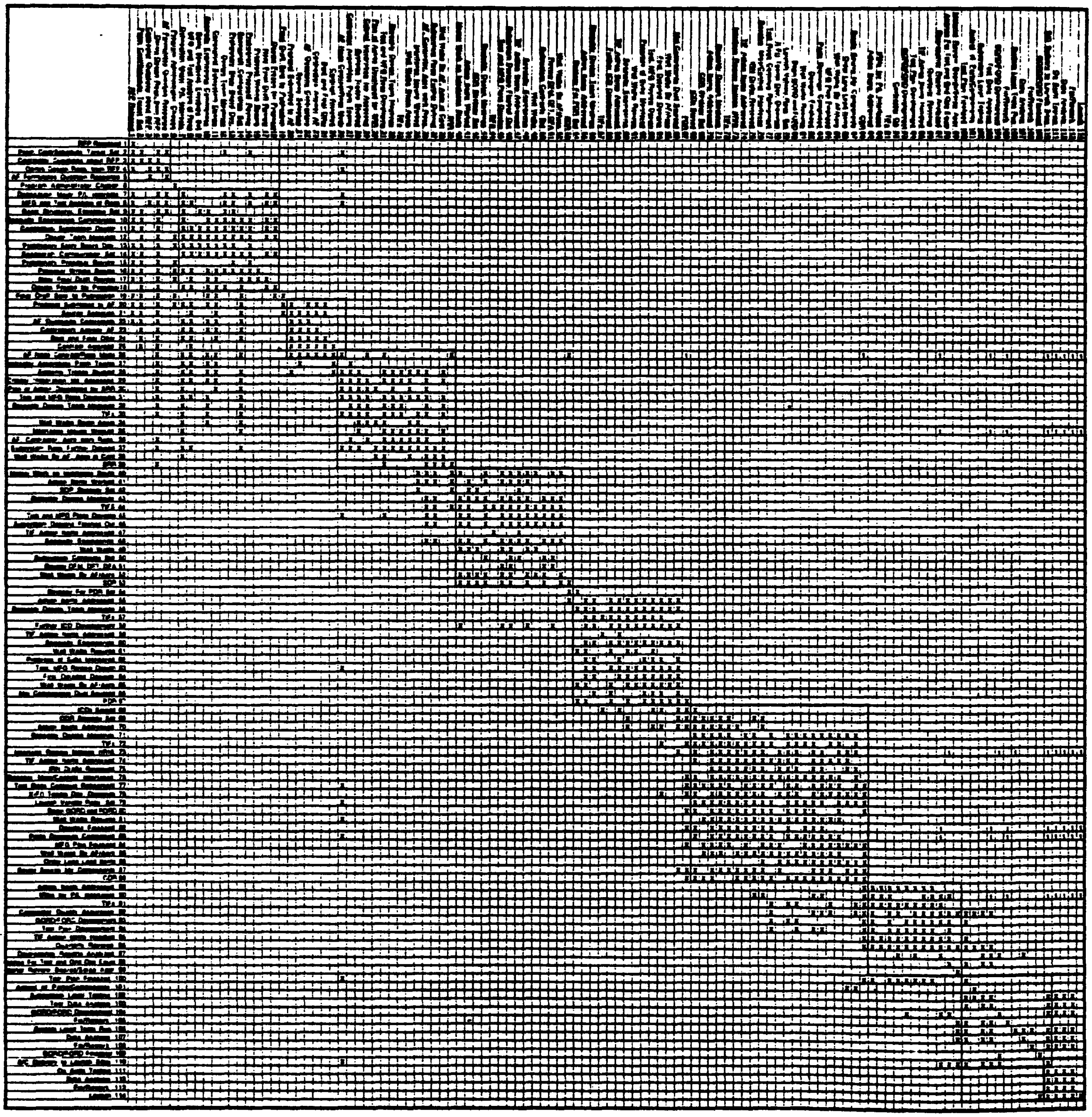

Figure 11 A Design Structure Matrix (DSM) for the Spacecraft Development Process

	RFP Released 1	Prgm Cost/Schedule Target Set 2	Contractor Questions about RFP 3	Derive Design Reqs. from RFP 4	AF Formulates Question Response 5	Program Administrator Chosen 6	Delineation Major P/L Interests 7	MFG and Test Analysis of Reqs 8	Basic Structural Envelope Set 9	Specialty Engineering Commences 10	Conceptual Subsystem Design 11	Design Team Meetings 12	Preliminary Story Board Dev. 13	Spacecraft Configuration Set 14	Preliminary Proposal Review 15	Proposal Writing Begins 16	Near Final Draft Review 17	Design Frozen for Proposal18	Final Draft Sent to Publication 19	Proposal Submitted to AF 20	Source Selection 21	AF Questions Contractors 22	Contractors Answer AF 23	Best and Final Offer 24	Contract Awarded 25	AF Negs Contract/Reqs Mods 26	Contractor Assembles Prgm Teams 27	Systems Trades Studied 28	Critical Integration Iss Assessed 29	Plan of Action Developed for SRR 30	Test and MFG Reqs Developing 31	Biweekly Design Team Meetings 32	TIFs 33	Wall Walks Begin Again 34	Interfaces Issues Worked 35	AF, Contractor, Aero work Reqs. 36	Subsystem Reqs Further Defined 37	Wall Walks By AF, Aero at Cont 38	SRR 39	Heavy Work on Interfaces Starts 40	Action Items Worked 41	SDR Strategy Set 42	Biweekly Design Meetings 43	TIFS 44	Test and MFG Plans Develop 45	Subsystem Designs Fleshed Out 46	TIF Action Items Addressed 47	Specialty Engineering 48	Wall Walks 49	Subsystem Contracts Bid 50	Review DFM, DFT, DFA 51	Wall Walks By AF/Aero 52	SDR 53	Strategy For PDR Set 54	Action Items Addressed 55	Biweekly Design Team Meetings 56	TIFs 57
RFP Released 1	X																																																								
Prgm Cost/Schedule Target Set 2	X	X		X	X							X			X											X																															
Contractor Questions about RFP 3	X	X	X	X																																																					
Derive Design Reqs from RFP 4	X		X	X	X																					X																															
AF Formulates Question Response 5			X		X																																																			
Program Administrator Chosen 6						X																																																		
Delineation Major P/L Interests 7	X			X	X		X					X	X		X		X	X								X																															
MFG and Test Analysis of Reqs 8	X		X	X	X		X	X				X	X		X		X	X								X																															
Basic Structural Envelope Set 9	X	X		X	X		X		X	X		X	X																																												
Specialty Engineering Commences 10	X	X		X			X			X	X	X	X	X	X		X	X																																							
Conceptual Subsystem Design 11	X	X		X			X	X	X	X	X	X	X	X	X		X	X																																							
Design Team Meetings 12		X		X		X	X	X	X	X	X	X	X	X	X		X	X																																							
Preliminary Story Board Dev. 13	X	X		X		X	X	X	X	X	X	X	X		X																																										
Spacecraft Configuration Set 14	X	X		X			X	X	X	X	X	X	X	X	X		X	X																																							
Preliminary Proposal Review 15	X	X		X		X							X		X																																										
Proposal Writing Begins 16	X	X		X		X	X	X		X	X	X	X	X	X	X																																									
Near Final Draft Review 17	X	X		X		X		X		X	X			X	X	X	X																																								
Design Frozen for Proposal18		X		X			X	X		X	X	X		X			X	X																																							
Final Draft Sent to Publication 19	X	X		X		X				X	X			X				X	X																																						
Proposal Submitted to AF 20	X	X		X		X	X	X		X	X			X					X	X		X	X	X																																	
Source Selection 21	X	X		X				X			X			X					X	X	X	X	X	X																																	
AF Questions Contractors 22	X	X		X			X	X		X	X			X						X	X	X																																			
Contractors Answer AF 23		X		X			X	X		X	X			X						X	X	X	X																																	
Best and Final Offer 24		X		X			X	X			X			X						X	X	X	X	X																																	
Contract Awarded 25		X		X				X												X	X	X	X	X	X																																
AF Negs Contract/Reqs Mods 26				X			X	X		X	X			X						X	X	X	X	X	X	X			X		X								X														X				
Contractor Assembles Prgm Teams 27				X			X	X		X	X										X				X		X																													
Systems Trades Studied 28				X			X	X		X	X			X						X					X	X	X	X			X	X	X	X	X	X		X																			
Critical Integration Iss Assessed 29				X			X	X		X	X			X												X	X	X	X		X	X	X	X		X		X																			
Plan of Action Developed for SRR 30				X			X				X			X												X	X	X	X	X		X		X		X																					
Test and MFG Reqs Developing 31				X			X	X		X				X												X	X	X	X		X	X	X	X	X	X		X																			
Biweekly Design Team Meetings 32				X			X			X				X													X	X	X		X	X	X			X		X																			
TIFs 33				X			X			X				X												X	X	X	X		X	X	X		X	X		X																			
Wall Walks Begin Again 34							X			X				X														X	X	X	X			X	X																						
Interfaces Issues Worked 35							X							X														X			X	X	X	X	X	X		X																			
AF, Contractor, Aero work Reqs. 36				X			X																				X		X		X	X	X	X	X	X		X																			
Subsystem Reqs Further Defined 37				X			X	X						X												X	X	X		X	X	X	X	X	X	X	X	X																			
Wall Walks By AF, Aero at Cont 38							X																							X	X			X		X	X	X																			
SRR 39				X																											X					X	X	X	X																		
Heavy Work on Interfaces Starts 40																																			X	X	X		X	X			X		X	X	X	X	X		X	X					
Action Items Worked 41																																			X	X	X		X		X		X		X	X	X	X									
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Biweekly Design Meetings 43																																				X	X			X	X	X	X		X	X	X	X		X	X	X					
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TIF Action Items Addressed 59																																																									X
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Resolve Miss/Conflict Interfaces 76																																																									
Test Reqs Continue Refinement 77																										X																															

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Designs Finalized 82																																																									
Parts Drawings Completed 83																										X																															
MFG Plan Finalized 84																																																									
Wall Walks By AF/Aero 85																																																									
Order Long Lead Items 86																																																									
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Action Items Addressed 89																																																									
IRNs for P/L Interfaces 90																																																									
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Test Plan Development 94																																																									
TIF Action Items Handled 95																																																									
Quarterly Reviews 96																																																									
Discrepancy Reports Analyzed 97																																																									
Arrange For Test and Gnd Ops Equip 98																																																									
Material Review Boards/Scrap Appr 99																																																									
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	Further ICD Development 58	TIF Action Items Addressed 59	Specialty Engineering 60	Wall Walks Resume 61	Progress of Subs Monitored 62	Test, MFG Review Design 63	First Detailed Designs 64	Wall Walks By AF/Aero 65	Maj Components Dual Sourced 66	PDR 67	ICDs Signed 68	CDR Strategy Set 69	Action Items Addressed 70	Biweekly Design Meetings 71	TIFs 72	Interface Review Notices (IRN) 73	TIF Action Items Addressed 74	IRN Drafts Reviewed 75	Resolve Mass/Conflict Interfaces 76	Test Reqs Continue Refinement 77	X-F() Teams Dev. Drawings 78	Launch Vehicle Reqs. Set 79	Begin GORD and FORD 80	Wall Walks Resume 81	Designs Finalized 82	Parts Drawings Completed 83	MFG Plan Finalized 84	Wall Walks By AF/Aero 85	Order Long Lead Items 86	Single Source Maj Components 87	CDR 88	Action Items Addressed 89	IRNs for P/L Interfaces 90	TIFs 91	Contractor QA 92	GORD/FORD Development 93	Test Plan Development 94	TIF Action Items Handled 95	Quarterly Reviews 96	Discrepancy Reports Analyzed 97	Arrange For Test and Gnd Ops Equip 98	Material Review Board/Scrap Appr 99	Test Plan Finalized 100	Arrival of Parts/Components 101	Subsystem Level Testing 102	Test Data Analysis 103	GORD/FORD Development 104	Fix/Rework 105	System Level Tests Run 106	Data Analysis 107	Fix/Rework 108	GORD/FORD Finalized 109	S/C Delivery to Launch Sites 110	On Sight Testing 111	Data Analysis 112	Fix/Rework 113	Launch 114
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Delineation Major P/L Interests 7																																																									
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Design Team Meetings 12																																																									
Preliminary Story Board Dev. 13																																																									
Spacecraft Configuration Set 14																																																									
Preliminary Proposal Review 15																																																									
Proposal Writing Begins 16																																																									
Near Final Draft Review 17																																																									
Design Frozen for Proposal18																																																									
Final Draft Sent to Publication 19																																																									
Proposal Submitted to AF 20																																																									
Source Selection 21																																																									
AF Questions Contractors 22																																																									
Contractors Answer AF 23																																																									
Best and Final Offer 24																																																									
Contract Awarded 25																															1									1						1		1					1	1	1	1	1
AF Negs Contract/Reqs Mods 26										1																																															
Contractor Assembles Prgm Teams 27																																																									
Systems Trades Studied 28																																																									
Critical Integration Iss Assessed 29																																																									
Plan of Action Developed for SRR 30																																																									
Test and MFG Reqs Developing 31																																																									
Biweekly Design Team Meetings 32																																																									
TIFs 33																																																									
Wall Walks Begin Again 34																																								1						1		1					1	1	1	1	1
Interfaces Issues Worked 35																																																									
AF, Contractor, Aero work Reqs 36																																																									
Subsystem Reqs Further Defined 37																																																									
Wall Walks By AF, Aero at Cont 38																																																									
SRR 39																																																									
Heavy Work on Interfaces Starts 40																																																									
Action Items Worked 41																																																									
SDR Strategy Set 42																																																									
Biweekly Design Meetings 43																																																									
TIFS 44																																																									
Test and MFG Plans Develop 45																																																									
Subsystem Designs Fleshed Out 46																																																									
TIF Action Items Addressed 47																																																									
Specialty Engineering 48																																																									
Wall Walks 49																																																									
Subsystem Contracts Bid 50																																																									
Review DFM, DFT, DFA 51																																																									
Wall Walks By AF/Aero 52																																																									
SDR 53																																																									
Strategy For PDR Set 54																																																									
Action Items Addressed 55	X	X	X	X	X	X	X	X	X																																																
Biweekly Design Team Meetings 56	X	X	X	X	X	X	X	X	X																																																
TIFs 57	X	X	X	X	X	X	X																																																		
Further ICD Development 58	X	X	X	X	X	X	X	X	X																																																
TIF Action Items Addressed 59		X																																																							
Specialty Engineering 60	X	X	X	X	X	X	X	X	X																																																
Wall Walks Resume 61	X		X	X		X																																																			
Progress of Subs Monitored 62		X			X	X	X		X																																																
Test, MFG Review Design 63	X	X	X	X	X	X	X	X	X																																																
First Detailed Designs 64		X	X	X	X	X	X	X	X																																																
Wall Walks By AF/Aero 65	X		X	X	X	X	X	X	X																																																
Maj Components Dual Sourced 66	X				X	X	X		X																																																
PDR 67	X		X		X	X	X	X	X	X																																															
ICDs Signed 68		X				X	X		X	X	X																																														
CDR Strategy Set 69			X						X	X	X	X	X	X	X			X	X																																						
Action Items Addressed 70			X			X	X		X	X	X	X	X	X	X	X			X																																						
Biweekly Design Meetings 71											X	X	X	X	X		X	X		X		X	X	X	X	X	X	X	X	X																											
TIFs 72							X			X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X		X											1						1		1				1	1	1	1	1
Interface Review Notices (IRN) 73									X		X		X	X	X	X	X	X	X		X	X	X		X	X		X	X	X																											
TIF Action Items Addressed 74											X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X																												
IRN Drafts Reviewed 75													X	X	X	X	X	X	X		X	X	X		X	X			X	X																											
Resolve Mass/Conflict Interfaces 76										X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X																											
Test Reqs Continue Refinement 77										X	X	X	X	X	X		X	X	X	X		X	X		X	X	X	X		X	X																										

	Further ICD Development 58	TIF Action Items Addressed 59	Specialty Engineering 60	Wall Walks Resume 61	Progress of Subs Monitored 62	Test, MFG Review Design 63	Final Detailed Designs 64	Wall Walks By AF/Aero 65	Mat Components Dual Sourced 66	PDR 67	ICDs Signed 68	CDR Strategy Set 69	Action Items Addressed 70	Biweekly Design Meetings 71	TIFs 72	Interface Review Notices (IRN) 73	TIF Action Items Addressed 74	IRN Drafts Reviewed 75	Resolve Mass/Conflict Interfaces 76	Test Reqs Continue Refinement 77	X-F() Teams Dev. Drawings 78	Launch Vehicle Reqs. Set 79	Begin GORD and FORD 80	Wall Walks Resume 81	Designs Finalized 82	Parts Drawings Completed 83	MFG Plan Finalized 84	Wall Walks By AF/Aero 85	Order Long Lead Items 86	Single Source Mfr Components 87	CDR 88
X-F() Teams Dev. Drawings 78							X			X	X		X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X
Launch Vehicle Reqs. Set 79											X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X
Begin GORD and FORD 80										X	X		X	X	X	X	X	X	X	X		X	X	X	X			X			X
Wall Walks Resume 81												X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			
Designs Finalized 82										X	X		X	X	X	X	X	X	X	X		X		X	X	X					
Parts Drawings Completed 83											X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X			
MFG Plan Finalized 84										X		X	X	X	X		X		X	X	X			X	X	X	X	X	X	X	X
Wall Walks By AF/Aero 85												X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X			X
Order Long Lead Items 86																			X		X	X	X	X	X	X	X	X	X	X	X
Single Source Mfr Components 87									X	X	X		X	X	X	X	X	X	X		X				X	X	X		X	X	X
CDR 88										X	X	X	X			X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Action Items Addressed 89																															X
IRNs for P/L Interfaces 90																		X	X						X	X					X
TIFs 91																				X		X	X				X			X	X
Contractor Quality Assurance 92																				X					X	X	X			X	X
GORD/FORD Development 93																				X		X	X								X
Test Plan Development 94																				X			X		X	X					X
TIF Action Items Handled 95																															X
Quarterly Reviews 96																															X
Discrepancy Reports Analyzed 97																															
Arrange For Test and Gnd Ops Equip 98																															
Material Review Boards/Scrap Appr 99																															
Test Plan Finalized 100																															X
Arrival of Parts/Components 101																													X	X	
Subsystem Level Testing 102																															
Test Data Analysis 103																															
GORD/FORD Development 104																															
Fix/Rework 105																															
System Level Tests Run 106																															
Data Analysis 107																															
Fix/Rework 108																															
GORD/FORD Finalized 109																															
S/C Delivery to Launch Sites 110																															
On Sight Testing 111																															
Data Analysis 112																															
Fix/Rework 113																															
Launch 114																															

	Action Items Addressed 89	IRNs for P/L Interfaces 90	TIFs 91	Contractor QA 92	GORD/FORD Development 93	Test Plan Development 94	TIF Action Items Handled 95	Quarterly Reviews 96	Discrepancy Reports Analyzed 97	Arrange For Test and Gnd Ops Equip 98	Material Review Boards/Scrap Appr 99	Test Plan Finalized 100	Arrival of Parts/Components 101	Subsystem Level Testing 102	Test Data Analysis 103	GORD/FORD Development 104	Fix/Rework 105	System Level Tests Run 106	Data Analysis 107	Fix/Rework 108	GORD/FORD Finalized 109	S/C Delivery to Launch Sites 110	On Sight Testing 111	Data Analysis 112	Fix/Rework 113	Launch 114
X-F() Teams Dev. Drawings 78																										
Launch Vehicle Reqs. Set 79																										
Begin GORD and FORD 80																										
Wall Walks Resume 81																										
Designs Finalized 82									1						1		1					1	1	1	1	1
Parts Drawings Completed 83									1						1		1					1	1	1	1	1
MFG Plan Finalized 84																										
Wall Walks By AF/Aero 85																										
Order Long Lead Items 86																										
Single Source Mfr Components 87																										
CDR 88																										
Action Items Addressed 89	X	X	X	X	X	X	X	X																		
IRNs for P/L Interfaces 90	X	X	X				X	X	X	X					1		1					1	1	1	1	1
TIFs 91	X	X	X	X	X	X	X	X	X																	
Contractor Quality Assurance 92	X		X	X		X	X	X	X	X	X	X	X	X	X											
GORD/FORD Development 93	X		X		X	X	X	X	X	X		X														
Test Plan Development 94	X		X	X	X	X	X	X		X																
TIF Action Items Handled 95	X	X	X	X	X	X	X	X	X	X		X														
Quarterly Reviews 96	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X											
Discrepancy Reports Analyzed 97				X		X			X					X	X	X			X							
Arrange For Test and Gnd Ops Equip 98										X		X		X	X											
Material Review Boards/Scrap Appr 99											X															
Test Plan Finalized 100	X		X	X	X	X	X	X				X														
Arrival of Parts/Components 101													X													
Subsystem Level Testing 102												X	X	X	X							X	X	X	X	
Test Data Analysis 103												X		X	X							X	X	X	X	
GORD/FORD Development 104					X				X	X						X						X	X	X	X	
Fix/Rework 105											X	X		X	X		X									
System Level Tests Run 106											X	X		X	X			X	X	X		X	X	X	X	
Data Analysis 107											X	X		X	X				X			X	X	X	X	
Fix/Rework 108																				X		X	X	X	X	
GORD/FORD Finalized 109																X					X					
S/C Delivery to Launch Sites 110									X	X	X	X		X	X	X						X				
On Sight Testing 111																						X	X	X	X	
Data Analysis 112																						X	X	X	X	
Fix/Rework 113																						X	X	X	X	
Launch 114																					X	X	X	X	X	X

Whereas, the DSM represents the information flow, concurrency, and complexity of the process well, it does not illustrate the relative time frames between the program phases. For instance, the *system requirements* , *system design*, and *preliminary design* phases all take place in as much or less time than the *critical design* phase. More importantly, the *fabrication*, *test*, and *launch preparation* subprocesses often take as much or more time together than does the entire rest of the spacecraft development process. The reasons for this will become more apparent in subsequent sections. Nevertheless, the DSM, for the reasons noted above, distinguishes itself as the best choice for mapping the spacecraft development process over other process mapping techniques such as flow, PERT, and IDEFO (Integrated Computer-Aided Manufacturing Definition Method) charts (Eppinger, 1994).

The information used to construct the basic flow of the DSM shown in Figure 11 comes predominantly from interviews with personnel from a defense aerospace contractor developing a space system for the Air Force, the Air Force system project office responsible for the acquisition of this system, and their counterparts at The Aerospace Corporation. The DSM contains modifications of and additions to this information that are the result of literature searches and other interviews with industry experts. These changes make this process map a general, as opposed to program specific, representation of the spacecraft development process.

2.1 Identifying "Feed-Forward" and "Feedback" Information

First, note that the left hand side and the top of the DSM contain the same list of tasks. The tasks are ordered according to their commencement in the process. Tasks that begin at the same time show up as subsequent tasks in the chart. This method of artificially ordering concurrent tasks is not a weakness of the DSM since the DSM has other ways of representing their concurrent relationship.

The presence of an "X" in any box means that the information from the task at the top of the column containing the "X" feeds information into the task listed at the left hand side of the row that the "X" also marks. A "1" represents a potential information feedback that occurs often enough in the process to be noted, but does not occur enough to be considered all the time as part of the process. Note also that the diagonal of "X's" from the upper left corner of the matrix to the bottom right corner of the matrix represents the obvious process condition that the information from each task in the process feeds into itself. "X's" below this diagonal represent "feed-forward" information flow, information from an earlier task influences a later task. "X's" above the diagonal represent "feedback" loops, information from later tasks influences the work performed in earlier tasks.

2.2 Identifying Subprocesses

The DSM also yields information about groups of tasks occurring in the process. Namely, it differentiates them as *serial, parallel*, and *concurrent*. Serial activities are a continuous series of tasks that use purely feed-forward information for the accomplishment of their goals. Figure 12 shows that Tasks 22-26 are serial.

	AF Questions Contractors 22	Contractors Answer AF 23	Best and Final Offer 24	Contract Awarded 25	AF Negs Contract/Reqs Mods 26
AF Questions Contractors 22	X				
Contractors Answer AF 23	X	X			
Best and Final Offer 24	X	X	X		
Contract Awarded 25	X	X	X	X	
AF Negs Contract/Reqs Mods 26	X	X	X	X	X

Figure 12 A Serial Subprocess

A concurrent subprocess is a group of tasks that occur roughly together in time and are very tightly linked through information feedback. These concurrent subprocesses are marked by squares drawn around the group of tasks. Figure 11 shows several of these. Finally, parallel tasks and subprocesses are those that occur roughly at the same time and use only feed-forward information in their completion; they are independent of one another. As a result, they can take place at the same time without the need for communicating with one another, i.e., in parallel.

2.3 Identifying Process Failures

The "1s" in the DSM represent program "horror stories," that is they show when information discovered "very far down the line," often as the result of a test failure, requires changes to occur in work completed much earlier. For instance, failure information obtained in Task 103, *Subsystem Test Data Analysis*, could cause the development team to realize that a certain performance criterion cannot be met with the current design. This information causes negotiation of requirements modifications between the prime contractor and the Air Force, Task 26. The modifications to information in Task 26 could, in turn, mean changes to the outputs of Tasks 29, *Critical Integration Issues Assessed*, 30, Plan of Action Developed for SRR, 31, *Test and Manufacturing Requirements Developing*, etc. Thus the DSM shows a large feedback loop can affect dramatically previously completed work. Hence, a horror story develops. Unfortunately, these horror stories occur often enough to be recorded in this spacecraft development process DSM. In part, they provide the motivation for this thesis.

The goal, however, is not to eliminate all feedback loops. Iteration through feedback is essential to producing a successful design. It is impossible to imagine achieving the correct results without some in-process evaluation of the information being produced. The goal, instead, is to achieve a greater number of small (nearer in time) feedback loops rather than a few large (more time elapsed) feedback loops. That is, avoid the feedback created by the "1s" and nurture the communication that takes place in the many, existing, concurrent subprocesses shown in Figure 11.

Many variations on the DSM notation exist.[1] Some weight the importance of information fed into a task. Algorithms can order process tasks based upon these weighting factors. Other DSMs record whether the information fed into a task is data needed to start that task, continue that task, or finish that task. Consequently, positive changes in process order are easier to identify than in the type of DSM shown in Figure 11. The primary goal of Figure 11, however, is not to change the order of tasks within Phase I as much as it is to identify symptoms of larger structural deficiencies in the spacecraft acquisition process.

3. Observations About the Spacecraft Development Process

Figure 11 shows that a series of seven concurrent subprocesses comprises the spacecraft development process: system requirements, system design, preliminary design, critical design, fabrication, test, and launch preparation. Their serial nature indicates that each of these concurrent subprocesses receives the existing information about the spacecraft and develops it to a greater level of detail. Eventually enough details exist for the fabrication and test of completed spacecraft hardware and software. These phases are consistent with the industry's model of the major steps followed during the spacecraft development process.

The ensuing subsections discuss several observations about conditions that exist or should exist but do not in the Phase I development process. The goal of these discussions are two fold. The first goal is to demonstrate the mechanics of using the DSM to make observations about a process. Second, using the DSM to observe characteristics such as large iteration loops, process concurrencies, and the lack of certain process steps, the thesis develops observations about the spacecraft development process which help to analyze more critically the entire spacecraft acquisition process and discover the reasons for program outcomes such as cost overruns, schedule delays, and performance shortfalls.

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[1]The bibliography at the end of this work lists various sources dealing with the design structure matrix (DSM). Some are more theoretical, describing the DSM's make up, origin, and potential uses. Others are more practical case examples of how different variations of the DSM helped in improving industrial practices.

3.1 The Need for Positive Organizational Relationships

The DSM suggests that, during development, good coordination of and communication between different organizations as well as excellent coordination and communication within any of these organizations must exist. For instance, Tasks 26, *Air Force Negotiates Contract and Requirements Modifications*, 36, *Air Force , Contractor, and Aerospace Work on Requirements*, 58, *Further Interface Control Document (ICD) Development*, 68, *ICDs Signed*, 73, *Interface Review Notices (IRNs)*, 96, *Quarterly Program Reviews*, 99, *Material Review Boards and Scrap Approval*, 110, *Ground Operations and Flight Operations Documents (GORD/FORD) Finalized*, 111, *Spacecraft Delivery to Launch Sites*, 115, *Launch*, as well as all of the design reviews and their planning, and the addressing of action items require that the Air Force and prime contractor work well together since they depend upon each other for the completion of these tasks. Furthermore, Task 68, *ICDs Signed*, affects among other things the refinement of test requirements, the creation spacecraft assembly drawings, the finalization of designs and parts drawings, and the single sourcing of major spacecraft components to subcontractors. All of these tasks depend on the timely and effective negotiation of the interface control documents (ICDs) and are critical to the completion of the spacecraft. The matrix structure of the DSM clearly represents these dependencies using the marking notation described in Section 2.1 of this chapter. Similar dependencies of equally vital tasks supported by information fed from accomplishment of the tasks enumerated above can be found in the same manner. The Air Force-contractor relationship is the most important of the interagency relationships. Yet, this relationship often begins to suffer as the result of conflicting goals or problems encountered during the program.

Each of the major subprocesses outlined in the Figure 11 illustrate the concurrent development activities requiring excellent communication within the prime contractor's design team. For example, Tasks 45-48, *Test and Manufacturing Plans Development, Subsystem Designs Fleshed Out, Technical Issues Forum Action Items Addressed*, and *Specialty Engineering*, which are a part of the *Preliminary Design Phase*, all require communication among technical specialists and systems engineering. One situation requiring this communication might be that the subsystem designs, when taken in total, require more power than the electrical power subsystem design provides. Study of the problem by the power group and systems engineering shows that all of the solar panels necessary to meet the added power demands cannot be added to the design without upsetting the mass properties (i.e., center of mass and moments of inertia) of the spacecraft. This conclusion requires the consultation of the Attitude Determination and Control (ADACS) subsystem group to determine whether or not they can modify their guidance system design to meet the new mass balance needs. The results of the study might yield a solution or compel allowing the present power requirements to exist. Otherwise, subsystem designers would need to make concessions on some of their power requirements. This example demonstrates that rapid and clear communication must continue among members of the spacecraft team for the mission to be accomplished. The DSM's concise representation of concurrency makes discerning the need for such relationships easier.

Good communications must also exist between the contractor and its subcontractors. The prime contractor rarely possesses all of the skills necessary to produce the entirety of equipment comprising the spacecraft. Often, the prime contractor contracts subcontractors for the production of components or even whole equipment boxes, e.g., Tasks 50, *Subsystem Contracts Bid*, and 66, *Major Components Dual Sourced*. Using a supplier requires that the subsystem specialists within the contractor communicate with the equipment box subcontractors, e.g., Tasks 64, *First Detailed Designs Developed*, 82, *Designs Finalized*, 83, *Parts Drawings Completed*, and 84, *Manufacturing Plans Finalized*. Otherwise, subcontractors lack the many size, weight, performance, cost, and schedule information needed to produce the equipment for which they are on contract. Furthermore, good communication is necessary when changes in the design occur on either side of the interface, e.g., Tasks 73, *Interface Review Notices (IRNs)*, and 75, *IRNs Reviewed*. Therefore, the contractor and the subcontractors must achieve rapid, two-way flows of communication to insure as seamless an integration of the spacecraft as possible later in the program.

The point that this subsection makes about the critical nature of good communications within and between players in spacecraft development might be considered obvious. It is noted here because the next chapter describes several structural deficiencies within the acquisition process that weaken these communication links. Therefore, showing the importance of these links is critical to justifying why conditions weakening them must be changed.

3.2 The Role of the Statement of Work (SOW) and Requirements

Most design texts speak of the importance that requirements play in the development of a new product. Nevertheless, the level of influence that the statement of work (SOW) and technical requirements document (TRD) have on spacecraft development, as demonstrated by the DSM, merits further discussion. The SOW and TRD are important for the following reasons. First, the requirements define the level of performance that the spacecraft must have in order for it to successfully complete the specified mission, Tasks 4, 26, and 36. Poorly written requirements increase the probability of difficulties later on during system development either because the requirements are unattainable, misinterpreted, or incomplete. Second, the SOW establishes the scope of the contractor's efforts. It also establishes the schedule and framework for the formal interactions (e.g., review processes, signature requirements, etc.) that must take place between the Air Force and the contractor. Agreement on the SOW means that the contractors are clear on the scope of the work that they must perform for the Air Force. Finally, the Air Force often uses the SOW and TRD to contractually bind the contractor to performing certain tests and following specified manufacturing best practices that the Air Force perceives are critical to producing a spacecraft that will successfully complete its mission.

The Air Force, however, often fails to write an effective set of requirements for the spacecraft developer.[2] Often, those writing the requirements do not judge effectively the technical feasibility of the finally TRD. Also, requirements are often stated in such a way that only one or a certain set of technologies can fill them (Fitzgerald, 1988). By specifying the use of certain technologies, requirements writers needlessly constrain industry's choices during the development process. That is not, however, to say that Congress, through its micromanagement, or contractor's, by pushing for the development of "dazzling" new technologies, do not contribute to the creation of bad or impossible requirements. One example of the effect that poorly written requirements can have on a program's outcome is described below.

The Low-Altitude Navigation Targeting Infrared for Night (LANTIRN) System

Several technical advances and tactical experiences during the 1960s and 1970s created the need for the LANTIRN system. First, the Air Force had procured a large number of single seat , F-16, aircraft. This meant that pilots were responsible for more functions in the new fighter craft than they had been in the two seat F-4s. To get the maximum results from the reduced amount of pilot attention paid to individual tasks, an improved weapons control system, making more of the targeting and firing process automatic, was required. The addition of precision, laser-guided missiles and bombs complicated the design of a new targeting and firing system further because the system had to perform the complex laser guidance functions required to target these weapons without the help of the pilot. Finally, experience during the Vietnam war showed that the Air Force was entirely incapable of nighttime precision attacks and had limited effectiveness with daytime attacks during poor weather. Thus, the Tactical Air Command (TAC) of the Air Force wrote a statement of need for a system that would "provide Tactical Air Forces with an improved 24-hour capability to acquire, track and destroy ground targets with a single seat aircraft" (Bodilly, 1993 b).

Implicit in this mission need were improvements in low-level night and poor weather navigation, nighttime and poor weather target acquisition, and display technologies. This need was translated, however, into a very specific set of design goals that proved difficult for the LANTIRN program to achieve (Bodilly, 1993 b):

- Ability of system to launch six Maverick missiles in a single pass, meaning locate, identify, and attack six targets in single pass.
  - Ability of an automatic target recognizer (ATR) to correctly identify 95 percent of military vehicles, 90 percent of tracked vehicles, and 70 percent of tanks, with a 5 percent false alarm rate.

[2]This is not to say that the Navy or Army are any better at writing specifications. Air Force appears here since it usually acts as the acquisition agent for the spacecraft serving DoD components.

- Ability of the ATR to command the Maverick missile to lock onto the target chosen by the pilot.
- Ability to follow terrain closely to avoid detection using a terrain-following CO_2 laser or radar ranger.
- Ability to bank aircraft at a 60-degree angle and still maintain target visibility.
- Ability to add advanced weapon guidance and advanced radar technology with minimal retrofitting.

Bodilly (1993 b) observes, however, that these technical requirements far exceeded the simpler operational needs statements:

> "The operational need for 24-hour-a-day capability could have been achieved without requiring the system to be able to locate, identify, and attack six targets in a single pass. To locate, identify, and attack a *single*[3] target at night or under poor weather conditions would have met the operational need and would have been a vast improvement over the capability of the F-16 and A-10."

These technical challenges were mastered eventually. While developing the technology, however, the program was restructured three times, went substantially over budget, doubled in schedule, and had performance requirements reduced from initial expectations (Bodilly, 1993 b). The final LANTIRN system provided greatly improved capabilities and created a tremendous advantage when it first became operational during the Persian Gulf War in 1991, which was more than a decade after the program's initiation. Nevertheless, whether or not all of this capability was needed, especially all at once (instead of evolving over time), is not clear. The high price of such exacting requirements, on the other hand, is.

3.3 The Relationship Between Evolutionary and Revolutionary Design

The DSM shows no clear distinction by task or process between activities which produce entirely new component or subsystem designs - revolutionary design - and activities building on previous work or modifying previously existing designs - evolutionary design. The contractor's program manager must, therefore, determine an overall program strategy that somehow balances the effort needed for both revolutionary and evolutionary design. The logical strategy, from a technical viewpoint, is to base the schedule and manpower estimates on the needs of the designers developing the entirely new designs. The other option uses optimistic estimates of revolutionary design development time and cost in establishing program cost and schedule estimates in effect using a compromise between estimates of revolutionary design and evolutionary design times to develop the program schedule.

The first strategy, although it is logical, does not produce a competitive proposal bid. Historically, budgetary pressures from DoD planners and Congress cause the Air Force to pressure the bidding contractors' program managers, during the best and final offer period of

[3] The emphasis is Bodilly's.

source selection, to reduce their proposed system cost and schedules. This pressure forces the bid team into optimistically estimating the effort necessary to make sizable leaps in spacecraft technology, but it creates a shortened schedule. Consequently, a decision to have an optimistic attitude towards development problems - wait and see and maybe everything will turn out okay - is adopted by the program. The usual result is that the program moves through the first part of the program (i.e., system requirements through much of critical design) on schedule. The program then handles the inevitable problems with the new designs in fabrication and test. The following example demonstrates the difficulties revolutionary design presents in managing highly coupled evolutionary and revolutionary design activities.

Fleet Satellite Communications System (FLTSATCOM)

In 1971, DoD initiated the FLTSATCOM program. Its aim was to provide the Navy, Air Force, and DoD "with versatile capability for communications in the UHF frequency band" (Reeves 1979). TRW won the source selection in November 1972 and became the program's prime satellite contractor. The schedule for development and completion of two demonstration and validation satellites was as shown below.

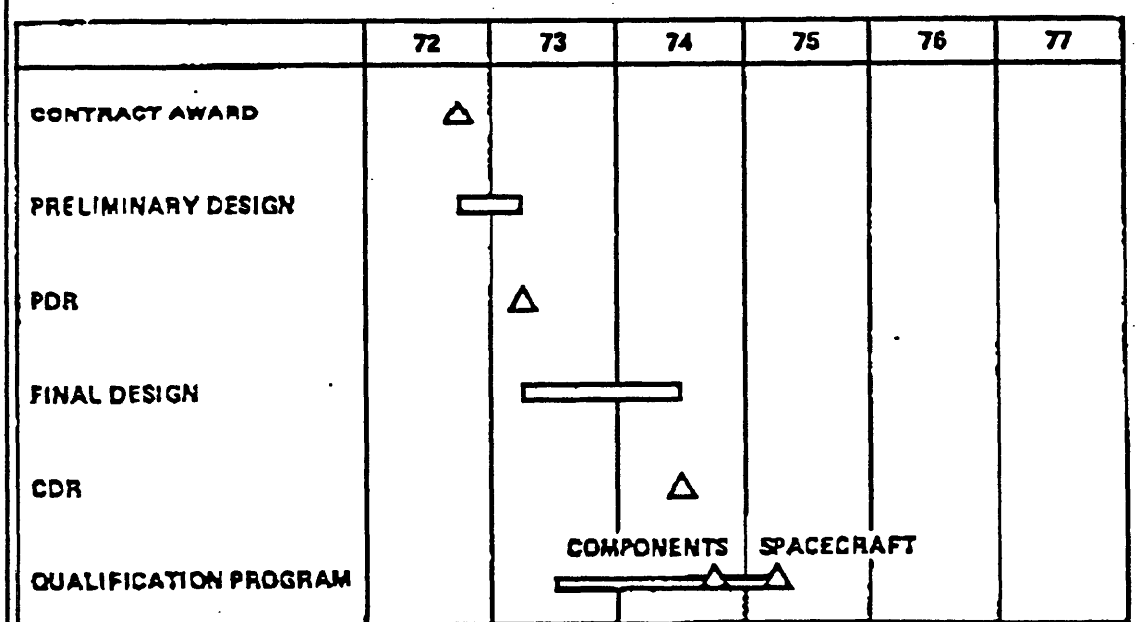

Figure 13 Schedule at Program Start (Reeves, 1979)

The schedule predicted a first launch in the middle of 1975 and a total program length of a little over 2.5 years. Reeves states that "this was a highly concurrent program and predicated on a smooth and successful development phase" (1979). The UHF payload design, however, required pushing the state of the art in electronics and antenna design. The significant development problems encountered during the design of the state of the art payload made the highly concurrent schedule unrealistic, resulting in schedule overruns for the FLTSATCOM program.

The mission required the FLTSATCOM payload to provide 22 communication channels in the UHF region (0.2 - 0.45 GHz) and one channel which used an X-band (7.9 - 8.4 GHz) uplink. One channel provided the Navy with the capabilities to broadcast to its fleets. Nine channels were used for fleet relay. The Air Force reserved the use of twelve of FLTSATCOM's channels and the remaining channel was for DoD (Reeves 1979).

The initial design called for a single antenna to carry out both the transmit and receive functions. This design was breadboarded[4] and tested during the critical design phase. Tests showed that intermodulation (linear combinations of the frequencies of multiple channels) of the signals the payload was transmitting, due to nonlinearities in the payload's electronics, created noise signals at high amplitudes within the frequency bands being used to communicate. These noise signals interfered with the payload's properly receiving transmissions from simulated earth-bound sources (e.g., ships and ground stations). Several months of work with conventional techniques for circuit noise isolation and filtering were not enough to meet the payload design requirements for the satellite's reception of signals. Finally, TRW informed the Air Force of the difficulties and several special technical teams were created at the contractor to explore different opportunities for mitigating the reception noise resulting from intermodulation (Reeves 1979).

Two months after the parallel team activities commenced, TRW had a solution that was approved by the Air Force. They had decided to decouple the transmit and receive antenna functions by incorporating a single off-axis helix antenna to handle satellite reception. This solution provided the noise isolation required and had the least predicted impact on the spacecraft's mass of all the possible design fixes. Figure 14 shows the amended FLTSATCOM design. This solution had its own adverse effects on the spacecraft design. These effects had to be corrected (Reeves 1979).

[4]Bread boarding refers to showing the basic feasibility of technologies by building lab bench versions of devices to be flown on the spacecraft.

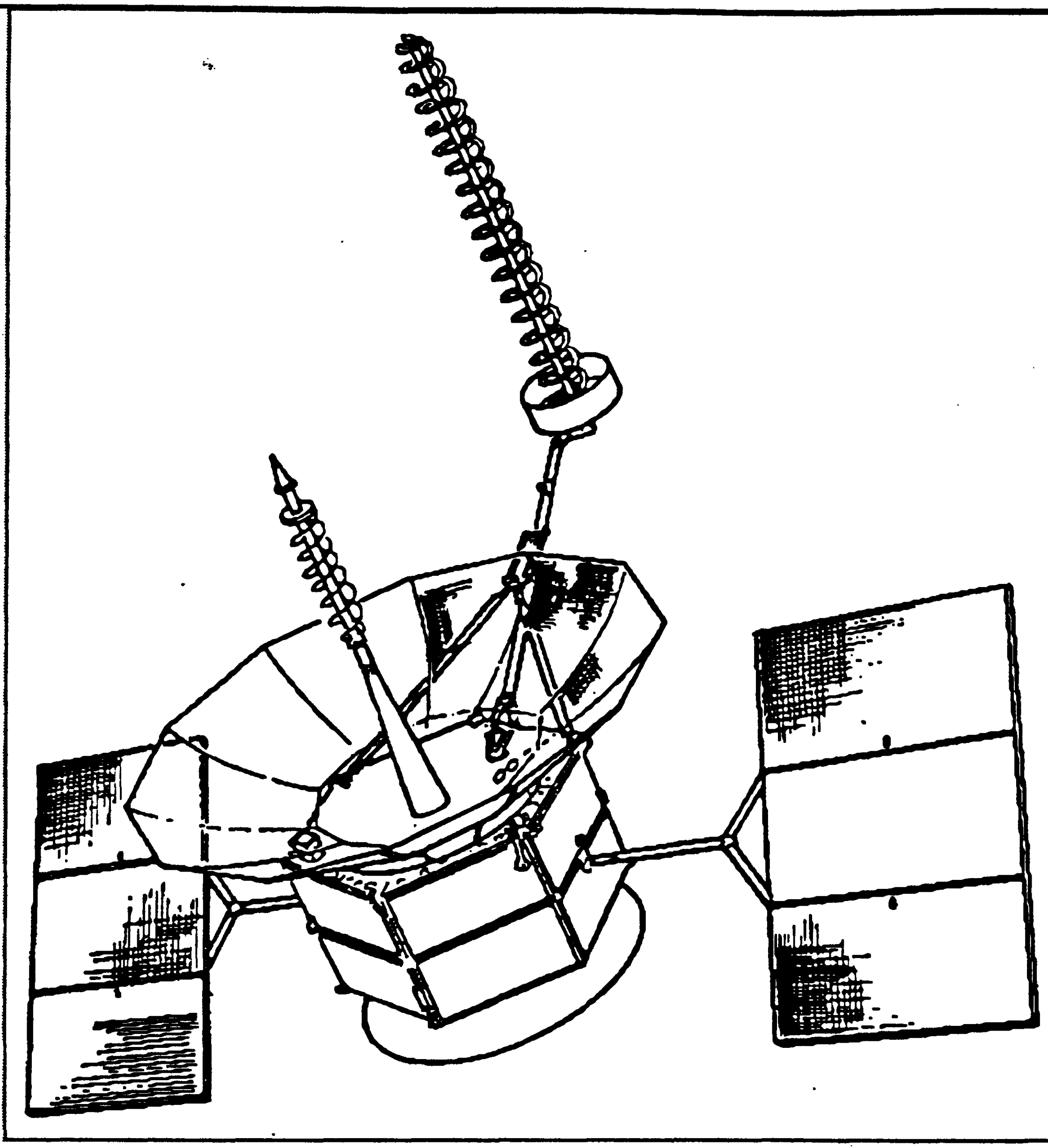

Figure 14 Amended FLTSATCOM Configuration (Reeves 1979)

The conflicts created by the new solution were of four types: (1) challenges associated with the new receive antenna, (2) the need for additional tests to measure precisely how much signal isolation was achieved with the new design, (3) effects of the new antenna on other subsystems, (4) changes in the program schedule.

The addition of a new antenna raised the mass of the spacecraft, which was already tightly constrained by program requirements. The off-axis antenna had to be stowed on launch and deployed once in space. Thus, the new antenna design required a new deployment mechanism design. A new deployment mechanism meant added mass as well as the potential for new design issues associated with its operation. Since the contractor had identified noise due to intermodulation as a problem, special testing was developed to measure noise with greater resolution that had been previously required. The program had to add a new set of tests to meet this need and then use these tests to verify the new design. Reeves also writes that "the effects of this [antenna] redesign rippled through most of the spacecraft subsystems and required considerable redesign of equipment already in advanced development state" (1979). For example, the new antenna blocked much of the field of view of two sun sensors required for the attitude control of the spacecraft. Designers had to move these sensors and modify the spacecraft's control code and dynamics accordingly.

Finally, the intermodulation problems caused a serious questioning of the feasibility of the entire program. As a result, the Air Force prohibited completion of the spacecraft until the new antenna design was built and tested. The rest of the program, now decoupled from the payload development, was delayed until TRW verified the new payload design. Following verification of the design, the demonstration and validation program continued on to a successful completion with launches in 1978 and 1979 (Reeves 1979). Figure 15 shows the actual schedule of the development program.

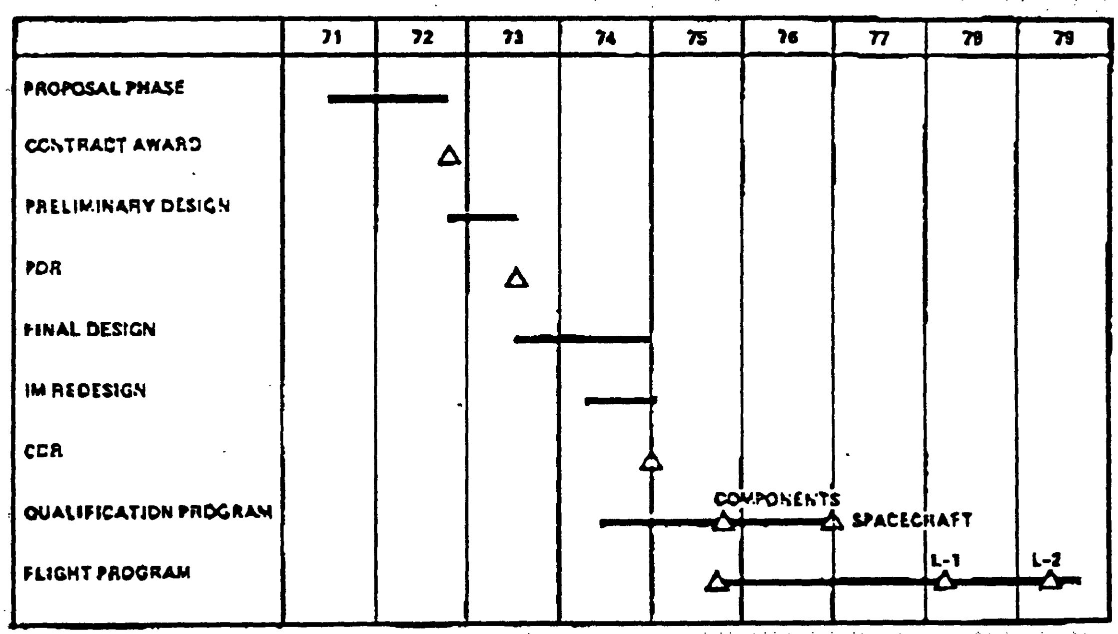

Figure 15 Final FLTSATCOM Schedule (Reeves, 1979).

In the end, the demonstration and validation program had lasted approximately 30 months longer than the original schedule had specified. This *doubled* the intended program length.

Clearly, the original schedule was in jeopardy from the moment the program assumed it could maintain a smooth development path with such a new payload design. Furthermore, tightly coupling the rest of the design development with that of the payload meant that the contractor and the Air Force lost a lot of time and money when difficulties that arose in the payload design required many changes to other spacecraft subsystems. This case history supports the notion of optimistic scheduling discussed previously. It is not alone, however. One GAO study reports that 16 of 29 space programs it studied exceeded their initial cost estimates by an average of 128.75 % in some part because of difficulties with technical complexity. Those programs were over schedule by an average of 43.5 months. None were under schedule, and 3 of those 16 programs were canceled prior to completion (GAO, 1992)..

3.4 The Role of Prototyping in Spacecraft Design

There is no explicit mention of prototyping in any of the 114 steps of the DSM in Figure 11. This does not mean that prototyping does not take place. Subsystem designers develop computer models of the various subsystems in the preliminary design and critical design phases. The FLTSATCOM example shows that functional physical prototypes are sometimes built during the critical design phase. Finally, during qualification testing, the equipment that undergoes rigorous testing is often thought of as prototype equipment. Nevertheless, the DSM does illustrates that a distinct lack of emphasis on prototyping exists.

It also turns out that the kinds of prototyping carried out by most programs neglect many issues that might affect the program. Software models can only sense those interactions that are understood and coded into the subsystem and component models. Hardware models, like in the FLTSATCOM case, are extremely helpful in capturing unintended system interactions which are detrimental to performance. Often, however, because of the naissance of the payload designs, enough information only exists for the construction of these functional models late in the design phases. By then, much of the detailed design of the rest of the spacecraft is already complete. Both software and functional models fail to identify issues arising from the final layout of components in equipment boxes. They also neglect the consideration of issues associated with the integration of these subsystems on the spacecraft. It usually takes until the fabrication and test phases, when the final design cannot be assembled or when the final design fails in one of its qualification tests, to discover these types of problems. Integration issues are especially critical in spacecraft design because designers always attempt to produce the lightest, most compact design possible.

3.5 The Subtle Influences of Source Selection Length on a Program's Future

Source selection has a very obvious effect on any program's future, namely the Air Force chooses the prime contractor for spacecraft development. Source selection may, however, have other more subtle effects on a program's future. One of these less recognized influences is the negative effects a long decision period between proposal submission and contract award in source selection can have on the program's conceptual integrity.

As described previously, sometimes it takes many months for the Air Force to decide which contractor should develop a new spacecraft. For example, Reeves records the Air Force source selection time for FLTSATCOM as approximately 6.5 months (1979). This time delay puts the contractor under a financial burden. Proposal costs are reimbursed only if the contractor wins the development contract. For this reason the contractor cannot afford to maintain the proposal team after completing the proposal, except for a few key members who participate in negotiations with the Air Force. During the waiting period between proposal submission and contract award, members of the proposal team find work on other projects already ongoing at the company. Some of the bid team personnel receive long term assignments to these other programs. Thus, when the time comes to reassemble the program team, some of its original members, having found other long term commitments at the company, cannot rejoin. The longer the wait between proposal submission and award of the contract, the more attrition there is on the program team.

The people on the proposal team are responsible for the original design concepts. If there are fewer proposal team members returning for follow-on development activities there is less program memory. This is because the short proposal window does not allow time for recording many of the decision processes that lead to the final design. Thus, the conceptual integrity of the original design concept is in jeopardy. This often results in more design changes in the period immediately following contract award. The design agreed to by the Air Force and the contractor and, more importantly, the cost and schedule associated with the original design become less relevant to the actual development process. Therefore, the period between proposal submission and contract award can have a dramatic effect on the final results of a program by influencing the composition of the development team at the contractor, which, in turn, affects the conceptual integrity of the proposed spacecraft design.

3.6 The Role of External Effects on the Demonstration and Validation Process

As described in Sections 2.1 and 2.3, the "1s" shown in the DSM of Figure 11 represent informational feedback that does not always take place. Yet, these feedback loops do take place often enough during the spacecraft development process and have a large enough effect on its outcome that they are included in the DSM. Most of these "process failures" result from discoveries of design or requirements problems late in the process, often during testing activities. For example, an equipment box fails to pass a qualification test. It may turn out that the mistake is from a fabrication error and a repair can be made fairly quickly. It may turn out, however, that the test failure is due a design that is unable to perform at the level of the requirements set for it. Therefore, a costly, both in time and money, redesign process is pursued or performance requirements are lowered. Either strategy means serious cost and schedule or performance setbacks or both to the ongoing program.

These failures usually lead to in-process fixes. For instance, if a failure in equipment is found at the system level testing activity, a new test might be added to the component level testing activity so that the program team can catch failures earlier. In the end, this test may be carried out on all future programs as well as the subsequent spacecraft in the original program. An unsatisfactory test performance due to fabrication errors may result in the writing of new requirements that attempt to regulate the component's upstream manufacturing processes. These new fabrication rules might also work their way into future programs. Finally, any failures may result in more oversight and reporting requirements since a compelling argument can be made almost always that more review might have caught the failure earlier.

Note that most of the in-process fixes applied to spacecraft development are in area of catching failures sooner by adding time and money to oversight or testing or both. This approach to achieving a final operational system is indicative of a process that does not possess a proactive approach of controlling the forces that cause error. Instead, it tries to minimize, as best as possible, the effect that errors have on the program outcome. The example of the FLTSATCOM case demonstrates that this strategy is ineffective because fixes are only created when failures occur; fixes, even when carried over to a new program, do not prevent new types of failures.

To create fixes that can be applied within a particular process, however, is a natural tendency since many of the real forces creating program cost and schedule overruns and reduced levels of performance result from the decisions made prior to Phase I, Demonstration and Validation (dem/val). Also, policy and funding decisions made at a much higher level than any particular program, have a great effect on each program's outcome. These structural flaws within the spacecraft acquisition process are beyond the prime contractor's or system project office's control. The next chapter will discuss the influence of these issues on the spacecraft development process.

4. Chapter 5 Summary and Conclusions

The DSM process map in this chapter provides an important tool for developing many important conclusions about the spacecraft development process. First, the dem/val processes are interrelated, having many concurrent development subprocesses. Within each of these subprocesses, effective, rapid, two-way communication must occur within the contractor and between the Air Force and the contractor and between the contractor and subcontractor.

Second, the extremely high level of concurrency requires a reduced level of uncertainty for each subsystem development effort, something that does not exist in many spacecraft development programs. The FLTSATCOM case demonstrates that the uncertainty introduced by revolutionary design requirements combined with the tightly coupled nature of the spacecraft development process and the complex interfaces that occur within any spacecraft can cause large technical problems late in a program. Significant schedule and cost overruns are associated with these problems.

Third, the DSM shows a need for much more study of concepts and requirements, both on paper and in the form of prototypes, prior to commencing full scale spacecraft development. The DSM shows that a poorly written set of requirements almost certainly guarantees a program full of failures and unintended iterations. The DSM also shows us that not dealing with such issues as production and integration before the test and integration process causes tremendous program difficulties.

In conclusion, Figure 11 shows a process that attempts to reduce the impact of errors rather than prevent them altogether. This strategy has only a limited effect on improving a process' outcome as measured in cost, schedule and performance. This system exists because program personnel have the leverage to create in-process fixes, whereas, they do not possess the ability to control the forces that create the conditions because of which so many process failures to exist. The next chapter shows, however, that controlling these forces and changing them is necessary to gain the leverage required for creating real change in the current acquisition and development process.

Chapter 6: Structural Deficiencies in the Spacecraft Acquisition Process

1. Introduction

Information from the previous chapters' study of the spacecraft development process indicates that there are two main structural faults in the spacecraft acquisition system: (1) the current DoD acquisition process, as applied to spacecraft, does not adequately reduce uncertainty before system design begins; (2) the players in the acquisition process often work at cross purposes creating a set of dynamic and conflicting goals which are unattainable. Problems with incomplete or poorly written requirements, the concurrency of revolutionary and evolutionary design, technical shortfalls, and cost and schedule overruns during spacecraft development are symptoms of the first structural ill. Underdeveloped lines of communication among the players in the acquisition process (e.g., between the prime contractor and the Air Force) and unreasonable performance, cost, and schedule goals result from the second of these two structural faults.

Resolution of these faults does not come from finding program specific solutions (i.e., adding more testing or more oversight) to the common, vexing programmatic issues which are symptoms of these structural ills. This is because making small changes in the process without changing the failed process' structure does not yield real change. Senge (1990) writes that the harder individuals push on a system to create change, without changing the system's structure, the more that system resists change. (The previous chapter's observations about the ineffectiveness of in-process fixes supports this assessment.). Therefore, policymakers must look to something broader than program specific fixes to find adequate solutions to problems seen in the acquisition process.

Instead, policymakers and industry leaders must find a limited set of points of leverage from which they can affect changes in all programs. Senge (1990) defines leverage as "seeing where actions and changes in structures can lead to significant, enduring improvements .... where the best results come not from large-scale efforts but from well-focused actions." Only positive changes to the structure of the acquisition system - some as the system affects the acquisition of spacecraft, and some as the system affects the acquisition of all military systems - will provide these points of leverage.

This chapter attempts to show that structural deficiencies in the reduction of risk and the generation of goals promote the programmatic instabilities and failures common to many space system development projects. It also identifies some points of leverage where changes can generate improvements in the acquisition process' outcome. Finally, this chapter discusses specific changes for each of these points of leverage which can result in better outcomes to the acquisition process. The next chapter takes a more dynamic approach by specifying an alternative process for the acquisition and development of spacecraft which diminishes or alleviates many of the symptoms of the present system's ills.

2. Increased Uncertainty Due to the Acquisition Process

The current acquisition system fails to adequately reduce risk before spacecraft development begins. There are four main reasons for this. First, the acquisition system is geared for middle to high volume production of systems, such as jet fighters or missiles. Next, methods for predicting schedule and cost tend to be inaccurate, misused, or wrongly interpreted, or some combination of the three. Furthermore, the system provides strong incentive for underestimating schedule an d cost. Third, the military spacecraft community fails to reap the benefits that cross program standardization and modular design[1] might contribute to cost and schedule reduction. Finally, conventional wisdom in the acquisition community fails to treat the role that politics play in the completion of a program like any other risk whose uncertainty can be managed. The following sections document the contribution of these factors to development uncertainty by discussing each of these issues in more detail.

2.1 Spacecraft and Middle to High Rate Production

The first major source of budget and schedule difficulties during spacecraft development is the acquisition and development process offered by the DoD 5000 series. The DoD 5000 series is a development process optimized for systems requiring middle to high volume production. That is, it assumes that production costs for the new system make up a large part if not dominate, altogether, the cost of making the new system operational. As a result of this assumption, the following three things are possible. First, the assumption of high volume production allows developers to decouple technology development and system design from one another, as is seen in the establishment of Phase I, Demonstration and Validation and Phase II, Engineering and Manufacturing Development which take place to Phase III, Production and Deployment. The second practice which assuming dominant production costs allows is the building of developmental test vehicles. This is because the cost of these vehicles is small relative to the entire program's cost and can be amortized over the large number production units of the new system. Finally, the DoD 5000 series' assumption of middle to high volume production fully expects high initial unit costs which are designed to diminish over the time of a long production run: "Low-rate initial production plans .... [should be] re-evaluated based upon: .... the relatively small number to be procured and *high unit cost*[2]" (DoDI 5000.2, 1991).

The spacecraft development process, however, does not fit this process model. This is because spacecraft, historically, have only been acquired in small volumes. Chapter 2 states that

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[1] Subsection 2.3 explains the meaning of these concepts as well as the implication of using them in the space system acquisition process.

[2] The emphasis is mine.

programs produce spacecraft in low numbers[3] with many spacecraft production runs tending to be in the range of 1 - 10 satellites, some of which are built in Phase I, Demonstration and Validation. As a result, development costs are a large part of total system development and production, and high initial unit costs never diminish. Realistically, DoDI 5000.2 recognizes that systems such as ships and satellites are different because of their low production quantities, but it does not propose a method for structuring such acquisition programs in an attempt to reduce development costs. The present acquisition system therefore is, by its own admission, created for middle to high production run systems and remains largely silent on the effective management of low production systems like satellites.

With no guidance to the contrary from the DoD 5000 series and pressures on them to keep down development and unit costs, space programs make the adjustments to the DoD 5000 series process that are observed in Chapters 3 and 4. First, these programs skimp on up front studies prior to the start of system design in order to save whatever money they can. This creates greater uncertainty as to what is feasible prior to the commencement of development activities. Then they couple technology development and system development. Chapter 5, in particular, the FLTSATCOM example, shows the schedule and budget uncertainties that this practice brings to spacecraft development process, especially if setbacks occur with the program's developmental technologies. This technical uncertainty leads to the budget, schedule, and performance difficulties that are often part of this process.

Clearly, new strategies for spacecraft development are necessary. First, the acquisition community must understand that greater up-front knowledge of technical risks is necessary prior to system development. The trade off is a simple one. Pay up front to understand and reduce technical risks or pay more later on to solve all of the development problems that arise. Specifically, Figure 16 shows one expert's estimate of the effect each phase has on the eventual life cycle cost of a space system. Note that 70% of that cost is determined by the work performed in Phase 0.

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[3]Until present, the largest number of any single spacecraft design to be fabricated is the 40 produced by Rockwell as part of the Global Positioning System (GPS) Block I and Block II. The Block I spacecraft were a series of six proto-flight models built during the Demonstration and Validation phase. Block II marked the beginning of production and allowed the Air Force to somewhat reduce its unit satellite cost because of the learning curve the contractor, Rockwell, enjoyed from building another thirty or so spacecraft. Another lower, but still "high volume", production run is the Defense Satellite Program (DSP) which will soon have launched 24 satellites of similar design since the mid 1960s.

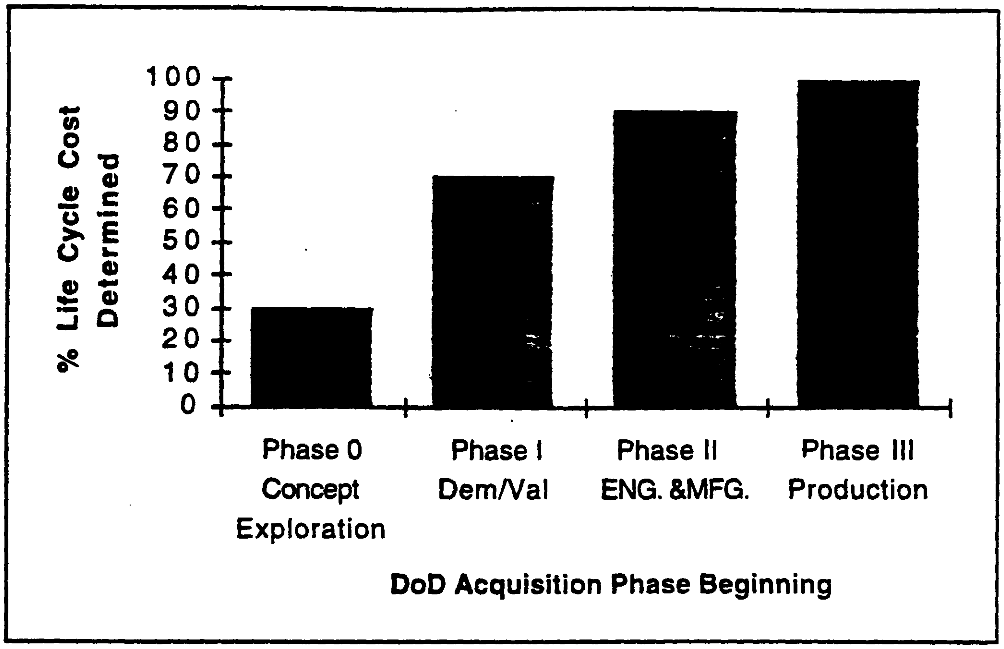

Figure 16 Percent Life Cycle Cost Determined by Phase (A^3 Study, 1983).

Early and in-depth knowledge of the effect that program requirements have on technical risk is critical since the set of specifications released to the contractor will greatly affect the program outcome. Smith and Reinertsen agree that specifications are the jumping off point for the product from which everything downstream derives itself (1991).

Specifications are so important because they determine product complexity which in turn greatly influences the schedule and cost of that project. Weak specifications often result from not understanding which are the important parameters and critical issues of the system, the specifications being weakly defined, failing to effectively verbalize crucial elements of the system, improperly assessing interactions, and not effectively balancing features, technology, and manufacturability (Smith and Reinertsen, 1991). The reasons for weak specifications therefore imply that the writers of a poor set of specifications lack the information necessary to write a feasible and complete set.

Chapter 3 shows that during Phase 0 activities DoD, typically, performs one set of design studies and iterates its requirements once or maybe twice prior to releasing the Request For Proposals (RFP) at the beginning of Phase I, Demonstration and Validation. Most flexible and iterative tools, such as cost engineering models (CEMs), do not have wide acceptance in concept exploration. Using such tools, however, would allow for much deeper exploration of the effects certain requirements have on determining the program's uncertainty. Since the Concept Exploration and Definition process is neither thorough nor very iterative, it is no wonder that the information funneled into Phase I fails to aid in the accurate prediction of the development cost or schedule for the new system. The lack of information, therefore, increases program uncertainty.

A second key to improving the development process is that some hardware prototyping also must take place before system design begins. This is because designing purely on paper can miss many important technical issues which arise later:

> "An even more costly procurement practice, which only superior management by the DoD can minimize, is the demand for ever greater weapon complexity at even greater cost. This starts with competitions that press the candidate contractors into severe "paper invention" contests. Each competitor promises to outdo the other in weapons performance and cites ever more speculative innovations, each of which adds to the complexity of the system being bid on" (Ramo, 1988).

Most successful acquisition programs, on the other hand, site prototyping as part of their reason for success (Drezner, 1992; Lorell, 1989; Larson, 1990). Yet, proposing more than just the most general prototyping strategies for a program without knowing its specifics is unwise (Drezner, 1992).

Determining an appropriate level of prototyping becomes an even more difficult issue with satellite programs. This discussion states already that other programs, such as a missile or jet fighter program, can build several test flight articles and amortize their cost with production runs of hundreds or thousands of operational units; spacecraft programs cannot. As a result, any prototyping strategy for spacecraft has to focus on building up particular components or subsystems rather than an entire flight article. Determining which subsystems to build and the relative cost effectiveness of such efforts is not an easy task for program managers, but it is necessary to successful system development (Drezner, 1992; Lorell, 1989; Larson, 1990).

Finally, the defense aerospace industry should consider the use of a more evolutionary approach to the development of spacecraft. Presently, existing space systems receive large technical updates during block upgrades (when an entirely new set of satellites are designed, built, and launched) which occur approximately once per decade. An evolutionary approach calls for smaller, but more frequent technical upgrades to systems which are fed by continuous non program specific upgrades to major payload and spacecraft technology. For example, a group in charge of researching infrared sensors could contribute to new defense weather satellites as well as new missile detection satellites. These research and development organizations would need close coordination with the different programs, but still their independence would separate technical development from the specific system development process and would have the added benefit of sharing more information on methods and techniques between programs related by certain critical technologies. Another benefit might be increased economies of scale since this evolutionary approach requires the fabrication of more spacecraft.

This evolutionary approach offers several attractive features over the current spacecraft development approach, but many questions must be answered prior to its implementation. First, with more satellites, methods for mitigating an increase in orbital debris and the filling of useful orbits with decommissioned spacecraft need to be considered. The high cost and less than desirable reliability of most launch vehicles becomes a greater concern because programs would have to launch more spacecraft more frequently. Under an evolutionary approach, new and old systems need compatibility, since multiple technical generations are likely to be orbiting at the same time. Finally, issues of how to compete contracts and maintain competition with a continuous process of upgrades need resolution. Finding solutions to these issues is beyond the scope of the work in this thesis, but that does not mean that this evolutionary policy is impossible. Rather it is a radical departure from the current method of developing spacecraft. Consequently, time must be spent gathering and analyzing the information necessary to determine whether this is a feasible and more attractive practice than the present practice of developing large block upgrades.

In summary, the present acquisition process' structure, established by the DoD 5000 series, creates uncertainty in the spacecraft development process by reducing the information on technical risks gathered prior to system design and by coupling system design and technology development. This uncertainty contributes to the common occurrence of cost and schedule overruns and performance shortfalls seen in the spacecraft development process. Part of the solution to this problem is the use of more flexible and iterative tools such as the cost engineering model (CEM) to perform concept exploration and trade studies. Also, some level of physical prototyping of critical technologies, most likely on the component or subsystem basis, is needed prior to the commencement of system design. Finally, radical approaches such as an evolutionary design process in which spacecraft technology is upgraded frequently in small steps might decouple technology and system development further while offering the added benefits of knowledge sharing across programs and increased economies of scale. More study is required, however, so that policymakers can compare these different acquisition approaches effectively.

2.2 Predicting A Program's Outcome

Poor schedule and cost performance are not entirely the result of incomplete information leading to unforeseen program difficulties. The methods used to predict schedule and cost partially contribute to the discrepancies between predicted and actual program outcomes. They are intrinsically inaccurate and often misused or wrongly interpreted. Specifically, schedule estimates use the *man-month* to measure the amount of time a task takes. The assumption behind this metric leads to erroneous initial estimates of schedule and the detrimental strategies for resolving schedule difficulties when they occur.

Several factors contribute to the inaccuracy of cost estimates. First, a cost estimate is a single best estimate derived from probability distributions of potential costs. Therefore, some variation in costs from the initial estimate should be allowed for during the development process. Furthermore, the commonly used method for developing these estimates, "roll-up costing," is mathematically invalid for summing these probability distributions, except in very specific cases. Finally, tremendous pressure to lower estimates exists during the best and final offer portion of source selection. This results in optimistic assumptions and an omission of some system costs during program cost estimation. The discussion that follows describes each of these points in more detail.

2.2.1 Predicting Schedule

A commons scheduling method used in many industries, including the defense aerospace industry, is the man-month. It provides a seemingly logical and rational way to estimate schedules by equating effort with progress. In other words, the more people that work on a project the faster it gets done. Brooks (1975), however, disagrees with this assumption: "Cost does indeed vary as the product of the number of men and the number of months. Progress does not." Brooks describes four different types of tasks to make this point: the perfectly partitionable task, the unpartitionable task, the partitionable task requiring communication, and the task with complex interrelationships. The following briefly explains each of these tasks and discusses their effects on program scheduling.

Only when a task can be partitioned among workers in such a way that no communication between them is required are workers and months interchangeable. This trade is shown in Figure 17a (Brooks, 1975).

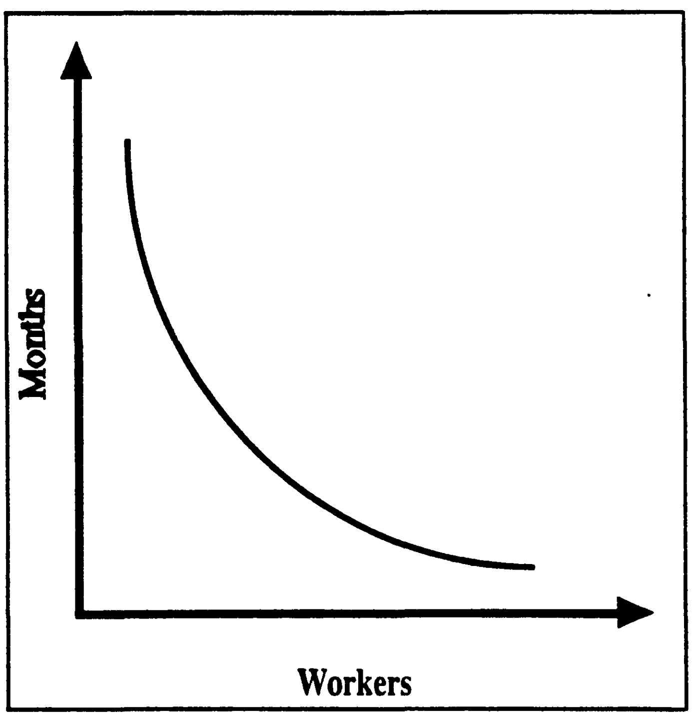

Figure 17a Time v. Number of Workers - Perfectly Partitionable Task (Brooks, 1975).

The opposite extreme occurs when a task cannot be broken up at all. This is usually the result of sequential constraints on the accomplishment of the task. Therefore, the application of more and more effort has no effect on the schedule. Figure 17b illustrates this condition (Brooks, 1975).

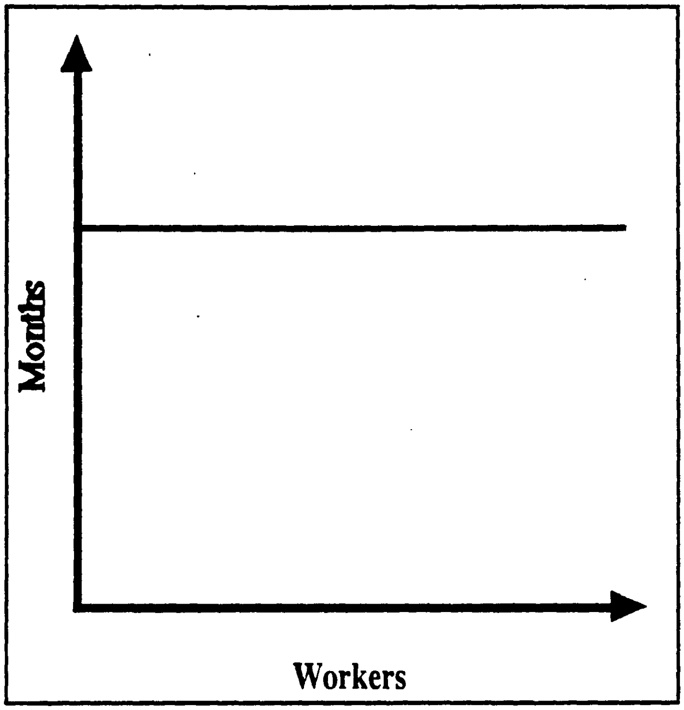

Figure 17b Time v. Number of Workers - Unpartitionable Task (Brooks, 1975)

The next two cases add communication to the accomplishment of tasks. Communication has two parts. The first is training; the second is intercommunication. Before beginning work, each worker must be informed about the technology, project goals, and the overall strategy and work plan. This added effort varies linearly with the number of workers. Intercommunication has more of a square effect on the amount of effort. That is, if each part of the task must be separately coordinated with each other part, the effort to accomplish the task increases as $n(n-1)/2$, where n is the number of tasks. If the workers on three or more tasks require conferences together, the amount of time spent communicating increases even more (Brooks, 1975). Figure 17c shows a partitionable task requiring intercommunication.

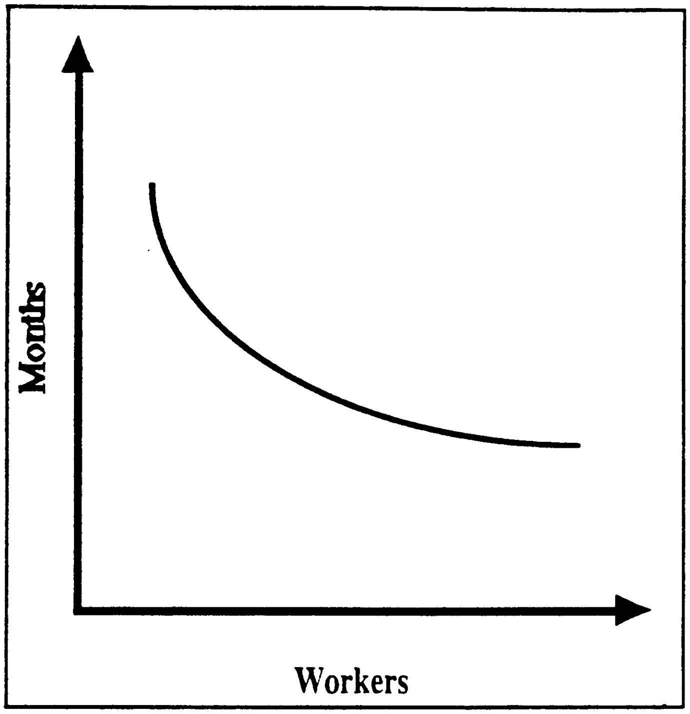

Figure 17c Time v. Number of Workers - Partitionable Task Requiring Communication (Brooks, 1975)

In a project with complex interrelationships (e.g., the spacecraft development process) communication effort quickly dominates the time spent working on the tasks as the largest component of the total effort required to complete the project (Brooks, 1975). Figure 17d shows this condition. Notice that at some point adding more people lengthens the overall time it takes to complete the project.

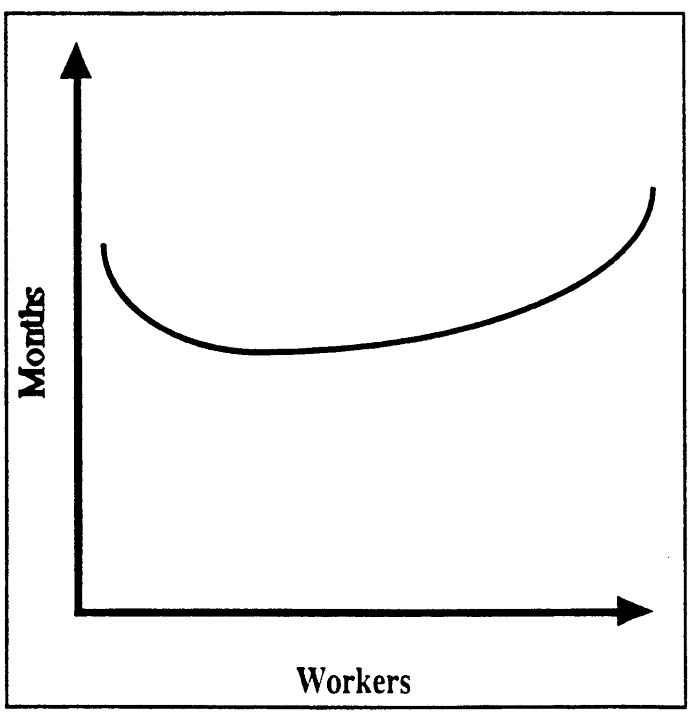

Figure 17d Time v. Number of Workers - Task With Complex Interrelationships (Brooks, 1975)

Brooks (1975) formulates his argument for explaining behavior observed in large software projects. His main conclusions from this argument, however, seem to indicate it is a plausible description of what occurs during the spacecraft development process. The first conclusion is "testing is usually the most mis-scheduled part of programming" (Brooks, 1975). The reason is that testing for and fixing mistakes is a very sequential process, i.e., testing of the hardware or software cannot continue very well until the previous problem is fixed. The introduction in the last chapter describes the major role fabrication and test play in determining the overall spacecraft development schedule. So far, then, the model seems to hold for the spacecraft development process. Brooks (1975) continues by saying that "failure to allow enough time for system test, in particular, is peculiarly disastrous. Since the delay comes at the end of the schedule, no one is aware of schedule trouble until almost the delivery date." This is very representative of the previous chapter's discussion of the wait and see attitude taken by most spacecraft development programs when determining their schedule based on the assumption that revolutionary design efforts should go as planned.

Brooks (1975) refers to his second conclusion as "regenerative schedule disaster." Since project management often discovers problems that affect the project's completion date late in the process, their typical reaction is to put more people on the task to make sure that the delivery date does not slip. At some point, however, tasks become unpartitionable (Figure 17b). After reaching this point, the project cannot be shortened any more. Furthermore, the new people must be brought up to speed on their tasks. Figure 17d shows us that, for this reason, adding more people late in the project probably ends up extending the project further than does fixing the problem with no change in project team size. Needlessly, the project takes longer, increasing costs as well. Quoting Brooks' Law: "Adding manpower to a late software project makes it later" (1975).

A Personal Experience

A spacecraft development program I observed had problems like this with several pieces of critical electronics equipment required for nominal operation on orbit. Their new chip design was lagging far behind completion of the rest of the spacecraft. Discovering the problem late in the critical design phase, the program manager redistributed program resources to focus on this newly discovered issue. Both workers and money were added to the problem area. The schedule was reassessed and lengthened accordingly. When time came for the next quarterly review, the schedule slipped further. More people and resources were added. Considering Brooks' arguments, one is left to wonder how much of the new schedule slip came from the addition of new people to the problem.

It seems then that Brooks' Law applies to spacecraft development as well. In fact, Brooks' entire analysis describes observed conditions in the spacecraft development process quite accurately. Specifically, Chapters 3, 4, and 5 show that a large amount of rapid and effective communication must take place in order to accomplish space system development tasks Therefore, the equal trade of personnel for months is not adequate in describing spacecraft development.

The attractiveness of the man-month is, however, that it allows the program manager to develop what looks to be rational estimates of the development schedule. It is more difficult to justify a schedule based on hunches, gut feelings, and "experience," even though they might yield a truer schedule estimate. Thus, the program manager uses the method that provides a justifiable, although erroneous, estimate. The pressure for lower than original bids on cost and schedule during the best and final offer period of contractor source selection makes estimates of schedule even more erroneous. Clearly, then, the industry needs two things to produce better estimates of schedule: a more accurate method for schedule prediction and incentive to estimate accurately their schedules.

Removal of the incentive for underbidding schedules can only be accomplished through reasonable cost and schedule estimates. Section 3 of this chapter has more to say about this. A more accurate scheduling method might include empirical data in the schedule determination process. For instance, the space system design team might assess the development effort required for the new system and give it a score which represents the amount of revolutionary design required for the new system. Using this score and a measure of the overall size of the development program as parameters, the design team determines a schedule based upon empirical relationships for similar past development programs. The ability to do this presently exists. Organizations such as The Aerospace Corporation are effective in developing empirical models like this since they possess the historical data and the technical expertise to interpret it. Still, both the military and industry must accept any new scheduling standards in order for them to be used. Section 3 has more to say about the relationship between industry and the military as well.

2.2.2 Estimating Cost

When deciding whether or not to approve a program, policymakers (e.g., Congressmen or members of the Defense Acquisition Board) ask for a single best estimate of cost for the new system. As the next discussion shows, the estimate they receive may not be the best indication of the eventual system cost for several reasons. First, the request for a *single* best estimate requires that the cost estimator choose a single cost from a distribution of costs which represents all of the potential system costs based on the likelihood of certain events occurring during the program. This cost distribution, or probability density function, at best, has a deviation of ±20%-50% around the mean predicted cost. Second, common mistakes by cost estimators in estimating the single best estimate further exacerbate inaccuracies in the cost estimates provided to policymakers. Finally, by demanding a single best estimate of cost, policymakers are prone to forgetting the true significance of the cost projection they receive.

Cost estimates in the defense aerospace industry are performed by using a top down costing procedure[4]. First, a work breakdown structure (WBS) is prepared listing the components of cost within a program. Figure 18 shows an example of a WBS.

[4]Methods such as activity-based costing (ABC) are not used because building most spacecraft is still a developmental effort. Therefore, the process is not well enough understood or standardized to develop accurate estimates of task time required by ABC.

0.0	Total Spacecraft Program
1.0	Space System
1.1	System-Level Costs
1.2	Space Vehicle (SV) Segment
1.2.1	SV Program Level
1.2.2	SV Prime Mission Equipment
1.2.2.1	Space Software
1.2.2.2	Space Vehicle
1.2.2.2.1	Space Vehicle Integration, Assembly, and Test
1.2.2.2.2	Payload
1.2.2.2.3	Insertion Vehicle
1.2.2.2.4	Survivability
1.2.3	Prototype Lot
1.2.4	Spare Parts
1.2.5	Technology and Producibility
1.2.6	Aerospace Ground Equipment
1.2.7	Launch Support
1.3	Engineering Change Orders (ECO)
1.4	Other Government Costs
1.5	Risk
2.0	Ground System
3.0	Launch System

Figure 18 Sample Work Breakdown Structure (WBS)

A mean and cost distribution around that mean is estimated for each of these components. Typically, the cost estimate comes from an equation that takes several technical parameters from the design of that component and uses these parameters to produce a cost estimate. For example, an electrical power subsystem's cost might be determined using the number of watts required by the satellite at the beginning and end of life, the type of batteries it uses, the efficiency of its solar arrays, and its total weight. The parametric equation is often developed from relevant empirical data of previous satellite programs.

Using these estimated distributions of cost, the estimator picks a single best estimate from each distribution and adds them to determine a final cost estimate for the whole system. Possible values to choose as estimates might include, the mean (average) cost, the median cost (50% of the cost probability is above this point and 50% is below), or the modal cost (the cost at which the probability density function peaks). Some estimators, instead, use percentiles (Book, 1993). This is called a "cost roll-up procedure" (Book, 1993).

For a normal (bell-shaped) distribution, it turns out that the mode, median, and mean are the same, and the sum of the means of a number of normal distributions is the mean of the sum of these distributions which also turns out to be bell-shaped (Drake, 1966). When the distributions are not all normal, however, or the value desired is not the mean, the roll-up procedure is no longer valid and an erroneous error is given by it (Book, 1993). Consequently, the single best estimate that the program reports many times is an erroneous estimate of the actual program cost.

The roll-up procedure often under estimates mean, median, and mode and over estimates 70th and 90th percentile costs which are often used to assess "risk dollars" (Book, 1993). Figures 19a-d show some examples of the erroneous answers produced.

Statistic	Each Input Distribution	Rolled-Up Value	Correct Value	**Over Estimate: Roll-Up Minus Correct**
Mean	266.67	1333.33	1333.33	**0.00**
Mode	200.00	1000.00	1412.50	**-412.50**
Median	255.05	1275.25	1325.90	**-50.65**
Standard Deviation	84.98	190.03	190.03	**0.00**
50th Percentile	255.05	1275.25	1325.9	**-50.65**
70th Percentile	310.26	1551.30	1429.40	**121.90**
90th Percentile	390.46	1952.30	1585.10	**367.20**

Figure 19a A Comparison of Rolled-Up v. Correct Total-Cost Statistics[5] for The Sum of Five Identical Triangular Distributions (Book, 1993)

Statistic	Each Input Distribution	Rolled-Up Value	Correct Value	**Over Estimate: Roll-Up Minus Correct**
Mean	3229.23	16146.17	16146.17	**0.00**
Mode	2540.20	12701.02	15375.00	**-2673.98**
Median	2980.96	14904.79	15817.00	**-912.21**
Standard Deviation	1345.13	3007.79	3007.79	**0.00**
50th Percentile	2980.96	14904.79	15817.00	**-912.21**
70th Percentile	3676.66	18383.30	17489.00	**894.30**
90th Percentile	4977.29	24886.43	20152.00	**4734.43**

Figure 19b A Comparison of Rolled-Up v. Correct Total-Cost Statistics for The Sum of Five Identical Lognormal Distributions (Book, 1993)

Statistic	Each Input Distribution	Rolled-Up Value	Correct Value	**Over Estimate: Roll-Up Minus Correct**
Mean	344.27	1721.35	1721.35	**0.00**
Mode	200.00	1000.00	1577.08	**-577.08**
Median	300.00	1500.00	1674.80	**-174.80**
Standard Deviation	144.27	322.60	322.60	**0.00**
50th Percentile	300.00	1500.00	1674.80	**-174.80**
70th Percentile	373.70	1868.48	1854.30	**14.18**
90th Percentile	532.19	2660.96	2169.40	**491.56**

Figure 19c A Comparison of Rolled-Up v. Correct Total-Cost Statistics for The Sum of Five Identical Exponential Distributions (Book, 1993)

Statistic	Each Input Distribution	Rolled-Up Value	Correct Value	**Over Estimate: Roll-Up Minus Correct**
Mean	300.00	1500.00	1500.00	**0.00**
Mode	NONE	NONE	NONE	**NONE**

[5] "Correct Total-Cost Statistics were determined using "Crystal Ball" software to run several hundred simulations over which the resultant probability distribution function was determined.

Median	300.00	1500.00	1500.00	**0.00**
Standard Deviation	114.47	258.20	258.20	**0.00**
50th Percentile	300.00	1500.00	1500.00	**0.00**
70th Percentile	380.00	1900.00	1900.00	**261.90**
90th Percentile	460.00	2300.00	1828.60	**471.40**

Figure 19d A Comparison of Rolled-Up v. Correct Total-Cost Statistics for The Sum of Five Identical Uniform Distributions (Book, 1993)

In fact, explicit mathematical methods for accurately adding probability distributions when they are not normal are difficult and time consuming to use. Instead, the estimator can use numerical simulations to generate an approximation of the final probability density function. The resultant distribution should be used in determining the desired values (e.g., mean, median, or mode) for a best cost estimate (Book, 1993).

At this point source selection, again, becomes a factor. Best and final offer, just like for schedule estimates, has a habit of driving down cost estimates given in the initial program proposal. If the estimate is wrong to begin with, then Figures 19a-d show that it is likely underestimated. As a result, the estimate only gets worse during best and final offer. Even if the estimate has no mistakes before source selection, it seems that the contractor's estimates following best and final offer become, at best, misleading (too low).

Another common method for lowering costs when bidding a program is to leave out mission elements in the cost estimation. For example, 11 out of 29 major NASA programs in the 1980s and 1990s lacked information such as the cost of launch services , mission operations, and data analysis in their initial cost estimates (GAO, 1992):

> "For example, the estimate for 15 years of operations and servicing costs for AXAF was not included in estimates until March, 1992 even though the program was approved for a new start in fiscal year 1989. The additional costs increased the total program estimate by $3.2 billion."

Finally, the single best estimate that the policymaker receives - if the estimate remains untainted to this point - is just that, a single best estimate. The uncertainties associated with that single estimate are easily forgotten upon transmission of the estimate. As a result, when a program goes over the cost estimated for it, policymakers panic and try to make changes that often create further cost overruns, even though the new, higher cost might be well within the bounds of the distribution that yielded the cost estimate.

It is no wonder then that programs overrun their cost estimates regularly. First, the best estimates have a moderate level of uncertainty (a deviation of 20%-50% of the mean cost) associated with them. Second, estimates are often erroneously computed, and, even if the estimate is computed correctly, cost pressures can force the estimate lower. Finally, the estimate's uncertain roots are forgotten by the policymaker who demands the single best estimate for program cost. Together these factors work to create what is an unstable and often unreliable estimate of eventual program cost.

The first three subsections discuss of Chapter 6 Section 3 discusses ways in which reasonable cost goals might be set, thereby reducing the pressure on contractors and the Air Force to submit unreasonably low bids on program cost. Second, cost estimators must correct their practice of roll-up costing and use more accurate methods such as simulation. Also, the entire acquisition community must understand and accept the inherent nature of uncertainty in cost estimation in order for them to abandon the idea of the single best estimate of cost. Finally, the next section discusses how the concepts of modularity and standardization might help to reduce some of the uncertainty in cost estimation. In the end, all of the methods for improving cost estimates already exist, but the acquisition community needs to become aware of them and accept them for the future output of the cost estimation process to improve.

2.3 Modularity and Standardization

The military satellite community fails to use two design principles that, together, might provide significant reductions in space system development costs - standardization and modularity. Component standardization presents the opportunity for achieving economies of scale in spacecraft component procurement. Some studies show that modularity and standardization, together, may also reduce the cost of spacecraft integration and test. Furthermore, modularity and standardization have the added benefit of reducing design, integration, test, schedule, and cost uncertainties. There are, however, penalties to be paid resulting from the costs associated with weight and size inefficiencies that standardization and modularity create. Prior to discussing the benefits and penalties of standardization and modularity, this section demonstrates how these concepts can be implemented in the spacecraft development process.

Modularity[6] as a concept is straight forward. Breakdown a spacecraft's functions into a set of modules, design and assemble the components that comprise the modules, and integrate the modules. Designers specify each module, then, by its form (dimensions), fit (interfaces), and function (performance criteria). Waltz (1993) describes it another way:

> Each module or submodule (equipment group) is an assembly of equipment specified and verified as a complete entity, and has:
>
> •Well-defined electrical, mechanical, data-processing and thermal functional characteristics

[6]The concept of modularity in spacecraft is almost as old as the space program. Its roots are in two particular ideas, first, an early 1960s proposal for a modular space station, and, second, the Multimission Modular Spacecraft (MMS) developed by NASA during the 1970s. The modular space station never received serious consideration, but the MMS was used to fly space missions such as the Solar Maximum Mission(SMM) and Landsat (Martens, 1990).

> •Simple, standardized physical interfaces to other equipment (ideally the electrical interface is bus power and digital signals only, no RF)
> •The capability to be manufactured and to undergo functional acceptance and qualification testing as an independent entity
> •Its own configured item specification, interface control documents (ICD), testable performance requirements, drawings, verification and validation program, and customer buy-off procedures
>
> In addition, it may have a common, stand-alone structure and may also be thermally isolated if these structures are weight- and cost-effective.

The concept of standardization applies to many different levels of system design. It might include standardizing the interfaces between modules, standardizing the modules, standardizing components within the modules, or standardizing the spacecraft's interfaces with the launch vehicle and ground systems.

Using the principles of modularity and standardization a set of "foundation hardware[7] " can be built. Foundation hardware is the equipment used over and over in spacecraft regardless of the specific mission. One study identifies six subsystems and nine components as especially good candidates for this kind of standardization. The subsystems are communications and data handling, structure, attitude control, electric power, thermal, and propulsion. The components are batteries, power control unit, inertial reference unit, reaction wheel, Earth sensor, Sun sensor, magnetic-torquer, thruster, and fuel and pressurant tanks (Waltz, 1993). These candidates represent much of the spacecraft bus which is defined in Chapter 2 as everything on the spacecraft except the payload equipment.

Modularity offers many of its advantages to cost and schedule during spacecraft integration and test. First, assembly and test crew time are reduced by performing operations in parallel and testing at lower assembly levels. Second, delays due to faulty equipment are greatly reduced because modules and specific pieces of equipment can be removed and replaced with a working replacement. As mentioned previously, flawed designs, production process difficulties, integration and assembly issues, and difficulties with harnessing new technologies come to a head all at the same time during fabrication, integration, and test causing huge snarls, right when the most resources are being devoted to the program. One estimate is that being able to rapidly substitute good equipment for faulty equipment would reduce by more than half the time lost due to these test failures (Waltz, 1993). Next, performance and interface issues arise earlier, before they become schedule pacing problems. Finally, delays due to late hardware and software can be reduced by using engineering model and brassboard simulators and modules as place holders during the early parts of payload/spacecraft integration. This also yields interesting opportunities

[7]The term "foundation hardware" is adapted from the software world. Foundation *software* is the result of separating out a particular application's generic functions so that they might be used over and over in other applications requiring similar functions (Best, 1990). The definition of foundation hardware is similar to this.

for early prototyping. Figure 20 shows one estimate produced by TRW of how reduced integration and test time, due to modularity, would reduce cost and schedule over the present way of doing business.

		Classical Flow		Modular Flow	
Number of Satellites		**4**	**8**	**4**	**8**
Schedule Comparisons					
Scheduled Assembly and Test Time	[Wks]	2 X 41	4 X 41	2 X 41	4 X 41
Average Lost Time Due To Equipment Failures	[Wks]	25	56	12	24
Total Assembly and Test Time Per Program	[Wks]	**110**	**220**	**54**	**108**
Cost Comparisons					
Total Scheduled Assembly and Test Costs	($M)	30.7	47.5	27.9	36.7
Assembly and Test Crew Cost for Lost Time	($M)	2.8	5.6	1.2	2.4
Total Assembly and Test Cost Per Program	($M)	**33.5**	**53.1**	**29.1**	**39.1**
Other Program Time-Related Costs	($M)	44.0	88.0	21.6	43.2
Total Program Cost During Assembly and Test Phase	($M)	**77.5**	**141.1**	**50.7**	**82.3**
	(Saved)	**(0)**	**(0)**	**(-35%)**	**(-42%)**

Figure 20 Relative program schedules and costs during assembly and test phase (satellites assembled two at a time) (Waltz, 1993).

Modularity also raises costs in some ways. Development costs for modular designs might be more than for optimized designs since they have to be able to meet a variety of programs' needs. Also, program managers are likely to have to pay for extra performance margins as well as increased size and mass. These penalties, however, are alleviated through standardization. Standardization of parts allows the hardware developers to defray development costs over many programs, thereby producing lower unit costs for hardware.

Standardization of interfaces, modules, and components also reduces cost and schedule uncertainty. Reusing designs saves the amount of new development time needed for each program. This reduces uncertainty as to whether or not development will go well. It also allows the program to focus on the program specific uncertainties that remain. Standardization also means that the cost estimators can determine the cost of a particular subsystem much more accurately, as well as the schedule for getting it built and integrated.

Table 13 shows that, as it is, very few contractors compete for the business of developing spacecraft subsystem components. Again, combining a strategy of physical, thermal, data, and electrical interface standardization (i.e., form, fit, and function standards) with that of component design standardization and modularity would allow for the creation of "parts bins" of rapidly interchangeable components, thereby increasing part quality and industry competitiveness. Also, with the form, fit, and function of major components established, new companies might be able to compete for business because they would not need to have a contract with a program prior to initiating component development. This is because they could design their products to be readily substitutable into all existing programs, which would further increase competition and reduce component cost.

Component	Maker(s)
Reaction Wheels	Honeywell Bendix
Space Data Processors	Honeywell IBM Harris
Earth Sensors	Barnes Ithaco
Solar Cells	ASEC SpectraLabs
Batteries	Eagle-Pitcher Hughes
Sun Sensors	Adcole
Thrusters	Marquart Rocket Research
Gyroscopes	Honeywell Bendix

Table 13[8] Common spacecraft components and their suppliers.

Modularity aids in the insertion of new technology once standards are set. Knowing how its designs must interface with the "outside world", a component producer can create new designs with improved performance using its own research and development funds. This is because the vendor has a fairly clear grasp of what form, fit, and function specifications it must meet so as to have a marketable design.

The use modularity along with design and interface standardization presents many opportunities for reducing program cost, schedule, and uncertainty. Not only is there an opportunity to greatly amortize design costs on an industry wide basis for the first time in the defense aerospace industry, a very real opportunity for the reduction of spacecraft development time exists. At least one aerospace contractor, Hughes Aircraft Company, has been very successful in reducing spacecraft development time and cost through the use of standardized spacecraft buses onto which it places a variety of communications payloads. Finally, by reducing the amount of development required for any particular program, each program can focus on reducing the uncertainty that remains specific to their program.

2.4 Politics As a Source of Uncertainty

Another major source of uncertainty in the acquisition process, whose management is often neglected, is politics. A program must navigate inter- and intra-service rivalries, the upper echelons of the DoD, and receive funding approval from Congress in order for it to get off the

[8]This table was developed from research and discussions with subsystem experts at The Aerospace Corporation.

ground. For it to be completed, the program must withstand yearly Congressional budget tests and excessive scrutiny whenever technical problems arise. Dr. Brenda Forman, a long-time Congressional staffer, now a political consultant for the defense contractor Lockheed Martin, says, "High-tech, high-budget, high-visibility programs are far more than engineering challenges; they are political battles of the first magnitude .... Politics is a determining design factor in today's high-tech engineering" (1993). Eric Larson of RAND concurs. He categorizes the political process as a set of external risks which are "non-technical in nature, and affects the stability of a program's course, as well as its outcome" (1990).

It is safe to say that many within the acquisition system, program managers, high-level service officers, DoD planners, and defense contractors recognize that politics play a strong role in the success of a program. Nevertheless, very few of these leaders build into their programs strategies for handling political uncertainty like they do strategies for handling technical uncertainty. According to Forman (1993), however, "In addition to the highest engineering skills, the successful design engineer must have an intimate understanding of this [political] process. The alternative is to be blindsided by political events and, worse yet, not to comprehend why."

The following discussion describes three methods for managing political risk. The first method is for program managers to use a simple set of heuristics throughout a program to evaluate the program's propensity and preparedness for political difficulties. The second is to adopt specific program practices and management tools dedicated to the management of political uncertainty. Finally, a program can also perform contingency engineering to prepare plans for different political eventualities. Using these tools program managers can reduce the amount of risk they face during their program's completion.

Heuristics for Reducing Political Uncertainty - "The Facts of Life"

Throughout a program's duration, program managers think about "The Facts of Life" when making key technical, cost, and schedule decisions. "The Facts of Life" are (Forman, 1993):

- Politics, not technology, sets the limits of what technology is allowed to achieve.
- Cost Rules.
- A strong coherent constituency is essential.
- Technical problems become political problems.
- The best engineering solutions are not necessarily the best political solutions.

The first two facts of life go hand-in-hand. Technology is, usually, only limited by the amount of money that is spent to develop it. If a particular technology costs too much it is not developed. Through politics funding levels are set. Therefore, without the political wherewithal to get the necessary funding, a program eventually implodes under its own budgetary pressures, even without experiencing technical difficulties. A large part of that political wherewithal is having a strong coherent constituency of supporters in the Armed Services, the Pentagon, Congress, and the White House. These are the groups that propose and approve the budgets that fund programs. A successful program then has a power base within each of these organizations and uses them wisely in fending off political attacks from those who are not convinced of the program's need or feasibility.

Political attacks often result from technical difficulties experienced by a program. Whether or not these technical problems are as bad as they are portrayed to be, they, most often, initiate bitter Congressional battles between supporters and critics of the program. This is the reason why Forman states that "technical problems become political problems." Political problems also arise when engineering goals do not match political ones. In the end politics determine a program's outcome. This means that the most viable engineering solution offered may not be the best, technically; instead, it is the one that is technically sound and meets political needs.

Tools for Managing Political Uncertainty

Certain practices and engineering tools, when adopted early in a program, facilitate the management of political uncertainty. One example of such a tool is from the Tomahawk Cruise Missile program.

Design-To-Cost (DTC) in the Tomahawk Cruise Missile Program

In the early 1970s DoD and the Congress established the Tomahawk Cruise Missile program. Its objective was to develop a family of long-range ship, submarine, air, and ground launched guided missiles for strategic (nuclear) and conventional purposes. Because the Tomahawk program had a set of wide ranging goals and had a large affect on two services, the Navy and the Air Force, DoD established a joint project office (JPO) with a Navy project manager and an Air Force deputy (Larson, 1990). This was the first part of managing political uncertainty. A joint project office with Navy and Air Force leadership meant that both services would be more likely to aid the successful completion of the program.

The Tomahawk program also took a different approach to setting requirements for the program. Larson reports that previous weapons programs were defined in terms of absolute performance objectives unconstrained, especially, by cost. This approach to requirements definition had given "gold-plated" weapon systems "almost mythic status .... in the litany of programmatic sins of interest to Congress" (Larson, 1990). Therefore, if this program was going to be a success, the Tomahawk project managers would have to demonstrate to Congress that their program was, somehow, different. Their approach was to trade off requirements using a two dimensional optimization of performance v. cost. Furthermore, they constrained their problem by setting a minimum acceptable level of performance and an upper bound on performance if it was affordable. The methodology they used was referred to as Design-To-Cost (DTC) (Larson, 1990). Larson (1990) says, "It should be clear that DTC, in seeking to minimize cost while preserving performance, was clearly an effort to manage external risk, by focusing management (and the Tomahawk's patrons) on system cost."

The DTC methodology was quite straight forward. The project office began by establishing a set of evaluation criteria for the development of the system. These criteria were then used to identify the effectiveness of the program's plans and progress. For instance, Larson reported that "during full-scale development the focus was on a *producible* [9]Tomahawk (including the selection of materials), manufacturing processes, application of MilSpec, electromagnetic pulse shielding, and similar areas" (1990). General Dynamics, the contractor, implemented a step by step procedure which was used for rigorous "trade studies" throughout the program. They helped the subcontractors establish DTC methods, as well. This approach turned out to be quite successful (Larson, 1990).

DTC was a success for the following reasons, (Larson, 1990):

- established and defined cost targets;
- made current costs available to all decisionmakers;
- used targets as principal design parameters;
- tracked and fed back updated predicted costs;
- used manage-to-cost by setting further year costs; and
- used manufacture-to-cost by collecting actual costs and monitoring trends.

In other words, DTC was successful because it established a clear set of goals, agreed to by all parties, that could be monitored by and regularly updated for policymakers at all levels. By accommodating their patron's (i.e., DoD and Congress) needs, the Tomahawk project suffered relatively little political upheaval even though it took approximately ten years of production to reach unit cost targets (Larson, 1990). The DTC approach also helped with technical development by creating a method by which all critical program decisions could be judged in a single, effective manner.

Contingency Engineering

A final method for managing political risk is through contingency engineering. The politically astute project perceives when their program might be subjected to serious changes in funding or objectives. Consequently, they plan ahead and develop contingency plans in order to quickly react to these changes if they come to fruition. One tool discussed earlier which would be a great help in contingency engineering is a cost engineering model (CEM). Very quickly, because all of the interactions between technical parameters and cost are already linked, the CEM analyzes changes in specific technical requirements or funding profiles. Instead of being paralyzed when changes occur, the adept program can rapidly and effectively adapt. This ability to adapt is essential to survival.

[9]This emphasis is Larson's.

Mentioned several times in this thesis are the detrimental effects that the political process can have on defense system acquisition. The last section demonstrates, contrary to what many believe, that the program does have some ways of managing political risks. Using Forman's "The Facts of Life," program managers can remind themselves how important political awareness is and assess their programs preparedness and propensity for political risk. By implementing engineering methodologies which take into account and more clearly define its patrons' desires, the program can avoid many political obstacles. The Design-To-Cost example above demonstrates this. Finally, when politics do force program change, the proactive program already has contingency plans for quick, effective reaction which increase the program's chance of survival.

2.5 Summary of Sources of Uncertainty

Section 2 identifies four major sources of uncertainty in the spacecraft acquisition and development process: very low production volumes, inaccurate, flawed, or underdeveloped cost and schedule estimation methods, a lack of modularity and standardization in space system design, and not recognizing politics as a manageable risk. After the definition of each source of uncertainty there is a justification for why that issue is a source of great uncertainty and then some discussion of how uncertainty might be reduced. Table 14 lists each of these sources of uncertainty, a justification for why they create uncertainty, and possible aids to fixing the problems that exist.

Source	Justification	Potential Solutions
Low Production Volumes	•Uncertain development costs become a large part of program costs (i.e., development costs cannot be amortized) •Revolutionary and evolutionary design are coupled in the development process •Fewer decision points and less information exist before committing much of the program's funding	•Develop much more information before key funding decisions (e.g., develop a CEM and a series of design meetings as opposed to performing one set of design studies) •Establish a process with greater intermediate results which do not require full system development in order to accurately determine system feasibility and cost •Decouple technical development from system development as DoD 5000 intends
Estimation Techniques	•Scheduling techniques assume all will go well •Scheduling techniques equate effort with progress •Single best estimate for cost "forgets" that cost estimates are uncertain •Common errors exist in cost estimating techniques	•Revamp industry estimating techniques focusing on: -Empirical Data -Simulation -Standardization and Modularity -Realism -Shared Knowledge -Shared Responsibility
Non-use of Modularity and Standardization	•Modularity improves ease of integration and test •Modularity allows for technology substitution •Standardization reduces design risks •Standardization increases economies of scale	•Create standardized interfaces •Create standard "parts bins" for common components •Enforce the use of standardization across programs •Explore the use of standardized spacecraft architectures
Politics	•Yearly funding approval necessary from Congress •Inter- and Intra-service rivalries	•Programs need to be politically aware •Develop preventative engineering tools (e.g., design-to-cost) •Develop program contingencies prior to changes in the program occurring (e.g., answer if-what questions by using the CEM)

Table 14 Summary of Major Sources of Uncertainty, Justification, and Potential Solutions

3. Shared Vision in Spacecraft Acquisition and Development

An equally important, if not more important, issue than the uncertainty in spacecraft development caused by the current way of doing business is the lack of shared vision or goals the exists among the major players in the acquisition process. This includes DoD, Congress, the Air Force and the defense industrial base. Senge (1990) argues that "one is hard pressed to think of any organization that has sustained some measure of greatness in the absence of goals, values, and missions that become deeply shared throughout the organization" (1990). Government experience with acquisition, having had very little shared vision, reflects this statement having had many difficulties in acquiring its defense systems throughout the history of the United States. There are three main reasons why shared vision is so critical to the acquisition process: (1) shared vision is required to accomplish any future reform in spacecraft acquisition; (2) the government must determine long range strategies for the acquisition of systems for the future defense of the country; (3) shared vision is necessary for reducing the adversarial relationships that exist within government and between government and the defense industrial base.

Shared vision is required to accomplish any future reform in spacecraft acquisition. An Office of Technology Assessment (OTA) report states that "future efforts to reform the acquisition system will require broad-based support within the DoD if they are to succeed" (1992). Arguably, this "broad-based support" must extend beyond DoD to other sectors of government since it is shown that DoD does not entirely control acquisition regulations or what takes place during the acquisition process. Chapter 2's discussion of the players in the acquisition system shows that both the Office of Management and Budget (OMB), through acquisition regulation A-109, and the Congress through various public laws also set rules of the acquisition process. Therefore shared governmental vision about defense and acquisition is necessary to reform the acquisition process.

Another reason why shared vision is critical is that the government must determine long range strategies for the acquisition of systems for the future defense of the country. The recent reduction in defense budgets are only likely to continue since most of the present threats facing our country are of a regional, non-nuclear nature (e.g., The Persian Gulf War and the on-going Yugoslavian civil war). Smaller budgets require greater increases in efficiency. This means that DoD cannot waste money fully or, even, partially developing systems that do not meet potential future needs. A strategy must be mapped out specifying the types of acquisition programs that will take place in the future to meet our force structure needs. Policymakers, deciding whether or not to fund a program or its particular acquisition strategy, can then compare that program against the overall strategy of United States in foreign military affairs and determine whether or not the proposed program will improve our defensive capabilities. Without a strategy, these decisions cannot be made in any coherent fashion.

Furthermore, for that strategy to have any credence it must have broad-based support, or elements not subscribing to it might require the performance of work that does not further the set strategic goals. For instance, a DoD plan not supported by Congress has limited influence because Congress makes the final program funding decisions. Also, the defense industrial base might waste their own, internal development resources in areas that do no bolster the long range plans of the United States by trying to sell programs it thinks are worthwhile. Thus, a shared vision is critical to setting long term strategic goals around which acquisition can be planned and carried out most efficiently.

Finally, shared vision is necessary for reducing the adversarial relationships that exist within government and between government and the defense industrial base. A 1988 DoD report notes that there exist "deeply ingrained adversarial relationships between Government and industry" and that these adversarial relationships "undermine industrial efficiency, responsiveness, and technological innovation" (DoD, 1988). Government and industry relations must also be improved if concepts like standardization and modularity are ever to be implemented. First, organizational isolation must be broken down in order to effectively implement and enforce interface and part standardization and modular design across individual space programs. Since they produce the actual hardware and software, defense contractors must agree to implement standards and produce the actual components if standardization is ever to take hold. Presently, however, shared vision does not exist within the defense community:

> "A corporation knows what its goal is: to make money. The government has no pre-determined goal, no 'bottom line.' Instead, its function is to decide what its goal should be by resolving all wildly conflicting goals and interests of this huge, various and cantankerous nation" (Forman, 1993).

Also, any existing goals shift rapidly due to the constant turnover in public office, as this most recent House of Representatives election shows.

To say what the right shared vision is may not be as important, necessarily, as determining how to frame the process of creating a shared vision. Understanding how to think about the basics of what their shared vision should be, policymakers might make a wrong policy decision, but it would, at least, be a consistent one and one that they could learn from in order to create a stronger vision. Also, correctly framing the vision decision process might also aid policymakers in creating the correct shared vision.

In summary, there are two pieces to the shared vision decision - how to acquire new systems and what new systems to acquire. The five tradeoffs below are listed to help frame the government's shared vision towards how it acquires systems. Similar lists of tradeoffs must be made in other areas, such as strategy to defend against threats, in order to decide what to acquire. There are the five tradeoffs to be make when defining how the government should acquire systems:

(1)Cost and Schedule v. Performance
(2)Up-front Costs v. Back-end Costs
(3)Minimizing Yearly Outlays v. Life Cycle Cost Outlays
(4)Micromanagement v. Efficiency
(5)Centralization v. Compartmentalization

The ensuing sections explain each tradeoff and comment on what some of the correct decisions are.

3.1 Cost and Schedule v. Performance

Presently, most upper-level policymakers judge a program's success along three dimensions. They are cost, schedule, and performance. Congress, especially, fails to recognize that the three must be traded off against one another. Instead, they believe that through concurrency and heavy oversight, programs can be brought in on time, within budget and at the performance that is required. The fact of the matter is that large increases in performance mean higher costs and longer schedules. The more time spent trying to achieve unreasonable cost and schedule goals, the higher the cost and the longer the schedule actually get.

These tradeoffs might be represented as a set of two dimensional situations. The first relationship to consider is that of actual program cost v. the planned program schedule for a given level of desired performance. Larson notes that "after controlling for the size of the project,[10] shortened development periods tended to be associated with greater cost growth, supporting the hypothesis that concurrent development strategies tended to cause the cost of a weapon system to be higher than strategies that used a sequential development approach" (1990). Figure 21a characterizes this relationship. Arguably, if the planned program schedule is stretched out too far, the program cost also rises over the optimal, minimum cost because the program expends extra resources to maintain staffs and facilities longer than might be necessary with a somewhat shorter schedule. This explains the tailing back up of cost at the right of the figure.

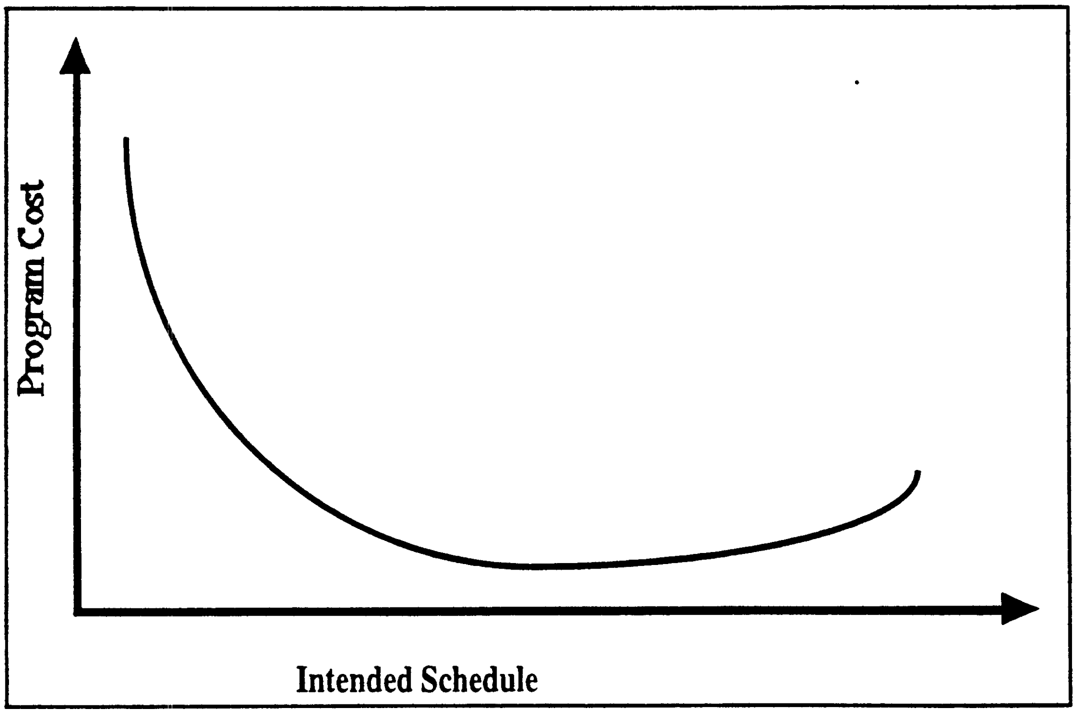

Figure 21a Total Program Cost v. Intended Schedule for Fixed Level of Performance

The second tradeoff to consider is program cost v. the desired level of performance for a fixed schedule. Numerous discussions and examples in this thesis argue that achieving a greater amount of performance per unit time requires greater concurrency between technical development and system design, and that greater concurrency creates higher costs for a program. to Figure 21b

10"Size of the project" refers to the level of development required. The level of development depends on technical risk and program size. For example, a highly risky development project for a major system would be a large project.

shows this relationship. Remember that money like effort does not necessarily equate with progress. In the end, only so much performance can be achieved in a specified amount of time no matter how much money is spent. (The example at the end of this section helps to make this last point clearer.) Yet, in some reasonable region it is realistic that more funding means more progress.

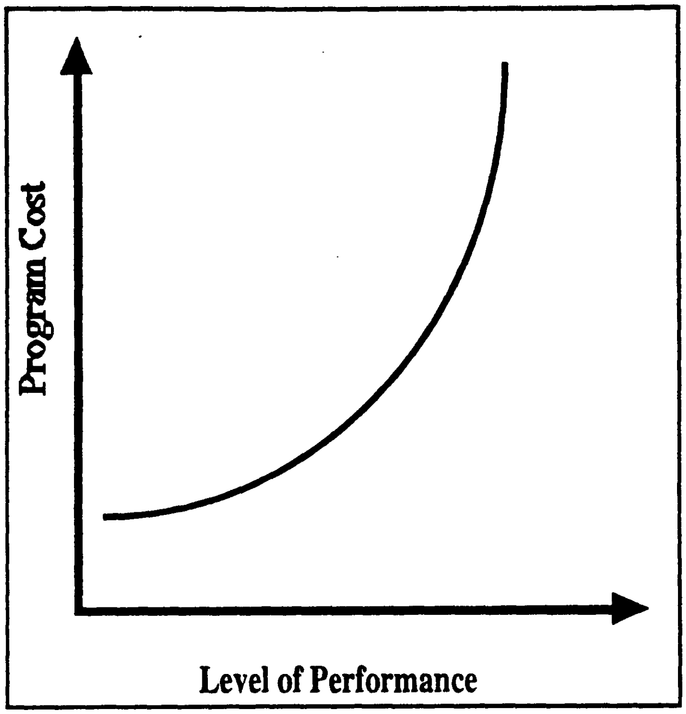

Figure 21b Total Program Cost v. Performance for Fixed Schedule

Figure 21c shows the other relationship of interest. That is, *actual* schedule length has only a limited effect of the performance of a system when expenditures are fixed. Most of the extra performance gained is from money saved because a longer schedule reduces the level of concurrency needed. Less concurrency reduces the amount of resources wasted on redesigning evolutionary components when developmental technology changes revolutionary components. Overly long schedules, however, decrease performance because more money must be spent on maintaining program critical personnel and facilities and cannot be devoted to development activities.

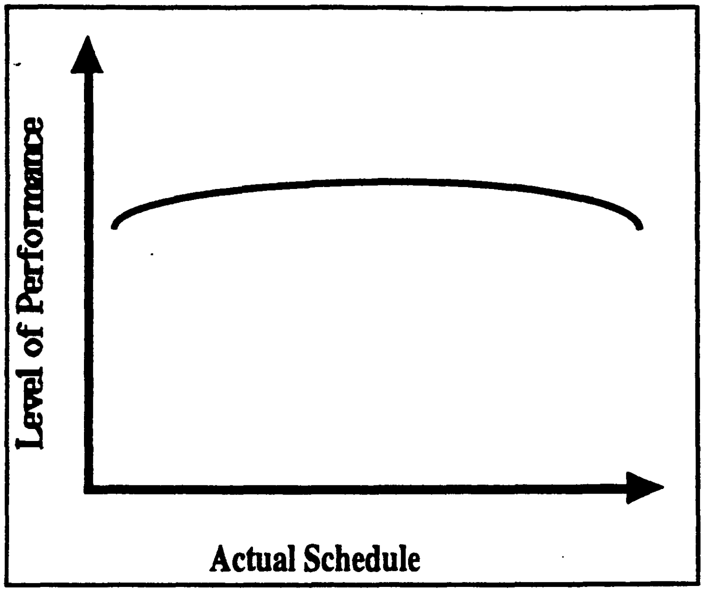

Figure 21c Performance v. *Actual* Schedule for Fixed Program Cost.

The example below shows what happens to performance when schedule and expenditures are both limited.

The B1-B Bomber Program

The B1-B bomber was the first bomber acquisition program in over 30 years to produce new bombers for the Air Force. Seen as an extension to the B1-A bomber program, which was canceled by President Carter in favor of a stealth, or advanced technology (ATB), bomber, the B1-B program was sold as a low risk program by the Reagan administration, the Air Force and the B1-A's prime contractor, Rockwell. Furthermore, the B1-B was touted as only filling an interim roll between the retirement of the B-52 as America's strategic bomber and the completion of the ATB which was slated for the mid 1990s. Finally the political climate at the time made approval of the B1-B a logical decision for both parties of Congress who wanted to appear strong on defense (Bodilly, 1993 a).

Congress approved the program by December, 1981. They imposed three conditions, however, which affected the program. First, they stipulated that an initial operational capability (IOC) date of 1987 had to be achieved. This meant that fifteen of the eventual 100 B1-Bs had to be completely ready for service by the end of 1987. Congress established this date to make sure that the bomber was not late in fulfilling its interim roll. Otherwise, an increased threat from the Soviets might have arisen, and, more importantly, a late B1-B meant that money would have been wasted because the newer ATB would have been closer to being in service without a B-1B ever having flown. The second restriction was that of total program cost. Congress prohibited total program cost from exceeding $20.5 billion in 1981 dollars. Last, President Reagan had to guarantee personally, in writing, that the program would produce the specified number of bombers, 100, within all deadlines and dollar caps. He did so and the program was born. Bodilly (1993 a) reports that these political "horse-trades" at such high-levels of government greatly constrained the Air Force system project office (SPO) and what it could do in managing the actual development program: "The only unconstrained area was performance. The program could always meet the budget and schedule constraints by not meeting performance goals. That is in fact what occurred."

The B1-B was not a low risk program. Certain technical problems with the B1-A design such as problems with movements in the swept wings, roll control, fuel leaks, vibrations in the weapons bay doors, and false alarms in the central control avionics systems had never been solved. Furthermore, the cost of the defensive electronics portion of the design which allowed the bomber crew to electronically baffle the enemy's air defense weapons had doubled in cost and fallen behind program schedule prior to the B1-A's cancellation. Compounding the technical problems was the addition of even greater performance requirements on the B1-B, like increased weapons capacity, the ability to fly at lower altitudes, and the quality of being one hundred times stealthier than the B-52. The B1-A by contrast had only to be ten times stealthier. Finally, in order to save the mark up on parts that usually arose from having a prime integrator, the Air Force assumed the role of integration from Rockwell which was made responsible only for the air frame under the B1-B program (Bodilly, 1993 a).

In the end, the budget and schedule targets were met, but the performance targets were not. The Air Force eventually lowered the capabilities it required of the electronic countermeasures with which it was having so much trouble. The terrain-following equipment for low-level flight was delivered with significant restrictions on performance. In November 1988, the B1-B was cleared to fly at its lowest altitude of 200 feet but only during daylight, in good weather, and over flat and rolling terrain. During wartime, that restriction was to be lifted, but higher risks were inherent with nighttime flights over rocky terrain at which the electronics were not adequately proficient. Also, the electronic countermeasures could not be run at the same time as the terrain-following equipment because they interfered with one another. This was quite a blow to performance since both were needed at the same time in order for the bomber to have any hope of fulfilling its mission of low-level nuclear bombing raids in areas under the protection of advanced Soviet air defenses. Follow-on upgrades to the electronics equipment were proposed for an additional cost, but as of 1990 Congress had not approved the funding (Bodilly, 1993 a).

By limiting cost and schedule, Congress and the president left only one dimension of freedom available to the actual program managers for managing risk. That was the bomber's performance. The high level of program risk and strict cost and schedule requirements forced the program to limit the performance that they would achieve prior to delivery of the new system.

The discussion above demonstrates that major system developers cannot achieve considerable increases in performance without having to give in the areas of schedule and cost. Yet, overwhelming emphasis on both low cost and high system performance is prevalent throughout the acquisition community. Acquisition officials must be realistic in their assessments of trades between performance and cost and schedule if circumstances are ever to improve from the present.

3.2 Up-front Costs v. Back-end Costs

Previous discussions raise the issue of up-front costs v. back-end costs many times. The decision is whether the government is willing to spend more resources in earlier program phases, such as during Concept Exploration and Definition, with the objective of these earlier outlays being to gain more control over technical risks before committing to total system development. The answer, seemingly, should be that Congress should spend more up-front money to reduce cost growth later in the program. Many times this thesis argues that combining the development of revolutionary and evolutionary technology leads to cost and schedule overruns that are the result having to control the new technology and redesign other components to accommodate changes in this less developed technology. This outcome is evident in the FLTSATCOM case. Also, authors such as Lorrel and Larson agree that clear separation of program phasing (i.e., avoidance of concurrency) aids in managing the risk of large-scale development programs (Lorrel, 1989; Larson, 1990). Much real program data seems to support the argument of spending resources up-front to mitigate program risk.

Nevertheless, if the acquisition community decides to maintain its historical approach of reduced up-front program funding, it should not be surprised when cost and schedule overruns occur later in programs. By consciously recognizing and agreeing that spending less up-front means greater costs at the end of the program, the entirety of the acquisition community must be willing to accept more responsibility for program debacles when they occur. More optimistically, the action of consensus building on this tradeoff decision might force the acquisition community to clarify and change its thinking by mitigating technical risk through greater up-front program funding.

3.3 Minimizing Yearly Outlays v. Minimizing Program Acquisition Costs

When determining a system design and acquisition plan, program mangers try to establish a system that will have the lowest overall life cycle costs. This means considering the system's cost of operation and maintenance as well as its acquisition cost. The DoD's five year budgeting strategy encourages this also. The budgeting strategy requires the leadership for all programs to list out five year's worth of program expenditures, including the previous and present spending years and the next three year's projections. This way a program plans out its expenses and the DoD can cover these in its budget requests. The government as a whole, however, approves funding yearly, i.e., Congress appropriates what the government can afford in the present year. Forman substantiates this by saying, "Overall life-cycle economies of scale repeatedly will be sacrificed in favor of slower acquisitions and program stretchouts because these require lower yearly appropriations, even if they cause higher unit costs and greater overall program expense" (1993).

The differing opinions over this issue must be brought together into a single approach.[11] Minimizing yearly outlays often means changes in program objectives and schedules because budget constraints change from year to year. These changes cost money. Former Secretary of Defense Richard Cheney writes that "the complexity and lack of coordination in the congressional defense process increases program costs by more than half a billion dollars and causes instability in planning" (OTA, 1992). An earlier review of cost estimation for new technologies concludes that "approximately one-half of cost growth [from that expected at the program's initiation] was blamed on scope changes (changes in program objectives after the start of development)" (Larson, 1990). It seems clear then that making multi-year commitments would be the best for achieving the lowest overall cost for each system. Nevertheless, even if the acquisition community establishes the goal to minimize yearly outlays matters would be better than they are now. Program managers would at least know to focus their acquisition strategy and system design on minimizing yearly expenditures. Knowing what to expect, even if the expectation is unpleasant, is much better than not knowing at all because there is time to plan for it.

3.4 Micromanagement v. Efficiency

The earlier description of the acquisition players describes the strong role that Congress plays in managing day to day acquisition activities. This micromanagement comes in the form heavy reporting requirements established by Congress on an individual program as well as a defense-wide basis. Also, a separate level of regulations for acquisition reside in the DoD. The level of micromanagement that currently exists is neither efficient nor good for the development of shared interests and goals among the defense players.

Figure 22 illustrates the effect that regulation presently has on program costs. From an economic viewpoint, at least, there is an excessive level of regulation that exists. A counter argument says, however, that the American public might prefer to pay more for detailed management of program activities than they would by allowing the few corrupt players in the

[11] Interestingly enough, attempts to balance long term savings goals and yearly savings goals might contribute to the acquisition community's inclination towards reducing up-front costs in exchange for higher back-end costs. The idea is this. In trying to reduce overall program costs, Congress limits up-front spending on studies and technology exploration not realizing that this will create higher costs later. When higher costs arise later on, the program is forced to increase its expected yearly outlays. Congress reacts strongly to escalating costs and orders greater oversight, and, as a result, even more money is spent. So by naively trying to control total expenditures by limiting up-front expenditures, Congress ends up creating a higher overall cost and higher yearly outlays at the end of the program.

system get away with making profits off taxpayer money (OTA, 1992). This might be true, but micromanagement may even have a more insidious result than cost escalation.

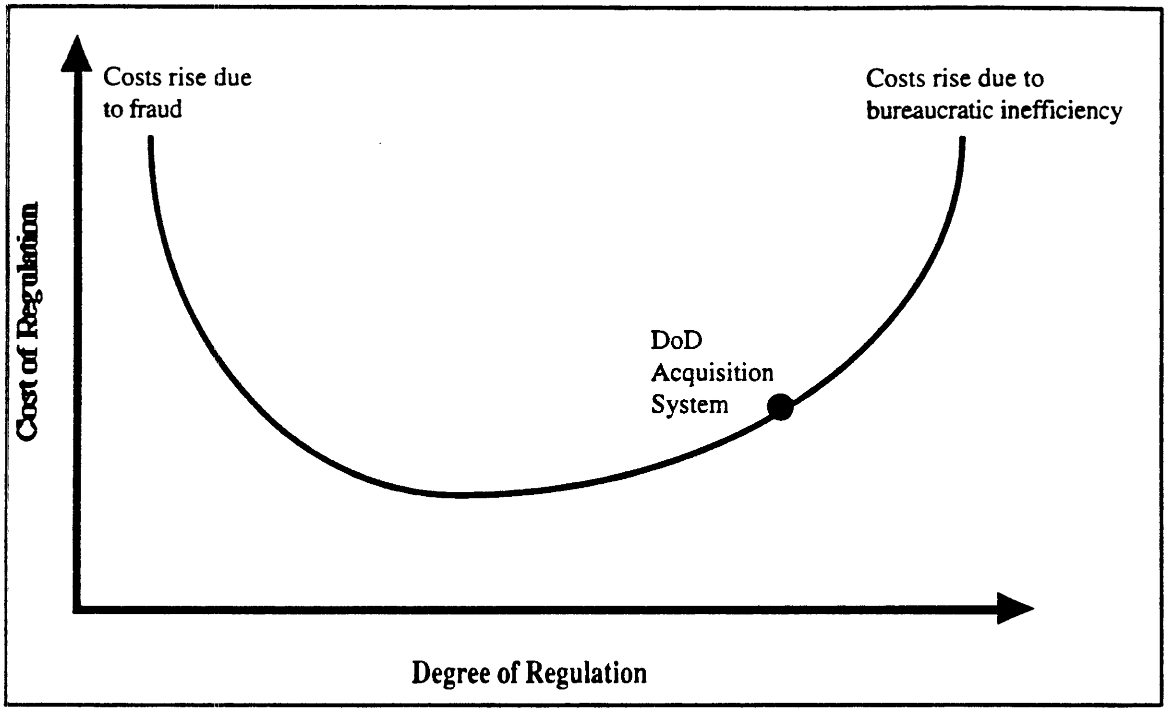

Figure 22 Program Cost v. Regulatory Intensity (OTA, 1992)

Figure 23 shows a mental model for the eroding level of trust among the players of the acquisition process that result from overwhelming micromanagement. Congress, often times, embellishes stories about hundred dollar hammers and thousand dollar toilette seats by not appropriately understanding or explaining to the American public the intricacies in the acquisition process that lead to many of these high costs.[12] Instead, by promising and implementing "reform-minded legislation," members of Congress gain political support from their constituency, most of whom do not understand the acquisition process. These stories also create distrust of the military, creating pressure to reduce the defense budget even further. These politics also create a blame game where each player in the acquisition process no longer trusts the other (Fox, 1988). Adelman and Augustine (1990) note DoD also plays a role in this when upper-level officials attempt to show that they are tough on corruption by mis-informing the American public in the same way. This blame game also clouds the acquisition community's view of the acquisition system. As a result, the players continually pass the blame around, instead of seeing the real structural flaws that exist within the system, thus never accomplishing real change.

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[12]Before disagreeing with this statement read Fox' section on the "Hidden Costs of Micromanagement" in his book *The Defense Management Challenge*. For an even better description of erroneous reports of overcharging by defense contractors, read Adelman's and Norman Augustine's first myth of defense acquisition in *The Defense Revolution: Strategy for a Brave New World*. Both sources are cited in the reference section at the end of the thesis.

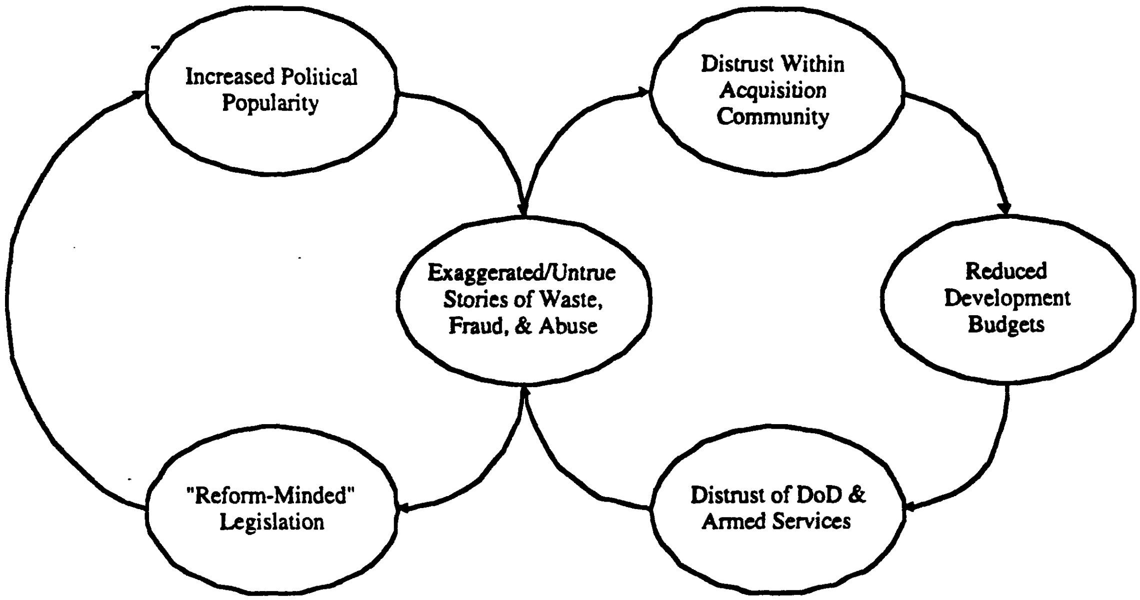

Figure 23 The Politics of Micromanagement in Eroding Trust in the Acquisition Process

Without being able to trust each other, players in the acquisition process will never be able to achieve a shared vision. Therefore, it seems that micromanagement stands in the way of the creation of shared vision. With defense budgets being strained as they are in the mid 1990s, greater efficiency is also a very good argument for reducing process micromanagement.

3.5 Centralization v. Compartmentalization

Centralization has several advantages over the traditional de-centralized compartmentalization of activities that exists in the defense acquisition process. They include improved efficiency, a reduced goal setting structure, easier administration, and greater retention of knowledge. Centralization also has some potential disadvantages such as less oversight and the chance of reduced innovation. Centralization also faces strong opposition from those in the acquisition community who face losing power in the space acquisition process (*Aerospace Daily*, 1994). This section describes two different types of centralization and uses an example to demonstrate these concepts. It also proposes a centralized space acquisition organization and concludes by discussing some of the issues members of the acquisition community raise in opposition of centralization.

Centralization of activities and decision making control is the logical alternative to the present system of stovepipes. There are two types of centralization. One is the centralization of roles. The other is centralization of organizations. One strategy for centralizing roles is to allow the President to set the overall space strategy, Congress to set the level of effort (i.e., the budget), and DoD to work out the details and execute policies (OTA, 1992). Furthermore, the role of acquiring a certain type of system might be given to one service alone. For example, the Air

Force might be put entirely in charge of acquiring space systems. This does not mean that the Navy or Army cannot have a space presence, it just means that these services would use the Air Force to acquire systems for it. Research and development activities might also be organized by tapping only one organization to carry out a particular type of research. Centralization of roles means that one organization, not many, fills a particular role in the acquisition process.

Organizational centralization means an end to completely separating the activities of one program from the activities of all other programs. One idea, for example, is to have a single space acquisition office which handles the acquisition of all space systems instead of the present system of having an individual program office for each space system. At least one precedent exists for this in the Air Force.

The Propulsion SPO

The late 1960s and early 1970s had seen great strides made in military aircraft engines. Pratt and Whitney had developed a fighter engine so powerful that the Air Force's fighters, for the first time in history, had a thrust to weight ratio of greater than one. General Electric was responsible for engine designs that paved the way for strategic bombers to achieve supersonic speeds also for the first time in history. These developments, however, came at great expense not only by being over budget, but by producing engine designs that were difficult to manufacture and maintain. This made these engines expensive to develop, expensive to produce, and as important, expensive to use. These problems had to be solved before the Air Force could not afford to fly its squadrons. In 1977 the Air Force created a single propulsion SPO as a focal point for solving these problems (Camm, 1993). The Air Force's propulsion SPO was a consolidation of all of the ongoing engine programs in the Aeronautical System's Division. Yet, Camm maintains that the SPO had a common vision: (1) bring better empirical data to bear on engine development; (2) take advantage of new formal methods for assessing risks associated with durability and supportability of engines; (3) field engines only after developers had demonstrated and verified the engines were sufficiently durable, operable, and supportable (1993).

There were two key contributors to the accomplishment of these goals. The first contributor was the SPO's use of a matrix organization of experienced and knowledgeable personnel. Much of the SPO's management was civilian. Camm states that this civilian management "brought with them a clear understanding of the reasons the SPO had been organized .... They sought fundamental changes in the Air Force's approach to engine durability, operability and supportability" (1993). This management staff helped to create stability while the SPO saw four commanders move through its organization in less than a decade. Although the SPO managers were already very experienced in engine development, they wanted that experience to grow further and to cross pollinate among the different programs. As a result, the matrix structure shown in Figure 24 arose. It adapted over time as needs changed.

Programs / Functions	Tactical Engines	Strategic Engines	Airlift and Trainer Engines	New Engines
Commander's Office	X	X	X	X
Management Operations	X	X	X	X
Program Control	X	X	X	X
Acquisition Support	X	X	X	X
Contracting	X	X	X	X
Manufacturing & Quality Assurance	X	X	X	X
Propulsion Logistics	X	X	X	X
Engineering	X	X	X	X

Figure 24 Matrix Structure of the Propulsion SPO

The matrix structure used functional offices to accumulate expertise for application to all programs. The program offices employed functional department personnel to handle specific engineering tasks. The SPO established program offices to maintain program unity (Camm, 1993).

The second key to the successful organization was the use of a set of efficient, formal procedures and tools for managing engine development programs and interagency relationships. These methods were of both technical and managerial. The SPO adopted and developed a four step development process to replace the two step engine development process employed during the 1960s and early 1970s. It had two major differences. It significantly reduced concurrency between development and production; durability became a cornerstone of operational capability. The SPO also established programs that focused on aspects of particular concern. For example, the Engine Structural Integrity Program (ENSIP), took a new approach to durability. It recognized that all components would eventually fail[13], and therefore there was a great need to develop methods to explore failure modes, consequences of failures, and maintenance procedures that could prevent catastrophic failures. On the management side, the SPO adopted a standard set of internal and independent reviews and operating procedures for ongoing program activities that promoted communication and learning (Camm, 1993).

The matrix organization combined with these standard procedures and frameworks provided many benefits to the SPO. Goals were clear and consistent across programs. Consistent goals helped to create stable acquisition programs. Internal reviews within the matrix organization allowed personnel from different programs to share technical and contractor experiences, creating a large experience base from which all SPO personnel could draw. Standard reviews and procedures also helped to manage relationships with organizations, such as

[13]This may sound like an obvious conclusion, but Camm says that up until that time designers implicitly assumed that components could be designed so that they would not fail (1993).

the Arnold Engineering Development Center (AEDC) and the Flight Test Center (AFFTC), that were outside of the SPO's control but critical to the SPO's operation. Independent reviews and standard reporting procedures also helped to manage political risks. Camm writes:

> "The SPO worked hard to prevent the development of rumors that could magnify routine difficulties out of proportion. This approach is reflected in the SPO commander's weekly activity reports to the ASD commander. These reports gave [an important program] disproportionate attention and often provided minutely detailed coverage of problems and efforts to resolve them from one week to the next. These reports also make clear that frequent communication of important information on problems was common."

Finally, this organization was able to accomplish creative and flexible solutions when large technical problems did occur. Much of this ability was the result of experience, standard procedures, and good communication (Camm, 1993).

The propulsion SPO was successful because it found a way to centralize and preserve information and experience. This allowed personnel to greatly advance the development of standardized processes and tools for managing both technical and political risk in aircraft engine development. The wealth of experience, clear lines of communication, and standard operating procedures also gave the SPO great creativity and flexibility to effectively manage technical failure. As a result, the Air Force was able to meet its goals of durability, operability, and supportability while staying on budget and schedule (Camm, 1993).

Several entities out of which a centralized space organization might arise already exist, namely the Air Force Space and Missile Command (SMC), The Aerospace Corporation, and the Air Force Phillips Laboratories. SMC presently manages space system acquisition through a series of program offices located at the Los Angeles Air Force Base. The Aerospace Corporation (Aerospace), a federally funded research and development center (FFRDC), offers the kind of civilian longevity and knowledge retention that was critical to the Air Force's Propulsion SPO. Aerospace is located at the Los Angeles and Kirtland Air Force Bases. Philips Labs, also located at Kirtland Air Force Base in Albuquerque, New Mexico already performs a significant amount of research and development on space system technology.

Although the organizations already exist, their structures have to change. SMC needs to abandon its purely stovepipe program office organization and become a matrix organization. Aerospace might have to sacrifice some of its impartiality and become more tightly coupled with government space acquisition efforts. Instead of performing basic research or generic research, Philips Labs would work much harder at meeting near-term program needs. The three groups might create a matrix organization which looks like the one in Figure 25.

Functions		Programs				
		Surveillance & Observation	Communications	Navigation	Experimental	Classified
Technical Development	Terrestrial R&D	X	X	X	X	X
	Payload R&D	X	X	X	X	X
	Spacecraft R&D	X	X	X	X	X
	Launch System R&D	X	X	X	X	X
Space System Development	Mission Architecture	X	X	X	X	X
	Systems Engineering	X	X	X	X	X
	Detailed Engineering	X	X	X	X	X
	Manufacturing	X	X	X	X	X
	Integration, Test, and Assembly	X	X	X	X	X
	Launch Activities	X	X	X	X	X
	Operations & Support	X	X	X	X	X
	Low Cost Engineering	X	X	X	X	X
Management Activities	Acquisition Management	X	X	X	X	X
	Contractor/Subcontractor Sourcing & Strategy	X	X	X	X	X
	Long-term Goals and Needs	X	X	X	X	X
	Low Cost Management	X	X	X	X	X

Figure 25 A New, Centralized Space System Acquisition Organization

The new organization has three parts. The Technical Development component focuses on the development of payload, spacecraft, launch system, and ground system technologies. The Space System Development group works with contractors and the Technology Development portion of the acquisition organization to integrate new technologies into new systems or upgrades for existing systems. Finally, the Management Activities portion sets acquisition strategies, monitors program progress, and facilitates user-developer and intra-governmental communication (including the management of political risk). Each system has a dedicated program office which might be part of larger multi-program offices for similar types of systems (e.g., a multi-program office for surveillance and warning systems). A small management and technology group is dedicated to each of these programs, but most of the program tasks are carried out by members of the different functional organizations listed on the left side of Figure 25.

For its success, this kind of organization requires a set of overarching goals for its members. Remember that a set of specific goals and a stable knowledge base were two keys to the success of the Propulsion SPO. There are four goals for the new space acquisition organization: (1) Understand, stabilize, optimize, and standardize the spacecraft acquisition and development processes; (2) Field systems only after developers have demonstrated and verified the critical technologies to be stable and readily producible; (3) Take advantage of standardization and modularity in space system development; (4) Maximize informational cross pollination by developing open and efficient communications with space system users (the Armed Services and other government agencies and developers (private industry).

These goals represent the major areas this thesis focuses on in discovering structural deficiencies with the current space system acquisition system. First, since the DoD 5000 series does not work well for cost and time effective development of high performance space system, this organization needs a new development process for optimized for systems acquired in low production quantities. Second, the coupling of technology development and system design is a major source of cost and schedule overruns in the present acquisition system. The new organization separates technology development from the specific programs. Successful acquisition certainly requires that the development groups and the program offices work closely, but their separation helps to ensure that a program does not pursue infeasible or unnecessary technologies. Third, because closer program coordination exists, system developers can obtain economies of scale and reduced development risk from multi-program purchases of standardized components. Finally, shared vision and trust are cornerstones of acquisition reform and future success. Therefore, the new organization must do everything in its power to promote the communication needed to achieve these ends.

Not everyone, however, agrees with such centralization strategies. The opponents of centralization commonly raise two issues to argue against centralization. The first argument relates to the centralization of decision making and goal setting control. Opponents feel that this kind of centralization dangerously reduces the amount of oversight that is given to different initiatives. For example, if Congress relinquishes its micromanagement of different programs, the thought is that contractors can obtain wild profits while defense officials line their pockets with financial favors from contractors given in exchange for political influence. It is for reasons like these that shared vision and trust among the various players in the defense acquisition process are so critical. Ample evidence (see Section 3.4 of this chapter) also suggests that such fears of corruption are largely unfounded. Furthermore, historical evidence supports (see Chapter 2, Section 3) that all sides, Congress, the President, and DoD wanted centralization of roles at the beginning of the Space Age, but political and security reasons did not allow it.

The second concern is that centralization reduces technical and operational concept innovation. The classic example given by opponents of centralization is that of the Poseidon missile. The Air Force, in the 1950s and early 1960s, had been trying to gain control over all strategic (nuclear) missile operations, including research and development of new weapons. The Navy, opposed to this course of action, invented a submarine launched missile, the Poseidon, which truly and completely changed nuclear strategy. For the first time, the military could secretly move nuclear missiles, making it much more difficult for the Soviets to defend against nuclear attack. The Air Force arguably would never have developed the idea, nevermind the hardware required for this weapon.

Yet, opponents must consider two things in response to this example. First, the number of organizations involved with space mission and hardware development is staggering, as well as the amount of rivalry and animosity that exists between them. It is arguable that centralization of activities would promote communication and allow for the synthesis of numerous ideas that are presently isolated by the compartmentalized structure which exists today. Second, in a time of lower funding, organizational downsizing, and reduced security threats, the primary goal of DoD programs should be efficient and effective acquisition of systems.

Consensus building on the centralization issue is not easy, however. As recently as the 1995 budget process, the Army and the Navy are both on record as opposing organizational centralization of space activities within the Air Force: "The three chiefs-Army Gen. Gordon R. Sullivan, Adm. Jeremy Boorda and Marine Gen. Carl Mundy-wrote [Chairman of the Joint Chiefs of Staff, John] Shalikashvili of their 'strong concern' over a recent [Air Force] 'recommendation to consolidate space organization and management under their department'." (Aerospace Daily, 1994).

In conclusion, history shows that the existing decentralized and compartmentalized structure is a result of Cold War political and security pressures. All sides, in the beginning, desired centralized and efficient organizational structures. Furthermore, defense budgets are no longer burgeoning; the United States is not in competition with any military super powers, and space is no longer the battle ground for national prowess that it once was. Instead, downsizing and efficiency are the order of the day. Examples such as that of the Air Force Aeronautical Systems Division's Propulsion SPO seem to indicate the positive role that centralization can play in increasing efficiency while actually improving the development of and retention of knowledge critical to managing and reducing technical and political uncertainty. Presently, the entities needed for a space system acquisition SPO similar in structure to the Propulsion SPO already exist. These entities require certain structural changes in these groups and the institution of a set of goals to guide them Nevertheless, a matrix organization like the one proposed allows DoD to address many of the deficiencies in the present acquisition system. The government no longer has the reason or the money to afford the inefficiencies in the space acquisition community that remain from the Cold War. Efficiency must be its goal; centralization can help to achieve that goal.

4. Summary and Conclusions

In conclusion, this chapter shows that the current spacecraft acquisition process fails to adequately reduce risk prior to the development of a new space system. Conflicting goals and a distinct lack of vision among the players in the process further complicate development once acquisition of the system begins. Using reasoned arguments, examples, and statistics this chapter documents how these structural failures contribute to program shortfalls in performance and overruns in budget and schedule. Finally, this chapter provides a framework for evaluating the of solutions proposed to different problems within the acquisition process - whether or not these solutions can create positive, structural change.

Section 6.2 of this chapter discusses the ways in which acquisition fails to reduce uncertainty. Namely, the acquisition process is not tailored to the effective and efficient acquisition of low production volume systems such as spacecraft. It lacks accurate tools for estimating final system cost, schedule risk, and technical risk. It fails to take advantage of potential sources of cost, schedule, and risk reduction, specifically modularity and standardization of common spacecraft components. Finally, the process encourages program managers to treat politics as an unmanageable project factor which reeks havoc in every program's life, instead of treating political risk as a manageable uncertainty. In total, these system deficiencies drive the creation of unreasonable development expectations which are placed on new system development programs. As a result, development problems often come as a surprise to programs unprepared to deal with them.

Section 6.3 argues that real change cannot come about without shared vision among the players in the acquisition process. That vision at present does not exist. Acquisition requires a vision with two parts - what to buy and how to buy it. The ensuing discussion tries to frame decision of how to buy systems as a series of five tradeoffs that must be made and agreed upon: (1) Cost and Schedule v. Performance; (2) Up-front Costs v. Back-end Costs; (3) Minimizing Yearly Outlays v. Life Cycle Cost Outlays; (4) Micromanagement v. Efficiency; (5) Centralization v. Compartmentalization. No decision on these issues means more of the same for military space system acquisition.

Chapter 7: An Alternative Space System Acquisition Process

Chapter 6 lists many possibilities for the improvement of the current acquisition system which are summarized in Table 14 and the vision tradeoffs at the beginning of Section 3. This chapter carries these suggestions further by proposing an alternative space system acquisition process. The process adopts the tenants of reducing technical uncertainty, establishing a shared vision, and achieving multi-program coordination. It also requires the development of the new spacecraft organization outlined in Chapter 6, Section 3.5. Figure 26 diagrams the new process. The rest of this chapter describes it.

1. Determining Mission Need

A key to this new process is much improved monitoring and communication of long-range plans and potential needs involving the use of space systems. The generation of mission need could remain largely like the present. The improvements in need anticipation and communication are required, instead, to feed the technology development process which takes place continuously under the new process. This is because the new acquisition system assumes that an adequate level of technology exists to meet the mission need prior to the commencement of space system development.

2. Phase 0 - Development Preparedness and Feasibility

Phase 0 has two goals. First, the space system acquisition organization (SSAO) evaluates the readiness of existing technologies to meet the critical technology needs of the new system. Second, the SSAO measures total system feasibility. To do this, the SSAO outsources two sets of contracts to industry. Under one set, subcontractors who have worked with the SSAO on the development of the relevant critical technologies assess the current capabilities and associated costs of these technologies. Under the second set, prime contractors develop cost engineering models (CEMs) for the proposed system. The SSAO independently prepares a CEM which it compares with the contractors' versions in an attempt to understand significant differences in the system assessment. These studies last three to six months and likely involve three to four subcontractors and four to five prime contractors. Their results feed into a milestone decision process.

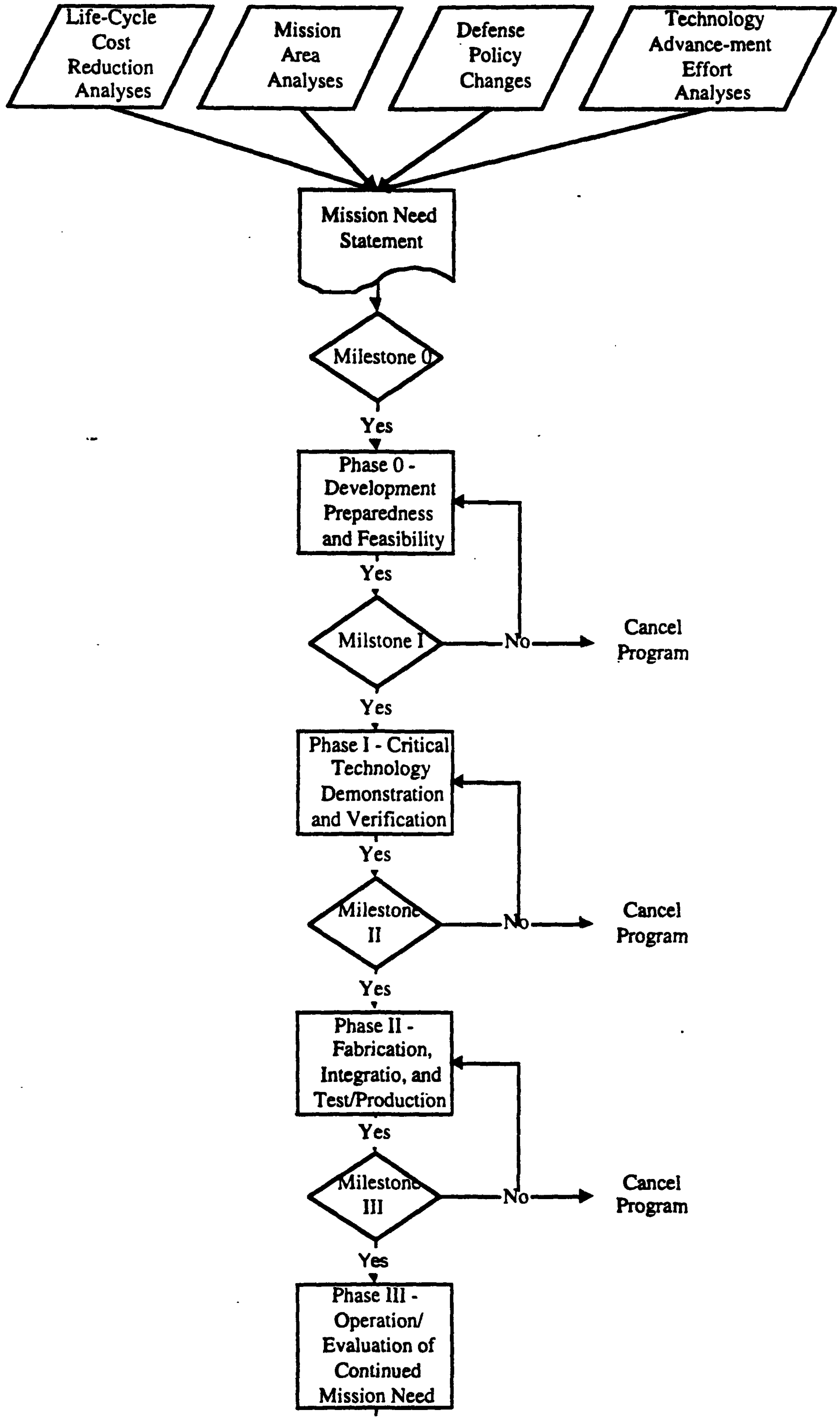

Figure 26 An Alternative Space System Acquisition and Development Process

The new acquisition process continues to use the Defense Acquisition Board (DAB) to review program progress. The DAB primarily considers the results of the technology reports and the CEMs to make its decision whether to initiate a new development program. If the technology reports state that the critical technologies are infeasible or the CEM results vary widely in terms of cost v. performance, then the DAB should assume the program has high technological risk. It might recommend that increased technology development effort be spent on these critical technologies, or it might recommend that meeting such a mission need as well beyond existing technologies and should be abandoned for the present. If the technology reports indicate that critical technology costs are too high or the CEMs agree but produce a system cost judged to be too high, the DAB might recommend six to eighteen months work on lowering costs after which a reevaluation of development feasibility takes place. Finally, if the CEMs and the technology reports agree that system development is feasible, the DAB recommends a new program start.

3. Phase I - Critical Technology Demonstration and Verification

At this time the SSAO management establishes a new system project office (SPO) within SSAO's existing matrix structure. The program office dual sources subcontractors to demonstrate the stability producibility and integrability of the technologies critical to the system's completion. Since the contractors have only a year, the need for feasible technologies prior to this phase is critical. At the same time, the SSAO program office down selects to two prime contractors to oversee low-level efforts that assure system feasibility. Specifically, the primes verify that the critical technologies are not likely to require too much of any system critical resources for nominal operation such as power, mass, volume, and data throughput.

The milestone decision process requires that the critical technologies subcontractors demonstrate the repeatability of their systems during the "flight" of "soft satellites." Soft satellite are software modules simulating the operation of the rest of the spacecraft around these technologies. Therefore, the technology developers must have their designs at the equipment box level of development. This is because their designs can only use the standard interfaces of the soft satellites to demonstrate their operability. Successful demonstrations likely mean the initiation of *Phase II, Spacecraft Fabrication, Integration, and Test/Production. (FIT/Production).*

4. Phase II - Fabrication, Integration, and Test/Production

At the beginning of FIT/Production the SSAO SPO down selects to a single prime contractor and technology developer to create the satellite. Using standard components, modules, and interfaces along with well-developed critical technology designs, the program works to fabricate, integrate, test, and launch the first satellite within 18-24 months of the source selection decision. After each of the first couple of launches, a review is held to evaluate the production process and the system's operational effectiveness. Barring major difficulties, the system continues to full production submitting to quarterly production evaluations which monitor such issues as cost, reliability, rework, and test and assembly time.

If the SSAO adopts an evolutionary acquisition policy, then it might create a two development team relationship in which one prime and subcontractor produce the first design during which the second prime and subcontractor team work on developing its upgrade. This would require the addition of reviews and decision periods to determine when is the most opportune time to deploy system upgrades. Also, the possibility of schedule setbacks and contractor rivalries become more of a reality under such strategy. Nevertheless, the opportunity frequently improve system performance is an intriguing one.

5. Phase III - Operation/Evaluation of Continued Mission Need

This phase begins as soon as the first spacecraft achieves orbit (i.e., it is partially concurrent with FIT/Production). During this phase the SSAO deals with issues that arise during the operation of the system, such as less than desired performance due to partial system failure. Frequent assessments of system cost effectiveness also occur. Finally, evaluations of the need for the system and any required or desired upgrades constantly take place. A milestone decision might be to discontinue system operation or to initiate an upgrade development process. Under an evolutionary process, the milestone decision might choose when to entirely recompete system and technology development roles ending the single or two team upgrade development arrangement that presently exists.

6. Summary and Conclusions

This chapter attempts to extend the suggestions for spacecraft acquisition improvements made in previous chapters of this thesis into an outline of an alternative spacecraft acquisition process. The process attempts to reduce technical risk and increase shared vision and trust. It is based upon the development of technology to a high level of maturity prior to system development and accomplishes this in two ways. First, the long-range needs and threat assessment activities within DoD are improved so that information from them can drive continuous ground, launch, payload, and spacecraft technology development efforts. Second, technology risk assessment and reduction are cornerstones of the first two phases in the process. Only after assuring the stability, producibility, and integrability of system critical technologies does system development begin. System development then benefits from spacecraft component and interface standardization and modularization which are the benefits achieved from a centralized space system acquisition organization (SSAO).

Certainly, this chapter is *only* a rough sketch of an improved space system acquisition process. Remember from Section 3.5 of Chapter 6 that one of the SSAO's chartered goals is to understand, stabilize, optimize, and standardize the spacecraft acquisition and development processes. This admits that DoD still must gather more knowledge about these processes. As a result of this data gathering a different process than the one proposed here might arise. Nevertheless, this alternative process seems to alleviate the structural deficiencies that exist in the current acquisition process. Namely, it focuses on decreasing technical uncertainty by decoupling technology and system development and implementing standardization and modularity as design techniques key to system design. Finally, through organizational centralization and dramatically improved channels of communication it helps to provide the coordination, shared goals, and trust so critical to space system acquisition.

Chapter 8: Summary and Conclusions

1. Space Missions and Spacecraft Design

Space offers a rich set of opportunities to carry out missions that might otherwise be technically or financially infeasible. With a constellation of only a few spacecraft military users can track the world's weather patterns, create global communications networks, detect and track missile launches, safely observe threats around the world, and effortlessly and accurately navigate their forces to desired locations. Still, the development of a space mission is an expensive and complex process producing many technical and managerial challenges.

The mass and volume constraints of launch vehicles often require spacecraft designers to specify the use of exotic materials and create innovative designs in order to miniaturize and lighten critical spacecraft mechanisms and equipment. Designers must overcome myriad integration issues that arise due to the close proximity of equipment requiring different operating environments. Technical challenges also exist once the spacecraft is in space. Space has a harsh temperature and radiation environment which can cripple the spacecraft. Furthermore, most satellites, once on orbit, are not repairable. Spectacular repair missions, like those to fix the Hubble Space Telescope, are a very rare exception rather than the rule. Most spacecraft are beyond the reach of the servicing capabilities that the United States does possess. Therefore, spacecraft designers need to design for high reliability and durability as well. Finally, each spacecraft has specific technical challenges associated with its payload, the reason for the mission, that must be overcome. Problems of this nature tend to be the most vexing and, at the same time, the most interesting issues faced by aerospace engineers.

Not all the issues, however, are technical. This is especially true when designing space systems to meet the needs of the military and intelligence communities. The project team must negotiate a complicated web of government agencies and private contractors in order to secure the funding and equipment required to develop and deploy the space system. Each of these organizations has its own goals and its own needs which it tries to impose on the program during development. Therefore, the project team must be part technical genius and part award winning sales force in getting a spacecraft's development successfully to completion.

2. Structural Barriers to Space System Development

There is no question that harnessing the technology and coordinating the organizations necessary to develop a spacecraft is not any easy job. Nevertheless, this thesis finds that there are many structural deficiencies within the spacecraft acquisition and development process which make this job much more difficult. First, the Department of Defense's strategy for major defense system procurement and the military spacecraft communities interpretation of it do not adequately reduce basic technical risks prior to the initiation of space system development. Low production volumes and the desire of policymakers for a fly before buy policy work to couple basic technology development with system development - a coupling that DoD policy states is undesirable. This coupling often leads to extensive rework and supplemental engineering at the end of development, creating cost and schedule overruns.

Second, the acquisition process lacks effective tools for determining project schedule and cost. Scheduling tools often equate effort with progress, but the observations of large product development experts tend to discount this one to one ratio of effort to progress. It is this misguided assumption, however, that yields the schedule measure referred to as "the man-month." Using the man-month, project managers often under estimate schedules early on and create added schedule delays when technical problems are encountered. Program managers have similar troubles anticipating program costs prior to development. Furthermore, the practice of asking contractors to lower cost and schedule estimates during the best and final offer period during of source selection contributes to the inaccuracy of these cost and schedule estimates. As a result, cost and schedule overruns often come as a surprise late in the program development cycle. These difficulties in adequately measuring uncertainty at the beginning of a project create budget and schedule overruns at the end of a project.

This thesis also that demonstrates vertically integrated organizations, known as stovepipes, and a very fragmented division of labor in the defense space community prevent programs from taking advantage of design practices that might reduce uncertainty. For example, opportunities to standardize and modularize components common to spacecraft are often ignored. One reason for this is the creation of a separate system project office (SPO) for each new program. Separate SPOs encourage project managers to optimize solutions for their own spacecraft, thereby requiring the unique design of parts such as reaction wheels and propellant tanks which are used on many spacecraft. Therefore, chances to build standard spacecraft hardware are neglected. Even when two programs use the same, exact component, the separation of their SPOs prevents them from buying components together and achieving cost savings from the economies of scale associated with a larger quantity buy. The result of such decentralization is that separate programs spend development funds to find new solutions to common problems instead of devoting their resources to creating solutions to mission specific challenges.

Finally, the acquisition process fails to recognize that politics are a part of major system acquisition. In fact, politics are a very important part of the acquisition process. Each program must be reauthorized every year in Congress. Congress also determines the amount of money each program receives. Forman (1993) also reminds us that technical problems become political problems. As a result, failing to manage political risk is just as likely to hurt a program as failing to manage technical risk.

This thesis discusses the issues summarized above because these structural failures adversely affect the acquisition of all major space systems. It devotes great detail to each of these issues for several reasons. First, the thesis attempts to establish the relationship of each of these deficiencies with problems often seen in spacecraft development. It also spends time explaining each of these problems so that solutions to them might more easily be found. These deficiencies are hierarchically organized so as to provide a framework for developing strategies that might work to improve the entire acquisition process at once, not just parts of it. Finally, it proposes an alternative acquisition strategy which addresses each of these deficiencies.

3. Shared Vision and the Future of Defense Aerospace

For a process change to take place, however, shared vision among all of the players in the acquisition process must be established. A program cannot meet conflicting goals, nor can it meet constantly changing goals without budget and cost overruns. Furthermore, any initiatives to fundamentally improve the spacecraft acquisition and development process take time to implement and judge adequately. Therefore, there must be a long term commitment by all parties involved with process changes. Otherwise, real change cannot be accomplished.

Yet, change must take place. Defense funding is shrinking and defense space funding is becoming a larger and larger percentage of the defense moneys that remain. At present, however, cost and schedule overruns are common in spacecraft development programs. Military space's increased prominence in budgetary battles require that it develop system's more efficiently or be subject to greater ire from Congress and the President. If acquisition results are not improved the level and effectiveness of the military's presence in space in the future is severely in question.

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