B-2 Systems Engineering Case Study

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **B-2 Systems Engineering Case Study**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Center for Systems Engineering,Air Force Institute of Technology,2950 Hobson Way,Wright Patterson AFB,OH,45433-7765**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**117**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

PREFACE

In response to Air Force Secretary James G. Roche's charge to reinvigorate the systems engineering profession, the Air Force Institute of Technology (AFIT) undertook a broad spectrum of initiatives that included creating new instructional material. The Institute envisioned case studies on past programs as one of these new tools for teaching the principles of systems engineering.

Four case studies, the first set in a planned series, were developed with the oversight of the Subcommittee on Systems Engineering to the Air University Board of Visitors. The Subcommittee included the following distinguished individuals:

Chairman

Dr. Alex Levis, AF/ST

Members

Brigadier General Tom Sheridan, AFSPC/DR

Dr. Daniel Stewart, AFMC/CD

Dr. George Friedman, University of Southern California

Dr. Andrew Sage, George Mason University

Dr. Elliot Axelband, University of Southern California

Dr. Dennis Buede, Innovative Decisions Inc.

Dr. Dave Evans, Aerospace Institute

Dr. Levis and the Subcommittee on Systems Engineering crafted the idea of publishing these case studies, reviewed several proposals, selected four systems as the initial cases for study, and continued to provide guidance throughout their development. The Subcommittee's leading minds in systems engineering have been a guiding force to charter, review, and approve the work of the authors. The four case studies produced in that series were the C-5 Galaxy, the F-111, the Hubble Space Telescope, and the Theater Battle Management Core System.

This second series includes the B-2 Spirit Stealth bomber. Additional case studies are under consideration for future publication in a third series.

FOREWORD

At the direction of the Secretary of the Air Force, Dr. James G. Roche, the Air Force established a Center for Systems Engineering (CSE) at the Air Force Institute of Technology (AFIT) campus on Wright-Patterson AFB, OH in 2002. With academic oversight by a Subcommittee on Systems Engineering, chaired by Air Force Chief Scientist Dr. Alex Levis, the CSE was tasked to develop case studies focusing on the application of systems engineering principles within various aerospace programs. The committee drafted an initial case outline and learning objectives, and suggested the use of the Friedman-Sage Framework to guide overall analysis.

The CSE contracted for management support with Universal Technology Corporation (UTC) in July 2003. Principal investigators for the four case studies published in the initial series included Mr. John Griffin for the C-5A, Dr. G. Keith Richey for the F-111, Mr. James Mattice for the Hubble Space Telescope, and Mr. Josh Collens from The MITRE Corporation for the Theater Battle Management Core System effort. These cases were published in 2004 and are available on the CSE website.

The Department of Defense continues to develop and acquire joint complex systems that deliver needed capabilities demanded by our warfighters. Systems engineering is the technical and technical management process that focuses explicitly on delivering and sustaining robust, high-quality, affordable products. The Air Force leadership, from the Secretary of the Air Force, to our Service Acquisition Executive, through the Commander of Air Force Materiel Command, has collectively stated the need to mature a sound systems engineering process throughout the Air Force.

Plans exist for future case studies focusing on other areas. Suggestions have included other Joint service programs, logistics-led programs, science and technology/laboratory efforts, additional aircraft programs, and successful commercial systems.

As we uncovered historical facts and conducted key interviews with program managers and chief engineers, both within the government and those working for the various prime and subcontractors, we concluded that systems programs face similar challenges today. Applicable systems engineering principles and the effects of communication and the environment continue to challenge our ability to provide a balanced technical solution. We look forward to your comments on this B-2 case, our other AF CSE published studies, and others that will follow.

AIR FORCE CENTER FOR SYSTEMS ENGINEERING
AIR FORCE INSTITUTE OF TECHNOLOGY

MARK K. WILSON, SES

Director, AF Center for Systems Engineering
Air Force Institute of Technology
http://cse.afit.edu/

PROLOGUE

The B-2 is a phenomenal weapon system… born out of the cold war as a strategic nuclear penetrator... now proving it's worth with a wide range of tactical precision weapon delivery capabilities. This case study deals with the early Full Scale Development (FSD) and Engineering Manufacturing Development (EMD) phases of the program, known today as System Design and Development (SDD)…there is a subtle but important difference…did you catch it? Hopefully, as you work through this case study, you see that the System Engineering process applied on the B-2 program from 1979 (as the Advanced Technology Bomber requirements definition phase) through completion of the first airplane build played a significant role in bringing about the superior capability the system has today; not just in the design of the airplane, but also the in the development of new manufacturing processes as well.

I was privileged to serve as the Program Director from June 1983 (just as the decision to redesign the airplane was being made) to June 1991. There were a number of programmatic issues that faced the program throughout this time period; and without the Systems Engineering process described in the case study, we would not have had the necessary quantitative data to be able to adequately address these programmatic issues in an authoritative way. The task of totally redesigning the aircraft two years into the program, having completed Preliminary Deign Review #1, while striving to maintain, or minimize, program impacts was a Herculean task. Because of the System Engineering process discussed in this case study, with the discipline and integrity that existed in the process, the B-2 Program was able to maintain the technical baseline across the entire government/contractor team and by so doing minimized the eventual impacts. The key factor in accomplishing this, after the professionalism and dedication of all the people involved, was the fact that the program had only ONE (near real time) design data base; which all of the program participants utilized…engineering, manufacturing, test, sub-contractors, and the government. As System Engineers, and particularly as Chief System Engineers, maintaining the technical baseline will be the most important part of your job… without it, the programmatic impacts will begin to accumulate to the point where the program will eventually become at risk.

I want to emphasize at this point that there is a difference between System Engineering roles and responsibilities and Program Management roles and responsibilities… both are important to the success of a program… but Program Directors can not succeed without a sound technical baseline and a solid System Engineering process. The most important responsibility for the System Engineer is to maintain the integrity of the technical baseline, regardless of programmatic issues; because it is absolutely fundamental to the integrity of the program management baseline.

Richard M. Scofield, Lt Gen, USAF, Ret

ACKNOWLEDGEMENTS

The authors would like to acknowledge the special contributions of people who dedicated their time and energy to make this report accurate and complete. We offer our sincere appreciation to all the people listed in Appendix 3, who volunteered their time and insight during the interviews. Very special thanks go to Lauren Proffit, Universal Technology Corporation, without whom we could ever have finished the editing and formatting of the report. Heartfelt congratulations to all the people involved in the program and particularly the systems engineers and design engineers at Northrop, Boeing, Vought, the vendors, WPAFB, Strategic Air Command, and EAFB for their tireless efforts in delivering this truly outstanding capability that has served our nation so well.

Additional special thanks to those no longer with us; Leonard Rose, Northrop B-2 Chief Engineer; Dave England, Col, USAF, ASD/XRJ program manager; John Paterno, Northrop vice president, B-2 Division. Great leaders, great men, they are missed.

We also provide a special thank you and note of appreciation to our AFIT Project Leader, Lt Col John M. Colombi, who provided editorial guidance to the authors, along with continuous motivation.

John M. Griffin
James E. Kinnu

EXECUTIVE SUMMARY

The B-2 Systems Engineering Case Study describes the application of systems engineering during the concept exploration, design, and development of the USAF B-2 Spirit stealth bomber. The case examines and explores the systems engineering process as applied by the Air Force B-2 System Program Office, the prime contractor, Northrop, and the two major subcontractors, Boeing and Vought, from the program's genesis in the late 1970s to the first flight of the first aircraft on 17 July 1989. The systems engineering process is traced from a vision of a few planners in 1978 to the production of 21 operational aircraft that are currently serving our nation. Numerous interviews were conducted with the principals who managed and directed the program and a story of the systems engineering process emerged.

The B-2 was conceived to profit from the advances in stealth technology that grew from a series of laboratory experiments and design studies during 1970 to 1976. The early work by both the government and industry during this timeframe resulted in feasible and practical stealth vehicles that exist throughout our military. The current operational fleets of fighters, bombers, UAVs, ships, and other stealth vehicles trace their heritage to the early technology maturation and engineering development programs. Stealth (or low observables, as it was called by the original practitioners) offered a new and revolutionary approach for penetrating the burgeoning growth of the Soviet defensive system of an integrated radar network. The fighter was the first type of weapon system to be studied for the benefits of stealth and the pay-off was assessed as substantial. The bomber was the next obvious candidate, and it too, showed great promise. Lockheed was in the lead for the technology application for fighters and was awarded the development contract for the F-117 stealth fighter. Northrop and Lockheed were competitors for the contract to develop the stealth bomber from late 1979; Northrop won the contract in November 1981. The first flight of the B-2 was 17 July 1989 with the first operational sortie of the aircraft occurring during the Balkan conflict in December 1995.

The Spirit is a long-range heavy bomber incorporating the key technologies of the time. First, as evident in Figure 1, it is a highly efficient flying-wing (tailless) aeronautical design. Secondly, the aircraft makes extensive use of composite materials. And third, it is designed for stealth. Figure 1 shows four views of the aircraft with each view showing the details of the control surfaces, doors, access panels, and other external features. Note the center of the aircraft from the bottom view, showing the large cut out of the structure to accommodate the weapons bay doors (4), engine access doors (4), and the main landing gear doors (2). The ability to achieve an efficient structural design in the presence of the large cutouts on the bottom skin of the vehicle is one of the significant achievements of the structures team.

The B-2 has significant range performance and payload capability. Table 1 shows the design weights and the range and payloads for the nuclear mission as well as the conventional missions. The bomber was primarily designed as a long-range strategic nuclear delivery system, but a significant conventional capability was designed in from the beginning. The table shows an abbreviated list of weapons currently certified for carriage. The list of weapons carriage capability continues to expand through ongoing B-2 modernization programs.

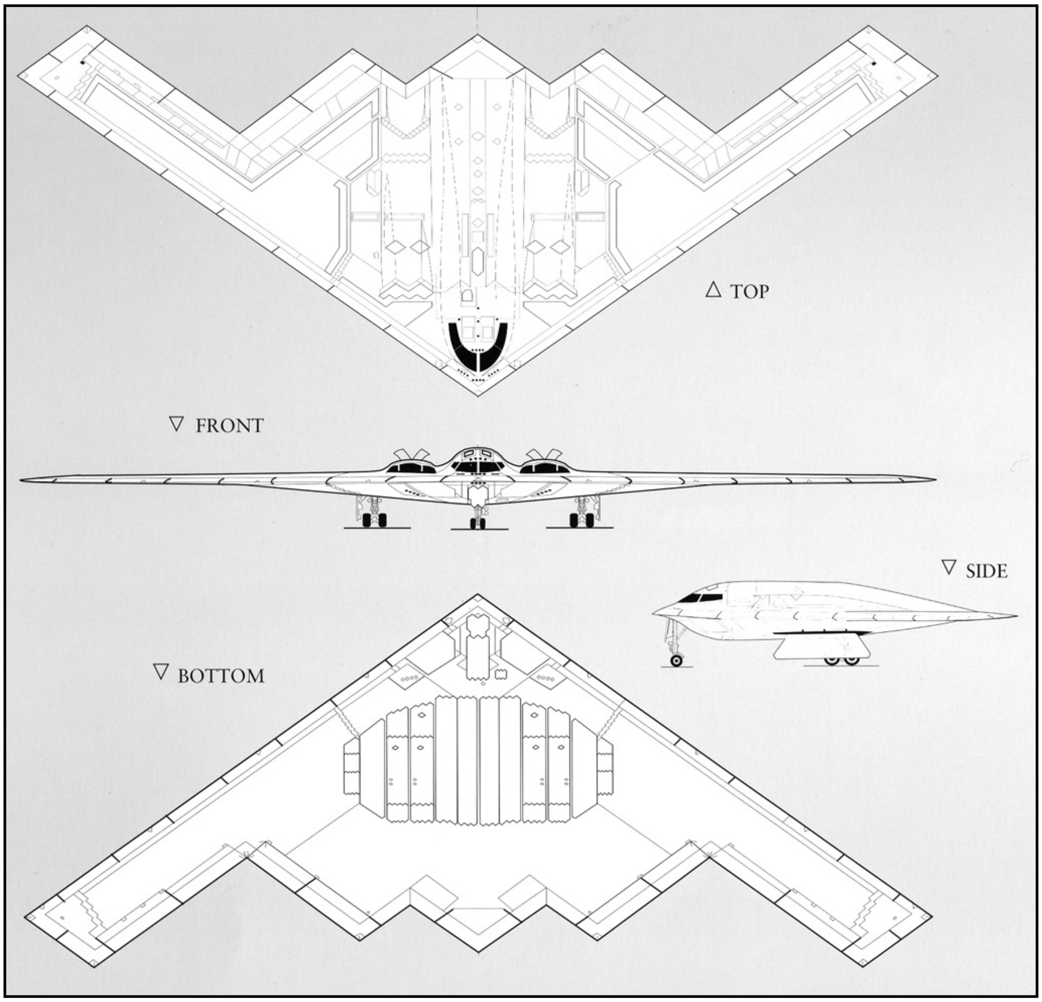

Figure 1. External View Drawings of the B-2 Aircraft [1]

Systems engineering was applied to the B-2 consistent with the maturity of the discipline circa 1978-1990 (the time frame of interest for this case study). The technical field of systems engineering was systemic with the design process throughout many aerospace companies. However, this was also the timeframe for continued recognition by the Air Force for the need for more formal documentation, tools, procedures, and organizational structure, initiated in the mid 1960s with the publication of both the Air Force Systems Command AFSC-375 series of Manuals and the issuance of the systems engineering military standard, MIL-STD-490A. It was also a time that concurrent engineering was in vogue in commercial ventures. This movement was an attempt to capture the Air Force and defense industry's recognition of the needs of logistics, manufacturing, supportability, and reliability in the early design effort. The degree to which programs followed the emerging formality of systems engineering was a function of the maturity of the systems engineering process in the companies involved in the project, the effort demanded by the procuring agency through emphasis in the Statement of Work, and the degree to which the design and subsystems specialists within the project were schooled and committed to systems engineering.

Table 1. B-2 Weight and Performance Capabilities [1]

	Features
Length	69 feet
Height	17 feet
Wingspan	172 feet
Power plant	4 GE F-118 engines (17,300 lbs thrust each)
Crew	Two pilots
	Weight Capability
Max takeoff Weight Max in-flight Weight Max Landing Weight	336,500 pounds 357,500 pounds 311,500 Pounds
Max payload	44,000 pounds
Max fuel	166,900 pounds
Min Flying Weight Weight Empty	161,385 pounds 149,900 pounds
	Performance Capability
Cruise performance	6,000 NM, unrefueled at high altitude
Airport performance Takeoff, Std day, Sea Level Landing, 240,000 Pounds	 8,000 feet at maximum takeoff weight 5,000 feet
	Weapons Payload
Nuclear payload	16 B-83 16 B-61-7 8 B-61-11
Conventional payload	16 GBU-31 (JDAM-84) 80 GBU-38 (JDAM-82) 16 AGM-154A (JSOW-97)

The application of the systems engineering process on the B-2 program benefited profoundly by an important early decision to integrate the customer's requirements development process into the company teams' design and development process. This resulted in a culture of continual systems engineering trade studies from the very top-level systems requirements down to the simplest design details that affected all aspects of the aircraft design, maintenance, supportability, and training. Specialists from the technical and management disciplines worked as a team to assess the need for a specific performance level of a requirement to enhance operational effectiveness or trade for a lower level of performance to reduce cost or risk. The team could balance the benefit of achieving a performance level against its impact on cost, schedule, and risk and present the results to the proper decision tier for action.

The advantages of the systems engineering being systemic to the operation of the development program through the 1980s were:

- Multiple systems-level trade studies. Systems engineering trade studies occurred for all technical disciplines, subsystems and at all levels of the work breakdown structure (WBS)

- Balanced performance, cost, schedule, and risk
- Agreement on the tasks to be performed and their priority
- Well understood and documented customer/supplier agreements.

In order to take advantage of the benefits that accrued from the integration of the requirements and the design/development processes, other program initiatives and decisions making process were crucial, including:

- Rapid decision process with the ability to get the proper information to the proper level, followed by timely action
- An organizational structure that utilized a system view to assess impacts
- Skilled professionals at all levels and in all technical and management disciplines
- Processes to accurately assess, assign, track, integrate, and close risks.

The organizational structures at the contractors (Northrop, Boeing, Vought, Hughes, General Electric, etc.) and government agencies (Aeronautical Systems Division, the B-2 Program Office, and the Strategic Air Command) were critical to the success of the program. The Air Force Systems Program Office (SPO) organization was a “classic” functional structure with a strong integration process that utilized the top two levels of the organization as the primary programmatic decision-making body. The contractors used a combination of strong project offices, along wit functional organizations to provide the decision base and the leadership for the program.

There were several different systems engineering organizations in each major functional organization. The workforce was arranged in WBS task teams, similar in construct to the Integrated Product Teams (IPT) to follow in the future, but with some fundamental differences. These WBS task teams were the critical functioning structure and were the primary process by which business was conducted throughout the development program. Risk Closure Plans were a key management process and were instrumental in providing focus to risk identification, tracking, and closure. Thus, the organizational structure, the WBS task team construct, the decision making process, the risk closure planning process, the systems engineering tools, and the dedicated, talented, experienced people in engineering, all the functional areas, and program management were essential features of the systems engineering process during the development process of the B-2.

The Five B-2 Learning Principles

The learning principles are those key factors that the authors considered as the most influential to the successful outcomes and to the failures of the program. They are developed in further detail, by following the chronological evolution of the program. In Section 4, the learning principles are then summarized and further emphasized as to why they were chosen as the major points.

LP 1, <u>Integration of the Requirements and Design Processes</u>: A key aspect of the implementation of the systems engineering process was the integration of the SPO requirement’s team with the contractors’ work breakdown structure (WBS) Task teams into a cohesive program effort. These contractor teams included design, manufacturing, Quality Assurance, and logistics. This integration facilitated continual trade studies conducted by the specialists from the User/SPO government team with the company specialists to fully assess the performance trade-offs against schedule, cost, and risk.

LP 2, <u>WBS Task Teams and Functional Hierarchy</u>: A well-defined contract work breakdown structure (WBS) stipulated the entire program content and tasking. The company organized the design/development effort into multiple teams, responsible to implement the WBS for sections of the air vehicle and for each subsystem. These WBS Task Teams were assigned complete work packages, for example, the forward center wing. The systems engineering WBS Task Team efforts were organized similarly, but with separate responsibilities, each reporting to the Northrop chief engineer or his deputies. The functional organizations assigned members to the task teams to assure accommodation of their program needs. A vital distinction from many of today's IPTs was retaining the WBS Task Team membership throughout the functional organizations' various management levels. This facilitated communication, integration, interfaces, and integrated the functional leadership of each of the company's technical and management disciplines into the decision process. The program management top-level structure was organized into a strong project office with centralized decision authority and strong leadership at the top of both the SPO and the contractor organizations.

LP 3, <u>Air Vehicle Reconfiguration</u>: When the identification of a major aeronautical control inadequacy was discovered just four months prior to formal configuration freeze, an immediate refocus of the Task Teams was required. Within several days, the air vehicle task teams were conducting trade studies, augmenting their skill sets, and integrating with the other program participants in a coordinated effort to derive an efficient, controllable, operationally useful system. At the same time, the program elements that were not markedly affected by the change maintained a course that preserved their schedule, but was sufficiently flexible to include any potential changes. In a program wide systems engineering effort, the prime contractor's program office integrated the teams, reviewed their efforts, coordinated the systems trades, and identified significant changes to the outer mode lines, the radar cross section (RCS) baseline, all major structure assemblies, and all major air vehicle subsystems requirements, with the exception of avionics and armament. The alternatives were derived by the end of the third month, the final choice was selected by the sixth month, and the seventh month was used to coordinate and garner the approval of all stakeholders. While the program response to the crisis was rapid and effective, and a significant impact on the downstream cost and schedule was anticipated by the management team, and the technical impact was predicted by the systems engineering process, it was not predicted to the fullest extent.

LP 4, <u>Subsystem Maturity:</u> The effect of the reconfiguration on the maturity of all the air vehicle subsystems (flight control, environmental control, electrical, landing gear, etc) was far greater than projected. The subsystems were mostly vendor-supplied equipments and some were in the selection process to the technical requirements of the original baseline when the reconfiguration occurred. After the new configuration was derived, the requirements for the subsystems changed to such a degree that they had to be resized and repackaged. It took longer than anticipated by the systems engineering process to recognize the growing problem of getting all the specifications updated and to identify the lagging equipment maturity that resulted. Thus, the reconfiguration required a second iteration of the design requirements and their flow-down to the many suppliers and their detailed designs. These iterations after PDR-2 resulted in the vehicle subsystems not achieving their Critical Design Review (CDR) milestone concurrently with the structure, but rather five months later.

LP 5, Risk Planning and Management: The program was structured so that risks affecting the viability of the weapons system concept were identified at contract award and were structured as part of the Program and WBS work plans. The initial risks were comprised of those "normal" risks associated with a large complex weapons system development as well as the new technology and processes necessary to mature the program to low to medium risk at PDR. Those initial risks were closed prior to PDR 2. The risk closure process continued throughout development and identified new risks and continuously identified new risk closure plans. Most importantly, the work associated with risk closure for each plan was integrated into the WBS task teams' work plans and into the Program Plans. These detailed plans showed all design, analyses, tests, tooling, and other tasks necessary to close the identified risks and were maintained as part of the normal design/program reporting activity.

The Friedman-Sage [2] Framework was used to examine the context of all the learning principles, their primary responsibility and their overall effect on the program. The Friedman-Sage construct and its associated matrix of nine Concept Domains and Three Responsibility Domains gives the systems engineering practitioner a powerful tool to examine a program's systems engineering effort.

As the reader delves into the full story of the B-2, it is important to keep in mind the environment surrounding the program. Conducted in utmost secrecy, it can be compared to the Manhattan Project of WWII that developed the atomic bomb. Security was the most important consideration. In fact, the Program Management Directive (PMD) specified the order of program priority as:

1. Security
2. Performance
3. Schedule, and
4. Cost.

The program was part of the Reagan weapons build-up, along with the B-1B and Peacekeeper Missile System in the early 1980s. This build-up can be considered to have caused the instability in the Soviet Union that eventually led to the collapse of that country and the end of the Cold War on 9 November 1989 with the fall of the Berlin Wall.

Table of Contents

PREFACE ii
FOREWARD iii
ACKNOWLEDGEMENTS iv
EXECUTIVE SUMMARY v
1.0 SYSTEMS ENGINEERING PRINCIPLES 1
1.1 General Systems Engineering Process 1
1.1.1 Introduction 1
1.1.2 Case Studies 3
1.1.3 Framework for Analysis 4
1.2 B-2 Friedman-Sage Matrix 6
2.0 SYSTEM DESCRIPTION 8
2.1 Mission 8
2.2 Features 8
2.3 System Design 8
2.4 Operational Background 10
3.0 B-2 PROGRAM EXECUTION 13
3.1 Concept Exploration 13
3.1.1 Early Stealth Programs 14
3.1.2 Advanced Strategic Penetrating Aircraft (ASPA) 15
3.1.3 ASPA Study Contracts 16
3.1.4 Source Selection 20
3.1.5 Development of the Weapons System Specifications 20
3.1.6 Development of the Low Observable (Stealth) Requirements 23
3.1.7 Low Altitude Modification Request (MR) 24
3.1.8 Contract schedule 25
3.2 Contract Award 26
3.2.1 Systems Engineering Organizations 27
3.2.2 Facilitization 33
3.3 Full Scale Engineering Development (FSED) Execution 36
3.3.1 Risk Closure Plans 36
3.3.2 Preliminary Design Review (PDR-1) 39
3.3.3 Configuration Freeze 40
3.3.4 Preliminary Design Review (PDR-2) 48
3.3.5 Interface Control Document (ICD) Closure Date 49
3.3.6 Critical Design Review (CDR) 49
3.4 System Checkout/First Flight 50
4.0 SUMMARY 51
5.0 REFERENCES 55
EDITOR'S NOTE 56
APPENDIX 1: COMPLETE FRIEDMAN-SAGE MATRIX FOR THE B-2 57
APPENDIX 2: AUTHOR BIOGRAPHIES 58
APPENDIX 3: INTERVIEWS 61
APPENDIX 4: ASPA RISK REDUCTION BRIEFING, 1979 62
APPENDIX 5: SELECTED TEXT FROM B-2 SEMP 73

List of Figures

Figure 1. External View Drawings of the B-2 Aircraft [1] vii

Figure 1-1. The Systems Engineering Process, Defense Acquisition University 2

Figure 2-1. External View Drawings of the B-2 Aircraft [1] 9

Figure 2-2. B-2 Air Vehicle Isometric View of Primary Manufacturers 10

Figure 2-3. B-2 Dropping MK 84 Class Weapons During Testing and Certification 10

Figure 2-4. B-2 in a turn at altitude [1] 11

Figure 3-1. Lockheed Have Blue (left) and Northrop (right) XST Aircraft [5]. 15

Figure 3-2. Northrop Tacit Blue [5] 16

Figure 3-3. Shown are Irv Waaland (left), Steve Smith, Aircraft Division Vice President and John Cashen (right) 18

Figure 3-4. Typical HI-HI-HI-HI Mission from 1980 DARPA Study. 22

Figure 3-5. Typical HI-HI-LO-LO Mission from 1980 DARPA Study 22

Figure 3-6. Risk Reduction Areas for Interim Full Scale Development [6] 37

Figure 3-7. Large-scale manufacturing for these layered composite materials was technologically immature and high-risk during the early program 38

Figure 3-8. Structural Bending of the Wing at First Bending 41

Figure 3-9. Dramatic Internal and External Differences 44

Figure 3-10. Work Share and Production Changes from the Reconfiguration 44

List of Tables

Table 1. B-2 Weight and Performance Capabilities [1] viii

Table 1-1. A Framework of Key Systems Engineering Concepts and Responsibilities [2] 5

Table 1-2. Friedman Sage Matrix with B-2 Learning Principles [2] 6

Table 2-1. B-2 Weight and Performance Capabilities [1] 12

Table 3-1. B-2 Events/Milestones 13

Table 3-2. RFP and Specification Requirements 21

Table 3-3. B-2 Major Program Milestones 26

Table 3-4. Schedule Milestones during the Reconfiguration Effort (1983) 45

1.0 SYSTEMS ENGINEERING PRINCIPLES

1.1 General Systems Engineering Process

1.1.1 Introduction

The Department of Defense continues to develop and acquire systems to provide needed capabilities to the warfighter. With a constant objective to improve the acquisition process, it strives at new and creative ways to acquire these technically complex systems. A sound systems engineering process, focused explicitly on delivering and sustaining robust, high-quality, affordable products that meet the needs of customers and stakeholders must continue to evolve and mature. Systems engineering is the technical and technical management process that results in delivered products and systems that exhibit the best balance of cost, schedule, and performance. The process must operate effectively with desired mission-level capabilities, establish system-level requirements, allocate these down to the lowest level of the design, and assure validation and verification of performance, meeting cost and schedule constraints. The systems engineering process changes as the program progresses from one phase to the next, as do the tools and procedures. The process also changes over the decades, maturing, expanding, growing, and evolving from the base established during the conduct of past programs. Systems engineering has a long history. Examples can be found demonstrating a systemic application of effective engineering and engineering management, as well as poorly applied, but well defined processes. Throughout the many decades during which systems engineering has emerged as a discipline, many practices, processes, heuristics, and tools have been developed, documented, and applied.

Several core lifecycle stages have surfaced as consistently and continually challenging during any system program development. First, system development must proceed from a well-developed set of requirements. Secondly, regardless of the evolutionary acquisition approach, the system requirements must flow down to all subsystems and lower level components. And third, the system requirements need to be stable, balanced and must properly reflect all activities in all intended environments. However, system requirements are not unchangeable. As the system design proceeds, if a requirement or set of requirements is proving excessively expensive to satisfy, the process must rebalance schedule, cost, and performance by changing or modifying the requirements or set of requirements.

Systems engineering includes making key system and design trades early in the process in order to establish the system architecture. These architectural artifacts can depict any new system, legacy system, modifications thereto, introduction of new technologies, and overall system-level behavior and performance. Modeling and simulation are generally employed to organize and assess architectural alternatives at this introductory stage. System and subsystem design follows the functional architecture. System architectures are modified if the elements are too risky, expensive or time-consuming. Both newer object-oriented analysis and design and classic structured analysis using functional decomposition and information flows/data modeling occurs. Design proceeds logically using key design reviews, tradeoff analysis, and prototyping to reduce any high-risk technology areas [3, Colombi].

Important to the efficient decomposition and creation of the functional and physical architectures and designs are the management of interfaces and integration of subsystems. This is applied to subsystems within a system, or across large, complex systems of systems. Once a solution is planned, analyzed, designed, and constructed, validation and verification take place to assure the requirements have been satisfied. Definition of test criteria, measures of effectiveness (MOEs), and measures of performance (MOPs), established as part of the requirements process, take place well before any component or subsystem assembly design and construction occurs.

There are several excellent representations of the systems engineering process presented in the literature. These depictions present the current state of the art in the maturity and evolution of the systems engineering process. One can find systems engineering process definitions, guides, and handbooks from the International Council on Systems Engineering (INCOSE), European Industrial Association (EIA), Institute of Electrical and Electronics Engineers (IEEE), and various Department of Defense (DoD) agencies and organizations. They show the process as it should be applied by today's experienced practitioner. One of these processes, long used by the Defense Acquisition University (DAU), is depicted by Figure 1-1. It should be noted that this model is not accomplished in a single pass. This iterative and nested process gets repeated to the lowest level of definition of the design and its interfaces.

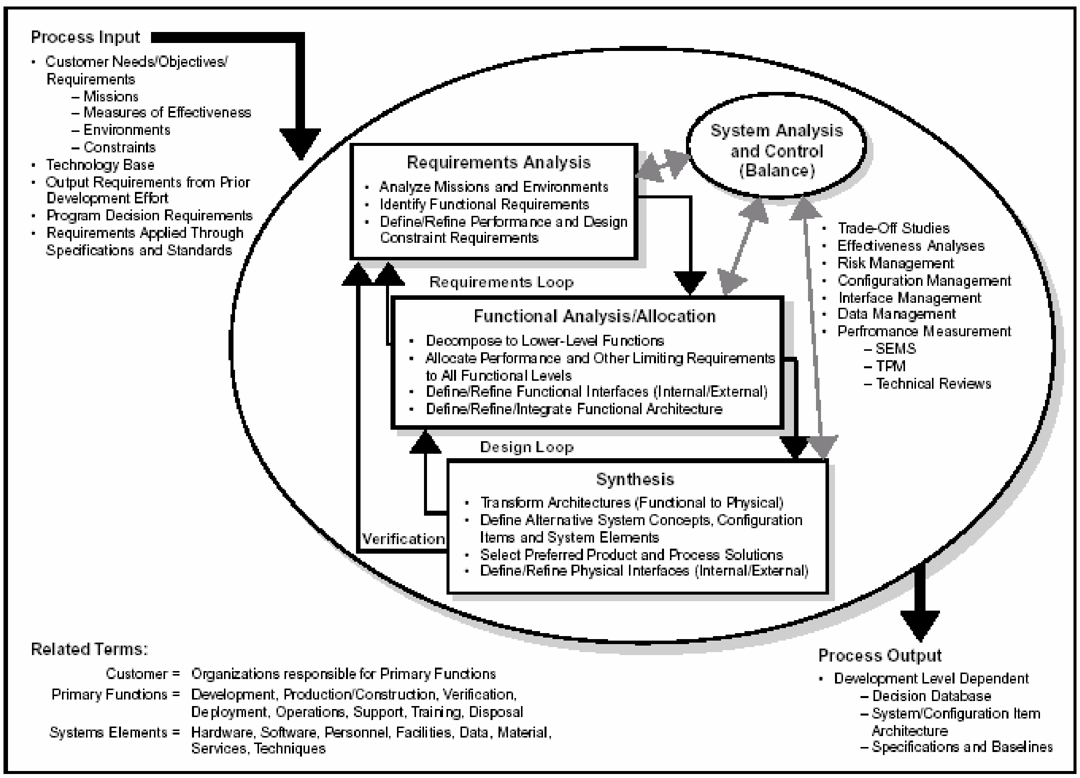

Figure 1-1. The Systems Engineering Process, Defense Acquisition University

The DAU model, like all others, has been documented in the last two decades, and has expanded and developed to reflect the changing environment. Systems are becoming increasingly complex internally and more interconnected externally. The process used to develop the aircraft and systems of the past was a process effective at the time. It served the needs of the practitioners and resulted in many successful systems in our inventory. Notwithstanding, the cost and schedule performance of the past programs include examples of some well-managed programs and ones with less stellar execution. As the nation entered the 1980s and 1990s, large DoD and commercial acquisition programs were overrunning costs and were behind schedule. The aerospace industry and its organizations were becoming larger and were more geographically distributed and culturally diverse. Large aerospace companies have worked diligently to establish common systems engineering practices across their enterprises. However, these common practices must be understood and be useful to the enterprise and across multiple corporations because of the mega-trend of teaming in large (and some small) programs. It is essential that the systems engineering process effect integration, balance, allocation, and verification and be useful to the entire program team down to the design and interface level.

Today, many factors overshadow new acquisition, including the system-of-systems (SoS) context, network centric warfare and operations, and the rapid growth in information technology. These factors are driving a more sophisticated systems engineering process with more complex and capable features, along with new tools and procedures. One area of increased focus of the systems engineering process is the information systems architectural definitions used during system analysis. This process, described in the DoD Architectural Framework (DoDAF) [4], emphasizes greater reliance on reusable architectural views describing the system context, concept of operations, interoperability, information and data flows and network service-oriented characteristics.

1.1.2 Case Studies

The systems engineering process to be used in today's complex systems and system-of-systems projects is a process matured and founded on principles developed in the past. Examination of systems engineering principles used on programs, both past and present, can provide a wealth of lessons to be used in applying and understanding today's process. It was this thinking that led to the construction of the AF CSE case studies.

The purpose of developing detailed case studies is to support the teaching of systems engineering principles. They will facilitate learning by emphasizing to the student the long-term consequences of the systems engineering as it influences program decisions, thereby influencing program success. Systems engineering case studies assist in discussion of both successful and unsuccessful methodologies, processes, principles, tools, and decision material to assess the outcome of alternatives at the program/system level. In addition, the importance of using skills from logistics, manufacturing, finance, contracts, Quality Assurance, and engineering disciplines and then collecting, assessing, and integrating varied functional data are emphasized. When they are taken together, the student is provided real-world detailed examples of how the process contributes to the effective balance of cost, schedule, and performance.

The utilization and mis-utilization of systems engineering principles are highlighted, with special emphasis on the conditions that both foster and impede good systems engineering practice. Case studies should be used to illustrate both good and bad examples of acquisition management and learning principles, to include whether:

- Every system provides a satisfactory balanced and effective product to a customer
- Effective requirements analysis was applied
- Consistent and rigorous application of systems engineering management standards was applied
- Effective test planning was accomplished
- There were effective major technical program reviews
- Continuous risk assessments and management was implemented
- There were reliable cost estimates and policies
- They used disciplined application of configuration management
- A well defined system boundary was defined

- They used disciplined methodologies for complex systems
- Problem solving incorporated understanding of the system within bigger environment (customer's customer)

The systems engineering process transforms an operational need into a system or system-of-systems. Architectural elements of the system are allocated and translated into detailed design requirements by the systems engineering process. The systems engineering process, from the identification of the operational need, through the development, and to utilization of the product, must continuously integrate and balance the requirements, while giving consideration to the cost and schedule to provide an operationally effective system throughout its lifecycle. Systems engineering case studies highlight the various interfaces and communications to achieve this balance, which include:

- The program manager/systems engineering interface essential between the operational user and developer (acquirer) to translate the needs into the performance requirements for the system and subsystems.
- The government/contractor interface essential for the practice of systems engineering to translate and allocate the performance requirements into detailed requirements.
- The developer (acquirer)/industry/user interface within the project, essential for the systems engineering practice of integration and balance.

The systems engineering process must manage risk, both known and unknown, as well as both internal and external. Identifying, integrating, and managing the internal risks within the scope of the directed program is an essential task of the systems engineering process. A second responsibility of the process is to quickly and accurately respond when asked to evaluate proposed changes to the directed program, external risks. The process must advise the program decision makers as to the consequences of proposed changes that may be imposed by external forces. The objective of this second responsibility will specifically capture those external factors and the impact of these uncontrollable influences, such as actions of Congress, changes in funding, new instructions/policies, changing stakeholders or user requirements or contractor and government staffing levels.

Lastly, the systems engineering process must respond to "Mega-Trends" in the systems engineering discipline itself, as the nature of systems engineering and related practices do vary with time and circumstances.

1.1.3 Framework for Analysis

This case study presents learning principles specific to the B-2 using the Friedman-Sage framework [2] to organize the assessment of the application of the systems engineering process. The framework and the derived matrix play an important role in developing case studies in systems engineering and systems management. It describes a nine row by three column matrix shown in Table 1-1.

Table 1-1. A Framework of Key Systems Engineering Concepts and Responsibilities [2]

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	2. Shared Responsibility	3. Government Responsibility
A. Requirements Definition and Management			
B. Systems Architecting and Conceptual Design			
C. System and Subsystem Detailed Design and Implementation			
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management			
I. System and Program Management			

Six of the nine concept domain areas in Table 1-1 represent phases in the systems engineering lifecycle:

A. Requirements Definition and Management

B. Systems Architecting and Conceptual Design

C. Detailed System and Subsystem Design and Implementation

D. Systems and Interface Integration

E. Validation and Verification

F. System Deployment and Post Deployment

Three of the nine concept areas represent necessary process and systems management support:

G. Life Cycle Support

H. Risk management

I. System and Program Management

While other concepts could have been identified, the Friedman –Sage framework suggests these nine are the most relevant to systems engineering in that they cover the essential life cycle processes in systems acquisition and systems management. Most other concept areas that were identified during the development of the matrix appear to be subsets of one of these. The three columns of this two-dimensional framework represent the responsibilities and perspectives of government and contractor, and the shared responsibilities between the government and the contractor. In teaching systems engineering in DoD, there has previously been little distinction between duties and responsibilities of the government and industry activities.

1.2 B-2 Friedman-Sage Matrix

Table 1-2 shows the Friedman-Sage matrix for the B-2 and the areas in the matrix most representative of the five learning principles.

Table 1-2. Friedman Sage Matrix with B-2 Learning Principles [2]

Concept Domain	**Responsibility Domain**		
	1. Contractor Responsibility	**2. Shared Responsibility**	**3. Government Responsibility**
A. Requirements Definition and Management		LP 1 Requirement and Design Integration	
B. Systems Architecting and Conceptual Design	LP 3 Reconfiguration		
C. System and Subsystem Detailed Design and Implementation	LP 4 Subsystem Maturity		
D. Systems and Interface Integration			
E. Validation and Verification			
F. Deployment and Post Deployment			
G. Life Cycle Support			
H. Risk Assessment and Management		LP 5 Risk Planning and Management	
I. System and Program Management		LP 2 WBS Task Teams and Functional Hierarchy	

B-2 Learning Principle 1. Integration of the requirements and design processes is represented by the first row of the concept domain, Requirements Definition and Management. The primary entry for this learning principle would be the Shared Responsibility because of the integration of the requirements team throughout the entire process, even preceding the development of the systems specification, and lasting for the duration of the program. The systems engineering process helps define and manage the requirements and document them in the system specification. Other B-2 vignettes indicative of this concept include the combined team's continuous trade analysis during the design process, the contractor's process for allocating the functional requirements to the design requirements, and the team's ability to develop alternate paths in the face of high risk or high cost requirements.

The responsibility for the beginning of the requirements process lies with the government to start the program that fits within a specific mission area. For the B-2, the DoD had already developed a mission area for strategic nuclear strike and allocated bombers to the Strategic Air Command (SAC), and further stipulated stealth as an operational enabler. However, the capability of stealth as an element of an operationally effective aircraft design was in the early development stages. The government requested industry to assess possible solutions for this mission, so the contractor shared in this responsibility. During the process, both the government and contractor personnel operated on the same team to derive the lower level requirements and to assess the effect of trades on the original top-level objectives. From the very beginning of concept exploration, the responsibility for requirements definition at the operational and the system architecture was a shared responsibility between the contractor and the government and was a vital part of the B-2 program systems engineering process. Initially the government specified a general set of top-level performance objectives and the competing contractors were funded to pursue solutions and to further allocate the technical requirements in an ever-increasing level of detail and specificity. This process iterated continually during concept exploration, and eventually converged to a contract specification.

B-2 Learning Principle 2. WBS Task Teams and Functional Hierarchy fall primarily at the intersection of System and Program Management and Shared Responsibility. While it was the government's responsibility to organize the SPO and the contractor's responsibility to select their own organizational structure, all parties agreed to organize consistent with the WBS. The three major air vehicle company program organizations and the SPO team became part of the WBS Task Teams. In the case of the SPO and the prime contractor, Northrop, and the two primary subcontractors, Boeing and Vought, all were aligned functionally, employed project managers, and constructed teams consisting of multi-discipline members.

B-2 Learning Principle 3. Air Vehicle Reconfiguration energized the team to conduct trade studies, integrate results, pursue alternatives suggested by members on the B-2 team, examine alternative design approaches recommended by interfacing technical disciplines and WBS Task Teams, and report the progress to the program technical and management decision making bodies. This was organized, conducted, and implemented under the contractor responsibility for the System Architecture and Conceptual Design.

B-2 Learning Principle 4. Subsystem Maturity was heavily influenced by the systems engineering process and is again representative of a Contractor Responsibility within the System and Subsystem Detailed Design and Implementation (third row, first column). The contractor and sub-contractor team was responsible for the overall performance and schedule of subsystems. At least a part of the 18 month schedule slip in first flight (from the original contract date of 60 months after go-ahead) may have been avoidable had the reconfiguration impact on subsystems immaturity not occurred.

B-2 Learning Principle 5. The Program employed Risk Closure plans that were constructed by the WBS Task Teams and included all the analyses, tests, demonstrations, and other necessary design work. The work packages were planned into the budget and schedule tools. The entire task teams conducted these activities jointly, so this too, was a shared responsibility. The importance of a single, integrated, jointly developed, program wide risk management process, shared and understood by all, cannot be overemphasized.

The Friedman Sage matrix is used herein retrospectively, as an assessment tool for the systems engineering process for the B-2 program. Its use in this case study does, however, highlight the effectiveness of the concept/matrix as an assessment tool. It should be clear to the student that the application of this tool to an ongoing program by the systems engineering staff and by the project/IPT/functional decision board would provide insight and guidance for action. This tool is highly effective in organizing an assessment of the ongoing effectiveness of the systems engineering process because it covers all aspects of a program. Additionally, since it includes responsibilities from both sides of the program (customer and supplier; industry and government), it is an excellent communication catalyst to assure understanding by both parties.

2.0 SYSTEM DESCRIPTION

The B-2 weapons system consists of the B-2 aircraft and onboard systems, support equipment, training equipment, facilities, and personnel. It includes all hardware and software to make it an operational system. The deployed B-2 weapons system consists of all of these systems working in an integrated manner. The systems engineering process is responsible for the decomposition of requirements, allocation of the requirements to all levels of the design and to all elements, equipments, subsystems, hardware and software of all parts of the weapon systems, and the verification that all requirements have been satisfied.

2.1 Mission

The B-2 Spirit is a multi-role bomber capable of delivering both conventional and nuclear munitions. A revolutionary leap forward in technology, the bomber represents a fundamental shift in the U.S. bomber modernization program. The B-2 brings significant and precise firepower to bear, in a short time, anywhere on the globe, through previously impenetrable defenses.

2.2 Features

The B-2 provides the penetrating flexibility and effectiveness inherent in manned bombers. Low-observables, or “stealth,” characteristics give it the unique ability to penetrate an enemy’s most sophisticated defenses and threaten its most valued, and heavily defended, targets. The capability to penetrate air defenses at high altitude affords the platform efficient long range cruise capability and holds even the most distant targets at risk, provides an effective retaliation capability, an effective deterrent, and a formidable combat force. When coupled with the sister bombers, the combined offensive capability is enormous. The B-52 provides significant payload capability and long-range missiles. The B-1 has a sophisticated Electronic Counter Measures (ECM) suite and largely low altitude penetration routes, further diluting the defenses forces.

The system’s low observability is derived from a combination of reduced infrared, acoustic, electromagnetic, visual, and radar signatures. The low signature levels in these spectra make it difficult for sophisticated defensive systems to detect, track, and engage the B-2. Many aspects of the low-observability process remain classified; however, the B-2’s composite materials, special coatings, and flying-wing design all contribute to mission effectiveness.

The aircraft has a crew of two pilots, a pilot in the left seat and mission commander in the right, compared to the B-1B’s crew of four and the B-52’s crew of five.

2.3 System Design

The B-2 configuration was developed by balancing aircraft performance and survivability based on the mission scenarios laid out by the Strategic Airlift Command (SAC) in the late 1970s and refined in the early 1980s. Views of the aircraft shown in Figure 2-1 show the surface details of the control surfaces, mating joints, access doors, and other interfaces. Of interest is the air data system, shown as sets of four small circles on the top view in front of the cockpit and on the bottom view engine bay doors. This air data system has no standard pitot-static system; rather it senses small changes in pressure and flow as the angle of sideslip and attack change. Another unique feature, also used in the Northrop B-35 flying wing of the 1940s, is the split, or clamshell rudders near the tip of the outboard wing. These surfaces open on one side at a time in response to rudder inputs to control sideslip. They can also be opened simultaneously to provide a speed brake function. They are augmented by asymmetric thrust of the engines to control sideslip during penetration mode[1]. The top view also shows the refueling receptacle aft of the cockpit in the center, about one third of the way back.

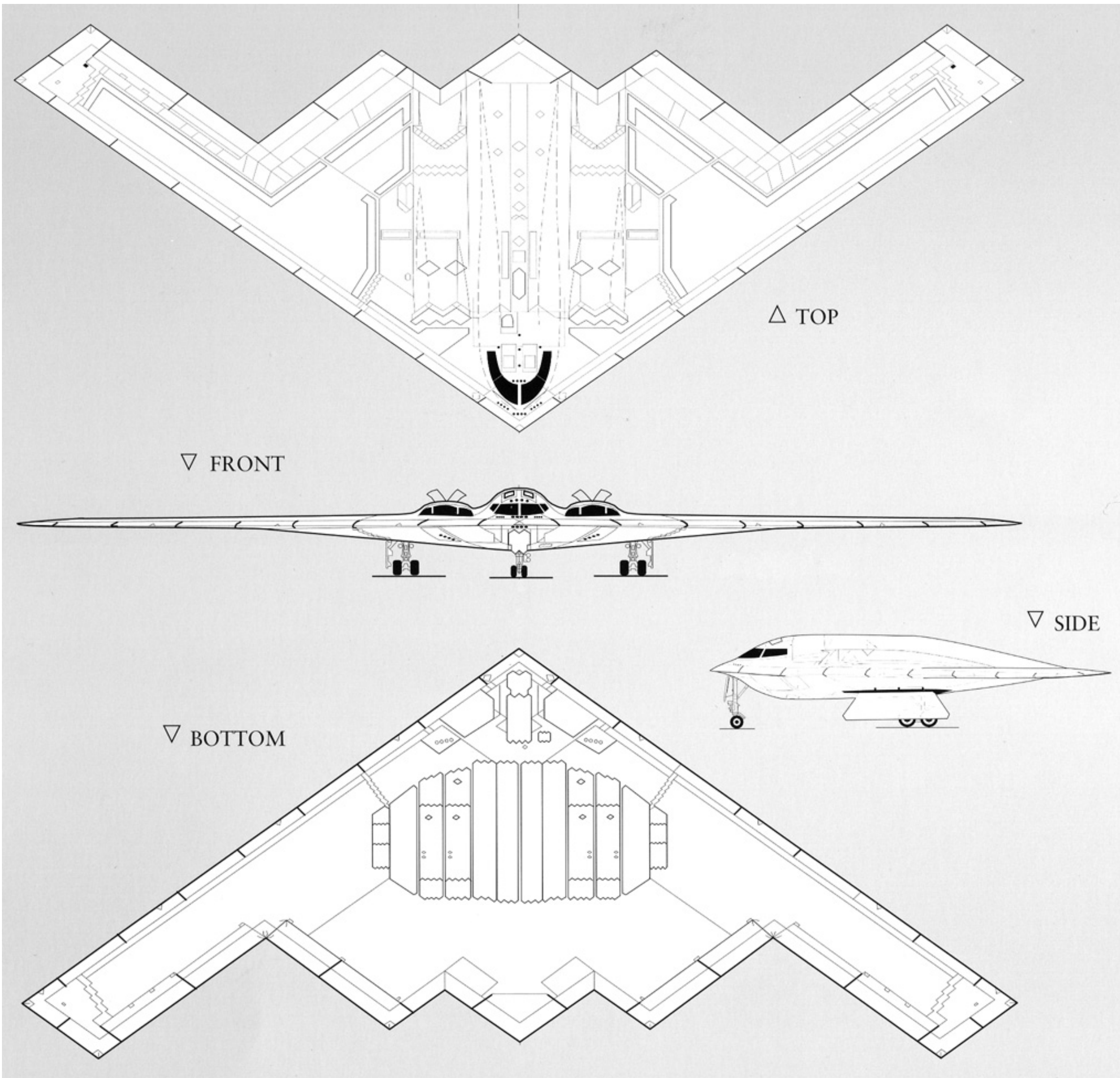

Figure 2-1. External View Drawings of the B-2 Aircraft [1]

The company responsibilities for the design and manufacturing of the air vehicle are shown in Figure 2-2. This was decided early in the program, prior to the company proposal. The prime contractor, responsible for overall system design and integration, was Northrop Corporation. Boeing Military Airplanes Co., Hughes Radar Systems Group, General Electric Aircraft Engine Group and Vought Aircraft Industries, Inc. were key members of the aircraft contractor team.

[1] Also noted in the front view are four auxiliary intake doors protruding above the inlets. These doors, now deactivated, provided additional engine air flow during low speed conditions to reduce the take-off distance.

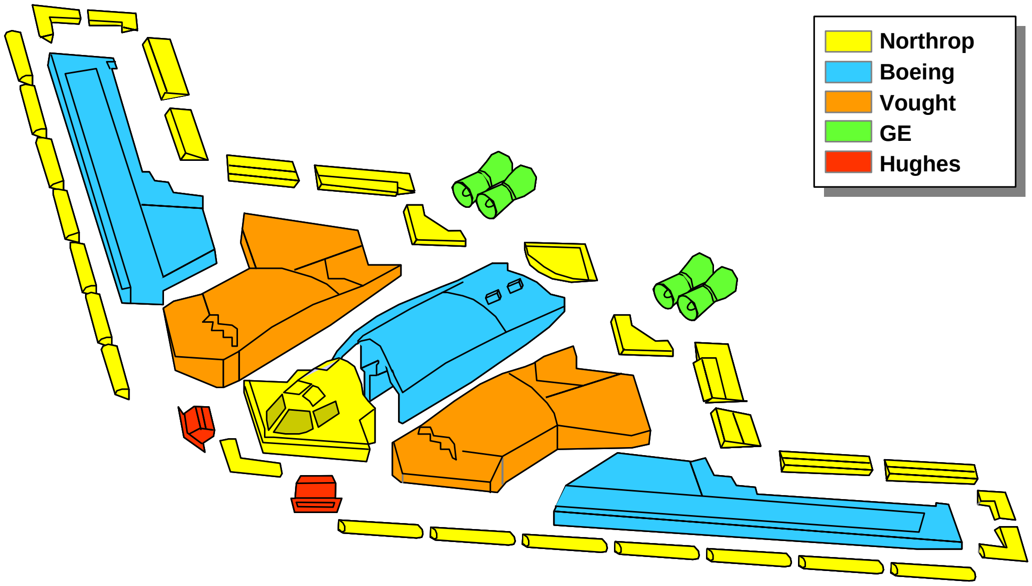

Figure 2-2. B-2 Air Vehicle Isometric View of Primary Manufacturers

2.4 Operational Background

The first B-2 was publicly displayed on November 22, 1988, when it was rolled out of the Engine Run Dock hangar at Air Force Plant 42, Palmdale, Calif. Its first flight was July 17, 1989. The B-2 Combined Test Force, Air Force Flight Test Center, Edwards Air Force Base, California, was responsible for flight testing the development aircraft**.** Figure 2-3 shows the B-2 dropping MK 84 class weapons during testing and certification.

Figure 2-3. B-2 Dropping MK 84 Class Weapons During Testing and Certification

Whiteman AFB, Missouri, is the only operational base for the B-2**,** with 21 aircraft in the active duty inventory. The first aircraft, *Spirit of Missouri*, was delivered December 17, 1993.

Depot maintenance for the B-2 is performed at the Oklahoma City Air Logistics Center at Tinker AFB, OK

Figure 2-4 shows the B-2 in a turn at altitude. Careful examination of the photograph shows the split rudders are deflected, denoting the air vehicle is outside the maneuver limits for the low observable penetration mode. When the aircraft is in penetration mode, the maneuvers are restricted to allow control of sideslip with differential thrust of the engines. When the rudders split to control sideslip, it causes an increase in radar cross section.

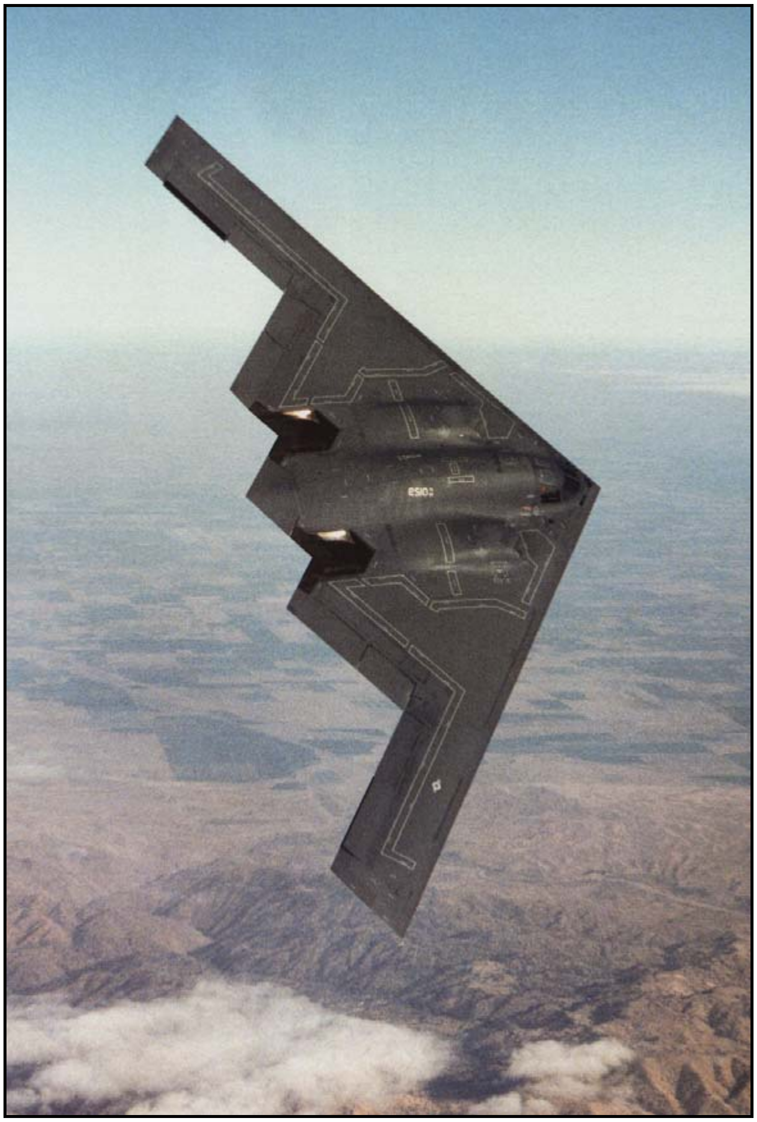

Figure 2-4. B-2 in a turn at altitude [1]

Table 2-1 lists the performance features and weight of the aircraft. The weapons payload in this table gives a quick snapshot of the flexibility of conventional and nuclear armament. The decision early in the program to retain the largest practical weapons bay size has served the growth capability of the air vehicle well, as the length, height, and configuration of the side-by-side weapons bay allows a wide range of carriage options. Additional weapons are planned for certification as the mission analysis shows the effectiveness of other armaments.

Table 2-1. B-2 Weight and Performance Capabilities [1]

	Features
Length	69 feet
Height	17 feet
Wingspan	172 feet
Power Plant	4 GE F-118 engines (17,300 lbs thrust each)
Crew	Two pilots
	Weight Capability
Max Takeoff Weight Max In-flight Weight Max Landing Weight	336,500 pounds 357,500 pounds 311,500 pounds
Max Payload	44,000 pounds
Max Fuel	166,900 pounds
Min Flying Weight Weight Empty	161,385 pounds 149,900 pounds
	Performance Capability
Cruise Performance	6,000 NM, unrefueled at high altitude
Airport Performance Takeoff, Std day, Sea Level Landing, 240,000 pounds	 8,000 feet at maximum takeoff weight 5,000 feet
Speed	High subsonic
Ceiling	50,000 feet
Payload	40,000 pounds
	Weapons Payload
Nuclear Payload	16 B-83 16 B-61-7 8 B-61-11
Conventional Payload	16 GBU-31 (JDAM-84) 80 GBU-38 (JDAM-82) 16 AGM-154A (JSOW-97)

The combat effectiveness of the B-2 was proven in Operation Allied Force, where it was responsible for destroying 33 percent of all Serbian targets in the first eight weeks, after flying nonstop to the Balkans from its home base in Missouri and back. In support of Operation Enduring Freedom, the B-2 flew one of its longest missions to date from Whiteman to Afghanistan and to Diego Garcia, changed crew, and flew back. The B-2 completed its first-ever combat deployment in support of Operation Iraqi Freedom, flying 22 sorties from a forward operating location as well as 27 sorties from Whiteman AFB and releasing more than 1.5 million pounds of munitions. The B-2 has been at full operational capability (FOC) since December 2003.

3.0 B-2 PROGRAM EXECUTION

This section will follow the execution of the B-2 program from the inception of an idea in 1978 to the first flight on July 17, 1989. The discussion will introduce the transition to production and operational activation, but the concentration of the case is on the application of the systems engineering process from the early days to the first flight.

Table 3-1 shows the milestones for the program. The learning principles, LP1 through LP5 noted in the Table, indicate the dates when they first surfaced. This Table should be a handy reference to the reader to keep dates and events in the proper chronological context.

Table 3-1. B-2 Events/Milestones

Event	Date
Concept Exploration	
Vietnam War	1965-1972
Technology investigations	1970-1976
Computer model development	1966-1970
DARPA Studies	1974-1978
XST Phase 1	June 1975-April 1976
Have Blue, XST Phase 2	April 1976-June 1979
Tacit Blue	1978-1985
F-117	Nov 1978 go ahead
ASPA studies	1978-1981
RFP release	Sep 1980 (LP1)
Source Selection	30 Nov 1980-30 Nov 1981 (LP2, LP5)
Low altitude Modification Request	April 1981
Third Crew Member MR	April 1981
Full Scale Engineering Development	
Contract award	Dec 1981
Initial Full Scale Engineering Develop	Dec 1981-Jun 1983
PDR 1	Oct 1982
Reconfiguration	Feb 1983-Aug 1983 (LP3, LP4)
Configuration Freeze	July 1983
PDR 2	Mar-April 1984
CDR	Dec 1986
First Flight	17 Jul 1989
Delivery	
First Delivery to ACC	17 Dec 1993
Full operational capability	Dec 2003

3.1 Concept Exploration

The Concept Exploration phase of the B-2 program started officially when the Advanced Strategic Penetrating Aircraft (ASPA) studies were conducted, which was preceded by several early stealth programs. This phase included the definition of needs by the Strategic Air Command (SAC) and the derivation of the system requirements for the Full Scale Engineering

Development contract. It also balanced the desires of the user between technology risk and capability.

3.1.1 Early Stealth Programs

The concept of stealth technology intrigued aircraft designers from the beginning of the invention of radar. Engineers and scientists investigated various techniques to avoid detection dating to the 1940s. Designs to reduce noise even preceded these efforts. By the mid-1960s, the Air Force Avionics Laboratory at Wright Patterson Air Force Base, Ohio had funded studies to develop radar cross-section prediction computer programs, camouflage techniques, models, materials and concepts [5]. Studies of radar absorbing materials (RAM) and shaping techniques were also funded and had yielded a concept called "iron paint", a technique to embed ferrite particles in a quarter inch thick flexible rubberized film. In the early 1970s, research had continued into methodologies to control the physical scattering of sensor outputs for representative aircraft shapes. Northrop had successfully developed a radar cross-section (RCS) prediction code called GEMSCAT and had successfully predicted the radar cross-section of the F-4. Teledyne Ryan had experimented and flown low radar cross-section drones and had developed analytical techniques for the design of leading-edge RAM.

The early work by both the government and industry during this timeframe resulted in proving low observables could successfully be applied to aircraft, ships, and other vehicles. The current inventory of stealth platforms throughout the military can all trace their roots to these early technology maturation programs and the initial prototype aircraft developed throughout the 1970s.

The experience in Vietnam showed Air Force planners the emerging trend of the expanding threat from radar detection and radar guided missiles. This trend was forcing a change in tactics to assure aircraft survivability. F-4 Wild Weasels were used to encourage the radars to try to illuminate them so the Weasel crews could try to destroy the radars. The constant threat of the more sophisticated and extremely capable radar/missile complexes became a priority in mission planning. However, it was the Yom Kipper War in Oct 1973 that provided the catalyst needed to bring the emerging stealth technology into the forefront of interest and to finally provide the impetus that would result in their emergence as operational systems. The vulnerability of U.S. aircraft to the new and expanding Soviet air-to-air and surface-to-air missiles and their companion radar was a disturbing fact of life. Many of the frontline Israeli fighter aircraft shot down in the Yom Kipper War were the frontline aircraft of their Allies. They were falling victim to the front line Soviet radars at an alarming rate. In 1974, the Defense Advanced Research Projects Agency (DARPA) initiated studies to determine radar cross-section levels required to defeat the Soviet threats and various ways these levels may be achieved. Northrop and McDonnell Douglas received contracts for this work. Lockheed was soon added to the list.[2] DARPA initiated the Experimental Survivability Testbed (XST) program in the summer of 1975 to conduct aircraft systems analysis on low RCS vehicles and to conduct radar cross-section testing of representative configurations and components. Northrop and Lockheed both received a Phase 1 contract to test models of their concepts mounted on a pole at the

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[2] An excellent summary of the early works in low observables, along with the details of Have Blue and the F-117A can be found in Reference 4.

government RCS test range at White Sands Missile Range, NM. Lockheed was selected as the winner for Phase 2 in a close competition in April 1976 and flew the first Have Blue aircraft December 1, 1977[3]. Figure 3-1 shows both the Lockheed and the Northrop XST proposal configurations.

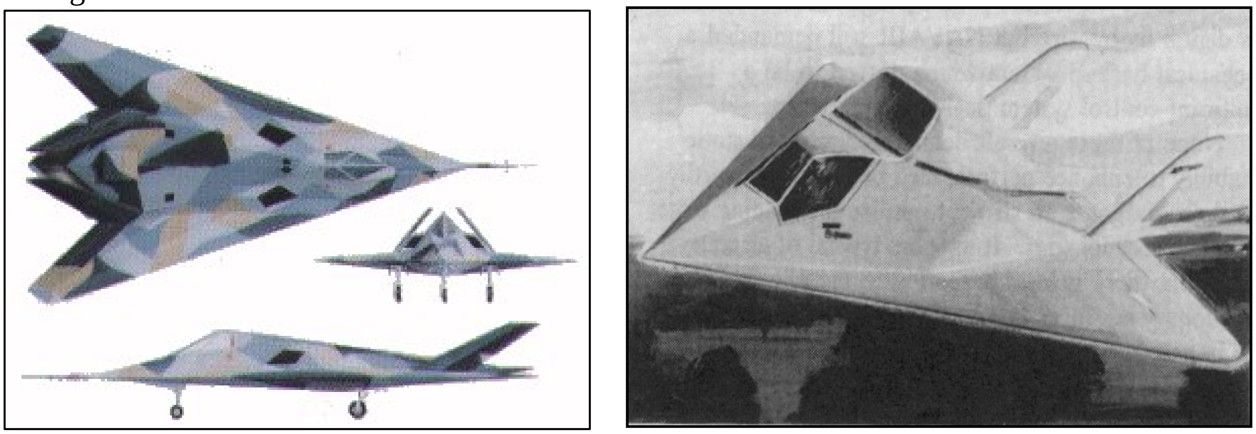

Figure 3-1. Lockheed Have Blue (left) and Northrop (right) XST Aircraft [5].

Northrop was encouraged by the Air Force and DARPA to continue their stealth technology efforts following the loss of the XST competition. Northrop continued research on new techniques to reduce RCS and predictive code development using IRAD funding and funding from DARPA. Their promising efforts resulted in the award of a contract to develop a low observable reconnaissance aircraft with a new radar concept offered by Hughes called Low Probability of Intercept (LPI). This program resulted in the Tacit Blue aircraft[4] which first flew in February 1982 and would complete 139 flights over the next four years. Most importantly, this aircraft became the radar cross-section demonstration vehicle that validated the design approach for the B-2. This aircraft played a significant role in the maturation of stealth technology, prediction codes, edge RAM, shaping (controlled curvature as opposed to flat sided shaping per the XST), engine inlet integration, coatings, and the tailoring of the RCS pattern, all of which were vital to the development of the B-2. The development program gave Northrop the experience and validated these vital aircraft details. The Tacit Blue aircraft is shown in Figure 3-2.

3.1.2 Advanced Strategic Penetrating Aircraft (ASPA)

The genesis of the Northrop B-2 stealth bomber program was a funded study initiated by the Air Force in January 1980 to examine the feasibility of developing a long-range strategic bomber employing low observables or stealth features. This aircraft study was named Advanced Strategic Penetrating Aircraft, ASPA[5]. Low observables had proven it was a practical

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[3] Both Have Blue aircraft were lost in flight test accidents, the causes unrelated to stealth technology.
[4] The aircraft is in the National Museum of the Air Force in Dayton Ohio.

[5] The aircraft was later officially named the Advanced Technology Bomber, ATB, by the end of the source selection. It was officially named the B-2 in September 1984.

technology during flight-tests of the Have Blue aircraft from December 1977 to July 1979. The development of the stealth fighter, the F-117 full scale development contract had been awarded to Lockheed Skunk Works in Burbank, California in November 1978, so the concept for operational deployment of stealth aircraft was evolving and maturing in the Tactical Air Command.

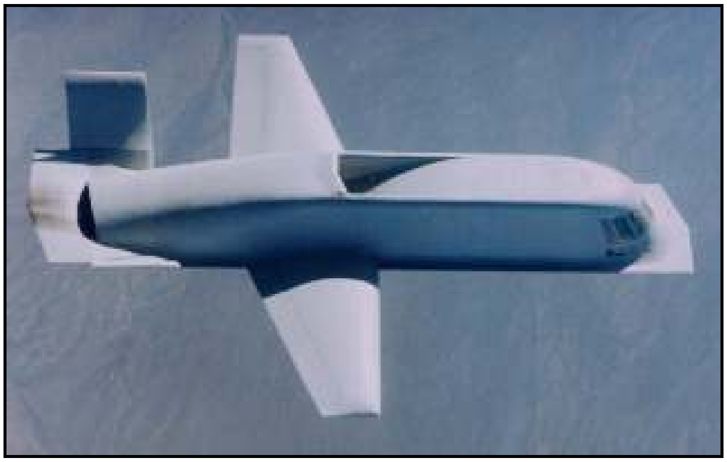

Figure 3-2. Northrop Tacit Blue [5].

The Strategic Air Command had taken notice of the potential opportunities afforded by stealth and the Plans Division initiated internal studies on the value of stealth to penetrate the extensive Soviet defensive radar suite in early 1978. SAC was particularly interested in the new technology as it may be applied to a new penetrating platform because President Jimmy Carter had cancelled the B-1A program in June 1977. This situation left the User faced with continuing their mission with the conventional and older B-52 and the FB-111.

3.1.3 ASPA Study Contracts

Northrop was approached by Lt. Gen. Stafford, USAF/RD, in the second quarter of 1979 and asked to study the application of their approach to the low observables technology to the ASPA[6]. Their approach to LO used smooth contoured shaping of the exterior surface, as opposed to flat-sided panels, as characterized by Lockheed's F-117. Once Northrop committed to conduct a company-funded study in mid 1979, USAF/RDQ and SAC provided a limited number of experienced, on-site/on-call representatives to provide functional and performance requirements guidance as Northrop examined various performance and planform alternatives for performing the strategic missions.

The LO technology knowledge base imposed constraints on the capabilities that could be examined for the ASPA – i.e. design of a LO treated supersonic inlet was beyond the state-of-the-art. Northrop's efforts soon began to focus on the feasibility of integrating a very aerodynamically efficient (high Lift/Drag ratio) and LO compatible planform – the flying wing. This was compared to a subsonic low altitude penetrator to glean the benefits of the competing approaches. Sufficient progress was made the rest of the year to induce the USAF to award Northrop a concept study and demonstration contract in January 1980. The contract called for

[6] Lockheed was already working under an Air Force contract to study a penetrating bomber feasibility for their faceted conceptual approach to low observables

wind tunnel model tests of the aerodynamic configuration and large-scale RCS model tests of the same external mold lines, in addition to continuing the development of the aircraft and weapon system conceptual designs.

Once Northrop had agreed to study the ASPA in the late spring of 1979, the Systems Analysis group within Northrop Advanced Projects formulated a matrix of analyses, each addressing a feature of the long range penetration bomber effectiveness. The independent variables were engineering parameters of systems and, in some cases, subsystem design. This analysis technique had generally been known as “Measures of Effectiveness” (MOE). Advanced Projects had started constructing MOE analysis models as early as 1976 during Northrop’s participation in the XST program and continued refining and expanding its models during the conceptual and preliminary design phases of Tacit Blue. Central to this capability was a very simple generic, all-aspect, multi-frequency RCS description that was empirically based on the knowledge accumulated by AP’s RCS engineers from the thousands of experimental tests on the radar range. This model construct was so flexible that it could be used to help the designers to synthesize aircraft configuration. All prior RCS models were far to complex and were only useful for analysis of already created configurations.

The ASPA studied the same objectives of all intercontinental strategic bombers, namely 6,000 nm range unrefueled and 10,000 pounds of payload. The attractiveness of stealth to enhance survivability gave the edge to the ASPA platforms over then conventional approaches, although all previous approaches were considered, including ECM. By appreciating that a wide variety of aircraft and configurations can be made to fly adequately with sufficient thrust and fly-by-wire stability augmentation, an aircraft’s wings-level best case range payload features can be estimated with just a two dimensional planform representation.

The MOE addressed as dependent variables a number of mission parameters such as range, penetration altitude, and, most importantly, the elements of what constitutes survivability, such as detection range, time-in-track, firing opportunity time, etc. Without a preconceived notion of what the weapon system would physically look like, engineering parameters, such as leading/trailing sweep, inlet/exhaust location, etc., were traded off as independent variables. Features of the three basic aircraft types, wing-body-tail, flying wing, and blended-wing-body (delta) were studied because the MOE analysis was made as deterministic and transparent as possible, widespread confidence in the engineering tradeoffs was easily achieved. In less than two months of study addressing worst case air defense scenarios projected 20 years to the future, the most effective RCS features became obvious. Significantly, the analysis showed it was possible to configure the bomber for survivable penetration (of air defenses) at high altitude. A less stressing low altitude penetration would be even more survivable, albeit with a less efficient aircraft [3, Griskey].

The effort during this period was focused on system engineering studies of the weapon system, air vehicle, avionics, and armament systems; conceptual design and trade studies of the airframe structure and subsystems concepts; development testing of large and small scale LO and aerodynamic models and representative structures; and the conceptual construct of manufacturing and logistics support plans. The presence of the SAC and RDQ representatives greatly facilitated these efforts, because Northrop did not have a large knowledge base of SAC operations and the SIOP missions.

By mid-year (1980), USAF had seen sufficient progress by both contractors that they instructed Aeronautical Systems Division (ASD) to prepare a request for proposal (RFP) for Full-Scale Engineering Development (FSED) of the Advanced Technology Bomber (ATB) [3, Glenn]. The contractors began to augment their staffs to respond to the RFP. Both Lockheed and Northrop elected to compliment their resources with out-of-company assistance for the program. Lockheed selected Rockwell as a partner in 1978, notwithstanding they were not currently pursuing any stealth programs with the Air Force or DARPA and were the obvious choice to build the B-1B if Ronald Reagan won the election over incumbent President Carter. Northrop selected Boeing and Vought as "teammates," notwithstanding their inexperience in low observables, and Boeing's reluctance to accept a contractual relationship as a subcontractor.

Throughout 1980, the program evolved rapidly from a Concept Study to a full-blown design and proposal effort on the Advanced Technology Bomber (ATB). It was the efforts of the government and industry during the time frame of 1979, through 1980, and ending in the summer of 1981, that the requirements for the B-2 were derived, traded and balanced, approved, and documented. This early study effort, the RFP preparation by the government, the FSED proposal response prepared by Northrop and Lockheed, and the subsequent source selection and contract negotiation were the key events during this crucial time for the program.

During the Study Phase, industry and government team staffing was minimal. The program management on the government and industry sides was able to convince their respective headquarters that the most experienced and technology-oriented personnel should be assigned to the preliminary design effort on a full-time basis. Northrop assigned Jim Kinnu from the Aircraft Division to be the program manager, Irv Waaland from Advanced Design as the Chief Engineer, John Cashen from Advanced Technology as the lead technologist and George Friedman, Vice President for Engineering from Northrop's Electronic Systems Group (ESG) to lead the avionics architecture derivation. See

Figure 3-3. Shown are Irv Waaland (left), Steve Smith, Aircraft Division Vice President and John Cashen (right)

Although there was no formal system engineering organization or construct in the study, the system architecture and preliminary design were accomplished using the systemic skills of the highly experienced team members. The small size of the group, coupled with their experience and their "systems thinking" attitude, examined the trade space available to low observables, including high and low altitude and from low subsonic to high subsonic speeds. This led to the eventual selection of a preliminary conceptual design and architecture which balanced aircraft performance requirements with emerging technology and innovative design. Some of this data is captured in Appendix 4. Crucial to this rapid convergence was the participation by Air Force management and technical personnel, increasing the speed and communication between government and contractor with a spirit of cooperation that has not been observed either before or after the B-2 program [3, Friedman, et. al].

Despite the lack of formal organization and processes, the systems engineering methods employed by the team would have been acceptable in today's manuals [3, Friedman] on how systems engineering should be conducted in the early phases: focus on mission requirements and campaign models – augmented by many in-depth discussions with operational personnel, functional flow diagrams, requirements flow down and trade studies. Communications were accomplished by a "sea of thousands of viewgraphs", with the decisions of each meeting compactly captured by a page or two of memos, signed by the stakeholders of that part of design. Several rooms with sheet metal walls were devoted to the building of the many presentations always in process, with a complex "configuration management" control on the status of approval of each slide.

It was during the study phase that the fundamental architecture of the B-2 avionics system was derived. The major architectural decisions were in the areas of the radar, navigation, crew station, computer, software, and data bus. Three primary objectives were established for the design trades: in order of priority [3, Wheelock]:

1. Survivability
2. Effectiveness
3. Range/payload and Lift/ Drag (L/D)

Survivability's components included reaction time, takeoff distance, observables, system hardness, altitude, speed and active defense. Effectiveness's components included range, navigational accuracy, target acquisition, bomb damage assessment, reliability, payload, weapon accuracy, and speed. Weight has long been, and continues to be, a driving system requirement. It is useful as a cost estimation relationship, but also drove the B-2 high altitude capability and range.

The navigation subsystem trade off for reliability indicated the need for redundant navigation subsystems. Other long-range bombers had two inertial navigators initialized by a period of gyro compassing and radar fixes during climb out, requiring updates by additional radar fixes at intervals along the route. Reaction time was a critical issue regarding initial air strikes against our bases; thus the bomber needed a navigation system that could be operational within the timeline of other startup functions. Also survivability concerns dictated minimum emissions for navigational updates, especially at high altitudes above enemy airspace. Other navigational considerations included the need to deliver gravity weapons with high precision after long periods over water where updates were not available. The derived architecture identified an astrotracker with dual inertial platforms along with Low Probability of Intercept (LPI) radar updates[7].

Radar subsystem decisions were also made early on that had far reaching implications. Although the primary mission was strategic nuclear strike, careful consideration was given to the likelihood of tactical, conventional weapon delivery. Tradeoffs were made, especially in the area of the radar resolution, where studies were made regarding the benefits of higher resolution: higher navigational accuracy, superior ability to acquire a wide range of target classes and to perform bomb damage assessment, pattern recognition and the ability to deliver weapons more accurately in a "relative guidance system" manner.

[7] While the system currently has GPS, it was not initially available but full provisions were incorporated as part of the FSED contract.

Myriads of technical decisions were made for the aircraft and the avionics subsystems. All were approached by an architectural flow-down to successively provide a more precise definition for the approach to achieving the best blend of aircraft, avionics, and stealth characteristics in an operationally useful, survivable weapons system that would stand the test of time in a wide range of conflicts. See Appendix 4 for portions of this final out-briefing of the Northrop study to Lt Gen Stafford. The study effort by the contractors formed the basis for the preparation of their responses to the ATB Request for Proposal, released by the Air Force on 1 September 1980 to Northrop and Lockheed.

3.1.4 Source Selection

The source selection and evaluation of proposals was accomplished in a unique manner. The proposals were evaluated at the contractor's facilities using a team of highly qualified experts assembled from across Air Force. The team consisted of 60 evaluators, of which 35 were engineers from Wright Patterson Air Force Base, OH. These engineers were handpicked from all the programs in development at WPAFB and represented the technical leader in each functional area. The people were assigned to the source selection team until the source selection was finished (estimated as 2-3 months full time, then as-needed until contract award), after which time they would return to their initially assigned programs. Because these people were working the most important projects in the Air force and held key positions, this decision showed an early and significant commitment by the leadership of the Air Force.

3.1.5 Development of the Weapons System Specifications

When the source selection started on November 30 1980, the government Source Selection Evaluation Board (SSEB) team, chaired by Col Joseph K. Glenn, traveled to the contractors' facilities to conduct the evaluation. The contractors each provided the SSEB with secure office space, isolated from the contractor's team, but in close proximity. Accomplishing a source selection at the contractor's location was an unprecedented approach for large weapons system procurement and it turned out to have a very positive benefit. It further cemented the close working relationship between the Air Force and the prime contractor that had started in the initial study phase and it assisted markedly in requirements development.

The general ASPA system requirements in the RFP were derived from the results of the company studies that started in 1979 and were underway in 1980 when the RFP was prepared. Each contractor had assembled design teams and performed many system engineering analyses and trade studies to define and refine their initial system conceptual approach. The requirements, however, had not been fully discussed with the government evaluation team, as most of the members were new to the program, having recently been briefed on the existence of the program. The iteration process of the requirements and the design occurred over the first six months of the evaluation of the proposals and was conducted jointly by both the Air Force requirements team and the contractor's design team.

Table 3-2 shows the key RFP requirements, the contractor's proposed value, and the value as included in the specification.

Lockheed and Northrop used their resultant conceptual designs from the study contracts as their preferred approach to prepare their responses to the RFP. Each had conducted many trade offs between classic aircraft performance characteristics (figures of merit) and levels of low observables (radar cross section, infrared emissions, visual, acoustic, and radio frequency emissions). Subsystem design approaches were evaluated against the general requirements for the study to select the best internal equipment and their arrangement. The derived design from Northrop was a very aerodynamically efficient, high altitude cruise design with a balance of good aircraft performance and low observables levels. The primary role of the ASPA was for long range, high altitude cruise penetration of the Soviet radar network. There were 14 missions stipulated in an appendix for calculation of range, payload, PSR, structural durability design spectrums, and anything requiring an operational mission for events, weapons, environments, and penetration corridors. The proposed system concept was designed for HI-HI-HI-HI missions, such as the one in Figure 3-4, which is duplicated from the original 1980 study. It is shown here for illustration of a typical HI-HI-HI-HI mission.

Table 3-2. RFP and Specification Requirements

Document	RFP	Proposal	Specification
Range nautical miles	6,000	8,500	6,000
Payload lbs	40,000	40,000	40,000
Low altitude alt above terrain Mach	 Residual Capacity	 400’ w/o TF 0.6M	 200’ w/ TF 0.7M
High altitude Cruise altitude Cruise Mach	 >35,000 ft >0.8M	 >50,000 ft >0.8M	 50,000 ft max >0.8M
PSR	0.90	0.90	0.90
Wing span	--	172 ft	--
Gross weight	--	269,000 lbs	--
Legend TF = Terrain Following PSR = Primary System Reliability			

There was also a mission for HI-LO-LO-HI operation stipulated in the original RFP, but this was a fallout capability, not a specific design point. See Figure 3-5, again duplicated from the original 1980 study, and shown with the low altitude concept as illustrative of a HI-HI-LO-LO mission. The low altitude mission in the original RFP did not stipulate the maximum speed or terrain following altitude capability. It should be noted that because this was neither a specified design point nor a primary mission, the contractors’ high-altitude design would not have added additional functionality to address a low altitude/ high speed operation.

A large scale radar cross-section (RCS) pole model of each contractor’s conceptual design was initially built and tested at the RASCAT facility, White Sands, NM as part of the Study Contracts. Both contractors modified their models and retested them during the evaluation. The data formed the basis of the RCS trade studies, the preliminary RCS specification, and the survivability assessment by the SSEB during the evaluation period.

Each contractor had prepared specifications, a Work Breakdown Structure (WBS), the contract Statement of Work (SOW), and model contract as part of their proposal submittal. When developing the specifications, each contractor documented its design approach in a very descriptive Part II specification format. These specifications, however, were far more descriptive than desired by the Air Force. The government desired only a performance-based Part I type specification for the contract, with the eventual Part II specifications to be developed during the conduct of the program by the selected contractor.

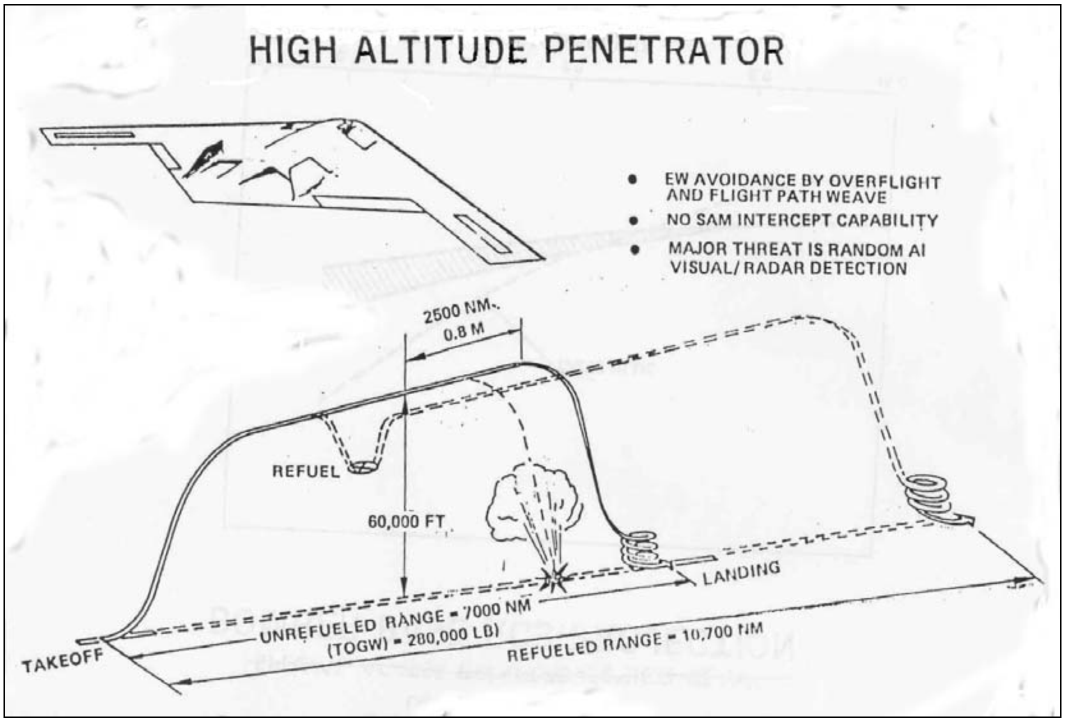

Figure 3-4. Typical HI-HI-HI-HI Mission from 1980 DARPA Study.

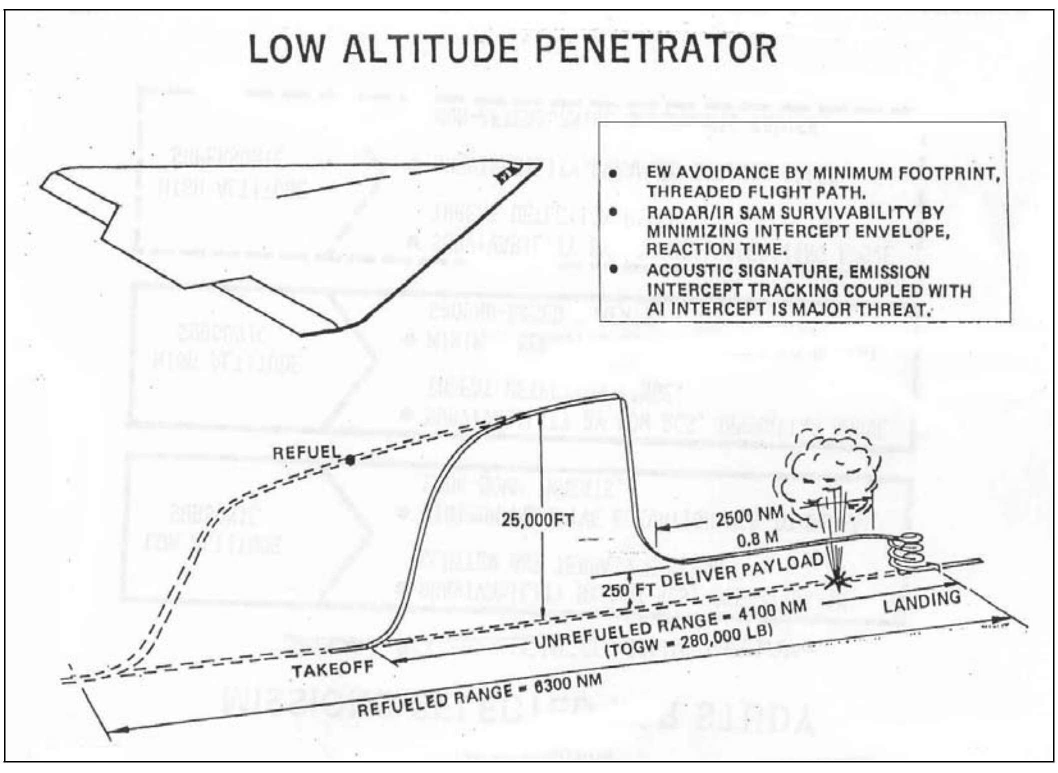

Figure 3-5. Typical HI-HI-LO-LO Mission from 1980 DARPA Study

The government team immediately started to prepare a complete set of performance-based specifications for the entire system (Weapons System, Air Vehicle and Engine specifications). Concurrently, they were conducting the evaluation of the proposals. Since each of the members of SSEB was handpicked for their expertise and was well experienced in the development of specifications, they were all given the latitude to leave the government evaluation area and speak directly with the contractor's engineer in their technical discipline. This dialog created an understanding by the evaluator of the implication of their proposed performance requirements on the difficulty to design and integrate its subsystem. It also gave the designer a detailed understanding of the objective of the requirements. This communication generated an outstanding understanding by both parties of the implications of each requirement and the difficulty of the design to achieve them.

If an evaluator did not understand why the contractor engineer had chosen a particular path, or the evaluator thought there might be a better approach, the evaluator was allowed to talk directly to the contractor engineer at their desk. They would discuss the mission, the design approach for the technical discipline, and develop an understanding of what they both thought was best for the overall system. Following the dialog, the government evaluator would construct proposed specification language and present the proposed requirements wording to the specification board for incorporation into the government performance-based specifications. If the proposed approach and the requirement wording could be defended before the board, it was incorporated. It was common for several iterations to occur between the technical area specialist, iterating the wording with the contractor counterpart and the specification board before the final language was adopted. Only the government personnel attended the specification board meeting. Northrop also had an informal board that examined and ruled on all of the Contractor Inquiries (CIs), Deficiency Reports (DRs), and Modification Requests (MRs) sent in by the government evaluators, most of which had been prepared with the help of the contractor counterparts. All specification changes were processed by MRs.

Another significant event occurred during the source selection, this one regarding the engine. The RFP stipulated the engine would be Contractor Furnished Equipment and the contractors bid accordingly. During the source selection, the SSEB [3, Abell] recommended to the SSAC (chaired by Gen Lawrence T. Skantze, with membership of Maj Gen James "Abe" Abramson, and Maj Gen Monroe T. Smith) that the engine should be a separate contract, managed by the SPO with support from the Engine SPO at WPAFB and the suggestion was approved. The engine was selected as Government Furnished Equipment and a separate source selection was conducted. General Electric was eventually selected over Pratt and Whitney.

3.1.6 Development of the Low Observable (Stealth) Requirements

Specifying the requirements for radar cross-section, infrared signature, visual, acoustics, and emissions was a new discipline and a new challenge, not only in developing format that could be tested and verified, but also in the required levels for each of the signature areas. The program specification tree developed as part of the contract required the Low Observables Specification to be developed as an addendum to the Weapon System Specification. During the B-2 source selection, the specification addendum was developed jointly by the Air Force and contractor using the data from the RATSCAT tests and with the evaluators estimating the operational effect of the patterns on penetration[8]. The operational effectiveness/mission analysis

[8] USAF/RDQ contracted with the Calspan, Buffalo, NY to conduct preliminary operational effectiveness/mission analysis that was running in parallel with the evaluation.

specialists from both the government and contractor assessed the required level of signature against a multitude of threat lay downs. Soviet threat radar capabilities were well known against various levels of cross-section vehicles and against some of the US countermeasures. As the two teams conducted their analyses and compared results, the required levels for the radar signatures were developed through an iterative process. However, it was only developed using preliminary patterns and estimates of penetrability and not a war game scenario against multiple, netted radars and specifically located targets as would typically be done in a full Analysis of Alternatives (AOA). The contractors did not have the means (tools, people, approved war-game computer programs) to conduct comprehensive penetration analysis. The government had the capability (but not full spectrum of capability for the conduct of the source selection) and shared their result with the contractors. The two teams then constructed the format and wording of the specification jointly, greatly enhancing the understanding of the requirements by all parties. The resultant RCS specification table was based on the estimated performance of the patterns against the radars and was written in terms of 50% and 90% "exceedances" for the azimuths and elevations of interest.

All the specifications developed during source selection were part of the contract between Northrop and the government except the RCS specification addendum. Both the contractor and government agreed the data on the configuration was not sufficiently mature and that the RCS model required updates and further testing. Further, they agreed on the need to conduct additional penetrability analysis with refined data before the table could be completed with the confidence necessary for a design basis. To assure this had time to mature; a B-2 specific force-on-force campaign model was developed and was functional by PDR 2. This model would test the B-2 force capability annually as the design matured and the nature of the threat improved. The independent variables were the bomber's projected aero and RCS performance. Target locations and the Soviet Union's estimated air defense order-of-battle were provided by the USAF. A number of unaided B-2 sorties, on the order of 25, were mission-planned using what ultimately became the operational B-2 mission planning computer model. The missions were "flown" against the un-degraded threat and the statistical outcomes combined into a "probability of mission success" for the forced structure. The force "probability of survival" was also addressed. This annual analysis effort helped give decision makers insight into the cost-benefit of the B-2 force as it was being developed [3, Cashen]. A contractual agreement was established to finalize the Observables Specification as a function of "mutual agreement" after both large scale high-quality model tests and after additional survivability/mission penetrability analysis could be conducted. The process to derive a final set of requirements was time consuming and put both the contractor and government at risk from contract award to signing. The benefit, though, was the derivation of a clearly understood set of requirements that all parties reached with mutual agreement. The specification addendum was placed under configuration control shortly after PDR 2 [3, Sunkes].

3.1.7 Low Altitude Modification Request (MR)

The evaluation of the contractors' proposals proceeded on site at the contractors' facilities throughout December 1980, through January and into February 1981. The Source Selection Advisory Council (SSAC) received regular briefings on the progress of the evaluation and the outcome of the ongoing survivability assessment. The SSAC concluded that growth provisions for low altitude capability would be a prudent hedge against an ever-changing and maturing radar threat operational throughout the Soviet Union. Accordingly, a Modification

Request to the RFP was issued in April 1981 to request a study for the impact on the design to include a significant low altitude penetration capability, beyond the fallout capability from the high altitude designs. The scope of the request was to examine completely new designs, in addition to studying a modification to proposal baseline of a high altitude cruise design approach currently favored by each contractor and the primary Air Force user, the Strategic Air Command (SAC). The redesign activity involved the contractors' design teams and the Air Force technical specialists (mostly from the list of the original evaluators who were called back to work on the program for several more weeks). The combined contractor/Air Force team jointly examined the trade-off between survivability, low altitude penetration speed and altitude, and the impact on the range and cruise performance of the primary high-altitude design point. The resultant design that emerged from this integrated systems engineering activity was a modification to the baseline high-altitude design approach. The structure was beefed up by about 10,000 pounds but the basic structural design approach was retained. Most of the subsystems were immature at this time and were not substantially impacted.

One of the changes added an isolation pallet to the Northrop configuration in the cockpit to mount the ejection seats and instrument panel. The purpose of the pallet was to improve ride quality to increase the crew's performance during long exposures to turbulence. Later system engineering studies on the effect of the pallet showed it was too low in frequency and amplitude to damp the damaging effect of turbulence on the crew's performance, so it was deleted. This interaction of the two teams during this redesign activity further solidified what would emerge as a highly integrated contractor/Air Force team that worked closely throughout the entire design, development, and production phases of the program.

A clean sheet analysis examined many alternatives to optimize low altitude penetration capability (which had originally been examined in the ASPA studies), but in every case, emphasizing the low altitude mission drastically reduced high-altitude mission range. Most of the configurations required afterburners to meet takeoff requirements and extensive refueling to meet the defined penetration missions. All new designs were discarded as poor candidates for an optimized strategic bomber. The study confirmed it was most cost effective and operationally effective to modify the high altitude design to perform the low altitude mission than to design for only low altitude and try to extend the range by making a larger aircraft.

3.1.8 Contract schedule

The contract schedule was developed by the Source Selection Evaluation Board, SSEB, (under the guidance of the Source Selection Advisory Council, SSAC) throughout the evaluation process in 1981. The contractors had proposed schedules based on reaching first flight in 48 months from go-ahead. This was responsive to the RFP but left many questions regarding risk reduction and risk mitigation prior to the commitment of the large amount of resources necessary for a Full Scale Engineering Development, FSED program. The SSEB judged the schedule as high risk and suggested to the SSAC a program of 60 months to first flight with a one year initial FSED program to allow time for risk reduction. This was briefed to the SSAC who requested a schedule that allowed 108 months to first flight. The SSEB disagreed with the long schedule, claiming it was also high risk because the team would proceed too slowly for too long; it would be unlikely that the team could accelerate to the required FSED pace once risk reduction had been achieved. After much deliberation, a 72 months schedule to first flight was approved. This allowed a two-year period for risk reduction and risk mitigation through the risk closure planning process.

One other key decision was to approve a combined Full Scale Engineering Development (FSED) program, together with an Initial FSED phase for formal risk reduction. The purpose of the Initial phase was to formally structure a risk reduction program prior to committing the large funding required to start the FSED. This allowed a risk reduction activity to lower the risk to "moderate to low" prior to PDR 2. The benefit of including it in a complete FSED program was to avoid separate contracts and avoid re-entering the Air Force decision process [3, Glenn]. Finally, a cost plus incentive fee structure was developed for the contract[9]. The funding profile for this program was then developed and became the baseline for the contract.

3.2 Contract Award

Northrop was announced as the winner of the competition on 17 October 1981 and the $9.4B FSED contract was signed on 4 December, 1981. The schedule for all major program milestones is shown in Table 3-3, which shows the original contract schedule and the actual date upon which the event occurred.

Table 3-3. B-2 Major Program Milestones

Milestone	Contract Date	Contract, MAC	Actual MAC Achieved
Contract Award	December 1981		
PDR 1[10]	October 1982	11	11
Configuration Freeze	July 1983	19	19
PDR 2	Mar- Apr 1984	28	28
ICDs	June 1984	30	32
CDR	December 1985	48	48 structures 51 Engine/inlet 54-56 subsystems
First Flight	December 1987	72	90
Legend PDR - Preliminary Design Review ICD - Interface Control Documents		CDR - Critical Design Review MAC- months after contract go-ahead	

A significant feature of the risk reduction phase was the incorporation of the Air Force Research Laboratory's Manufacturing Technology Division (MANTECH) efforts into the B-2 program. This was a vital strategy to reduce manufacturing and fabrication risk of the large-scale composite parts required for the program success. Through the B-2 SPO, contracts were given to Vought for fastener insertion in composites, large scale articulating head tape laying machines, composite water jet cutting techniques, and non-destructive verification of completed parts. Boeing received MANTECH contracts for pultrusion, autoclave methods, ultrasonic inspection and machining. Northrop received authorization for development of a Material Handling System and loading of radar absorbing material (RAM).

[9] Fixed price contract strategies were discussed during the source selection process, but were never a serious consideration [3, Glenn].

[10] PDR 1 was a milestone to approve several of the subsystem specifications, the defensive suite specification, and the weapons complement. PDR 2 was a classic PDR.

3.2.1 Systems Engineering Organizations

The Air Force System Program Office (SPO) was very interested in a formal systems engineering organization and formal systems engineering processes that would be defined, documented, and followed by the prime contractor and the two major subcontractors. A formal Systems Engineering Management Plan (SEMP) was not a contract requirement in the original contract, but the work plans stipulated a formal flowdown of the top level weapons systems requirements into system functional specifications as part of the approved specification tree[11]. The contract required development of six configuration item specifications at a level below the Air Vehicle specification:

- Flight control
- Avionics
- Radar
- Armament
- Low observables
- Software

Systems engineering on the B-2 program was federated with many organizations participating in the execution of the systems engineering process. Described herein are the primary organizations that existed during the majority of the time frame from program go ahead to one year after CDR. These organizations were instrumental in implementing the systems engineering process throughout the program, for allocation of requirements, and assuring the design WBS Task teams were integrated in their efforts. [3, Griskey]

Weapons Systems Engineering (WSE)

The Weapon Systems Engineering (WSE) organization was established purposefully to focus on the evaluation of the weapon system's mission effectiveness, survivability, and vulnerability, and at the same time be the repository for all stealth technology development and evaluations. This unique "marriage" of the classical weapon systems analysis system engineering functions and the stealth technology design development activities was driven by two factors: (1) the fact that the technology development activities were heavily directed by the constant interchange with the survivability analysis function to assess the "value" of the RCS signature achieved in the context of the threat systems; and (2) the fact that by combining both these activity groups into one organization, the Program had consolidated the two generators and repositories of Level IV, Top Secret data which required special handling and protection even in program areas. (The Air Force also organized their functions similarly and they reported to the Director of Engineering through the Chief Systems engineer.)

The WSE organization consisted of eight separate groups: system analysis; survivability analysis; vulnerability analysis (including nuclear hardening); Low Observables (LO) technology engineering; LO materials & processes development; LO materials laboratory; anechoic laboratory; and Grey Butte test range. The last two groups were removed from the B-2 Program chain and became a Division facility for use by the entire Division three years later. The

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[11] The SEMP in Appendix 5 is reflective of the organization in 1989.

activities of the six principal organizations are discussed in the following paragraphs. The latter two organizations roles are inferred by their titles: the anechoic laboratory was a specific facility that could accomplish RCS measurements of specific full-scale, embedded aircraft antenna models and aircraft full-scale, edge assemblies; and the latter, was a company-owned, test range where small-scale complete aircraft models and large-scale models of specific design features (e.g. inlets) could be tested on a pole at various bandwidths, polarities, and attitudes.

The classical weapon system analysis functions – mission effectiveness, survivability and vulnerability – were established as separate organizations because of the amount of activity that each had to perform. The mission effectiveness group was the repository for all threat data furnished by the USAF's Foreign Technology Division (FTD) and the "what if" Red Team of scientists that the USAF/RDQ employed at MIT to "challenge" the development team. The mission effectiveness organization developed a "force-on-force" campaign model that was used to evaluate the effectiveness of the B-2 force capability annually as the design matured and the nature of the threat improved. Target locations and the Soviet Union's estimated air defense order-of-battle were provided in threat documents. A number of unaided B-2 sorties (approx. 25) were mission- planned using what ultimately became the operational B-2 mission planning computer model. The missions were "flown" against un-degraded threat defensive systems and the statistical outcomes combined into a "probability of mission success" for the force structure. Force "probability of survival" was also addressed as a function of stealth capability. This annual analysis effort helped give decision-makers insight into cost-benefit of the B-2 force as it was being developed [3, Cashen].

The survivability analysis group provided support for the mission effectiveness group by providing "probability of survival" data for the aircraft against each of the defensive systems individually, as well as survivability against integrated defensive systems. In addition, the group provided data to guide the LO technology development staff to help focus their development efforts by identifying where improvements were required against specific threat systems. The group was the repository of all signature data for the B-2 for each signature type: radar cross section (RCS); infra-red (IR); visual; electromagnetic emissions; and acoustic. The data included: frequency, polarity, and elevation for RCS; wavelength and emissivity for IR; brightness, background, etc. for visual; Low Probability of Intercept RF characterization; and decibel, range from source, etc. for acoustic. The LO technology group and a series of small, specialty sub-contractors employed by them helped develop the data base as part of the Program effort.

The vulnerability group had the responsibility to analyze the aircraft design and identify vulnerable areas against conventional weapons, electromagnetic pulse, etc. This group also had the responsibility to assure the design provided "hardening" of the aircraft against nuclear radiation as a function of encountering such an environment as part of conducting a SIOP mission. To assure this requirement was satisfied; a specialist contractor in nuclear hardening was used to augment the Program team. The expanded group reviewed all the detailed design, identified areas for re-design or modification for all vulnerabilities, and reported directly to the Chief Engineer and the Program Manager any areas of deficiency. They also established the test requirement for the special test facility of the USAF for testing nuclear hardness.

The LO Technology group was the group that had total responsibility for defining the aircraft's external shape that would satisfy the LO requirements and achieve the signature levels ascribed in the contract specification addendum. They had responsibility for advising the design organizations on design details that would affect the aircraft's signature; conducting tests of all external features that could affect the signature to verify the design approach; maintaining a signature budget and status report for each major assembly of the aircraft; and reporting periodically to the senior engineering and program management of both parties. They also had responsibility, in conjunction with the LO Materials & Processes development laboratory, to develop and test all materials and processes used for achieving the signature, in addition to aircraft shaping. For the latter, they had the responsibility, in conjunction with the Aerodynamics group, to ascribe the requirements for shaping the aircraft and "buy-off" of the external mold lines and internal lines of the engine inlet and exhaust ducts defined by the Loft group.

The LO Materials & Processes group had the responsibility for developing and verify all LO materials and processes used in the build of the aircraft. They conducted material reviews with industry, developed new materials required to achieve solutions to detailed aircraft design issues, and tested the materials and application processes in both the classical "M&P" sense and for their signature effectiveness. This group was an unsung "hero" of the Program and accounted for many technology breakthroughs.

Avionics Systems Engineering (ASE)

The avionics systems engineering group continued from their system baseline developed during the proposal phase and matured the flowdown of requirements from the avionics equipment and into the other subsystems that provided power, cooling, and other services. The avionics systems engineering group was responsible for all aspects of the critical item specifications within the avionics group and responsible to coordinate and approve other subsystems specifications and vendor design approaches. They were responsible to allocate requirements and monitor the progress of other subsystems in meeting the avionics requirements. Avionics also ran their own avionics technical review control board (ATRB) within their group to make reallocations within their own subsystems without going to the program configuration control board. The head of avionics systems engineering chaired the avionics ATRB up to PDR 2, after which all changes were remanded to the program CCB [3, Conklin]. For the B-2, the avionics architecture drove the weapons system architecture and much of the subsystems design service requirements.

The avionics systems engineering organization also defined requirements for the flying test bed (FTB), a KC 135 bailed by the Air Force to Northrop to install the brass board and breadboard avionics systems in their early development stage. This outstanding integration tool assisted in early identification of problems, led to early resolution of incompatibilities, and greatly facilitated the maturity of the avionics suite. The FTB tested much of the equipment before it was flown on the B-2. Systems engineering also derived requirements and built the Systems Integration Laboratory (SIL) at Pico Rivera and managed the testing conducted at this facility. The SIL eventually included all the hardware and software operating together prior to first flight as a further risk reduction to late discovery of system problems.

One founding principle for the design and development process was the extensive use of ground testing in a pyramid from component to subsystem to subassembly to integration.

Air Vehicle System Engineering (A/V SE)

Air Vehicle System Engineering was organized to encompass air vehicle configuration management in the broadest sense. The responsibility for classic configuration data management was located in the Program Operations and Control organization reporting to the program office. The group consisted of the following sub-groups: Configuration Design & Loft; Flight Sciences; Flight Controls; Structures Technology (incl. External Loads; Structure Analysis; Structure Dynamics); Mass Properties; Safety Engineering; Human Factors.

Logistics Systems Engineering

The Logistics Organization at Northrop was assigned the classic responsibilities associated with the supportability requirements for a future weapon system. A new feature was added to this organization that was unique to the Aerospace industry and clever in its execution. This new feature of the Logistics Systems Engineering group was Reliability and Maintainability (R&M) engineering cognizance. The purpose of this construct was to emphasize the importance of R&M and elevate its authority. This construct operated exceptionally well by integrating their personnel across the design teams. The Air Force SPO retained R&M responsibility within engineering. The net effect was that R&M had two voices through the management chain to surface their issues, effectively raising the importance and reporting levels of the "ilities". The process achieved a substantial milestone in weapon system reliability for hardware and software, which even today is remarkable for a complex weapon system.

In examining the current maintenance data for the B-2, the bulk of the maintenance effort is performed on the surface treatment to maintain low observability. The systems engineering process noted this was a problem for second or third generation stealth aircraft and included surface preparation in the original initial FSED risk reduction/mitigation plan. The state-of-the-art in 1981-1985 when the LO surfaces and treatments were baselined was not as mature as current processes and materials. Today, aircraft are performing much better in this area of LO maintainability, but the B-2's performance (higher manhours per flight hours for LO maintainability) is more a fact of the technology of the mid-1980s than a failure on the systems engineering process.

The Logistics Systems Engineering group, working in concert with their engineering counterparts within Northrop, Boeing, Vought, and from the SPO, established the allocation for supportability requirements to each subsystem, system element, and the structure assembly. They established design criteria based on lessons learned from similar equipments; assured inclusion of supportability requirements into all procurement specifications; established reliability growth test criteria for all system complements; closely monitored the progress of subcontractor and vendor designs and testing. This group also developed the specifications for all automated test and training equipment, and simulators and directed the development of the new support process for maintaining low observables in the field. This group was a very effective part of the program systems engineering process. Much of the success for the achieved R&M for the hardware and software can be attributed to this group.

Lastly, there was an additional feature that had a very large impact on the design and development of the B-2 weapon system - Primary System Reliability (PSR). The establishment of a very ambitious level of PSR, combined within the logistics systems engineering construct, were the two primary factors contributing to the demonstrated system reliability. PSR was such an overwhelming and difficult requirement to achieve, it may well have been the single most difficult of all the requirements, overshadowing even radar cross-section. The basic PSR requirement stipulated in the System Specification was a 90% probability that the last weapon of the suite of missions had to be delivered within the required circular error probability (CEP). This was an enormously difficult requirement to meet. The requirement was derived from the SAC mission criterion that computes how and what type of weapon is assigned to specific targets. The algorithm computes the probability of damage given such factors as the probability of a successful strike and the reliability of the weapon. The process to allocate this very difficult requirement necessitated each and every subsystem to design for very high reliability and an added degree of redundancy. During operations in the Balkans, the B-2 demonstrated a PSR of 0.89 [5].

Vought Systems Engineering

Vought organized their engineering staff into a classic project organization with a system engineering office and lead project WBS Task Team leaders reporting directly to the chief engineer. The function for the intermediate wing was primarily structures, zone management, composite design and construction, interface management, and subsystems routing in installation. Vought had two major development responsibilities; they had to develop & prove the process for fabrication and assembly of the inlet assembly and they had to develop and test and verify the concept for cooling the aft deck assembly. The requirements were derived requirements from their specification and ICD's with Northrop and Boeing. Vought's organization was not fully implemented as an IPT structure because they stopped short of assigning cross-functional people to the project lead.

Boeing Company Systems Engineering

Boeing organized its program structure in a form that met the B-2 Program needs and incorporated its previous experience in both Military and Commercial programs. A Systems Engineering function was established from the very beginning. A senior Program SE manager was assigned. His role included several functions: Systems Engineering integration, coordination with Northrop and the significant contractors, such as Vought, technical specifications and interface control document management, and overall program technical integration, including our business and contracts functions. Boeing had specific areas of responsibility: outboard wing, aft center wing, landing gear, fuel system, offensive avionics, weapon launchers, and integration. Each area had its own sub-team management. There was a huge effort to integrate with the rest of the B-2 program using the WBS Task team structure. Each area had its systems engineering team. The leaders of these sub-teams reported both to their chief engineers and to the Program Systems Engineering Manager. The work was very complex. The nature of the work started at the typical product definition, requirements flow down and Spec/ICD level, then phased into very detailed activity, and finally into demonstrating compliance with all technical, form, fit, and function requirements. The reconfiguration and ensuing changes to the internal systems affected the work. Fully stuffed structure, stealth implications, internal avionics tie integration, software, etc created a demanding environment to assure internal and external integration by the SE group. The aircraft would have not been successful without the System Engineering function [3, Spitzer].

Air Force SPO Systems Engineering

The original B-2 engineering team during the source selection consisted of 35 engineers. As those 35 engineers migrated back to their original program offices, new personnel were assigned to the program to manage the development activity. As new engineers were assigned, the original lead engineer for the technical discipline would accompany his (her) replacement to meet their contractor counterpart. This facilitated the continuation of the already established working relationship forged during the source selection process and assured a continuation of this philosophy.

The SPO Engineering Directorate was a classical organizational structure with four divisions:

- Systems Engineering
- Airframe
- Avionics
- Crew Station

The Chief Engineer, (later elevated to the Director of Engineering) always had a deputy chief engineer. The people integrated their efforts with the other SPO Directorates at the working level and always worked closely with their Projects Directorate counterparts.

The program progressed from the initial full-scale development program and the risk reduction areas to a full-fledged, fast-paced development program by the time of the reconfiguration in the middle of 1984. The SPO engineering cadre grew to 60 people by early 1985 and still consisted of highly experienced, well-trained engineers with exceptionally strong backgrounds and experience. The process to staff the SPO at the time of contract award was interesting and effective.

An engineer would receive a phone call from the secretary of Mr. Fred Rall, the technical director for Aeronautical Systems Center. Bessie would tell the engineer that he (she) was needed for a meeting in Mr. Rall's office at 2 p.m. tomorrow. The engineer would show up typically 15 minutes ahead of time and wait on the couch until 2 p.m. The door to Mr. Rall's office would be closed and no one would go in or out. At 2 p.m., Bessie would tell the engineer it was okay to go into the room. No one would be there but the B-2 chief engineer, who himself no longer existed on any organization chart. He would be sitting in Mr. Rall's chair at the conference table. After the engineer looked around and saw no one else was in the room, they would be asked to sit down. The chief engineer would explain that the person was wanted in the "black hole" for a project. They would ask what they would be doing and receive the answer, "I can't tell you". They would ask numerous questions, all receiving the same answer! After several minutes of this, and there would be a resigned sigh and finally, after being assured it was a great program and an important job, every single one said, "okay". After the agreement, they had a short period of time to close any actions ongoing in their past assignment before reporting to the black hole and essentially disappearing from the organization chart. The engineering functional (ASC/EN home office) still kept their records but they were co-located and not shown on any other organizational chart. It was the responsibility of the chief engineer and Mr. Rall's staff to assure that the engineers received their promotions and performance increases consistent with their performance in the B-2 SPO. Since these engineers were among some of the best, they regularly competed for and won bonuses and promotions. This helped assure that new engineers would be willing to be assigned to the SPO because they knew they could still compete with their unclassified program ("white world") counterparts on an equal basis.

It was essential to continue to staff the B-2 SPO with experienced engineers who understood their technical discipline and the role of requirements in development programs. These people were committed to cooperate with each other, with the contractors, and with the user to develop a balanced design and to make and implement the decisions required to make this weapons system development successful. During design reviews at the working level, the engineers from the SPO would regularly attend the meetings and assist in the process. The using command was also invited to design review meetings and technical interchange meetings and they attended on a regular basis. SAC had a staff of about 20 officers stationed at SAC headquarters in Omaha Nebraska who were assigned to the program with responsibility of a continuous presence in the program. These officers played a vital role in helping the engineers understand the conduct of the SAC mission and the needs of the crew and maintenance people. The SPO engineers helped the using command personnel understand the implications of requirements that exceed that which would be required to satisfactorily conduct operations. The constant interaction of the three groups, SAC stating their needs, the SPO defining requirements, and the contractor teams designing and developing the hardware and software was a key ingredient in the operation of the process.

Chief Engineers Meetings

The company chief engineers and the Air Force SPO chief engineer met every four to six weeks for a one-day meeting. The purpose of these meetings was to rapidly resolve integration and design issues. The meeting host was rotated between the chief engineer for Northrop, Boeing, Vought, and the Air Force. Responsible engineers and their team for a particular area under study would brief the problem and alternatives. The team would consist of membership from all the companies and the SPO. The decision was made as to how best to proceed and the chief engineers agreed to implement the decision immediately. It was responsibility of each chief engineer to assure the decision was communicated to the program manager and throughout his or her own organization; it was also their responsibility to insure contractual integrity of the decision.

These meetings were a highly effective systems engineering process tool. Prior to the meetings, significant integration effort and assessment of alternatives was required by the staff to present a sound solution to the program engineering leadership. None of the engineers wanted to present an incomplete resolution in this forum. This was essentially a technical configuration control board although each of the design teams had dedicated contracts, financial management, manufacturing, and logistics membership as part of their team. This facilitated communications and contract efforts to implement the decisions.

There were other major subcontractors that also became involved in the chief engineers meetings particularly Hughes and General Electric. The Hughes contract was a subcontract to Northrop and the General Electric contract was managed by the SPO for the basic engine. Northrop also had a separate contract with GE for the design and development of the exhaust nozzle/tailpipe. The working relationships with these two contractors, and in fact, all of the subcontractors and vendors were excellent and consistent with the working relationships among the four main entities.

3.2.2 Facilitization

The B-2 program scope was so large that conducting the program within a single aerospace corporation was considered impractical. The program started at the same time the

Aerospace industry was in a general boom. In the Los Angeles basin, several aerospace corporations were vying for the engineering talent. During the source selection Lockheed had announced they would team with Rockwell even though Rockwell was preparing a proposal to develop and build 100 B-1B's in response to Reagan's campaign promise to restart the program. Northrop's corporate team included Boeing and Vought and was considered a viable competitor even though Northrop had not been a prime contractor on a large bomber program since B-35/B-49 flying wings in the 1940s. They had been the prime contractor for the T- 38/F-5 programs and considered themselves a "fighter house". It had taken several persuasive conversations between the Air Force senior leadership, Lt. Gen. Stafford, and the CEO of Northrop, Tom Jones, before Northrop agreed to participate in the 1980 study contract that founded the B-2.

The full-scale development program required a significant infrastructure expansion from the very beginning for facilities, capital equipment, laboratories, staff, and security. All three of the major corporations undertook a substantial capital investment program that exceeded $2.5 billion[12]. A brief description is provided in order to capture the magnitude of these investments[13].

Northrop Facility Capitalization

Two separate office buildings were constructed to house material procurement, subcontract management organizations, facilities engineering, and the operations organization. Expansion of the outdoor radar cross-section range modernized the capability to increase data production rates. A large (2.5 million square foot ex-Ford plant) was acquired, gutted, and equipped to house a new Northrop Division. The new secure facility at Pico Rivera, California was required for design, development, research, laboratory testing, and sub assembly of the Forward Center Wing and all the edge structures. Program Management and all the major functional managers from the program also had their offices in this central location. This facility provided:

- Workstations and offices for 2,500 engineers, scientists, and support staff
- Dedicated computer complex and computer design rooms
- Flight simulation laboratory with accommodations for a full-scale iron bird
- Avionics laboratory for display development
- Workstations for individual avionics software development and hot benches for hardware/software integration
- An integrated Avionics and Flight Control Laboratory
- Model shops (wind tunnel and radar cross-section models)
- Anechoic chambers

[12] All indemnified by the DOD/USAF.

[13] One of the pre-contract events that had a significant impact on the cost of the program was the effect of security. Security was listed as the first priority in the government Program Management Directive, PMD. The remaining order of priority was technical, schedule, and then cost. During the 1980-1981 timeframe, a new program security guide was implemented by the DOD for special access programs, which increased the cost of maintaining security by requiring new procedures. This was to have a profound cost impact, later assessed at 15 to 20 percent of the total program cost, little of which was included in the original cost estimate.

- Composite fabrication and sub assembly facility, including clean rooms
- Manufacturing facility with automated material, tool handling, and inventory storage system
- Five autoclaves
- A major structural assembly area for the Forward Center Wing assembly.

Northrop accepted responsibility for the design, construction, and acceptance of a secure final assembly facility at Palmdale as part of their Total System Performance Responsibility (TSPR) by executing a separate contract obligation with the Air Force. Northrop was responsible to equip the building at Site 4 of Plant 42 in Palmdale to accomplish the integration and final assembly, system checkout, engine run-up, and taxi testing. The company was also responsible for modification of a building to provide for the aircraft's surface preparation and coatings applications.

Boeing Facility Capitalization

Modifications were made to major portions of the existing Development Center at the Seattle Boeing Field location to accommodate the design, development, and production of the Aft Center Wing and the Outboard Wings. This included:

- Workstations and space for 1,200 – 1,300 engineers, scientists, and support personnel
- Full-scale mock up areas for their sub assemblies
- Structural test laboratory
- Armaments laboratory for the development of the rotary launcher
- Office space for the managers
- Development and installation of the world's largest autoclave (125 ft by 25 ft);
- A composite pultrusion facility
- Large-scale composite skin bond assembly capability
- Fuel laboratory was updated to test the entire fuel system on a fuel table capable of rotating to simulate in-flight attitudes

Vought Facility Capitalization

Modifications were also made to Vought facilities. These consisted of:

- An office building to accommodate a dedicated computer complex
- Offices and workstations for approximately 750 engineers and support personnel
- Modification of the metal fabrication facility to accommodate automated handling of working process and raw material distribution
- Modification of assembly building to accommodate design development and production of the Intermediate Wing; design development and installation of a composite tape laying machine to construct three-dimensional surfaces
- Installation of a drive-matic machine for titanium fasteners

- Developed and installed automated waterjet cutting capability for large composite panels

Air Force Facilities

In addition to facility space in Palmdale, CA for the final assembly, construction of a secure facility at Edwards Air Force Base called South Base was funded. This facility provided office space, computers, flight test instrumentation, flight test operations, flight test range instrumentation for both Air Force personnel and the contractor's contingent of the Combined Test Force.

3.3 Full Scale Engineering Development (FSED) Execution

3.3.1 Risk Closure Plans

Risk closure plans were the primary tool used throughout the program to identify, document, and mitigate risks. Individual Risk closure plans were integrated into the program, organization, and WBS Task Team work plans. The specific risk activities that were assigned to task teams included:

- RCS testing and materials development
- Aero/propulsion integration with the low observables requirements
- Large scale composite and Radar Absorbing Structure development
- Radar antenna design and construction of a working model
- Inlet/engine/exhaust integration and validation of aft deck air flow and temperatures
- Aero elastic structural response
- Avionics suite definition
- Subsystem design approach and performance testing
- Reliability assessment and development growth testing

The Initial FSED (IFSED) risk reduction areas that were to be reduced by concentrated effort leading up to preliminary design review (PDR-2) are shown in Figure 3-6. Risk closures plans were constructed for each of the nine areas and the responsible WBS Task team was assigned to close the risks. For a description from the B-2 Systems Engineering Management Plan (SEMP) on Risk, see Appendix 5.

The risk closure plan concept was introduced by the Northrop program manager, first on Tacit Blue in the Spring-Summer of 1980, and then to the ASPA proposal team in September, 1980. It was the dominant program tool for the two and one half years during the IFSED program for risk reduction and was used to develop the work plans for the individual risks in Figure 3-5. It was also integrated by the Program Operations and Control (PO&C) organization into the Management Information Control (MIC) room and the Responsible Engineer (or logistics specialist, manufacturing lead, Quality Assurance person, etc.) briefed the status during internal reviews and during the Quarterly Program Management Review (QPMR).

The risk closure process was used throughout the entire development and production program. It was one of the key elements that contributed to the program success. From the beginning, the risk closure plans were constructed by the WBS Task team, owned by them, and closed by them. At no time did any other organization manage, track, chase, or in any other way provide a non-value added oversight function. PO&C only provided space in the MIC room.

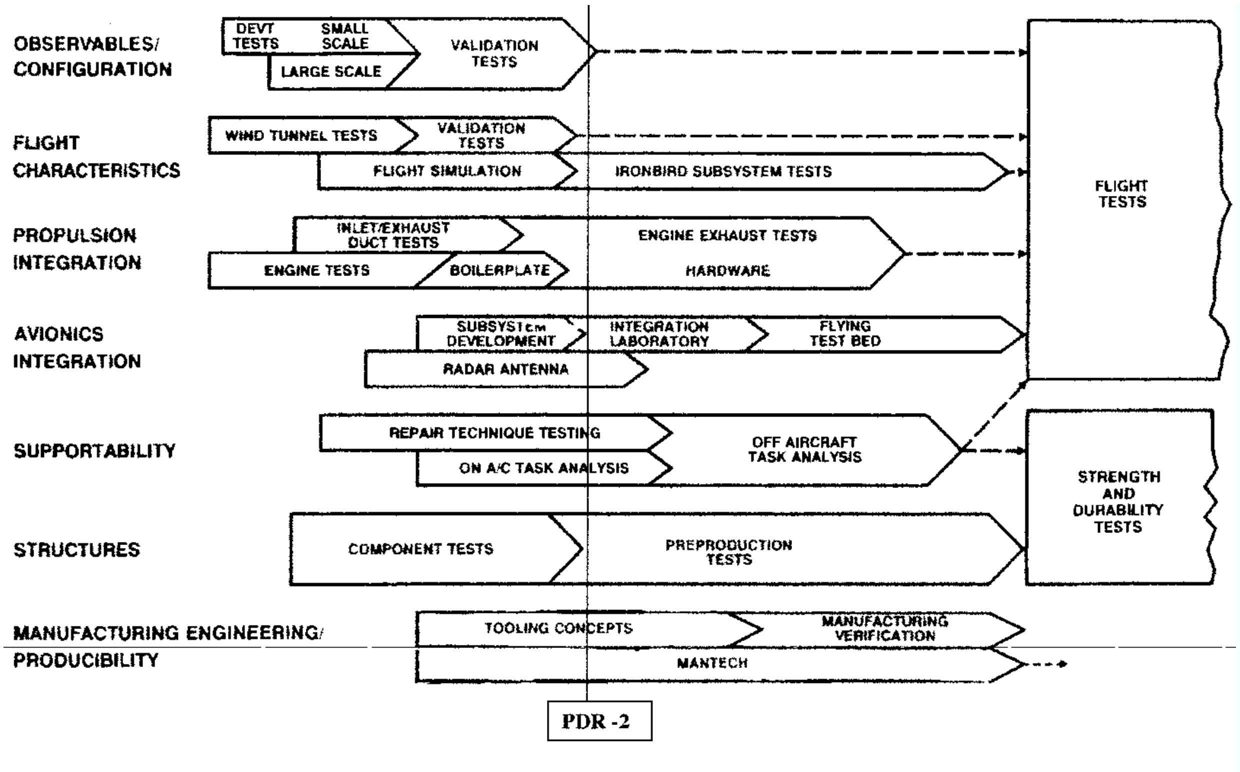

Figure 3-6. Risk Reduction Plan - Areas for Interim Full Scale Development [6]

Wing Material Decision

A significant area of risk for the B-2 air vehicle was in the area of composite materials. Northrop and two major subcontractors, Boeing and Vought, designed the original proposal aircraft with a significant amount of composite structure. Northrop proposed all of the edges as composite structure, primarily for the radar cross-section requirement that dictated radar-absorbing structure. Boeing's proposal for the aft center wing and the outboard wing included significant use of composites as major aircraft structure. Vought's proposal was largely composite and titanium primary structure, with conventional aluminum where it was more cost effective [3, Patton]. The Northrop forward center wing was proposed (and still is) largely aluminum construction.

Composite structure, like those shown in Figure 3-7, for large aircraft sub assemblies was a new endeavor in the 1980- 1981 timeframe. Composites had been employed for secondary structure for several major weapons systems, but the engineering data base and operational experience was very limited. Production applications for primary structure developed by the Laboratory through contracts with industry were Advanced Technology Demonstrators (ATD), such as the F-15 wing, but none of these were put into production. The B-2 team faced the very difficult task of employing a new material on a scale that no program or company had employed. To further complicate the task, the proposed design approach had complex load paths driven by the mission, the low observables requirements, aerodynamics, and the large cutouts on the bottom for the engine bay doors, landing gear doors, and weapons bay doors. All of these requirements necessitated the use of large, complex composite structures to achieve the strength required, using the flexibility of design and manufacturing promised by the emerging composite technology. If only conventional metallic structural materials like aluminum, steel, and titanium were employed in the design, the structures experts predicted the resultant design would weigh so much that there would be no practical use for the aircraft [3, Wilson]. Therefore, the extensive use of composites required in the design was considered a major risk.

The B-2 program constructed a risk closure plan for the composites as part of the FSED risk reduction phase of the program and set September 1983 as the wing material decision date (WMDD). The team of the best talent in composites from Northrop, Boeing, Vought, and the Air Force, to be led by Boeing, was assembled at the development center in Seattle, Washington. The team met in December 1981 and developed criteria for success for design allowables, manufacturing, tooling (tool life), producability (repeatability and cost basis data), and supportability. The team built three 50 foot long wing sections representative of the outboard wing panels. They also built several wing box sections of the outboard wing. These pieces were extensively tested and inspected. Teardown of every tested piece was accomplished and results were analyzed against the pre-test predictions and against the criteria.

The team also initiated an aluminum wing design of the air vehicle made of conventional metals. This design was to compare the weight, cost, schedule, risk, and manufacturing approach to the composite design. It was a risk mitigation strategy in the event the composite design was not successful. The team met in September 1983 to review the work and results of the tests, inspections, and analysis; they declared the risk closed and the composite approach as viable, thus establishing it as the B-2 program baseline.

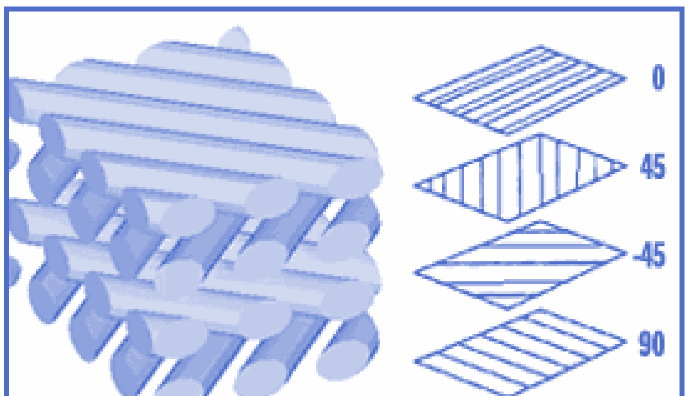

Figure 3-7. Large-scale manufacturing for these layered composite materials was technologically immature and high-risk during the early program.

The primary process to construct the Risk Closure Plan for the composites was proposed by Northrop in the December 1980 response to the RFP where the contractor proposed a set of manufacturing and fabrication risk reduction studies, tasks, and development of tools, techniques, and the facilities and equipment to mature the composites technology. The concept put forth was to use the existing Air Force Materials Laboratory contracts to fund initiatives to mitigate manufacturing and fabrication risk. The Air Force program office formed a team of specialists to refine the list of required efforts that would be implemented using the combined talents of the government and industry, and augment the ongoing efforts of the Air Force Wright Aeronautical Laboratory's Manufacturing Technology (ManTech) Division. This was a vital strategy to reduce design, manufacturing, and fabrication risk of the large-scale composite parts required for the program success and was managed and funded by the B-2 SPO through the B-2 FSD contract. Using program money, a series of studies and funded projects were conducted by the program participants. Tasking was given to Vought for fastener insertion in composites, large scale articulating head tape laying machines (working with Ingersol), composite water jet cutting techniques, non-destructive test and verification of completed parts. Boeing developed processes and equipment for pultrusion, autoclave methods, autoclave control systems, ultrasonic inspection, and tape laying equipment with Cincinnati Milacron. Hughes received Mantech money to build new antenna mechanically scanned in one direction, electronically scanned in the orthogonal direction. Northrop was funded for their large scale edge design and manufacturing facility. This process to reduce risk and mature the state of the art in manufacturing also had a positive effect on the overall design because the manufacturing process was maturing with the engineering. Manufacturing and the logistics functionals (through the emphasis on reliability, maintainability, and supportability) were well represented in the early design process in the program. The ManTech efforts with the B-2 contractors were conducted during 1981 to 1985.

3.3.2 Preliminary Design Review (PDR-1)

PDR 1 incorporated two new, major engineering activities, both of which had significant changes to the baseline configuration. The first of these changes resulted from the culmination of the avionics suite defensive countermeasure study. Avionics systems engineering and the avionics contingent from the Air Force SPO had been conducting a trade studies on various defensive suite alternatives as an enhancement to the penetration of Soviet defenses. The study examined survivability enhancement through the use of countermeasures specifically applicable to stealth vehicles. The study results were completed at PDR 1 and formally presented to the Air Force SPO and the recommended avionics suite was approved. The approved suite became part of the new avionics program baseline and was incorporated in the avionics specifications.

The second change was the incorporation of certain provisions for a third crewmember. Mission proficiency and crew workload studies were conducted after contract award and showed that with the combination of penetration aids, mission planning software, display algorithms, automation, and redundancy, a two-man crew was fully adequate to complete the specified missions. However, the Air Force planners reasoned that new missions and unforeseen complexities in the future may well force an increase in workload to the point where a third crewmember would be necessary. Therefore, after an extensive trade study was conducted in the months leading up to PDR 1, the SPO decided to incorporate space and structural provisions for the third crewmember. This necessitated moving the avionics that was currently installed in the aft part of the crew station to a new location in the aft of the aircraft, behind the weapons bays. The upper section of the aft crew station bulkhead was canted backwards at the angle of the back of the ejection seat to allow for the installation of the seat rails. This further resulted in moving weapons bay rotatory launchers back slightly to allow for weapon clearance for this new canted bulkhead.

A major integration tool that started to emerge after contract award and eventually achieved program wide acceptance was computer aided design and classified networking. NCAD/NCAL was a Northrop Computer Aided Design (NCAD)/ Northrop Computer Aided Lofting (NCAL) tool developed under independent R&D that was extremely effective and useful for the task of integrating all the companies and their design staffs. It was a major aide to the systems engineering process. The system was user friendly, very capable, and easily adaptable to a classified network among the companies. While CAD tools are commonplace now, this technology did not exist in the early 1980s; the B-2 was the first all-CAD designed aircraft [3, Myers]. Its ease of use and simplicity facilitated the design evolution, spatial allocations, requirement tradeoffs, was a great aid to integration across the interfaces, and a boon to the ease of integration of the assemblies during manufacturing.

3.3.3 Configuration Freeze

The next major milestone after PDR-1 was "Configuration Freeze," scheduled nine months prior to PDR-2. It was one of the last "Configuration-Driver" risk closure activities still open from the Interim FSED risks. It was four and one half months prior to this contractor-imposed milestone that the need for a major redesign became apparent. The redesign would be the largest single internal event that occurred during development and contributed both to the slip in the first flight date and to the cost increase of the program.

The Pre-contract award Modification Request for high subsonic, low altitude penetration capability imposed a derived requirement for an additional low altitude gust capability. The team recognized that the higher gust loads and more severe spectrum would have a major influence on the structural design loads. The team developed a sophisticated model of the complex aero-servo-elastic characteristics of the air vehicle, including steady and unsteady aerodynamics, structural dynamics (derived from a NASTRAN finite element model), as well as the flight control laws and actuation dynamics in order to quantify the achievable level of gust load alleviation. This integrated structural analysis program would confirm the internal loads concurrently while controlling the aircraft. The program was to be a key factor in assessing the adequacy of the structural design during operations at low altitude/high speed operations in the presence of significant gust loads. In particular it would assess the adequacy of the flight control system to actively reduce the airframe's dynamic response. Northrop drew on the expertise and help of national scientific and technology leaders from USAF, NASA, members of all three airframe companies' technical staffs, and both General Electric and Minneapolis Honeywell's Advanced Design Center to facilitate the development of the analytical program[14].

The analysis was scheduled for completion in December 1982 but because of its complexity, it was not yielding data until January 1983. Meaningful results were obtained in early February 1983 at which time Air Vehicle Systems Engineering (A/V S/E) WBS task team leader advised the Northrop program manager that the results revealed a substantial wing bending moment increase over earlier estimates due to more severe aero-elastic effects incurred at high speed, low altitude flight conditions and the inability of the controls to provide adequate load alleviation, while still controlling flight and maneuvers. Eighty percent of the wing bending moment came from the first bending mode, which had a node line that curved behind the outboard controls as depicted in Figure 3-7.

The center of pressure for the primary pitch control surfaces was nearly coincident with the first wing bending node line. This reduced the effectiveness of the control system to damp the gust induced loads associated with this mode. The analysis also revealed that distribution of the carry through loads across the centerline was strongly asymmetric with the forward weapon bay bulkhead receiving 70 percent of the total root bending moment, leaving only 30 percent through the rear bulkhead. The combination of increased bending moment and poor load distribution led to high internal loads in the inboard forward wing structure. The inefficient fore and aft load paths were brought about in part, because of the large cutout in the bottom of the aircraft for the weapons bay doors, engine bay doors, and landing gear doors. While the cutouts were there from the beginning and the team knew they would affect the ability to control the

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[14] Of particular note were the significant contributions made by Dick Stone of Minneapolis Honeywell and Jerry Newsom and John Edwards of NASA Langley

balance of loads between the fore and aft load paths, the computer model confirmed the unexpectedly poor 70% - 30% split.

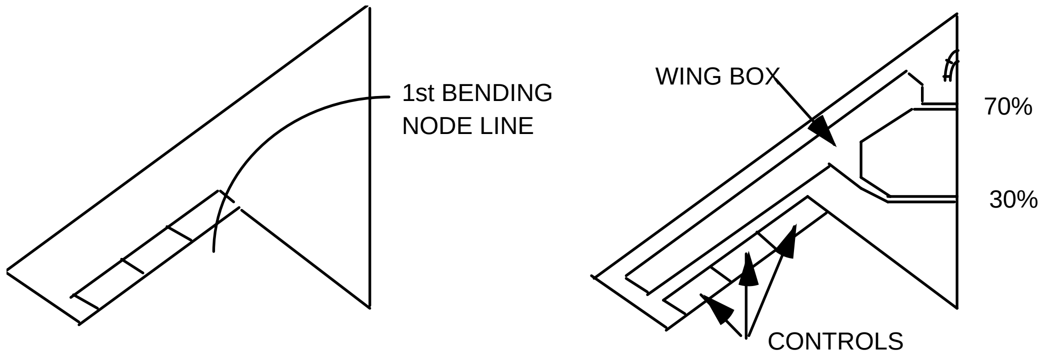

Figure 3-7. Structural Bending of the Wing at First Bending

A second and equally important problem was the aero-elastic instability of the structure (either open or closed loop) of the original design [3, Arthurs]. In correcting the air vehicle's response to atmospheric turbulence, it was necessary to modify the planform and reconfigure the surfaces such that the control system could effectively decouple the flight control harmonics from the first structural vibration mode, shown on the left side graphic in Figure 3-7.

3.3.3.1 Baseline Change

Based on the serious nature of the problem and faced with the likelihood of significant revision to the baseline configuration, the Northrop program manager ordered a number of actions:

- The Flight Controls, Aerodynamics, and the Configuration groups were directed to study alternative control configurations that would provide adequate control and to provide the necessary level of gust load alleviation.
- A structures design "Red" team with members from all three airframe contractors, nationally renowned experts in structures, and in concert with A/V S/E & WSE groups, was tasked with reviewing the structural arrangement and proposing alternative approaches to alleviate the poor internal load distribution.
- All program elements were tasked to review all existing concerns and potential alternatives to ensure that potential future change requirements were not overlooked.

The response to these directions was a multi-pronged examination by the WSE and A/V SE WBS task teams, with support from the other teams as required, to identify all existing problems or concerns and generate and evaluate potential solutions. A daily stand-up meeting provided status and further direction from the Northrop program manager. The concerns identified by the teams included:

- Insufficient primary control power under severe gust conditions
- Poor load transfer from the outboard wing inboard
- High risk of fatigue and single point failure problems for the load path around the engine inlet ducts
- High risk inlet configuration due to an internal vane for engine face RCS masking

- Severe high angle of attack static and dynamic instability due to the effects of the full span, sharp leading edge of the wing.

3.3.3.2 Controllability

The flight control system for the B-2 had the dual function of controlling the aircraft's flight path and providing active gust load alleviation. The analysis results in early 1983 indicated adequate aero-elastic control margins in smooth air, but insufficient control power to achieve the required level of gust load alleviation. Since the trailing edge controls provided both pitch and roll, this affected both the pitch and roll control margins. Solving the controllability issue would require moving or adding pitch controls inboard of the wing first bending node line, namely, inboard of the trailing edge notch. Alternative arrangements were generated for analysis and rapid low speed wind tunnel evaluation. The inboard wing trailing edge area dominated by the engine exhaust was considered unsuitable for adding controls. The remaining span of the baseline planform could not provide the necessary control effectiveness. It was determined that modification of the trailing edge by addition of an extra notch would accommodate new inboard control surfaces. Alternative control surface arrangements were tested in the wind tunnel and on the RCS test range. By the first of May 1983, the testing confirmed a configuration that provided both high control effectiveness and low RCS risk. The new inboard controls provided control effectiveness for both pitch and roll functions while the outboard control surfaces would be utilized to primarily augment low speed roll control. The new control scheme provided a balance of control power for maneuvers and effective gust load alleviation.

The structural load/flight control analysis of the gusts input revealed the aircraft's pitch instability yielded an open loop time to double amplitude at these conditions on the order of 100 milliseconds. This necessitated an immediate response from the control surface and resulted in a derived requirement to provide large, high rate surfaces. It was determined that the no-load rate for the large inboard controls should be 100 degrees/second which, coupled with their large hinge moments, would require adding an additional hydraulic pump to each engine (two pumps per engine). This also necessitated a change to the air data system. Since the feedback from the measured air vehicle angle of attack was crucial to gust load alleviation, the air data system was moved closer to the aircraft leading edge to reduce the sensing time delay.

An additional controllability issue was a low speed lateral-directional cross coupling concern due to development of leading edge vortex flow at high angles of attack that caused decay in outboard control surface effectiveness. Aerodynamics indicated that leading edge rounding could alleviate the situation and the LO engineers were asked to examine the possibility. They indicated a theoretical basis for acceptance of the change as long as the edge was sharp at the tip and center. That feature is readily seen in the airplane today. After experimental verification, a wing leading edge shape was developed and accepted which inhibited vortex formation and maintained flow energy over the outboard aileron. This was an enormously important change to the aerodynamics and stability and control of the vehicle because it provided a piecewise linear set of stability derivatives for the control systems designers.

3.3.3.3 Inlet

An ongoing problem with the baseline configuration inlet was a requirement for an internal vane to mask engine face from radar detection. The vane design had started as a thin structure with a RAM coating. Better understanding of its loads environment resulted in a change to a honeycomb radar absorption structure (RAS) design of increased thickness. The enlarged vane and added support struts impacted both inlet pressure recovery and inlet distortion characteristics. RCS testing also indicated marginal shielding performance from the vane. The vane configuration was becoming an intractable design and manufacturing challenge.

A particularly brilliant inlet analyst/designer was brought in to review the problem and recommended a duct shape of more aggressive curvature to provide engine face masking without the need for a vane. Testing of this design showed satisfactory RCS characteristics and significantly improved inlet performance. The serrated inlet leading edge geometry was also revised from a “V” shape to a “W” shape to reduce inlet distortions from the inlet notches under certain conditions. This change also reduced RCS at certain aspects. The revised lip and duct geometry resulted in an aft shift of the inlet and effectively decoupled the inlet design from the wing box forward spar structure.

3.3.3.4 Structural Arrangement

The three-company airframe design team was tasked with examining improved load path balancing alternatives and other means of reducing the weight and risk impacts of the baseline structure. The primary problem was the wing carry-through structural load path. The outboard wing box mated to a forward box structure outboard of the inlet but the load in the box had to transfer to the box rear spar and into spar caps above and below the inlet duct before mating to the weapons bay bulkhead. A derived design requirement, arising from system requirements flow-down analyses by the WSE group, raised the additional issue of avoiding single point failures due to enemy fire. The design team generated a general recommendation that the single spar/bulkhead carry through structures, forward and aft of the weapons bay should be replaced by a more structurally efficient box arrangement extending from the outboard wing to the centerline both ahead of and aft of the weapons bay. The change in planform required to achieve this controllability allowed more room outboard of the engine bays to distribute the load path fore and aft but the primary challenge was generating space for a forward box structure across the centerline.

Theoretical RCS studies indicated the potential of reducing the chord of the RAS edge structure without sacrificing RCS performance. This was rushed to experimental verification and proven acceptable allowing the cockpit/windshield to move forward. The direction at PDR-1 to provide space and primary structure provisions for a potential third crew member had required creation of an aft avionics bay, aft of the weapons bay, to accommodate avionics displaced by the third crew member volume. A byproduct of the controllability changes was a reduction in gust induced vertical accelerations at the crew station which provided acceptable ride qualities without the baseline crew station isolation pallet. The reconfiguration of the crew station led to the ability to incorporate a substantial carry through box structure under the cockpit floor ahead of the weapons bay bulkhead. The revision of the cockpit lines was coordinated with aerodynamics and resulted in improved flow over the front end of the aircraft at transonic speeds with an associated reduction in high-speed drag.

Taken together, the structural designers were able to define a structural arrangement consisting of:

1) A forward box providing a redundant low risk load path from the outer wing, traversing ahead of the inlet and across the centerline and

2) An aft box that also provided good load transfer out of the outer wing panel transiting around the engine tailpipes and across the centerline.

Analysis of this arrangement showed a more balanced load distribution of 60 percent forward and 40 percent aft. The forward box structure also provided additional fuel capacity. The primary concern with the arrangement was the necessity of keeping the load from trying to go into the top skin of the inlet and over the engines and weapons bays. RCS considerations ruled out the use of either “breathing structure” or significant bending. Revision of the upper skin structure above both the engine bays and the weapons bays was required to achieve a “soft” load path that minimized the bending resistance. See Figure 3-8.

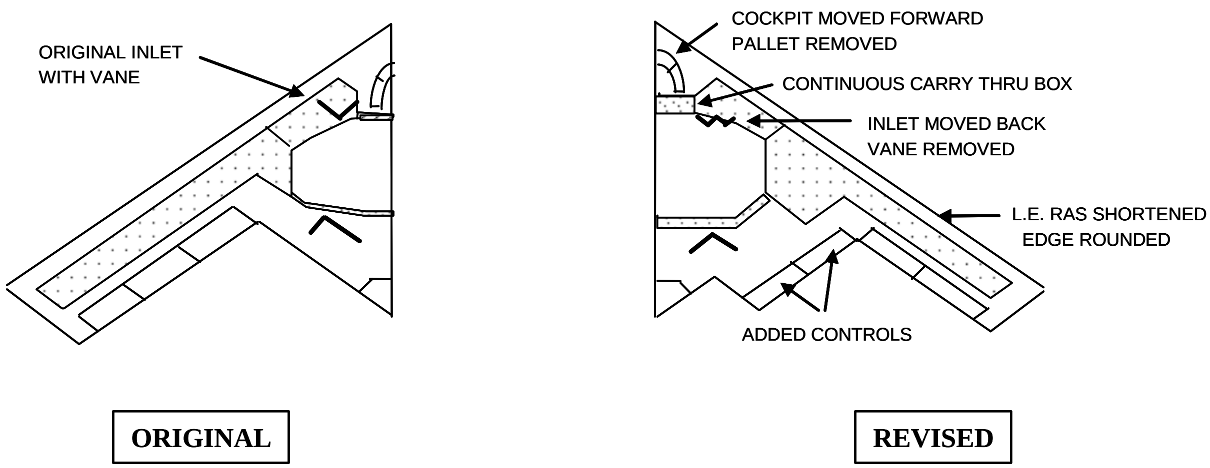

Figure 3-8. Dramatic Internal and External Differences

The revised structural arrangement required revision of the component manufacturing and assembly for the aft center wing and the intermediate wing. The revised structural arrangement added an additional wing segment to the Vought Intermediate Wing Assembly to accommodate the added portion of the planform change as shown on the right sketch of Figure 3-9 and incorporation of the centerline box into the Forward Center Wing Assembly. Overall weight increase for the redesigns was on the order of 6000 pounds.

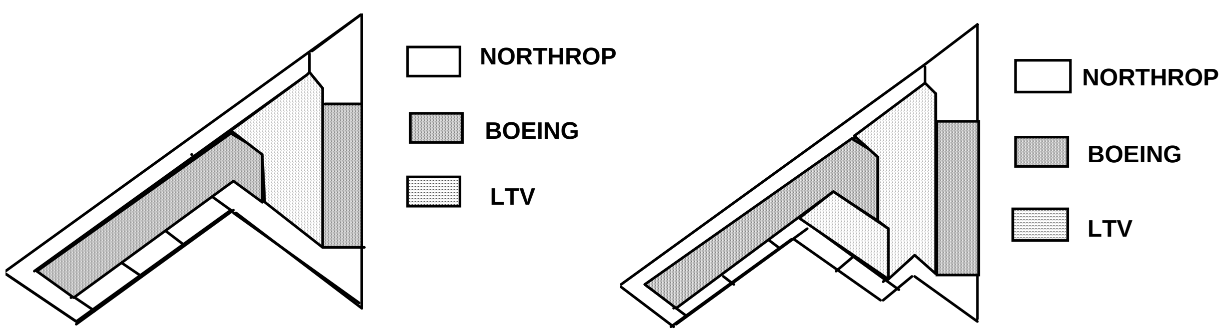

Figure 3-9. Work Share and Production Changes from the Reconfiguration

The design solutions were arrived at through a series of sequential technical decisions based upon sound systems engineering analysis and multi discipline trade studies. After initial concept definition and analysis of the solution, wind tunnel and observables tests of multiple alternative solutions were conducted; modes constriction was facilitated by the use of NCAD for model design and fabrication, selected layout definitions of the structural design solution and subsystems, weight, and performance impact studies. The chronology of these actions is captured in Table 3-4.

The cited decisions were made by the Northrop program manager, in consultation with his program management team, while keeping the Northrop B-2 Division General Manager, John Paterno, and the SPO current. The SPO's Technical Directorate's key staff members were working directly with the contractors' Engineering and Manufacturing staffs during this period.

Table 3-4. Schedule Milestones during the Reconfiguration Effort (1983)

Mid February	Identification of the Problem
Early March	Conceptual Definition of a new trailing edge/controls arrangement
Mid March	Observables identify reduction in leading edge RAS depth. Configuration Group identifies ability to compress Flight Station length. Observables also accepts a prescribed change in leading edge radius
Mid March	Initiated Low Speed and High Speed lines changes to existing models to reflect the trailing edge and leading edge changes
Mid April	Aerodynamics, Observables and Structures Design recommend shortening the inlet and eliminating the vane
Late April	Structures Technology, Structures Design, Observables, and Aerodynamics submit recommendation re structural arrangement
Late April	Wind tunnel tests confirm control power adequacy
1 May	Authorize development of a new OML definition for the Baseline aircraft
Mid-May	Finalization of the OML and structural arrangement are established
Early-June	Lines for new (verification) models released
Mid June	Subsystems requirements updated and block diagrams revised
End of June	New OML definition for baseline aircraft available to Program

The Northrop program manager's decision to consider this whole redesign a "contractor-initiated" change to satisfy the Contract Specification's requirements was a major consideration. This issue was discussed with the General Manager and both agreed that it was the appropriate contractual position, notwithstanding the $1.5- 2.5 Billion dollar (rough order of magnitude) estimate of the program impact at that time. Their conclusion was predicated upon the fact that these configuration and structural arrangement changes provided a viable solution of the aircraft design, and that the original design would not have met the original specification without them. The list of changes included:

- A control system design that could simultaneously control the gust response of the aircraft and reduce the wing bending moment impact of gusts
- A more balanced bending load distribution on the wing (60/40 in lieu of 70/30)
- A significant reduction in local internal loads

- A redundant load path for the bending load in the event of a primary structural element failure or damage
- A significant reduction in the susceptibility of the structure design to fatigue failure during the life of the aircraft
- A solution to the high angle of attack lateral-directional coupling of roll and sideslip
- Decouple the inlet from the front spar structural design
- Improvements in propulsion efficiency and drag reduction

Although the changes were implemented on the Program and the development effort was proceeding, the Division General Manager also had his Senior Technical Management Committee review the changes in June to provide affirmation that they concurred with the need and the solution to the baseline aircraft's problems. Independently, Northrop's Corporate Office established a three-man panel of very senior technical managers to review the change. Their investigation also concluded that the new structural arrangement and the other changes were appropriate to achieve a viable design. Senior Corporate Managers from the other airframe contractors also concurred with the change.

3.3.3.5 Programmatic Decisions

Concurrent with the technical management decisions that the Northrop program manager faced was the choice of a Class I or II change[15]. As noted, the Northrop program manager and the General Manager identified the change as Class II and none of the senior management reviews had challenged that decision. There were a series of major program decisions required as well, including:

- Completion of the pre-requisites for the "Configuration Freeze" milestone
- Ability of the Program to attain the PDR-2 milestone as scheduled
- Viability of the "downstream" Program Milestones beyond PDR-2
- Program cost and funding impact of the change

Examining each of these issues individually, the Northrop program manager, in conjunction with all members of the contractors' management team, initiated a "bottoms-up" task schedule and cost reassessment of the remaining ("To-Go") work effort using both functional and WBS Task Team inputs for both the non-recurring and recurring efforts. Recurring cost estimates were also made independently by the pricing organizations of all three airframe companies using their parametric databases and each company developed independent parametric estimates of the non-recurring design effort for the period from PDR-2 to the initial drawing release and for subsequent changes using updated definitions of drawing types and quantities, and tool and part requirements.

From that schedule and cost reassessment, several things became evident:

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[15] For Government controlled baselines, change requests are classified as Class I or Class II. A Class I change proposes to modify the form, fit, or function of an item. A Class II change is needed to meet a performance requirement. In a cost plus contract, the difference is funding for fee.

- The “Configuration Freeze” milestone could be achieved with the exception of two activities being carried over for 2 months. The in-depth re-definition of the “Inboard Profile” and top level Zone Drawing Layouts depicting equipment and structure locations in the various equipment bays would not be initially complete. Also, the internal “Design-To” loads would not be available until September. The design group/task team managers responsible for these “slippage” elements predicted recovery of their schedules prior to PDR-2.
- The PDR-2 milestone could be achieved but the design analysis database for the vehicle subsystems was questionable. The subsystem task teams were confident that they could have the systems schematics and equipment sizing defined, the penetration locations established and the size of their routings defined, as required. The dilemma was that this “confidence” was based on limited supplier input/knowledge.
- The attainment of the “Interface Control Documentation” milestone was in jeopardy because of the inability of the vehicle subsystems task teams to know what the impact of the required changes would be on their suppliers’ PDR & CDR milestones and the completeness of suppliers’ design analyses supporting equipment development at those milestones.
- The CDR milestone was in jeopardy because of the lack of supplier inputs for the changes required to each system by the configuration change and the fact that many of the subcontracts for this equipment were in the process of being initiated using specifications that did not reflect the changes. Accordingly, the subsystem managers could not be sure when the supplier’s CDR’s would be scheduled relative to the Program CDR.

Based on these findings, the PM elected to proceed with the then current Program Schedule for the “Configuration Freeze” milestone. However, in concert with the other Airframe Contractor PM’s, he elected to define a new baseline Program Schedule downstream of “Configuration Freeze” as follows:

Table 3-5. Program Manager’s Schedule Change Recommendation

Milestone	Program Plan	Schedule Change
PDR-2	Mar/Apr 1984	2 months later, May/June 84
ICD	2 months after PDR-2, June 84	5 months after PDR-2, Nov 84
CDR	18 months after ICD, Dec 85	20 months after ICD, July 86
First Flight	24 months after CDR, Dec 87	26 months after CDR, July 89

The motivation for the conservatism implicit in the Northrop program manager’s decision was to preserve the integrity of a “best practices” approach, namely retention of the coordination between structures and subsystem design releases and minimizing fabrication tool changes. The total change for the revised program was approximately 9 months later than the Contract Schedule and the Target Cost was estimated to be exceeded by about $ 2.3 -2.9 B. This schedule accommodated the concerns of the status of the subsystem definitions, procurements, and design development. It also accommodated updated assessments of the time required to achieve completion of the air vehicle’s production design using the 3D system modeling of the manufacturing process, and the weight growth and parts quantity estimates for manufacturing the aircraft.

After development of this plan, and following discussions with the GM, the SPO Director, and the senior Technical Advisory Committee, alternative schedule components were identified for management consideration. Essentially these alternative plans examined ways to offset or minimize the schedule and cost growth issues of the PM's plan by the following:

- Reduce the manufacturing schedule by eliminating "stuffing" of major assemblies (i.e. installation of all equipment and system routings) prior to shipment to the Final Assembly facility. This would save 2-3 months of schedule but add costs for relocation and per diem expenses of the traveled work force plus loss of efficiency.
- Hold the PDR-2 and CDR milestones where originally planned with the provision that if the subsystem design was not mature at the planned CDR milestone, potential alternatives to the downstream Program Plan would be reviewed. This would save 4 months of schedule time but required the addition of a cost contingency for a schedule slide at CDR
- Hold the ICD milestone in July 1984 in lieu of September 1984. This would save 2 months but require added contingency for rework of "production released" ICD's and the expected resultant design changes.
- Reduce the historical "change factor" used in engineering and manufacturing estimates because of the use of a 3D database.
- Use the original estimating factor for production design drawing development and increase the estimate only for the increased drawing quantity estimate.

The development of these alternatives was completed in time for the September 1983 quarterly CEO/Commander meeting scheduled at WPAFB, OH. Initially the review focused on the configuration changes, the rationale for each, and the new projected system performance. The alternative plans' assumptions and input variations were reviewed. There was acceptance that schedule slippage might occur, but it was believed that maintaining the original schedule would provide the lowest overall cost and shortest time to first flight. The selected plan had a projected cost impact of approximately $1.5 -2.0 B. The subcontractor program managers were encouraged to use their "best efforts" to hold the Contract Program Schedule

3.3.4 Preliminary Design Review (PDR-2)

Following the resolution of the Contract Plan, the Program proceeded to close all the remaining technical and producibility risks required to support PDR-2 except for the Radar Antenna performance demonstration. PDR-2 was successfully conducted in the March/April 1984 period with all requirements satisfied. Test data from the low speed and high-speed verification wind tunnel tests and from verification tests on a new, large-scale observables model of the aircraft demonstrated compliance with the contract specification. At PDR-2, the SPO added a requirement for Reliability Design Growth Testing (RDGT) so that all weapon system elements would achieve significant system reliability maturity by IOC.

The radar antenna design failure that occurred during the risk reduction phase had been diagnosed and the contractor (Hughes) had initiated a series of risk closure activities, which were presented at PDR-2. At the completion of those closure activities (August'84), the antenna performance and its observables characteristics were demonstrated in compliance with the contractor team's PDR-2 commitment.

Although the subsystems' WBS Task Teams were able to meet the requirements for PDR-2, the desired depth of analyses and vendor design development supporting the design definitions was not achieved. This became evident when the contractor team attempted to meet its next Program milestone.

3.3.5 Interface Control Document (ICD) Closure Date

This milestone was originally scheduled for June 1984, but was not completed on time. It took approximately two additional months to satisfy the criteria for this event. The major deficiency was the lack of specific data for the vehicle subsystems caused by the changes to those systems necessitated by the reconfiguration. The implementation of these changes was impacted by the need for substantive subcontract changes, even though letter contract authority was utilized. The difficulty was the need for specification revisions which required supplier engineering's analyses before making commitments on price.

3.3.6 Critical Design Review (CDR)

The B-2 Critical Design Review was held per the Contract Schedule (December 1985). The structure design completion goal of 90% drawing release was met but the subsystems design release was only 20% complete versus a goal of 90%. Action plans to address these shortfalls were generated and incorporated as part of the CDR closure. No change in contract schedule was made as a result of the action plans but there was tacit acceptance by the SPO program manager of the Northrop program manager's decision to revise the Program's internal work plan/schedule whereby a one year delay in first flight was defined (i.e. December 1988 in lieu of December 1987).

To partially offset the Vehicle Subsystems design definition shortfall and the 12-15 months delay that the Program was then projecting, the Northrop program manager elected to initiate a change to the work plan whereby the major assembly stuffing would be deferred to aircraft final assembly. This action reduced the delay by approximately 2-3 months resulting in the projected flight date of March 1988. The actual accomplishment of the 100% release point took about five months. Not all of that delay affected the build of A/V #1 but it did impact the availability of production hardware for qualification testing, conduct of complete system tests in the various laboratories, and the reliability growth test program.

Leading up to this critical review, the preparations were initiated in the early summer of 1985. There were indications at this time that the subsystems were lagging in progress to their entry criteria for the review. Numerous discussions were conducted within the SPO and with the contractor concerning CDR preparation and our readiness to conduct the review. The SPO chief systems engineer, Tim Sweeney, reported to the principles that all of the criteria were not yet satisfied. The SPO principals finally concluded that the CDR would be held on the stipulated date and coordinated the decision with the contractor principles. The conclusion that the structure was sufficiently mature was a key consideration, with the objective of conducting the CDR and holding open action items for those items not completed to the criteria. This was consistent with the decision that was made after PDR 2 at the program CEO meeting in the fall of 1983. At this meeting between the company CEOs, the Air Force senior general officer at Aeronautical Systems Division, and their program managers, it was agreed that relieving the schedule would remove the pressure from the team and would increase the risk of an even further schedule slip than was being projected. CDR was held in October and November 1985, with the final wrap-up held on December 5, 1985.

At the conclusion of the CDR the entire team recognized that the schedule was indeed in jeopardy and that first flight in December 1987 was at risk. The program debated the wisdom to re-baseline a new schedule, construct a new target baseline and develop a new over target cost (OTC) profile. The majority of the decision-makers concurred in maintaining the current program schedule and delaying the construction of an over target baseline until there was sufficient maturity to define a new schedule with high confidence.

3.4 System Checkout/First Flight

The first flight event was scheduled to occur in December of 1987 as an original contract milestone. As a result of the reconfiguration, the Northrop program office had assessed at CDR that this milestone would occur in December 1988. The actual flight date was 6 months later (July 1989). The Northrop program manager made the decision to set the schedule down by 12 months by deciding to incur the additional costs associated with the two airframe subcontractors and Northrop's Pico Rivera facility relocating their subsystems installation work force and support organizations to the final assembly facility for what was anticipated to be A/V #1 – #3. As envisioned, the additive costs were essentially the per diem costs for that work force for 6 months. The reality was that the time actually extended until A/V #7 due to the level of change activity and other unforeseen events not related to the configuration change. Major contributors to the further delay; were the inefficiencies in stuffing the first aircraft, delayed completion of the electrical system installation/check-out, the time required to perform the functional system check-out the first time on a very complex aircraft system, and the re-assessment by the Combined Test Force (CTF) of A/V #1's maiden pre-flight test requirements.

4.0 SUMMARY

The story of the B-2 engineering development is rich with the trials and tribulations of a very complex aeronautical system. In order to scope this case study, the authors determined there were five top Learning Principles for the B-2 program.

LP 1, Integration of the Requirements and Design Process: *A key aspect of the implementation of the B-2 systems engineering process was the integration of the SPO requirement's team with the contractors' design team, including manufacturing, Quality Assurance, and logistics functionals into a cohesive program effort. This facilitated continual trade studies conducted by the specialists from the User/SPO government team with the company specialists to fully assess the performance trade-offs against schedule, cost, and risk.*

The systems engineering process of the B-2 development program was systemic to the design process and the engineers, manufacturing, Quality Assurance, logisticians, and program specialists from the customer, User, and contractors all participated as equals. Everyone contributed to the development of the requirements and the evolution of the design. When a requirement was causing a design risk that would manifest itself as a cost, schedule, or performance impact, the team would construct alternative approaches, the SPO members would assess the change to performance with the User to evaluate the necessity to achieve full compliance or rebalance capability. Cost and schedule alternatives would be developed. Many times, the problems could be resolved within the teams or traded within interfacing capabilities. The day-to-day involvement with the technical specialists kept the team ready to make rapid assessments.

It is vital to control the specifications at the proper time. While the combined team developed the specification, it is the role of the customer to own and control the specifications, but to be ever vigilant for cases where the requirements become difficult to meet. In this case, it is the final decision of the customer to either fund the effort to meet the specification or change it. This was particularly true for the specifications that were not part of the initial contract. The specifications that were prepared by PDR 1 for the SPO were all reviewed for changes in scope. But, it was always part of the strategy and the program funding to baseline these specifications as part of PDR 1. PDR 1 was different from a Systems Requirements Review (SRR) where the requirements are typically reviewed across the entire system. Rather, this review developed the subsystem specifications as derived from the top level specifications, which were approved and controlled at the contract signing. The strategy to require the system, air vehicle, engine and training specifications at contract award, the performance based subsystems specifications at PDR 2, and the detailed design specifications at Product Verification Review was a factor to the success of the systems engineering process within the program. This was even true for the RCS specification addendum to the Weapon System specification, which was placed on contract as a no cost change.

Beside the obvious lesson learned from the efficiencies gleaned from the combined efforts of the specialists and the overall program philosophy of cooperation, there is a subtle, but important point that must be highlighted to caution the practitioner of the potential pitfalls of this strategy. After the CDR milestone, it is vital to control this working relationship. The effort from CDR to first flight is centered on manufacturing the parts, assembling the aircraft, qualifying the components, and checking out the assembled system. This is simply hard work, and any unnecessary or superfluous change is an enormous and unwanted burden on an already burdensome time frame. Since the WBS Task Teams worked so closely and had implemented the design in conjunction with the Using command, and since there is always a "better" way to implement some of the features of the design, there is a constant pressure at the working level to make enhancements. In order to control this culture after the CDR, all the Using command officers were only participants in formal Technical Interchange Meetings (TIM), and all TIMs were mandated to have minutes prepared, signed by the contractor responsible engineer (RE), cosigned by the SPO counterpart, and have an action item list for approval at the Chief Engineer level. The engineering leadership continuously stressed the necessity to control changes and make only "must have to work" or safety related changes.

LP 2, <u>WBS Task Teams and Functional Hierarchy</u>: *The contract Work Breakdown Structure (WBS) stipulated the entire program content and tasking and the company organized the development effort into WBS teams responsible to implement the contract WBS. These WBS Task Teams were assigned complete work packages - for example, the forward center wing. The systems engineering WBS Task Team efforts were organized similarly, but with separate responsibilities, each reporting to the Northrop chief engineer or his deputies. The functional organizations assigned members to the task teams to assure accommodation of their program needs. A vital distinction from many of today's IPTs was retaining the WBS Task Team membership throughout the functional organizations' various management levels. This facilitated communication, integration, interfaces, and integrated the functional leadership of each of the company's technical and management disciplines into the decision process. The program management top-level structure was organized into a strong project office with centralized decision authority and strong leadership at the top of both the SPO and the contractor organizations.*

The WBS task team construct was unusual because it had the inherent checks to mitigate against the tendency to become independent. Since the WBS task team leader did not own the assets, the members had a responsibility to their functional organization to report and seek guidance. The functional leadership instilled a balancing factor in decisions. The functional leadership was forced to provide assistance to the project managers, who had the mandate to deliver products. A strong centralized program management/leadership role was crucial to provide the guidance and focus for each company and for the integrated program. The process could quickly surface the problem to the appropriate decision level and the program would efficiently reach a consensus and resolve the issue. Awareness, knowledge, experience, consistency in the work force, and the authority to act were ingrained in the participants.

One particularly important and very illustrative event that underscores the effectiveness of the WBS Task Team effectiveness was a decision made early-on that would have profound and positive impact on the program 6 years later. The Air Vehicle systems engineering group identified a manufacturing risk (well prior to PDR 1) for the potential difficulty of mating the various wing sections during final assembly. Working in concert with the Manufacturing Engineering and Tool Design Groups, the joint SPO/contractor team developed a plan to reduce that risk (and in the case of Air Vehicle #2 save the aircraft assembly's compliance with the specification) by designing a special mating tool for both the Intermediate Wing to aft center wing/forward center wing, and the Outboard Wing to Intermediate Wing. This machine implemented precise, computer-controlled, micro adjustments with 6 Degrees-of-Freedom (DOF) of each of the major assemblies during the mating operation.

LP 3, <u>Air Vehicle Reconfiguration</u>: *The identification of a major aeronautical control inadequacy of the baseline configuration just four months prior to the formal Configuration Freeze milestone caused an immediate refocus of the Task Teams to develop a substantially revised design. Within several days, the air vehicle task teams were conducting trade studies, augmenting their skill sets, and integrating with the other program participants in a coordinated effort to derive an efficient, controllable, operationally useful system. At the same time, the program elements that were not markedly affected by the change maintained a course that preserved their schedule, but was sufficiently flexible to include any potential changes. In a program wide systems engineering effort, the prime contractor's program office integrated the teams, reviewed their efforts, coordinated the systems trades, and identified significant changes to the outer mold lines, the radar cross section (RCS) baseline, all major structure assemblies, and all major air vehicle subsystems requirements, with the exception of avionics and armament. The alternatives were derived by the end of the third month, the final choice was selected by the sixth month, and the seventh month was used to coordinate and garner the approval of all stakeholders. While the program response to the crisis was rapid and effective, and a significant impact on the downstream cost and schedule was anticipated by the management team, and the technical impact was predicted by the systems engineering process, it was not predicted to the fullest extent.*

By the time the student has reached this point in the case study, it should be clear that the true underlying principle of LP3 is the necessity to stop all the baseline effort when a problem of this magnitude arises and concentrate all efforts on finding a solution. The program did this well. The people who knew there was a problem had the ability to go to the appropriate decision level, the program manager accepted the bad news professionally, the teams put in place an immediate recovery plan, the program responded quickly, and the new plan was developed and implemented. This can also be parsed to a lower level, even to the subsystems and component level.

LP 4, <u>Subsystem Maturity</u>: *The effect of the reconfiguration on the maturity of all the air vehicle subsystems (flight control, environmental control, electrical, landing gear, etc) was far greater than projected. The subsystems were mostly vendor-supplied equipments and some were in the selection process to the technical requirements of the original baseline when the reconfiguration occurred. After the new configuration was derived, the requirements for the subsystems changed to such a degree that they had to be resized and repackaged. It took longer than anticipated by the systems engineering process to recognize the growing problem of getting all the specifications updated and to identify the lagging equipment maturity that resulted. Thus, the reconfiguration required a second iteration of the design requirements and their flow-down to the many suppliers and their detailed designs. These iterations after PDR-2 resulted in the vehicle subsystems not achieving their Critical Design Review (CDR) milestone concurrently with the structure, but rather five months later.*

As in LP3, where the program concentrated in developing a new plan, here, the program also constituted a new plan but it did not have the complete design and installation impact. The program had several options such as moving CDR or analyzing the subsystems to determine what additional resources it would have taken to meet the original date for CDR with a new baseline.

The configuration change had a major impact on the Program's conduct in all aspects-technical, schedule, and cost. The technical impacts went beyond the late completion of the structure and subsystems design. The subsystem design delays necessitated a higher level of structural changes. This necessitated retention of more structural design staff on the program for a longer period. The execution of the subsystems development on a compressed basis (even though not attained) necessitated a significantly larger staff for a longer period. These same impacts existed at each of the major airframe locations. In addition, the majority of the subsystem suppliers were pressed into significant overtime usage in attempts to complete their design and build of early pre-production units to support system level verification and validation tests. The lateness of the subsystems' definitions had its maximum cumulative effect on the finalization of the electrical circuitry design which impacted the initial build of wire harnesses and the completion and checkout of the aircraft. Both of these issues became problems in their own right in final assembly. The relocated subsystem installation teams at the final assembly facility were less efficient due to aircraft access, schedule "work-a-rounds," the long supply chain from their "home" facility, and iterative design changes.

LP 5, <u>Risk Planning and Management</u>: *The program was structured so that all risks affecting the viability of the weapons system concept were identified at contract award and were structured as part of the Program and WBS work plans. The initial risks were comprised of those "normal" risks associated with a large complex weapons system development, as well as the new technology and processes necessary to mature the program to low to medium risk at PDR. Those initial risks were closed prior to PDR 2. The risk closure process continued throughout development and identified new risks and continuously identified new risk closure plans. Most importantly, the work associated with risk closure for each plan was integrated into the WBS task teams' work plans and into the Program Plans. These detailed plans showed all design, analyses, tests, tooling, and other tasks necessary to close the identified risks and were maintained and reviewed as part of the normal design/program reporting activity.*

The program's use of a disciplined, decentralized risk management program was a major contributor to developing an integrated, funded, resourced plan. It helped drive everyone to seek the right solution in the most efficient manner. Treating Risk Management as a discipline with a definitive process and locating it at the level where work was accomplished was a major success story. Everyone participated; the lowest level of the design team was responsible for closure, status, and reporting. All the resources necessary to close the risk were incorporated in the WBS, including the basic plan and all the alternatives, if required. The Risk Closure Plans were reviewed at quarterly program management reviews (QPMR) and the leader of the WBS task team had to get the agreement of all the participants from all the sides of the program before it could be presented to the program management team. This forced a major systems integration/systems engineering activity to assure agreement before the results, recommendation, and alternatives were presented.

Thus, the concept for risk planning was unique in that the approach was predicated upon logic rather than procedures. It required all functions to identify their primary risk issues (related to the product or the processes to develop the product), develop the logic trail of data and decision points for resolving those issues, identify the associated activities for that resolution and only then develop the appropriate work plan, schedule, and costs for accomplishing those activities and the remainder of their functional/discipline work plan. In some cases, the risk closure issues were of such high risk that "dual parallel paths" were developed for their closure.

5.0 REFERENCES

1. Official Photographs by USAF of a B-2, back side drawing, 1996 and official charts from the Air Force B-2 Systems Program Office, Wright Patterson Air Force Base.
2. George Friedman and Andrew P. Sage, Case *Studies of Systems Engineering and Management in Systems Engineering* (advance copy), University of Southern California, CA and George Mason University, VA, 22 September 2003.
3. Griffin, J.M, Personal Interviews and editorial reviews of the first version, June 2004 to February 2006, see Appendix 3.
4. DoD Architectural Framework, Version 1.0, 9 Feb 2004.
5. David Aronstein, Albert Piccirillo, *Have Blue and the F-117A: Evolution of the "Stealth Fighter"*, AIAA, Reston, VA, 1997.
6. Northrop Grumman B-2 Case Study, Propriety.

EDITOR'S NOTE

Having been involved in the writing, editing and review of five Systems Engineering case studies, I must remind the reader of scope and viewpoint. Time and money force the management of these cases to reflect upon only a few (4-6) key points which the authors deem most important. Many, many more interesting vignettes could have filled out the entire Freidman-Sage Matrix for a program the size of the B-2. While the authors often found themselves on a historical quest for more (more information, documentation, interviews and confirmations), I was forced to continually scope the writing effort to completion.

The authors and those interviewed often may disagree on the top learning principles. Clearly author viewpoint and unintentional bias may find its way onto these pages. I have made all attempts to remove unnecessary or overtly biased statements. Every additional review of past cases would uncover disparate viewpoints and recollections of facts and/or decisions made on those facts. It was my belief that having co-authors on this B-2 case, one from the government and one from the prime contractor, would instill an overall balanced perspective in the final document.

Lastly, I hope that reading the AF CSE cases, together with other case study materials, will allow practitioners and Systems Engineering students alike to be thoughtful of the lessons learned across the nine concept areas and three responsibility areas of the F-S framework. Each program has unique technical, political, and managerial characteristics, so the lessons first need to be understood in the unique, historical context, but can often be generalized and rationalized for current environments.

APPENDIX 1: COMPLETE FRIEDMAN-SAGE MATRIX FOR THE B-2

Concept Domain	Responsibility Domain		
	1. Contractor Responsibility	2. Shared Responsibility	3. Government Responsibility
A. Requirements Definition and Management	Northrop was responsible to develop a conceptual design responsive to the requirements of the initial study contract.	The contractor and the SPO integrated the requirements process and the design process into one cohesive team. The using command, Strategic Air Command was an integral part of the team in functionally allocating operational needs to design implementation.	The government funded research for low observable aircraft, both at the AF laboratories and with industry. They established the need for a long-range strategic bomber and solicited the contractors for design studies. The government prepared and distributed the RFP and conducted the source selection.
B. Systems Architecting and Conceptual Design	The architecture for the avionics system was developed during the study contract and the proposal phase. The weapon system architecture dictated a long-range high-altitude stealth bomber with low altitude capability.	During the development of the avionics defensive systems trade study prior to PDR 2, the Air Force participated with the contractor in the assessment alternatives and in the final recommendations.	The Air Force established basic architectures for the weapon system and for the avionics for the contractors to conduct trade studies and propose alternatives
C. System and Subsystem Detailed Design and Implementation	The contractor allocated the functional requirements from the systems specification throughout all the configuration item specifications and computer program critical item specifications. The contractor held design meetings with the major subcontractors, engine contractor and the avionics suppliers.	The Air Force participated actively with the contractor's design team in technical interchange meetings for systems engineering, for the subsystems, logistics, manufacturing, and flight testing.	The government engineers and functional specialists provided the contractors' teams with experience on other weapon systems relevant to the development of the B-2.
D. Systems and Interface Integration	The interfaces between the subcontractors and the equipment's in the aircraft were organized by solemn and assigned to zone managers. Interface Control Definition (ICD) was a contract program milestone.	The air vehicle was partitioned into zones and a zone manager was assigned to assure matching interfaces and installation of equipment within the zones. Chief engineers meetings between the Air Force and the three airframe contractors were held routinely to settle interface conflicts.	The SPO managed contracts with Northrop and with General Electric. The SPO established and funded Air Force Plant 42 at Palmdale CA as the production site and Edwards Air Force Base, South Base, as the flight test facility.
E. Validation and Verification	Extensive laboratories were used employed for testing to verify integration of components, subassemblies, and subsystems. A flying test bed was used to prove in-flight integration of complex avionics suites prior to commitment to the weapon system.	The Air Force maintained a presence with the contractor team for all major ground testing in the laboratories. During assembly and checkout prior to first flight, the Air Force assigned 27 people to work on site as part of the checkout team.	The Air Force established a combined task force and men aged the flight test program. The Air Force participated in ground laboratory testing and was responsible for approval of all test plans.
F. Deployment and Post Deployment	Northrop deployed a team of engineers and logistics support personnel to Whitman Air Force Base.	The Combined Task Force was established early in the program and led by personnel from Edwards Air Force Base and included the contractor personnel. The team conducted joint testing with the Operational Test and Evaluation (OT&E) community.	The Air Force established Whiteman Air Force Base, Missouri, as the operational base and managed the preparation of the base for the arrival of the operational fleet.
G. Life Cycle Support	The contractor provided contractor logistics support in continuous sustaining engineering, along with a product warranty.	. The Air Force and contractor team jointly developed the supportability strategy for the program, including the warranty philosophy.	The Air Force approved the life-cycle support strategy.
H. Risk Assessment and Management	Risk closure plans were an integral part of the program. They were proposed by the contractor during the source selection as a process to assure mitigation plans were integrated into the work breakdown structure (WBS).	The team managed risk to the risk assessment process with risk closure plans. Risk closure plans were developed jointly and were an everyday way of doing business.	The Air Force requested a risk assessment in management process and participated actively in the risk closure plan process.
I. System and Program Management	The contractors' program management teams were organized by functional specialty with a project management focus for major subcontracts.	The top-level communication and decision-making process was expedited by frequent meetings among the company and AF principles. Decision-based Quarterly Program Management Reviews (QPMR) were scheduled and attended by all principles.	The SPO was organized in a classic functional structure. A project office was established to manage across product areas. Most of the teams that work on product areas were integrated product teams, with personnel assigned to their functional organizations

APPENDIX 2: AUTHOR BIOGRAPHIES

JOHN M. GRIFFIN

John Griffin is President, Griffin Consulting, providing systems engineering and program management services to large and mid sized aerospace firms. He provides corporate strategy planning initiatives for company CEOs, reviews ongoing programs to assess progress and recommend corrective actions, and participates as an integral member of problem solving teams. He is active in numerous leading-edge technologies and advanced system development programs.

Experience/Employment Highlights:

- Director of Engineering, Kelly Space and Technology, Inc, San Bernardino, CA
  Conceptual design process of a space launch platform
- Director, Development Planning, Aeronautical Systems Center, Wright-Patterson Air Force Base, OH
- Chief Systems Engineer, Engineering Directorate
- Director of Engineering, B-2 Spirit Stealth Bomber, B-2 System Program Office
  Engineering leadership /and management from inception through 1st flight
- Source Selection Authority for two source selections
- Chief engineer, F-15 Eagle
- Chief Airframe Engineer, F-16 Fighting Falcon
- Chief Airframe Engineer, Air Launched Cruise Missile

Honors/Awards:

- Two Meritorious Service Medals
- Distinguished Career Service Medal for his 37 years of achievement, 1997
- Pioneer of Stealth, 1998
- University of Detroit Mercy; Engineering Alumnus of the Year, 2002

Education:

- University of Detroit, Detroit MI, 1964: Bachelor of Aeronautical Engineering
- Air Force Institute of Technology, WPAFB OH, 1968: MS of EE
- Massachusetts Institute of Technology, Cambridge MA, 1986: Senior Executive Sloan Program

Affiliations:

- Founder (1993) and President (1993–1997), Western Ohio Chapter Senior Executive Association.
- Co-founder (1995) and President (1996–1997), Defense Planning and Analysis Society.

JAMES A. KINNU

Mr. Kinnu is a retired Vice President of the Northrop Grumman Corporation, consulting to the Aerospace and Defense Electronics industries and certain U.S. Government agencies. He led the Northrop Grumman Corporation's successful Advanced Technology Bomber (B-2) proposal team and development efforts on the B-2 from September 1980 through 1988.

Experience/Employment History:

- United States Army, 1953 – 1955
- Lockheed Corporation, 1955 – 1971
  - Design Engineer and Project Engineering for the Electra Project
  - Contracts Manager for Commercial Aircraft
  - Advanced Systems Marketing Representative
  - Program Manager, Advanced Fighters
  - Program Manager, L-1011 Wing & Empennage
- Rockwell International Corporation, 1971 – 1977
  - Business Area Manager, Advanced Programs
  - Program Manager, Quiet STOL (QUESTOL)
  - Program Manager, Highly Maneuverable Aircraft Technology (HIMAT)
- Falcon Jet Corporation, Vice President and Assistant to the President, 1978
  - Modification & Overhaul Center, Teterboro, NJ
  - U. S. Coast Guard's Falcon 20 Development Program, Little Rock, AK
- Northrop Corporation, 1979 -1992
  - Staff Engineer, Advanced Systems
  - Manager, Advanced Design
  - Manager, Advanced Systems & Long Range Planning
  - Proposal Manager, Advanced Technology Bomber (ATB)
  - Vice President & Program Manager, B-2 Full Scale Engineering Development (FSED) Program
  - Corporate Vice President for Programs
  - Deputy General Manager, Aircraft Division
  - Corporate Vice President for Programs
- Management Consultant, 1992 - 1995
  - Hewlett Packard Inc., Northrop Grumman Corp., Visionaire Corp.
  - McDonnell Douglas Corp., Bombardier Corp. – Short Brothers Division, Andersen Consulting Inc. and Aerospace/ Defense Electronics clients

- Varilite International Inc., 1995-1997

  Chief Operating Officer and Board of Directors Member

- U. S. Department of Justice, Expert Witness for A-12 Litigation, 1998 - present
- Northrop Grumman Corporation, Management Consultant, 2004 – present

  Integrated Systems Sector

Education:

- University of California , Los Angeles, CA 1953: Bachelor of Science

  Majors: Physics & Business Administration

Honors/Awards:

- U.S. Army Commendation Ribbon w/ Medal Pendant, 1955
- NASA, Aircraft Design Award for B-2 Aircraft, 1989
- Patent Award, Patent No. Design 314,366 (B-2 Aircraft), 1991
- AIAA Associate Fellow, 1991

APPENDIX 3: INTERVIEWS

The company affiliation and positions are those held on the B-2 during the timeframe of the case study. Alphabetical list of interviews include:

James Bottemely, Lt. Col., Manufacturing Director, B-2 SPO

Dave Conklin, Northrop, Avionics Manager

Llewellyn "Doc" Dougherty, Lt. Col. Deputy SPO Chief Engineer

George Freidman, Northrop, Avionics and Chief Technical Officer

Joseph Keith Glenn, Colonel, Air Force, Program Manager

Tom Griskey, Northrop, Systems Engineering

Chris Hernandez, Northrop, System Engineer

Tom Marsh, General, AFSC Commander

Al Meyers, Northrop, Flight Control Manager

Stanley Richey, Air Force, Financial Manager

Richard Scofield, Brigadier General, Air Force, Program Manager

Lawrence Skantze, General, Air Force, Source Selection Advisory Board Chairman

Erich Smith, Vought, Test Engineer, Systems Engineer, Chief engineer

Henry Spence, Vought, Chief Engineer

James Sunkes, Air Force, Survivability Engineer

Tim Sweeney, Air Force, Chief Systems Engineer

Irv Waaland, Northrop, Chief Engineer

Mark Wilson, Air Force, Lead Structures Engineer

Howard Wood, Air Force, Structures engineer

Reviewers of the first draft version:

John Cashen, Northrop Weapons Systems Engineering Chief
(and patent holder with Kinnu and Waaland)

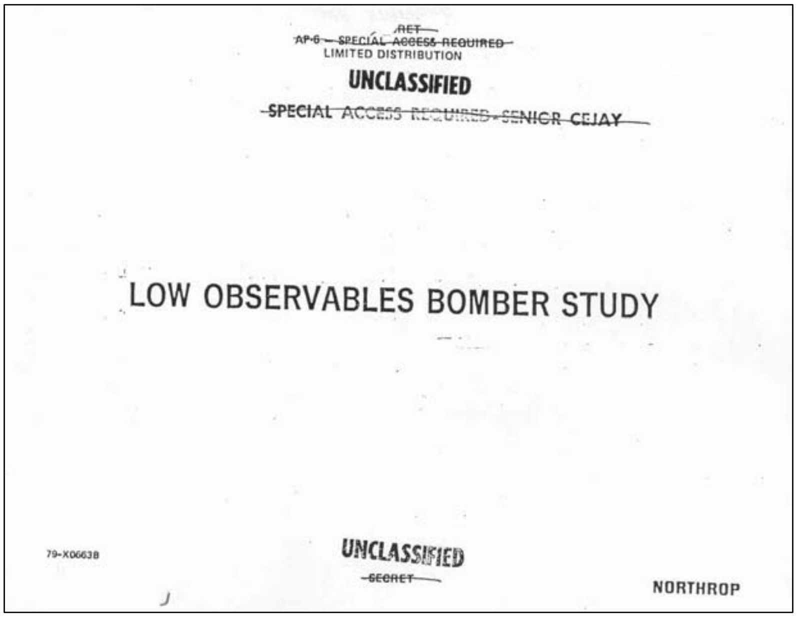
James Mattice, Wright Laboratory, ManTech Director

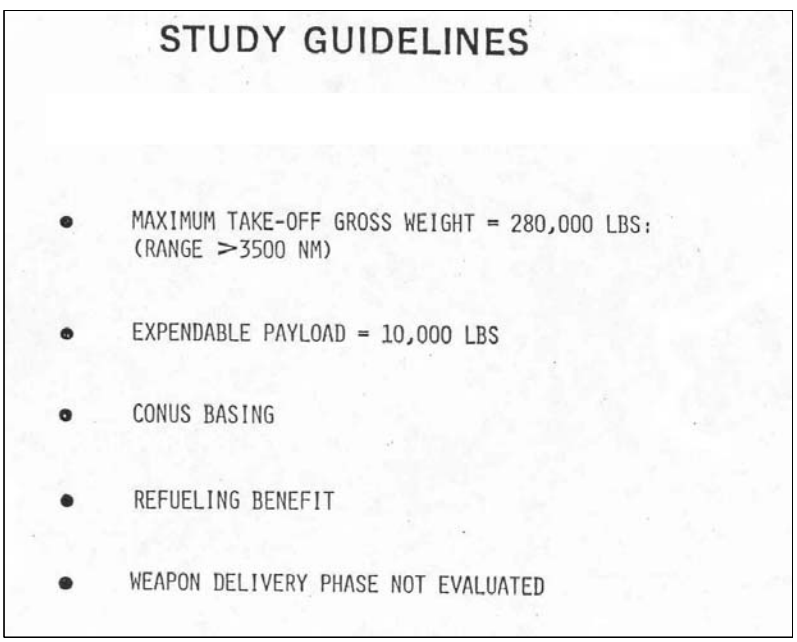
Robert Patton, Vought Program manager

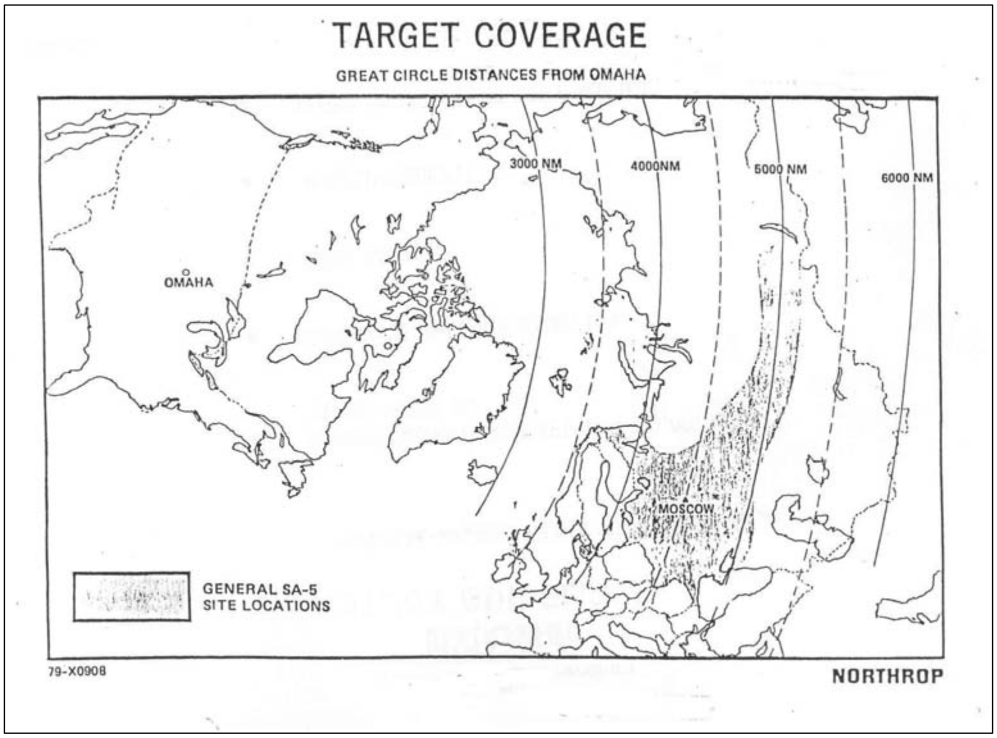
Mark Wilson, Air Force Center for Systems Engineering

APPENDIX 4: ASPA RISK REDUCTION BRIEFING, 1979

This appendix provides a sampling of the early trades for a stealth bomber. These slides, at the time, were originally SECRET – SPECIAL ACCESS REQUIRED, but have since been downgraded to UNCLASSIFIED. Most of the slides have been graphically cleaned for readability.







MISSIONS SELECTED FOR STUDY

LOW ALTITUDE SUBSONIC

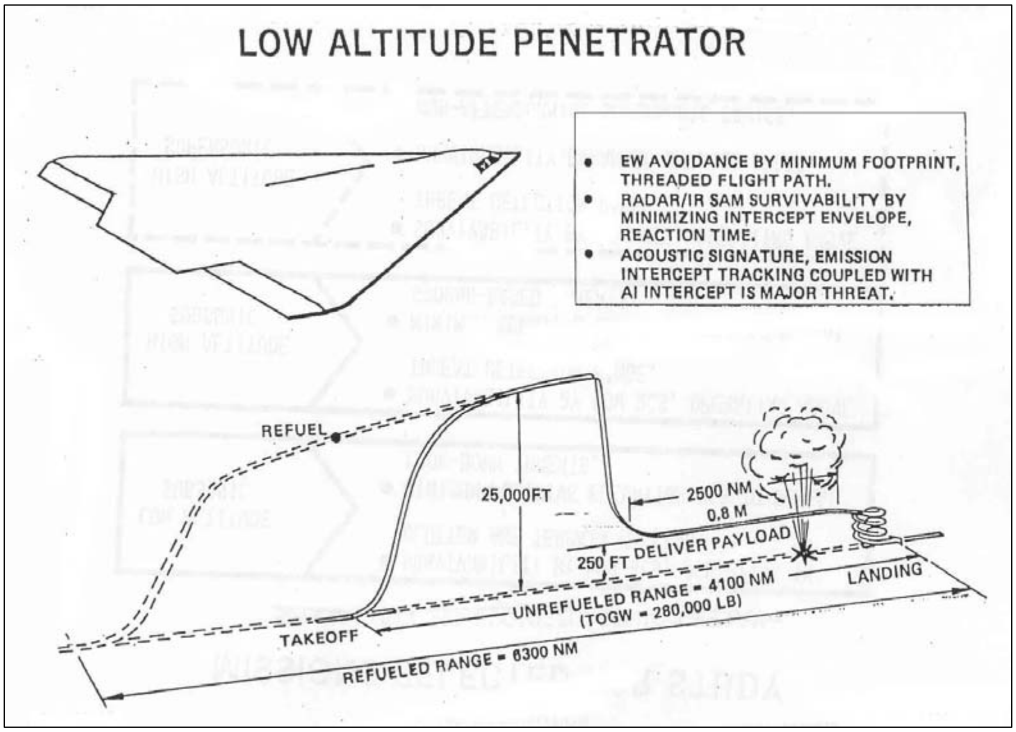
- SURVIVABILITY BY LOW RCS, OPERATING IN CLUTTER AND TERRAIN MASKING.
- MINIMUM POSITIVE ELEVATION RCS TO DEFEAT LOOK-DOWN THREATS.

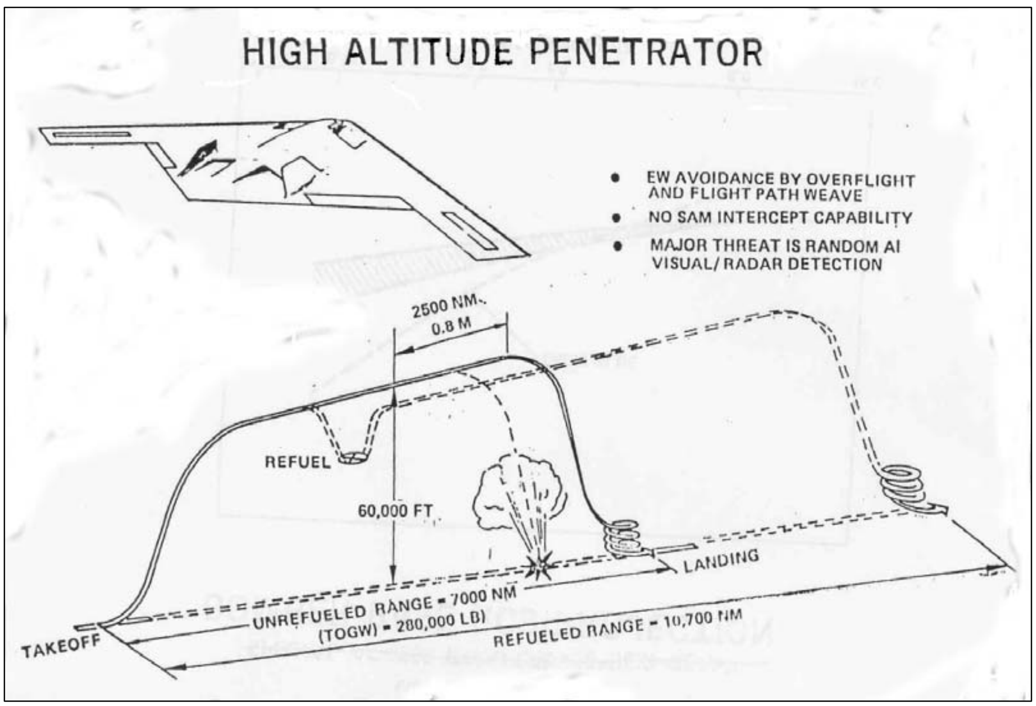
HIGH ALTITUDE SUBSONIC

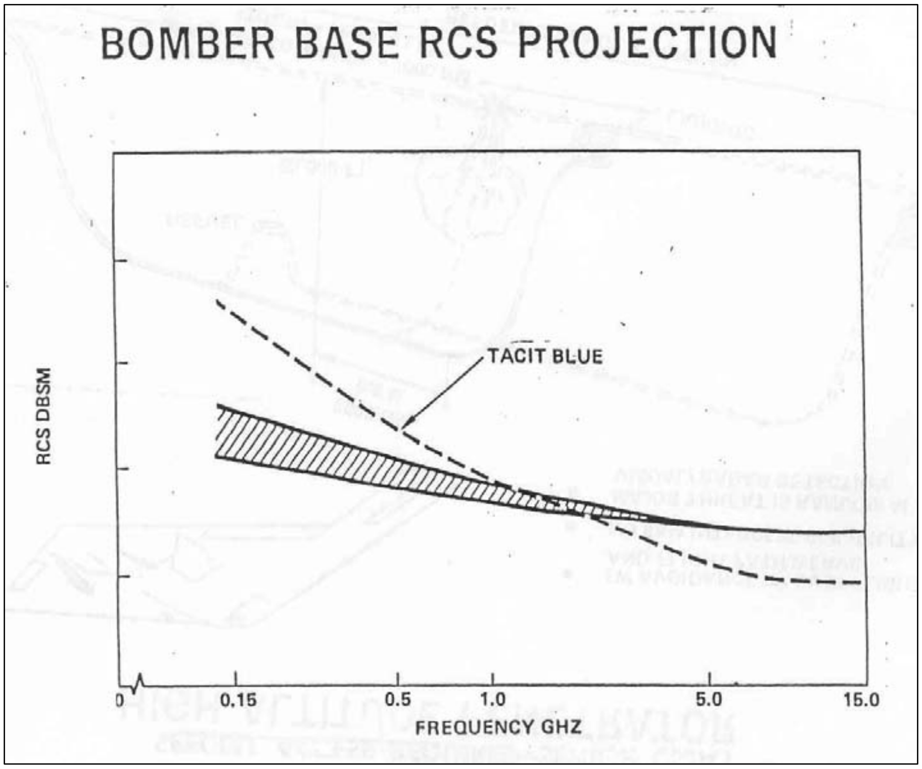
- SURVIVABILITY BY LOW RCS, OPERATING ABOVE THREAT DETECTION RANGE.
- MINIMUM NEGATIVE ELEVATION RCS TO DEFEAT GROUND-BASED THREATS.

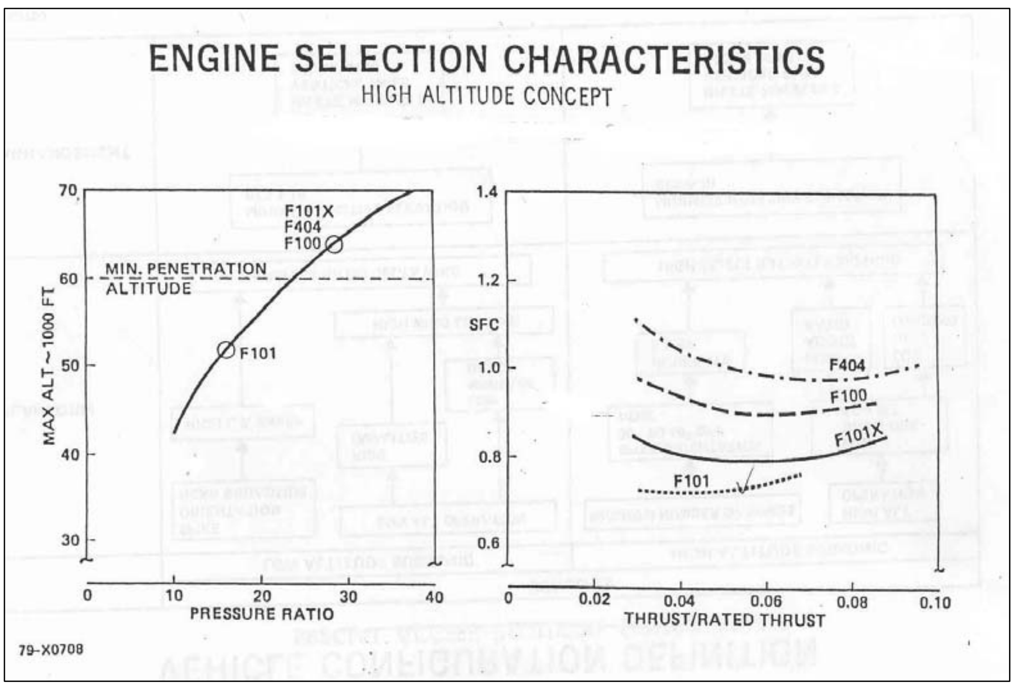
HIGH ALTITUDE SUPERSONIC

- SURVIVABILITY BY LOW RCS, OPERATING ABOVE THREAT DETECTION RANGE.
- SURVIVABILITY ENHANCED BY HIGH SPEED.
- NON-AFTERBURNING SUPERSONIC CRUISE.


LOW ALTITUDE PENETRATOR
• EW AVOIDANCE BY MINIMUM FOOTPRINT, THREADED FLIGHT PATH.
• RADAR/IR SAM SURVIVABILITY BY MINIMIZING INTERCEPT ENVELOPE, REACTION TIME.
• ACOUSTIC SIGNATURE, EMISSION INTERCEPT TRACKING COUPLED WITH AI INTERCEPT IS MAJOR THREAT.
REFUEL
25,000FT
2500 NM
0.8 M
250 FT
DELIVER PAYLOAD
LANDING
UNREFUELED RANGE = 4100 NM
(TOGW = 280,000 LB)
TAKEOFF
REFUELED RANGE = 6300 NM


HIGH ALTITUDE PENETRATOR
• EW AVOIDANCE BY OVERFLIGHT AND FLIGHT PATH WEAVE
• NO SAM INTERCEPT CAPABILITY
• MAJOR THREAT IS RANDOM AI VISUAL/ RADAR DETECTION
2500 NM.
0.8 M
REFUEL
60,000 FT
LANDING
UNREFUELED RANGE = 7000 NM
(TOGW) = 280,000 LB)
REFUELED RANGE = 10,700 NM
TAKEOFF

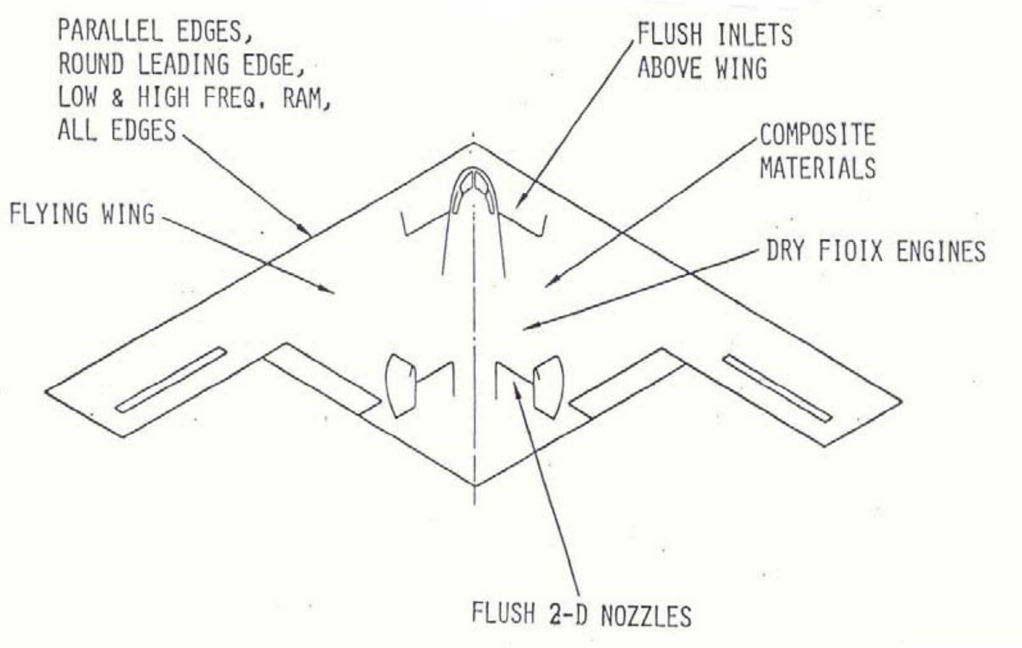

BOMBER BASE RCS PROJECTION
TACIT BLUE
RCS DBSM
0
0.15
0.5
1.0
5.0
15.0
FREQUENCY GHZ

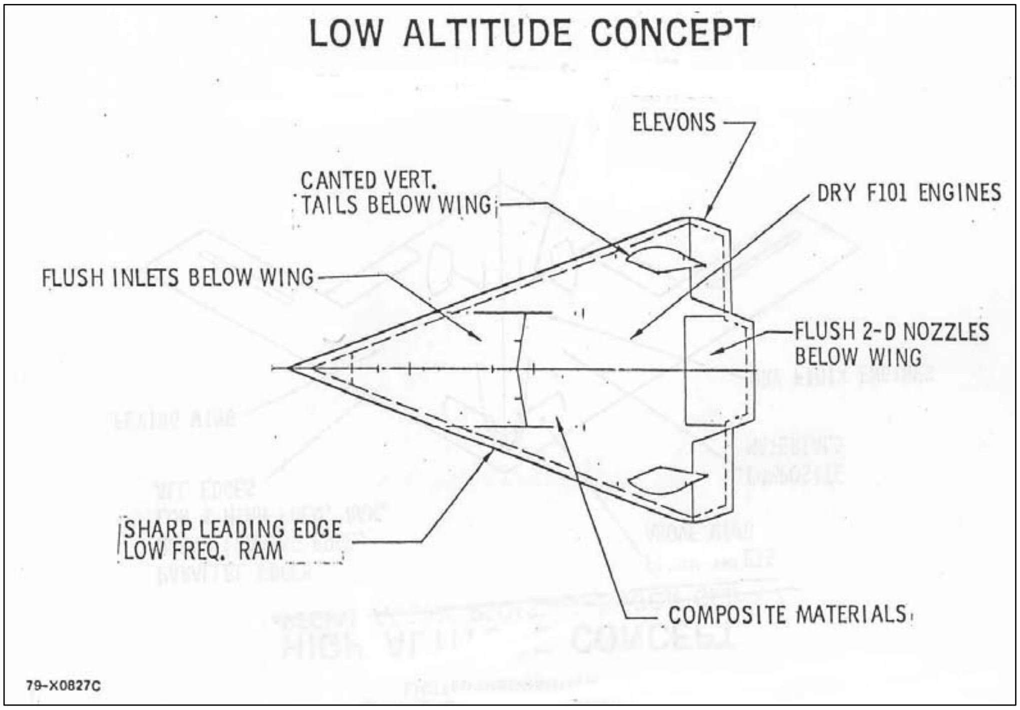

ENGINE SELECTION CHARACTERISTICS
HIGH ALTITUDE CONCEPT
MAX ALT ~ 1000 FT
70
60
50
40
30
F101X
F404
F100
MIN. PENETRATION
ALTITUDE
F101
0
10
20
30
40
PRESSURE RATIO
SFC
1.4
1.2
1.0
0.8
0.6
F404
F100
F101X
F101
0
0.02
0.04
0.06
0.08
0.10
THRUST/RATED THRUST
79-X0708

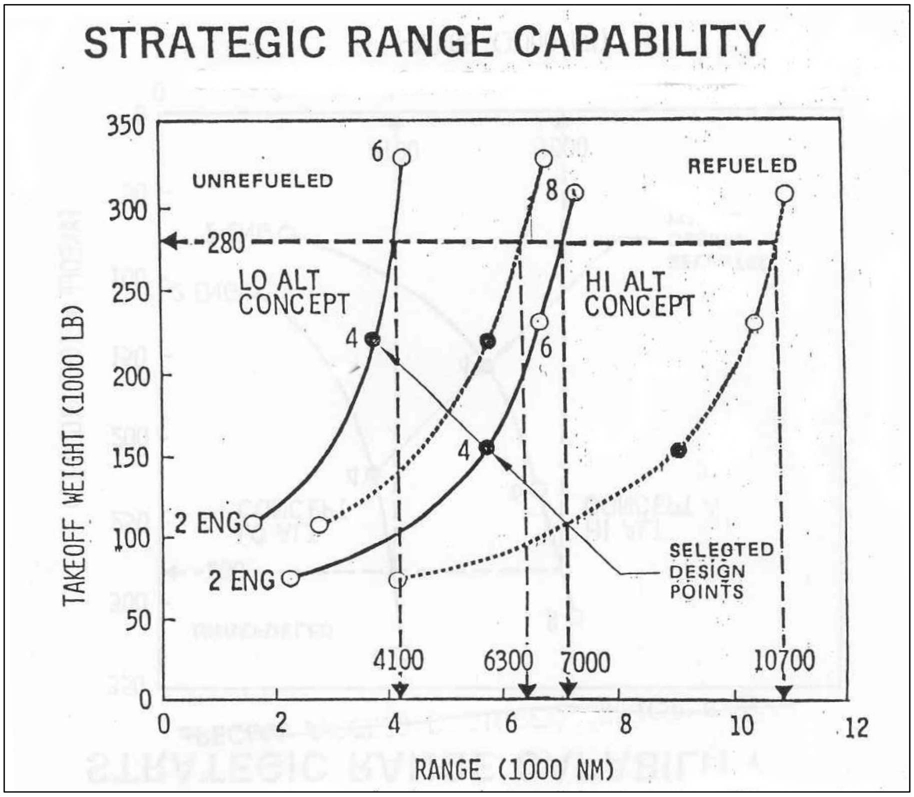
SURVIVABILITY REQUIREMENTS

		LOW ALTITUDE	HIGH ALTITUDE
DETECTION SYSTEMS	TALL KING/ SQUAT EYE	MINIMUM ALTITUDE RCS < DISCRETE SIDE SPIKES	ALT ≥ 60,000 FT RCS ≤ ALL ASPECT, FEW, NARROW SPIKES SWEEP < 40°
	OTH		
	SUAWACS	RCS < NARROW SPIKES	RCS < NARROW SPIKES
	SUSAT	SHIELD EXHAUST	SHIELD EXHAUST MINIMIZE SKIN TEMP.
	VISUAL	VARY FLIGHT PATH	CONTRAIL SUPPRESSION
	ACOUSTIC	VARY FLIGHT PATH	SONIC BOOM AVOIDANCE
KILL SYSTEMS	RADAR SAMS	MINIMUM ALTITUDE RCS < HIGH SPEED	ALT ≥ 55,000 FT RCS < HIGH SPEED
	IR SAMS	MINIMUM ALTITUDE HIGH SPEED IR SIGNATURE <	ALT > 40,000 FT
	AIRBORNE INTERCEPT	RCS < NARROW SPIKES SHIELD EXHAUST IR SIGNATURE <	RCS < NARROW SPIKES SHIELDED EXHAUST HIGH DASH SPEED

HIGH ALTITUDE CONCEPT




LOW ALTITUDE CONCEPT
ELEVONS
CANTED VERT. TAILS BELOW WING
DRY F101 ENGINES
FLUSH INLETS BELOW WING
FLUSH 2-D NOZZLES BELOW WING
SHARP LEADING EDGE LOW FREQ. RAM
COMPOSITE MATERIALS
79-X0827C


STRATEGIC RANGE CAPABILITY
UNREFUELED
REFUELED
280
LO ALT CONCEPT
HI ALT CONCEPT
2 ENG
4
6
8
SELECTED DESIGN POINTS
4100
6300
7000
10700
TAKEOFF WEIGHT (1000 LB)
RANGE (1000 NM)
0
50
100
150
200
250
300
350
2
4
6
8
10
12

WEIGHT SUMMARY

HIGH ALTITUDE CONFIGURATION

	WEIGHT - LB	PERCENT GROSS WEIGHT
STRUCTURE	31,500	20
PROPULSION	19,400	12
RAM & CONTRAIL SUPPRESSION	7,800	5
SYSTEMS & EQUIPMENT	13,300	8
AVIONICS	4,500	3
WEIGHT EMPTY	76,500	48
PAYLOAD	10,000	6
FUEL	73,500	46
GROSS WEIGHT	160,000	100

VEHICLE CHARACTERISTICS

FOUR ENGINE DESIGNS (PAYLOAD = 10,000 LB)

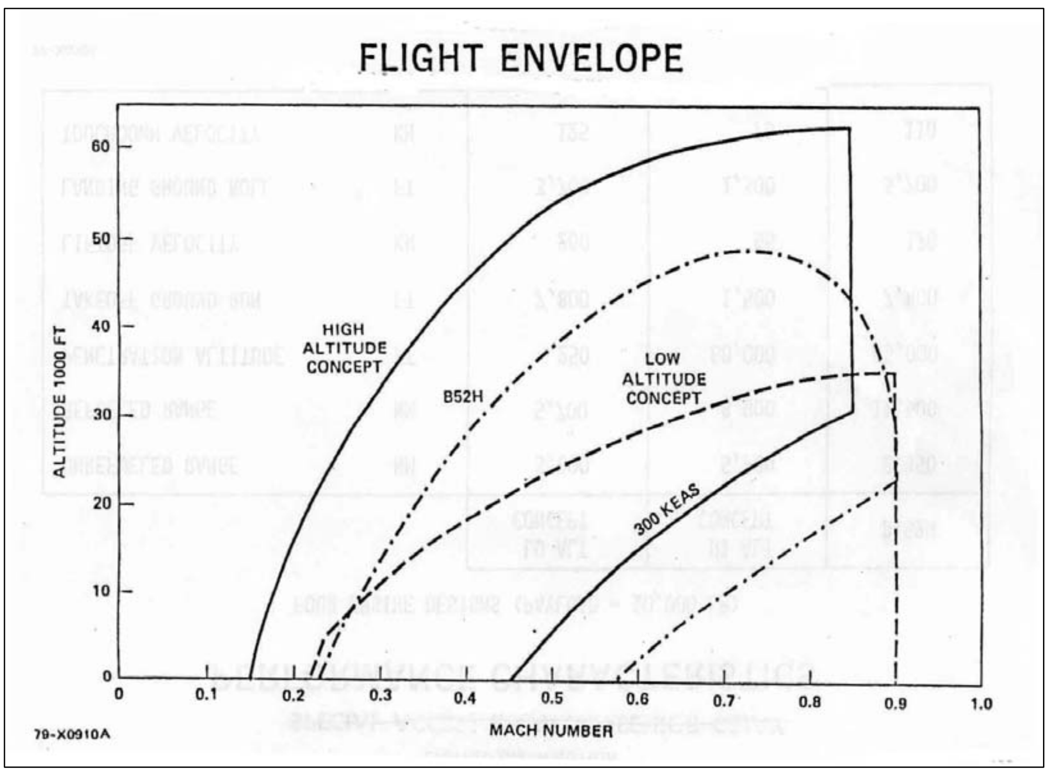
	LO ALT CONCEPT	HI ALT CONCEPT	B-52H
TAKEOFF WEIGHT LB	220,000	160,000	488,000
THRUST/WEIGHT	0.29	0.43	0.28
WING LOADING PSF	78	32	122
INTERNAL FUEL LB	137,500	73,500	298,300
FUEL/WEIGHT	0.63	0.46	0.61
OPER. WT. EMPTY LB	72,500	76,500	179,700

PERFORMANCE CHARACTERISTICS

FOUR ENGINE DESIGNS (PAYLOAD = 10,000 LB)

		LO ALT CONCEPT	HI ALT CONCEPT	B-52H
UNREFUELED RANGE	NM	3,800	5,700	8,350
REFUELED RANGE	NM	5,700	8,900	12,500
PENETRATION ALTITUDE	FT	250	60,000	45,000
TAKEOFF GROUND RUN	FT	7,800	1,500	7,400
LIFTOFF VELOCITY	KN	200	95	170
LANDING GROUND ROLL	FT	3,700	1,300	3,700
TOUCHDOWN VELOCITY	KN	125	70	110

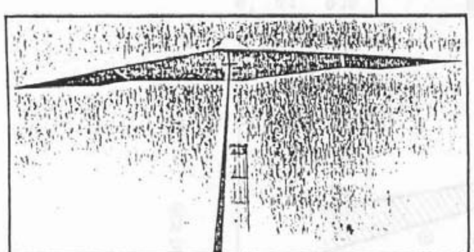
79-X0906



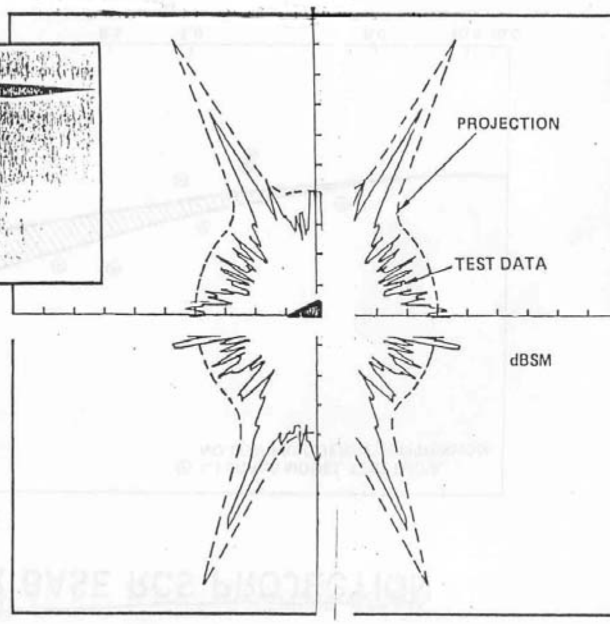
1990 LOW OBSERVABLES BOMBER THREATS

CONCEPT	DETECTION SYSTEMS	KILL SYSTEMS	
		SAMS	AIRBORNE INTERCEPTORS
LOW ALTITUDE	• IMPROVED SQUAT EYE • OTH RADARS • SUAWACS • EMISSION INTERCEPT • ACOUSTIC SENSORS	• SA-3 IMP. • SA-X-10 • SA-5 IMP.	• FOXBAT/ FENCER • ADVANCED INTERCEPTOR
HIGH ALTITUDE	• IMPROVED TALL KING • OTH RADARS • SUAWACS • SUSAT IR DETECTION • EMISSION INTERCEPT	• SA-2 IMP. • SA-X-10 • SA-5 IMP.	

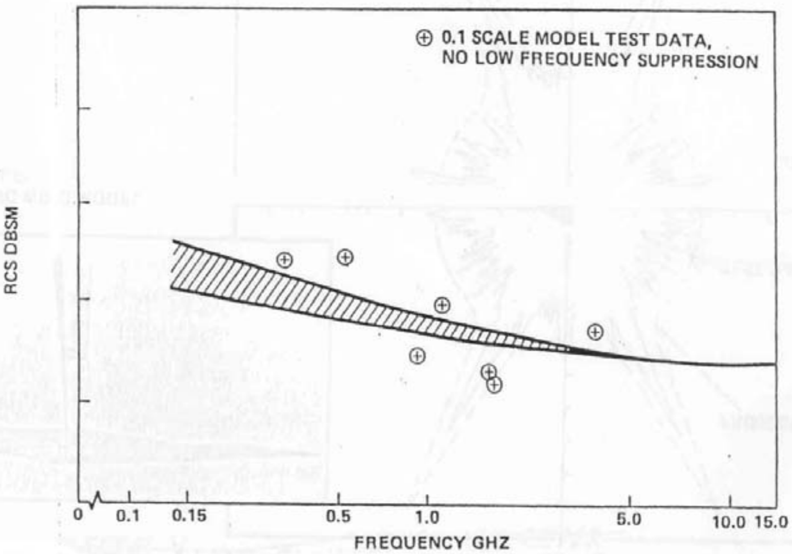
RCS VALIDATION



25° SWEEP FLYING WING MODEL
(APPROX 0.1 SCALE)



BOMBER BASE RCS PROJECTION



TECHNICAL RISK ASSESSMENT

HIGH ALTITUDE CONCEPT

- PROPULSION
  - F101X DERIVATIVE OF F101 ENGINE IN DEVELOPMENT, FLIGHT TEST IN 1981
  - INLET USES TACIT BLUE CONCEPT
- AERODYNAMICS
  - BASED ON FLIGHT PROVEN FLYING WING TECHNOLOGY
  - APPLICATION OF PROVEN SUPERCRITICAL AIRFOIL TECHNOLOGY
- CONTROLS - ACTIVE CONTROLS FOR LONGITUDINAL AND DIRECTIONAL AXES, INSTABILITY WITHIN STATE OF THE ART
- STRUCTURE - APPLICATION OF ALUMINUM AND COMPOSITE MATERIALS CONSISTENT WITH USAF SPONSORED DEVELOPMENT
- RCS - BASED ON TACIT BLUE TECHNOLOGY DEVELOPMENT
- IR - DRY ENGINES, COOL AIR INJECTION, 2-D NOZZLES, SHIELDING

79-X0903

ACCEPTABLE TECHNICAL RISK

CONCLUSIONS

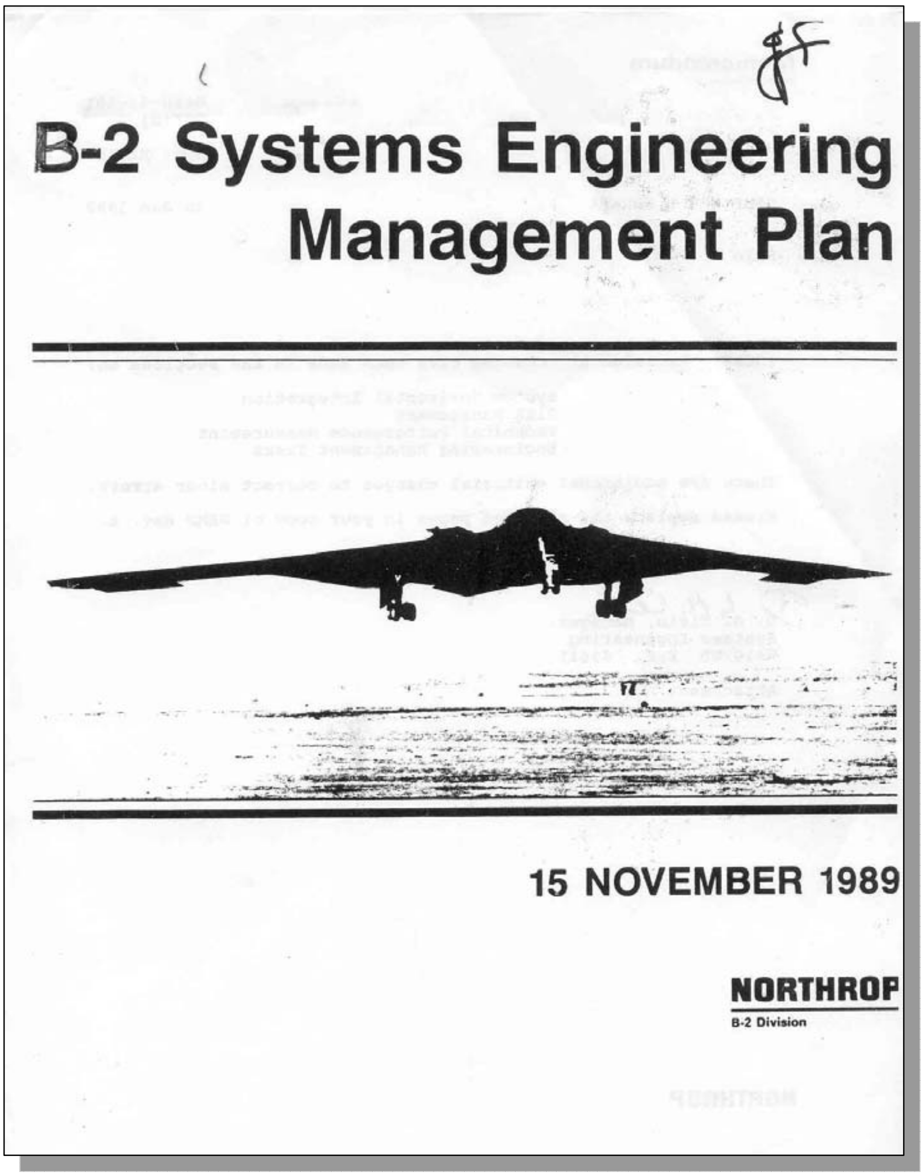
- STRATEGIC PENETRATING BOMBER MISSION IS SUITABLE APPLICATION OF LOW OBSERVABLES TECHNOLOGY
  - MAJOR IMPROVEMENT IN SURVIVABILITY AT LOW OR HIGH ALTITUDES
  - TECHNOLOGY IS COMPATIBLE WITH MISSION REQUIREMENTS AT LOW OR HIGH ALTITUDE
- LOW OBSERVABLES BOMBER CONFIGURATIONS LIMITED TO 280,000 LB CAN ACHIEVE RANGES OF:
  - LOW ALTITUDE 4100 NM (6300 NM, REFUELED)
  - HIGH ALTITUDE 7000 NM (10,700 NM, REFUELED)
- FOUR ENGINE HIGH ALTITUDE CONFIGURATION PREFERRED
  - CAN REACH 100% OF USSR TARGETS WITHOUT REFUELING (5700 NM)
  - MINIMUM LOW OBSERVABLES PENALTY
  - SURVIVABLE, EFFICIENT, PENETRATION APPROACH

79-X0876B

Appendix 5: Selected Text from B-2 SEMP

This appendix contains selected sections from the B-2 Systems Engineering Management Plan (SEMP)

- Section1 Introduction
- Section 3 Organization
- Section 4 WBS, Baselines, Specifications
- Section 4 Risk Management



B-2 Systems Engineering Management Plan

15 NOVEMBER 1989

NORTHROP

B-2 Division

SECTION 1
INTRODUCTION

1.1 OBJECTIVE

The objective of this SEMP is to provide a management guide for identifying and accomplishing the systems engineering functions within the B-2 program and to provide the process for improved horizontal integration across organizational boundaries. The SEMP allocates systems engineering functions to appropriate elements of the B-2 Division. The SEMP describes technical program planning and control, formal risk management, life cycle cost management, engineering specialty integration, and technical performance measurement throughout the B-2 Program. Charters and procedures have been refined to focus program resources on the completion of full scale development, the transition to production, and the completion of production.

1.2 APPLICATION

The SEMP presents the systems engineering management disciplines which define, document, and control the requirements of the B-2 weapon system and the integration of the air vehicle with the other elements of the system. Elements of the SEMP apply to selected subcontractors and suppliers for new B-2 subcontracts. New subcontractors are required to submit data in accordance with the requirements of the SEMP.

The SEMP focuses on the assignment of authority, responsibility, interface control, traceability, and change management. References to command media are made in each section where supporting information is available. Command media vital to the systems engineering process are discussed in Section 3.10.

Systems Engineering tasks, primarily active for early phases of system acquisition, are not expanded in detail. Exceptions occur where functional analyses and requirements allocations are appropriate in exploring new requirements and assessing impacts of configuration changes.

Because the B-2 is well advanced within its life cycle, the system baseline configuration (see 4.2.6) is tracked by Configuration Management. During the current phase, test and transition to production, the primary emphasis is on assuring completeness of requirements definition, demonstration of system capability, integrity of subsystems interfaces, production readiness, and confirmation of system supportability.

The SEMP supports the integrated efforts for development, test, evaluation, and transition to production which will successfully transform the U.S. Air Force military need for the Advanced Technology Bomber into an operational B-2 weapon system fulfilling that need. To do this, the SEMP must be properly implemented throughout the B-2 Program.

1.3 IMPLEMENTATION

Systems engineering is not just a special engineering organization; it is also a set of essential technical management tasks which are allocated throughout the B-2 organization and assigned to the most appropriate organizational departments. All program personnel participate in the systems engineering process. Hence, there is a need for the SEMP as an internal manual and procedural guide for effective implementation.

The system engineering process is federated on the B-2 program. The up front requirements analysis and flowdown, systems integration and verification efforts are the responsibilities of the design integration or project engineering organizations. With the implementation of this SEMP, the B-2 program committed to centralizing the responsibility for requirements analysis and flow down processes for new major changes with the systems engineering organization.

Systems engineering procedures are described in many of the Division Operational Procedures (DIVOPs). Organizational responsibilities for systems engineering tasks are defined in the Division Management Charters. Much of the documentation produced by systems engineering tasks is described in Division command media; the remaining items are being covered now. Many of the systems engineering tasks are assigned to councils, boards, and committees as described in the DIVOPs and discussed in Section 3.9.

1.4 TAILORING

The SEMP is responsive to MIL-STD-499A, "Engineering Management," and is selectively tailored to focus on issues related to the completion of the B-2 full scale development phase, with increasing emphasis on the transition-to-production phase of the program. The SEMP focuses on the functional and design integration aspects of the program, software-hardware qualification, specification compliance, and how configuration changes affect system performance, affordability, supportability, and risk. The SEMP is a dynamic document, subject to change as the program evolves and procedures are refined by experience gained.

1.5 SUMMARY

Section 2 is a list of many documents which influence Northrop's management procedures. Documents required by contract are identified; the remaining documents are used as guides, at Northrop's discretion.

Section 3 is organization oriented. It describes how the systems engineering activities are assigned and controlled within the B-2 Program organization. Systems engineering task allocation is discussed, participants identified, audit and review responsibilities presented, and program interfaces described. This Section focuses primarily on programmatic tasks. Systems engineering-related command media are discussed.

Section 4 is planning and control oriented. It focuses on the methods for conducting and controlling the systems engineering management activities. Procedures are summarized and responsibilities assigned for planning and controlling task assignments, configuration management, risk management, technical performance measurement, major subcontract management, internal and external reviews, audits, and management of engineering data. This Section also focuses primarily on programmatic tasks.

Section 5 is methodology oriented. It describes the methods for performing the systems engineering process and how the B-2 organizations work together to assure B-2 system integrity. This Section focuses primarily on technical requirements tasks.

Section 6 is engineering specialty oriented. It identifies the responsible organization for each engineering specialty, describes the process for engineering specialty integration, and summarizes individual engineering specialty plans.

The appendices include a list of applicable Division Operating Procedures, a description of the responsibilities and interfacing relationships of the Responsible Engineer.

SECTION 3
SYSTEMS ENGINEERING MANAGEMENT STRUCTURE

This section describes how the systems engineering activities of the B-2 Program are assigned and controlled. This section focuses on the management of the systems engineering tasks, identifying the participants, the responsibilities for audit and review, and interactions between Engineering and non-Engineering organizations.

3.1 B-2 SYSTEMS ENGINEERING OBJECTIVE

The overall objective of the B-2 systems engineering effort is to achieve balance among system performance capability, affordability, schedule, producibility, testability, and supportability, at an acceptable level of program risk. Affordability analysis considers design and verification cost, unit production cost, and operating and support costs.

3.2 B-2 PROGRAM ORGANIZATION

The B-2 Division President and General Manager has the overall responsibility for the B-2 Division. The Vice President and B-2 Program Manager has the responsibility for the B-2 Program, as shown in Figure 3-1. The shaded boxes indicate the functional organizations which participate in accomplishing the systems engineering tasks.

Because this SEMP focuses on systems engineering functions rather than department organization and because the Northrop B-2 Division maintains a separate document depicting the Division organization, this SEMP contains no organization chart below the level of Figure 3-1.

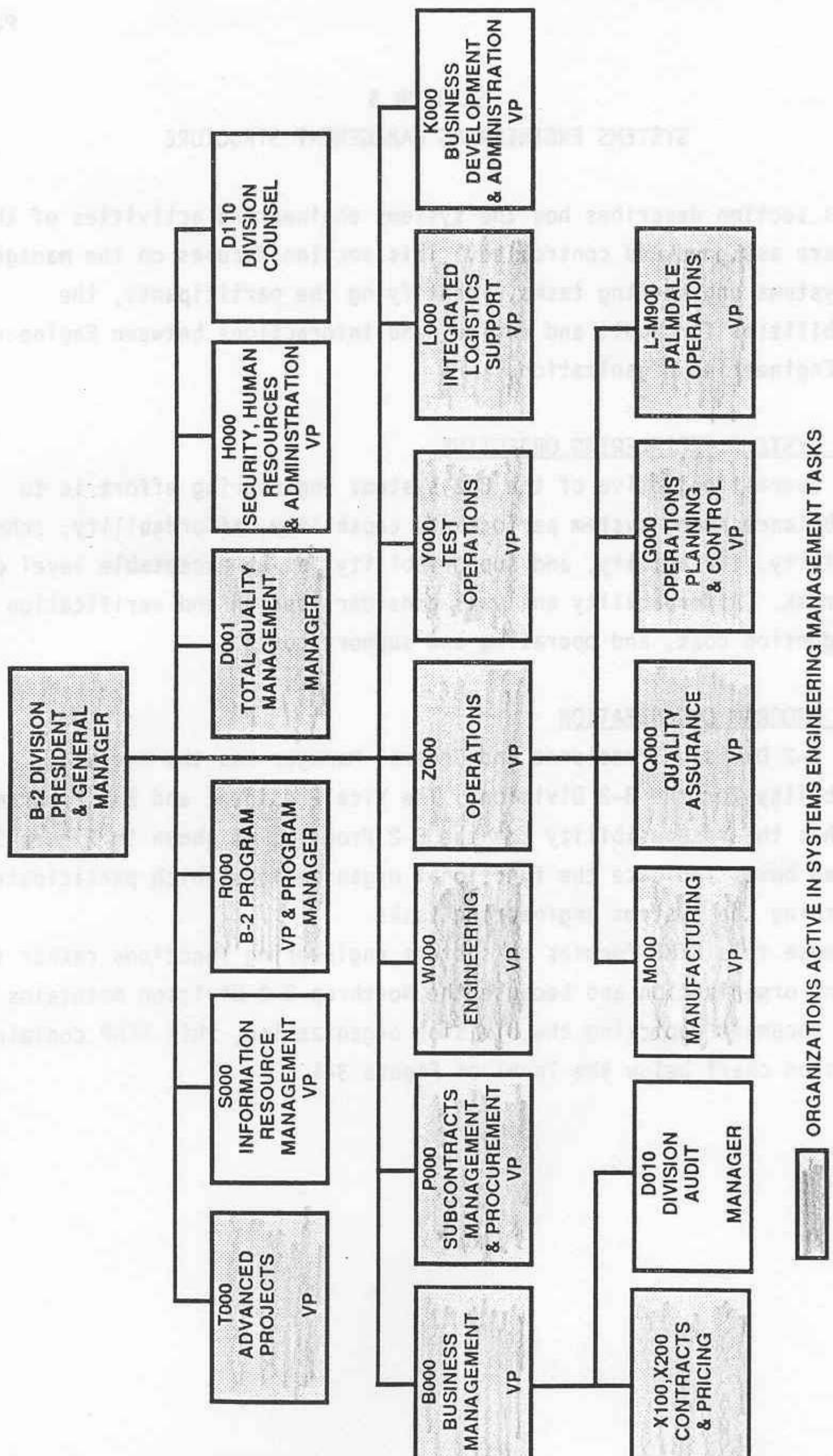


FIGURE 3-1. B-2 DIVISION ORGANIZATION

3.3 SYSTEMS ENGINEERING MANAGEMENT TASK ALLOCATION

Systems engineering management tasks are allocated throughout the B-2 Division as shown in Figure 3-2. These tasks fall into two categories as defined below.

a. Programmatic tasks are related to providing an overview of the B-2 program status and to providing evidence that the technical requirements are being satisfied within the planned budgets and schedules. These tasks are managed by the B-2 Program Manager (R000), who delegates the primary management authorities to the Deputy Program Manager for Program Systems Management (R500), as illustrated in Figure 3-2. Programmatic issues are directed to Program Systems Management.

b. Technical requirements tasks are related to defining the current and future contractual technical requirements and applying the systems engineering process needed to achieve those requirements. These tasks are allocated primarily to Engineering (W000) and to Integrated Logistics Support (ILS) (L000), although other organizations also participate. Technical issues are directed to the organization performing horizontal integration [(1) the Manager of the appropriate technical organization or (2) a Design/Build Team or (3) the Office of Primary Responsibility for one of the key functions or (4) the Responsible Engineer, depending upon the circumstances].

3.4 B-2 PROGRAM MANAGEMENT (R000) RESPONSIBILITIES

3.4.1 Program Systems Management (R500)

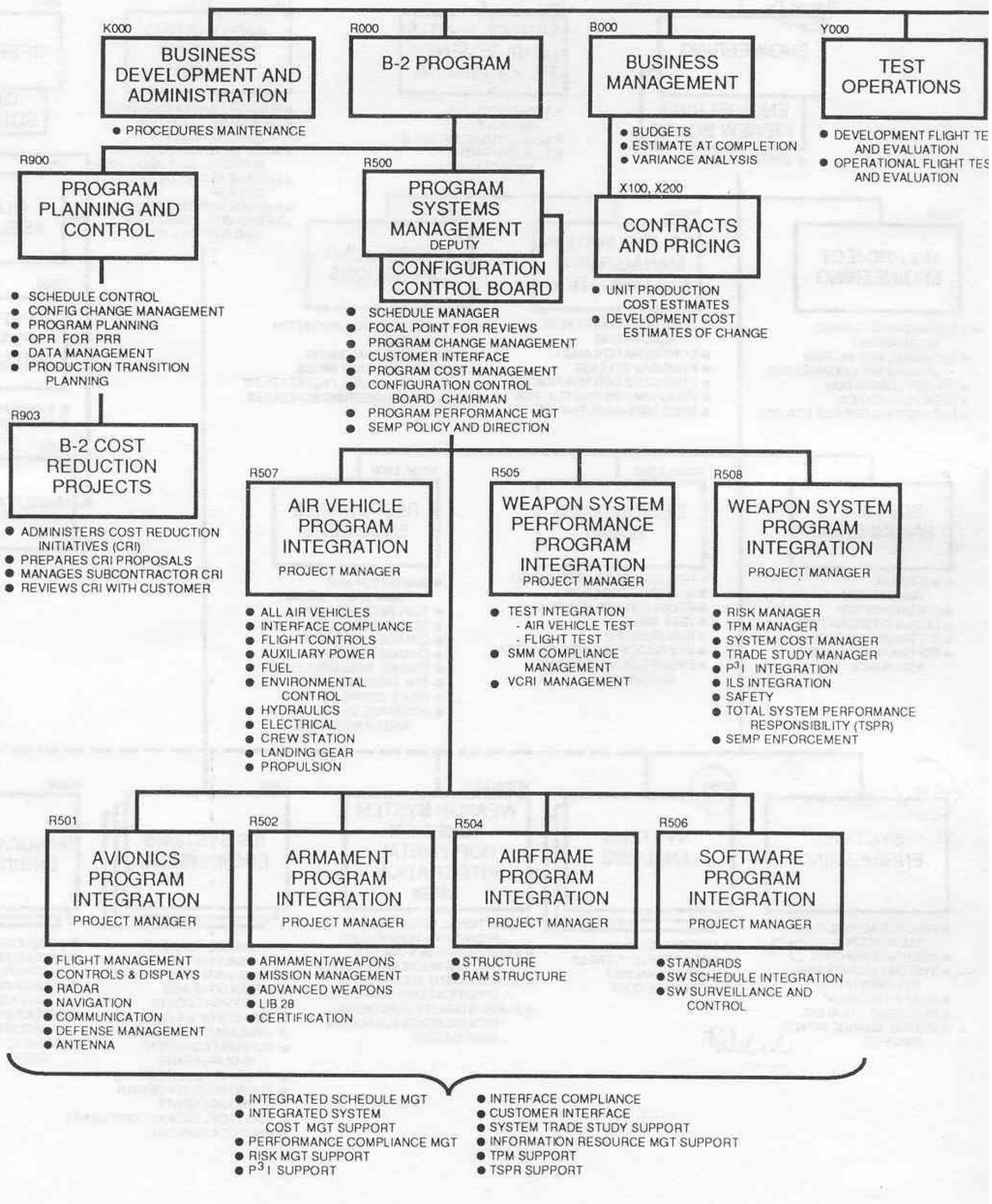
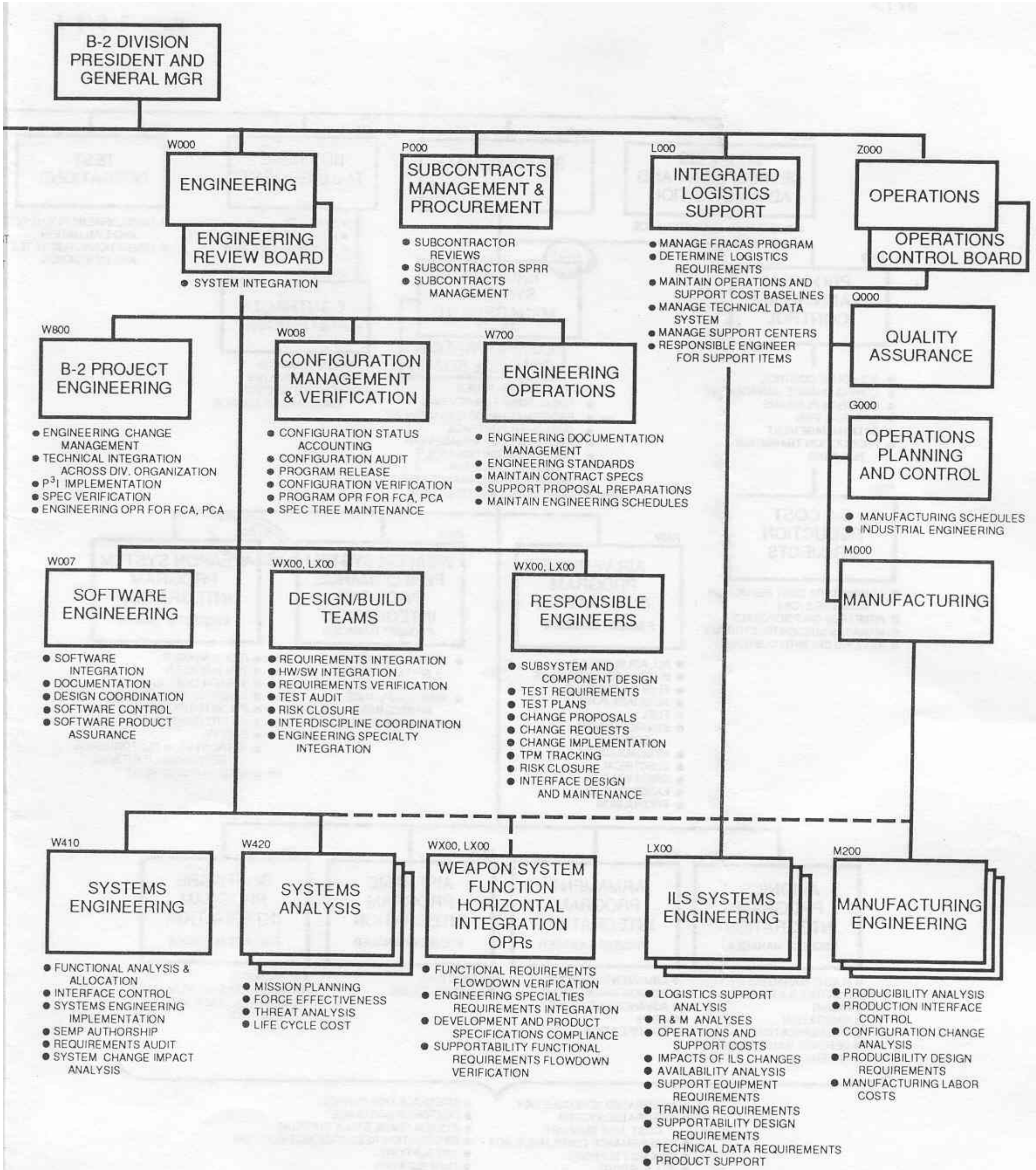


FIGURE 3-2. DISTRIBUTION OF SYSTEMS ENGINEERING MANAGEMENT TASKS THROUGHOUT THE B-2 DIVISION


B-2 DIVISION PRESIDENT AND GENERAL MGR
W000
ENGINEERING
ENGINEERING REVIEW BOARD
SYSTEM INTEGRATION
P000
SUBCONTRACTS MANAGEMENT & PROCUREMENT
SUBCONTRACTOR REVIEWS
SUBCONTRACTOR SPRR
SUBCONTRACTS MANAGEMENT
L000
INTEGRATED LOGISTICS SUPPORT
MANAGE FRACAS PROGRAM
DETERMINE LOGISTICS REQUIREMENTS
MAINTAIN OPERATIONS AND SUPPORT COST BASELINES
MANAGE TECHNICAL DATA SYSTEM
MANAGE SUPPORT CENTERS
RESPONSIBLE ENGINEER FOR SUPPORT ITEMS
Z000
OPERATIONS
OPERATIONS CONTROL BOARD
Q000
QUALITY ASSURANCE
G000
OPERATIONS PLANNING AND CONTROL
MANUFACTURING SCHEDULES
INDUSTRIAL ENGINEERING
M000
MANUFACTURING
W800
B-2 PROJECT ENGINEERING
ENGINEERING CHANGE MANAGEMENT
TECHNICAL INTEGRATION ACROSS DIV. ORGANIZATION
P³I IMPLEMENTATION
SPEC VERIFICATION
ENGINEERING OPR FOR FCA, PCA
W008
CONFIGURATION MANAGEMENT & VERIFICATION
CONFIGURATION STATUS ACCOUNTING
CONFIGURATION AUDIT
PROGRAM RELEASE
CONFIGURATION VERIFICATION
PROGRAM OPR FOR FCA, PCA
SPEC TREE MAINTENANCE
W700
ENGINEERING OPERATIONS
ENGINEERING DOCUMENTATION MANAGEMENT
ENGINEERING STANDARDS
MAINTAIN CONTRACT SPECS
SUPPORT PROPOSAL PREPARATIONS
MAINTAIN ENGINEERING SCHEDULES
W007
SOFTWARE ENGINEERING
SOFTWARE INTEGRATION
DOCUMENTATION
DESIGN COORDINATION
SOFTWARE CONTROL
SOFTWARE PRODUCT ASSURANCE
WX00, LX00
DESIGN/BUILD TEAMS
REQUIREMENTS INTEGRATION
HW/SW INTEGRATION
REQUIREMENTS VERIFICATION
TEST AUDIT
RISK CLOSURE
INTERDISCIPLINE COORDINATION
ENGINEERING SPECIALTY INTEGRATION
WX00, LX00
RESPONSIBLE ENGINEERS
SUBSYSTEM AND COMPONENT DESIGN
TEST REQUIREMENTS
TEST PLANS
CHANGE PROPOSALS
CHANGE REQUESTS
CHANGE IMPLEMENTATION
TPM TRACKING
RISK CLOSURE
INTERFACE DESIGN AND MAINTENANCE
W410
SYSTEMS ENGINEERING
FUNCTIONAL ANALYSIS & ALLOCATION
INTERFACE CONTROL
SYSTEMS ENGINEERING IMPLEMENTATION
SEMP AUTHORSHIP
REQUIREMENTS AUDIT
SYSTEM CHANGE IMPACT ANALYSIS
W420
SYSTEMS ANALYSIS
MISSION PLANNING
FORCE EFFECTIVENESS
THREAT ANALYSIS
LIFE CYCLE COST
WX00, LX00
WEAPON SYSTEM FUNCTION HORIZONTAL INTEGRATION OPRs
FUNCTIONAL REQUIREMENTS FLOWDOWN VERIFICATION
ENGINEERING SPECIALTIES REQUIREMENTS INTEGRATION
DEVELOPMENT AND PRODUCT SPECIFICATIONS COMPLIANCE
SUPPORTABILITY FUNCTIONAL REQUIREMENTS FLOWDOWN VERIFICATION
LX00
ILS SYSTEMS ENGINEERING
LOGISTICS SUPPORT ANALYSIS
R & M ANALYSES
OPERATIONS AND SUPPORT COSTS
IMPACTS OF ILS CHANGES
AVAILABILITY ANALYSIS
SUPPORT EQUIPMENT REQUIREMENTS
TRAINING REQUIREMENTS
SUPPORTABILITY DESIGN REQUIREMENTS
TECHNICAL DATA REQUIREMENTS
PRODUCT SUPPORT
M200
MANUFACTURING ENGINEERING
PRODUCIBILITY ANALYSIS
PRODUCTION INTERFACE CONTROL
CONFIGURATION CHANGE ANALYSIS
PRODUCIBILITY DESIGN REQUIREMENTS
MANUFACTURING LABOR COSTS

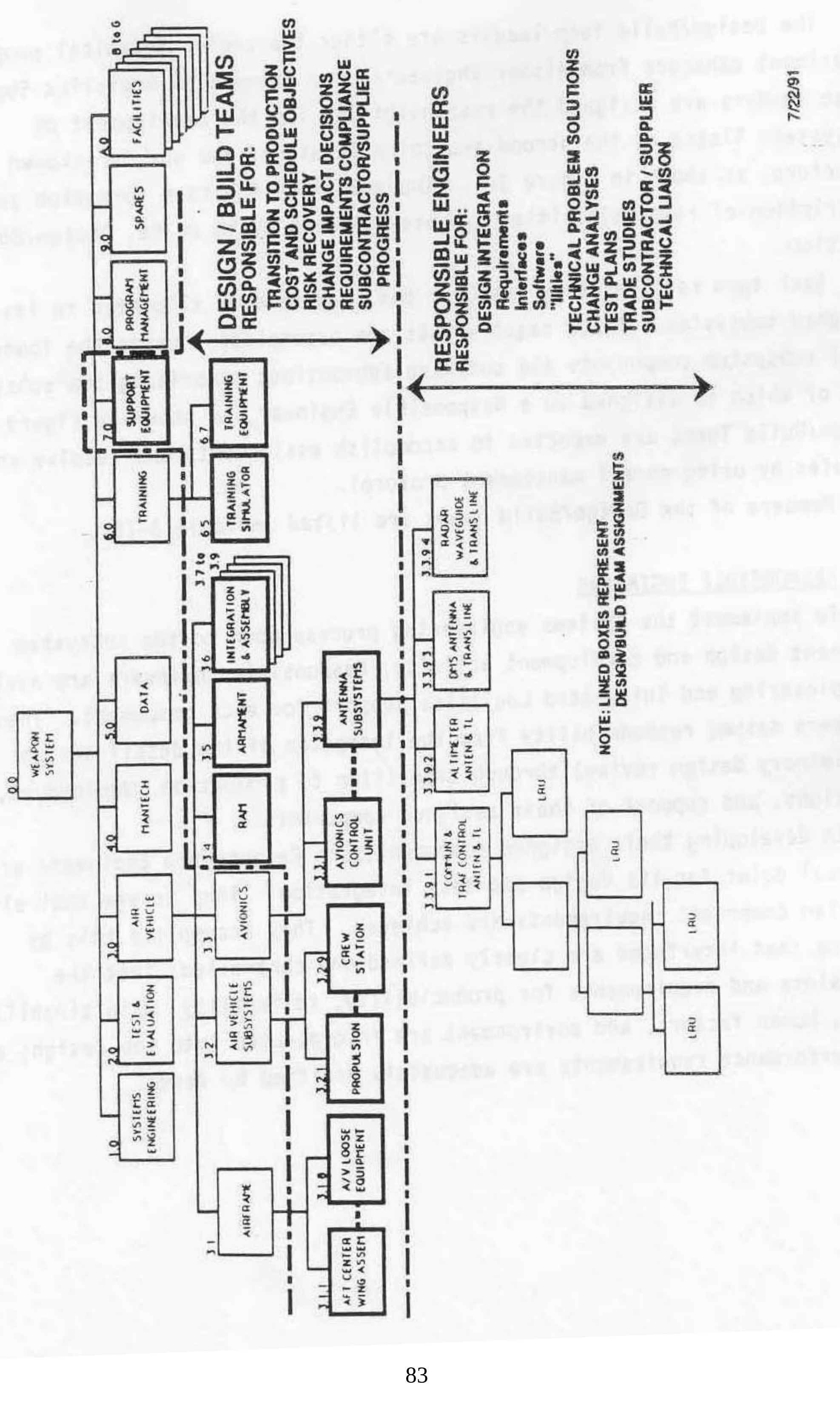


FIGURE 3-4. DESIGN/BUILD TEAMS AND THE
RESPONSIBLE ENGINEERS

TABLE 3-III. B-2 DESIGN/BUILD TEAM LIST (SHEET 1 OF 2)

AIRFRAME		RESP ORGN
3.1.1	After Center Section	W612
3.1.2	Intermediate Section	W612
3.1.3	Outboard Wing Section	W612
3.1.4	Forward Center Section	W610
3.1.5	Control Surfaces	W611
3.1.6	Structural Integration	W610
AIR VEHICLE SUBSYSTEMS		
3.2.1	Exhaust Subsystem	W540
3.2.2	Landing Gear Subsystem	W512
3.2.3	Electrical Subsystem	W520
3.2.4	Engine and Auxiliary Power System	W511
3.2.5	Hydraulic and Mechanical Subsystem	W512
3.2.6	Flight Control System	W200
3.2.7	Fuel Subsystem	W515
3.2.8	Environmental Control Subsystem	W514
3.2.9	Crew Station	W513
AVIONICS		
3.3.1	Avionics Control Unit	W124
3.3.2	Flight Management Subsystem	W132
3.3.3	Radar Subsystem	W121
3.3.4	Defense Management Subsystem	W140
3.3.5	Controls and Displays Subsystem	W124
3.3.6	Navigation Subsystem	W121
3.3.7	Communication and Traffic Control	W125
3.3.8	Mission Management Subsystem	W035
3.3.9	Antenna Subsystem	W914

TABLE 3-III. B-2 DESIGN/BUILD TEAM LIST (SHEET 2 OF 2)

AIRFRAME		RESP ORGN
OTHER		
3.4	Ram Structures	W611
3.5	Armament Subsystem	W030
3.6	Integration, Assembly, and Surface Treatment	W612
	Air Vehicle Software Development	W007
SUPPORT		
6.5	Weapon System Trainer	W810
6.7	Training Equipment	L540
7.0	Peculiar Support Equipment	L870
7.1	Automatic Test Equipment	L680

SECTION 4
TECHNICAL PROGRAM PLANNING AND CONTROL

This section describes the systems engineering major tools to plan and control the programmatic and technical activities in the Full Scale Development and the Transition to Production phases of the B-2 Program. Procedures are summarized and responsibilities assigned for planning and controlling task assignments, configuration management, program risk management, technical performance measurement, major subcontract management, system cost management, internal and external reviews, management of engineering data, and provisions for pre-planned product improvement.

4.1 TECHNICAL PROGRAM CONTROL

The B-2 program planning and control of technical efforts supports five major tasks.

a. Satisfy the program's major technical requirements with acceptable technical, cost, and schedule risks.
b. Manage the technical risks to produce practical and producible designs.
c. Control support functions to operate within budget constraints.
d. Control inputs to requirements definitions to preclude expansion beyond that necessary to satisfy the Weapon System Specification requirements.
e. Measure progress toward achieving system performance objectives by initiating remedial actions to assure success: alleviate risk and forestall cost growth.

4.1.1 Contract Work Breakdown Structure

The contract work breakdown structure is a primary means of identifying the tasks to be accomplished, allocating budget to program tasks, collecting expenditures, and providing data for management control. This work breakdown structure follows the format of MIL-STD-881 and contains definition and terminology of tasks down to the third level. The work breakdown structure dictionary provides the basis for discrete and detailed work package definition, budgeting, and scheduling in the cost account plans.

The work breakdown structure, when extended to lower levels of detail, establishes functional discrimination among the weapon system configuration elements. Responsible Engineers can then be assigned to assume technical responsibility for the design and development of each element. The Responsible Engineers assure compatible interfaces with related configuration subsystems and components. These assignments form the basis for program control of technical activity.

Design/Build Teams are designated for each hardware and software element of the contract work breakdown structure to assure that all engineering, manufacturing, quality assurance, supportability, test, and safety disciplines support the Responsible Engineers in the development of the assigned designs through transition to production.

The work breakdown structure is also used as a spread-sheet for the flowdown of unit production cost as part of the system cost management process described in Section 4.5. The cost estimates for the work breakdown structure elements of the B-2 baseline configuration are assigned as "not-to-exceed" values to the Responsible Engineers. These values are used as a means to prevent cost growth and to stimulate cost reduction initiatives.

Note that the Responsible Engineers (Section 3.7) and the Design/Build Teams (Section 3.6) are responsible for Work Breakdown Structure elements, whereas, the Offices of Primary Responsibility (OPRs) are responsible for assuring that weapon system functions are accounted for in the weapon system design (Sections 3.5.5 and 5.4).

4.1.2 <u>Specification Tree and Contract Work Breakdown Structure Integration</u>

There is a correlation between the specification tree and the B-2 contract work breakdown structure (Full Scale Development, AAA8100-001 and Low Rate Initial Production, AAA8100-004). The B-2 Program Specification Tree (PAA8110-012) contains a list of basic specifications which defines B-2 program hardware and software requirements. Specifications in the tree are grouped according to contract work breakdown structure number, as shown in the example in Table 4-I. Similar correlation exists in other product legs of this work breakdown structure.

TABLE 4-I. EXAMPLE OF SPECIFICATION TREE AND CONTRACT WORK BREAKDOWN STRUCTURE (CWBS) CORRELATION

Level	Item	CWBS No.	Specification No.
1	System Specification		SS02000
2	Air Vehicle	3.0	CP02100
3	Air Vehicle Subsystems	3.2	None
4	Landing Gear Subsystems	3.2.2	DAA3220P001
5	Main Landing Gear	3.2.2.2	DAA3222P500

Contracts Change Management (X130) and Master Program Scheduling (R930) are responsible for the initial extension of the contract work breakdown structure and any modifications to reflect revisions to the contracts. These activities are coordinated with the affected organizations during the contract negotiation process, prior to release for internal use. This internal coordination process ensures that the extension reflects the way that the work will be accomplished, while being consistent with MIL-STD-881.

Maintenance of the B-2 Specification Tree is the responsibility of Program Configuration Verification (W090), using information provided by Systems Engineering (W410), and Configuration Management (W008). Any changes to the specification tree, along with changes to the specifications themselves, are processed in accordance with the change control system as specified in DV 01.38.01.

4.1.3 Cost/Schedule Control System

The Cost/Schedule Control System covers several important topics which are discussed in either the Work Instruction books or the Cost Account Manager notebooks:

a. Tasking

b. Work package definition

c. Budget and resource allocation
d. Scheduling
e. Work package rationale
f. Techniques for evaluating cost, schedule, and variance trends
g. Techniques for projecting costs at completion of tasks
h. Work package planning cycle
i. Work authorization authority and documentation
j. Budget transfer process
k. Earned-value measurement process
l. Variance measurement and thresholds
m. Cost accumulation and reporting.

The implementation of Cost/Schedule Control System in accordance with DoD Instruction 7000.2 and the overview of organizational tasks and documentation are the responsibility of Business Management (BOOO). Individual cost account plans are developed by the Cost Account Managers. Business Management develops a report for budget variances and a report for schedule variances.

Northrop's implementation of the Cost/Schedule Control System Criteria is described in DTM 01.12.01, "Cost/Schedule Control System Description," and in the Northrop documents listed in Appendix A, Paragraph A-2. The following DoD documents were used: DoD Instruction 7000.2, "Cost/Schedule Control System Criteria" and AFSCP 173-5, "C/SCS Joint Implementation Guide."

4.1.4 Task Assignment and Control

The contract work breakdown structures for the Full Scale Development contract and Low Rate Initial Production contract identify all the products, services, and data to be delivered. The Northrop systems engineering tasks are included in the following legs of this work breakdown structure: System Engineering (1.0), Test and Evaluation (2.0), Air Vehicle (3.0), Training (6.0), Support Equipment (7.0), and Program Management (8.0). Boeing and LTV systems engineering tasks are identified in elements 1.7 and 1.8, respectively.

The extension of each contract work breakdown structure down to the cost collection level, in conjunction with the Cost/Schedule Control System, provides the primary means of assigning systems engineering and other tasks to specific organizations, measuring the progress in accomplishing individual tasks against assigned schedules and budgets, and determining variances between scheduled and actual performance of the tasks. Budgets and schedules are negotiated and flowed down from total contract budgets to individual cost accounts. A single cost account manager is responsible for the work packages in his assigned cost account. A responsibility assignment matrix identifies the specific organization responsible for each cost account in the Full Scale Development and the Low Rate Initial Production contracts.

4.2 CONFIGURATION MANAGEMENT

4.2.1 Purpose

The purposes of configuration management are to document the released system baseline configuration, to maintain the current configuration status and accounting records, to control all changes in the process of implemention, and to audit the end products to assure that they are as specified and defined in the approved data.

4.2.2 Objectives

The objectives of the configuration management organizations are to ensure that the fundamental elements of Configuration Management are implemented for each configuration item during each phase of its life-cycle and to ensure that the fundamental elements are compatible with the Weapon System Specification and the Prime Item Development Specifications throughout the life of the program.

4.2.3 Authority

Configuration Management and Verification (W008) has the authority to perform the configuration management functions of configuration identification, status accounting, audits, procedures, and practices as contractually required by the Air Force. These activities are performed in compliance with applicable Division operating procedures (Ref: Appendix A, paragraph A-3); the Air Force-approved Division Configuration Management Plan; and the requirements specified in DOD-STD-480A, MIL-STD-483, MIL-STD-490, and MIL-STD-1521A. Program Change Management (R950) is responsible for those configuration management functions which control changes, including the status of changes and potential impacts, ending with the incorporation of the change.

4.2.4 Configuration Management Requirements Allocation

The configuration management requirements are allocated to subcontractors through a subcontractor Statement of Work and the Subcontractor Data Requirements List. The requirements of the above-mentioned DOD and military standards are selectively tailored before they are flowed down to the subcontractors.

4.2.5 Configuration Management Functions

The fundamental functions of the organizations responsible for configuration management are discussed in the following four subsections. For detailed descriptions of functions and tasks for configuration management, see the Air Force-approved B-2 Division Configuration Management Plan (AAA8110-001).

4.2.5.1 Configuration Management Primary Organizations

Configuration Management (W080) releases and controls configuration baseline technical documentation. This documentation primarily consists of specifications, engineering drawings, logic diagrams, flowcharts, technical manuals, interface control documents, software documents, nomenclature, part and lot numbering, serialization, reference and type designators, and minutes of technical reviews and configuration audits. The technical documentation not only identifies and describes the functional and physical characteristics of each configuration item, but it also provides the ability to trace changes throughout the configuration item's life-cycle. A configuration tracking system is used to document flight-by-flight configurations of each air vehicle and its support equipment.

Program Configuration Verification (W090) has primary responsibility for configuration audits. The purpose of configuration audits is to verify that the configuration item description is accurate, complete, and has met program needs. Program Configuration Verification develops the detail plans and procedures for compliance audits of subcontractors, the Functional Configuration Audit, and the Physical Configuration Audit required by the Air Force.

Program Configuration Verification provides support to Engineering and Quality Assurance during technical reviews which establish documentation requirements and configuration item selection criteria. Technical reviews confirm that the development of the configuration item has reached contract milestone requirements.

4.2.5.2 <u>Site 4 Configuration Verification and Release</u>

Site 4 Configuration Verification and Release (L-W094) coordinates with the Air Force and subcontractors on the implementation of deviations, waivers, and interface documentation changes. Physical audits, parts reconciliation, software control, and deviation and waiver coordination are critical elements of the processes performed and coordinated with the Air Force to assure accurate delivery configuration documentation. Site 4 Configuration Verification and Release coordinates with Manufacturing, Engineering, and ILS to resolve problems relating to effectivities, rolling of dash numbers, and accurate change documentation for air vehicles and support equipment undergoing test.

Site 4 Configuration Verification and Release maintains the configuration description documentation for tracking the flight-by-flight configurations for each vehicle and support equipment and with control of change activity during the flight test program.

4.2.5.3 Configuration Status Accounting and Verification Reporting Organizations

The Configuration Status Accounting and Verification Reporting (W091, W092, and W093) organizations report configuration status and provide traceability to established configuration baselines and changes to the baselines. During the Full Scale Development and Low Rate Initial Production phases, the configuration status accounting system ensures that tasks resulting from configuration changes are accomplished.

Configuration Management DIVOPs are listed in Appendix A, Paragraph A-3.

4.2.5.4 Program Change Management

Program Change Management (R950) establishes program change management policy. Systems Requirements Management (W411) establishes risk tracking methodology and tracks the impact of changes affecting functional and physical characteristics of an end item. Systems Requirements Management assures that the impacts are analyzed by the appropriate organizations such as Engineering, Manufacturing, Producibility, Materiel, Integrated Logistics Support, Systems Engineering, Quality Assurance, Reliability, Maintainability, Operations, Operational Readiness, and Test and Evaluation. Program Change Management monitors risk tracking to assure that these factors are defined and evaluated before changes are made to the configuration item and its interfaces. Program Change Management provides administrative support to the Configuration Control Board by reviewing the documentation for completeness and accuracy, preparing the agendas, and tracking completion of action items resulting from the Configuration Control Board decisions.

The configuration control process is responsive to the Air Force and the B-2 Division requirements for change proposal initiation, justification, coordination, evaluation, decision, release, incorporation, monitoring, and reporting.

4.2.6 Baseline Management

Configuration baselines represent the configuration of the B-2 as described by appropriate engineering and other technical documents, formally designated, and fixed at specific points in time. Baselines serve as bench marks or points of departure to facilitate the management of change. Configuration baselines are the object of configuration control. The government establishes configuration baselines keyed to milestones within the overall system life cycle. Northrop also establishes internal configuration baselines to manage changes at the program level.

4.2.6.1 Government Baselines

There are three government-established and controlled baselines; Functional Baseline, Allocated Baseline, and Product Baseline.

The Functional Baseline was initially established with the B-2 Weapons System Specification at full scale development contract go-ahead. This baseline was supplemented by the authentication of the Training System Segment Specification.

A partial Allocated Baseline was established by the Air Vehicle Prime Item Development Specification at full scale development contract go-ahead. The allocated baseline will be completed with the authentication of the development requirements specifications (type B-1, B-2, B-5, non-complex, systems requirements specification as contractually required) for Configuration Items, Selected Critical Items, and Computer Program Configuration Items. These documents are identified in the B-2 Weapons System Specification and in Appendix 70 of the B-2 Configuration Management Plan, AAA8110-001.

A summary of the status and the technical and maintenance responsibilities for both the functional baseline and the allocated baseline is presented in Table 4-II.

A Product Baseline will be established for each Configuration Item, Selected Critical Item, and Computer Program Configuration Item upon successful completion of a Functional and Physical Configuration Audits of

TABLE 4-II. BASELINE DESCRIPTION AND MAINTENANCE

ITEM	SPECIFICATION TYPE	B/L	TECHNICALLY RESPONSIBLE	MAINTENANCE RESPONSIBILITY	
				PRIOR TO AUTH/APPR	AFTER AUTH/APPR
WEAPON SYSTEM	SYSTEM	F	N/A	AUTHENTICATED	W733 ENG DOC INT.
AIR VEHICLE	PRIME ITEM DEVELOPMENT	A	N/A	AUTHENTICATED	W733
BOMB RACK ASSEMBLY	PRIME ITEM DEVELOPMENT	A	W030	W030	W733
ROTARY LAUNCHER ASSEMBLY	PRIME ITEM DEVELOPMENT	A	W030	AUTHENTICATED	W733
OPERATIONAL FLIGHT AND OTHER SOFTWARE	SOFTWARE REQUIREMENT	A	ENGINEERING ORGANIZATION	W007	W084
RADAR	CRITICAL ITEM DEVELOPMENT	A	W121	AUTHENTICATED	W733
DEFENSE MANAGEMENT SYSTEM ITEMS	CRITICAL ITEM DEVELOPMENT FOR EACH SELECTED CRITICAL ITEM	A	W140	W733	W733
HYDRO MECHANICAL SUPPORT EQUIPMENT (NON ATE SUPPORT EQ)	PRIME ITEM DEVELOPMENT + CONFIGURATION ITEM DEVELOPMENT + SOFTWARE REQUIREMENT	A	L870	W733	W733
AUTOMATED TEST EQUIPMENT	PRIME ITEM DEVELOPMENT + CONFIGURATION ITEM DEVELOPMENT + SOFTWARE REQUIREMENT	A	L860	W733	W733
ENGINE	PRIME ITEM DEVELOPMENT	A	ENGINE CONTRACTOR	ENGINE CONTRACTOR	ENGINE CONTRACTOR
TRAINING SYSTEM	SYSTEM SEGMENT	F	L540	AUTHENTICATED	W733
TRAINING SYSTEM EQUIPMENT	PRIME ITEM DEVELOPMENT	A	L540	AUTHENTICATED	W733
TRAINING SYSTEM SOFTWARE	SOFTWARE REQUIREMENT	A	L540	L540	W733

*POST CDR F = FUNCTIONAL BASELINE A = ALLOCATED BASELINE

I89-681-61H

4.4 PROGRAM RISK MANAGEMENT

Program risks are associated with the uncertainty in achieving program technical performance, cost, schedule, and supportability goals. Risk management encompasses risk identification, assessment, analysis, and closure. Much of the activity associated with risk analysis uses trade studies, specialty engineering plans, contingency plans, work-around plans, supportability analyses, and Cost/Schedule Control System reports. A procedural description of the risk management process is presented in DV 15.01.22.

4.4.1 Organizational Responsibilities

All of the B-2 Program organization elements are involved in the risk management process. The roles of the primary participants are shown in Figure 4-5. Risks may be identified by any organization including the Air Force. The functional organizations assign a risk closure manager for each risk closure plan. This assignment includes analyzing the risk, developing a risk closure plan, coordinating with affected organizations, implementing actions to be accomplished,

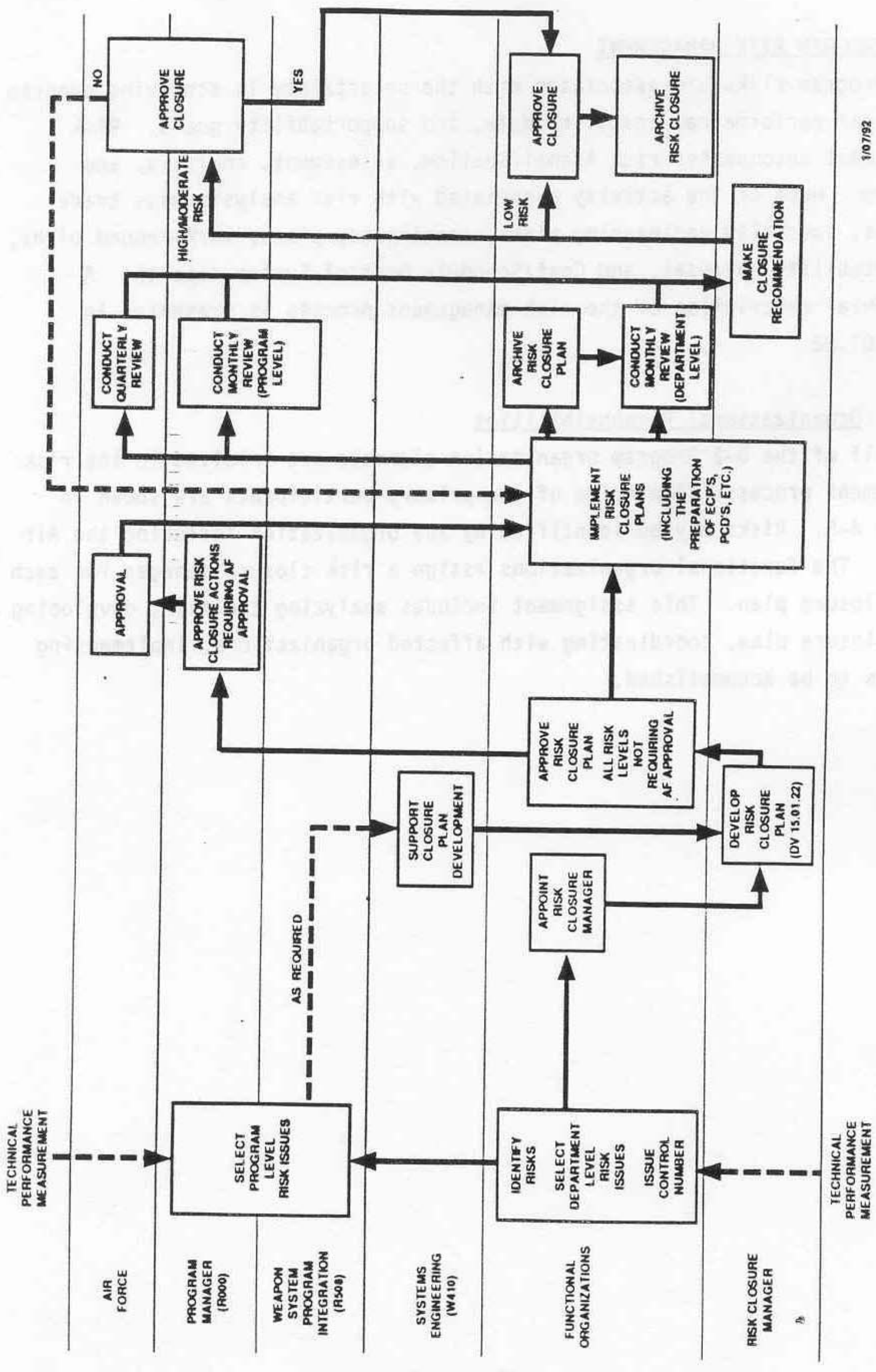


FIGURE 4-5. B-2 RISK MANAGEMENT PROCESS

tracking progress and reporting progress to management.

Monthly reviews of risks (Figure 4-5) are conducted within the responsible functional organization. Risks are also reviewed monthly with Program Management.

Weapon System Program Integration (R508) is the B-2 Program Risk Manager. In certain cases risk plans and plan closure must be approved by the Air Force. In these cases Weapon Systems Management (R500) will review and, together with the Program Manager, approve and submit the requisite documentation to the Air Force.

Each functional organization maintains its top issues list in the Management Information Center. The B-2 Program Manager conducts monthly reviews of each functional organizations issues and briefings to assess risk closure progress. Each functional organization will prepare summary charts (Figure 4-6A) in addition to its normal risk plan documentation.

4.4.2 Risk Identification, Tracking

Risks are initially identified as part of normal technical reviews and as a result of monitoring the Technical Performance Measures. For example, in engineering, weekly project reviews are held during which new risk areas are presented. Once a month the project review is dedicated to status the highest risk Engineering Issues and to propose and select new candidates for this Top Issues List. Similar processes occur in other functional organizations. The functional department Top Issues are briefed monthly at the program review. Weapon Systems Management (R500) selects the top program technical and business issues primarily from the functional department Top Issues lists. Risk identification extends to schedules as well as technical, business and cost issues. DIVOPs 01.12.02 (Cost/Schedule Control System-Scheduling) and 01.33.04 (Red Flag Report) specify the procedures to be followed. Once identified, the issue becomes a subject for risk tracking. In case of functional operating schedules (FOS) a constraint analysis report (CAR) may be required per DV 01.12.02.

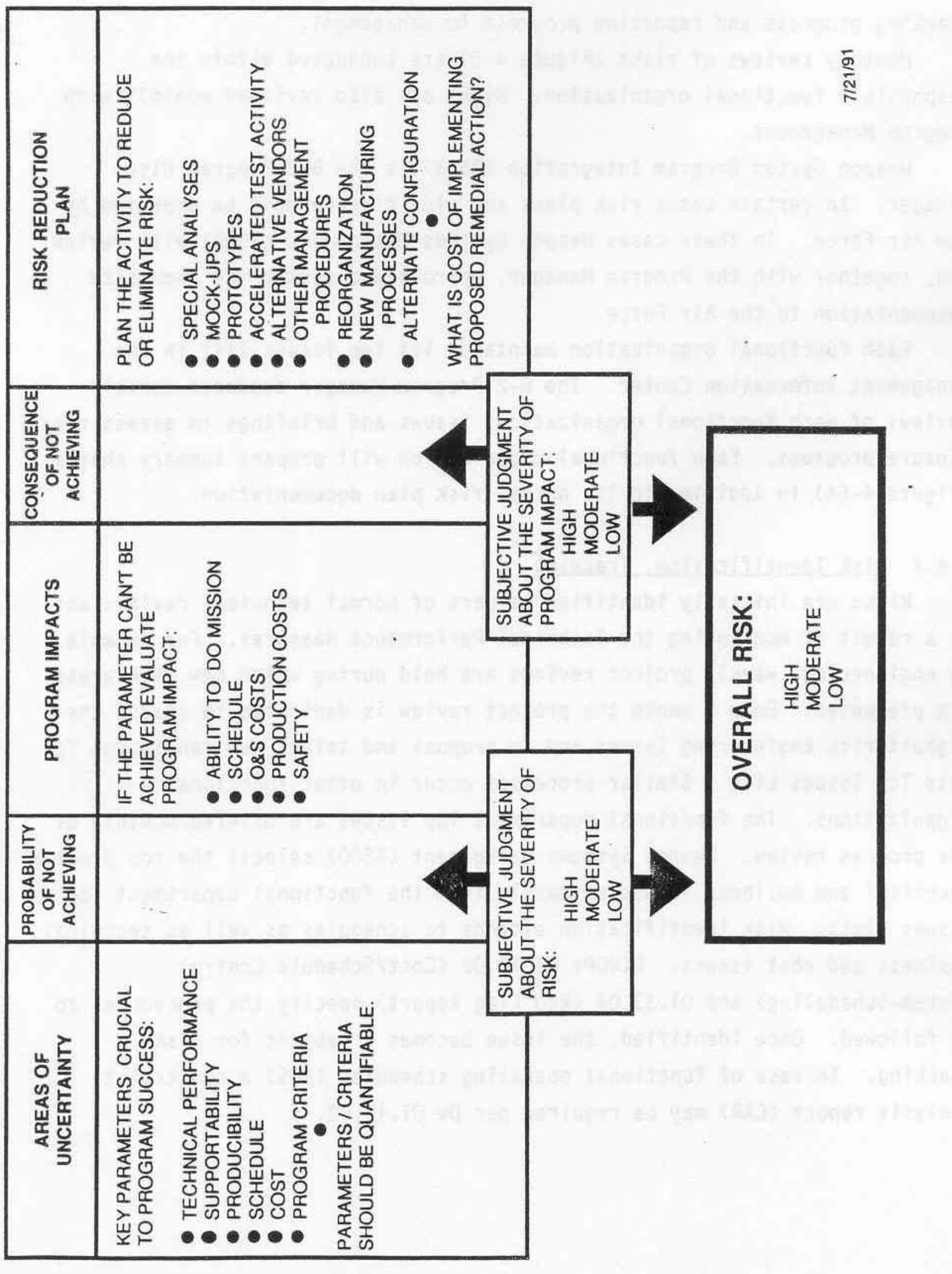


FIGURE 4-6. RISK IDENTIFICATION AND ASSESSMENT

The intent is to actively manage only the very significant risks at the Program Manager level and allow each organization to manage lower level risks, with appropriate controls on closure.

Control numbers are assigned by the functional organizations in accordance with management information center (MIC) protocol (e.g., engineering no. E-xx) and each risk issue is tracked by this control number, as shown in Figure 4-5 and 4-6A, until formally closed. Figure 4-6A shows the potential evolution of an issue from "emerging" to "program" (technical or business) and then to closure.

Assessment of risks includes subjective judgments of the probability and consequences of not achieving a required program objective. This assessment results in the classification of the risk as shown in Figure 4-6 and the designation of the management level responsible for review of progress made toward risk reduction or elimination. Risk analysis includes the assessment of the risk and its potential program consequences, identification of possible risk reduction actions, and selection of actions to be pursued by the responsible organization. Risk analysis also includes careful examination of the costs of various alternatives; while a certain action may be technically preferable, the implementation costs may be prohibitive.

4.4.3 Risk Reduction and Closure Plan

Having identified the approach to be followed to reduce or eliminate a specific risk, a risk closure plan is developed by the risk closure manager and approved at an appropriate management level.

Risk closure plans follow a prescribed format, which includes risk control number, risk level, responsible technical and project engineer, brief descriptions of 1) the issue, 2) impact on performance, schedule and cost, 3) closure actions and milestones. It also includes flow diagrams and schedules (DV 15.01.22). This common format is used for functional and program reviews as well as for Quarterly Program Management Reviews with the Air Force.

EMERGING ISSUE
WXXX-XX ISSUE TITLE

PROJECT LEAD: **SYSTEMS AFFECTED:**

TECH LEAD: **ESTIMATED CLOSURE DATE:**

ISSUE:

IMPACT:

CLOSURE:

(DATE) **(MGR,DEPT)** **NORTHROP**
B-2 Division

DSF 1328A (R4 91)

FIGURE 4-6A. RISK MANAGEMENT SUMMARY
(SHEET 1 OF 4)

ENGINEERING TECHNICAL ISSUE
E-XX ISSUE TITLE

PROJECT LEAD:

TECH LEAD:

SYSTEMS ENG:

SYSTEMS AFFECTED:

ESTIMATED CLOSURE DATE:

RISK LEVEL:

ISSUE:

IMPACT:

CLOSURE:

(DATE) (MGR,DEPT)

DSF 1328A (R4 91)

NORTHROP
B-2 Division

FIGURE 4-6A. RISK MANAGEMENT SUMMARY
(SHEET 2 OF 4)

PROGRAM TECHNICAL ISSUE
E-XX ISSUE TITLE

PROJECT LEAD:
TECH LEAD:
SYSTEMS ENG:

SYSTEMS AFFECTED:
ESTIMATED CLOSURE DATE:
RISK LEVEL:

ISSUE:

IMPACT:

CLOSURE:

(DATE) (MGR,DEPT)

NORTHROP
B-2 Division

OSF 1328A (R4 91)

FIGURE 4-6A. RISK MANAGEMENT SUMMARY
(SHEET 3 OF 4)

RISK CLOSURE SUMMARY

RESPONSIBLE MANAGER:
TECH LEAD:
SYSTEMS ENG:
PROJECT ENG:

ISSUE:

CLOSURE DATE:

APPROVAL:

____________________ **RISK CLOSURE MANAGER**

____________________ **FUNCTIONAL VP**

____________________ **PROGRAM OFFICE**

E-XX **WXXX**

NORTHROP
B-2 Division

DSF 1328A (R4 91)

FIGURE 4-6A. RISK MANAGEMENT SUMMARY
(SHEET 4 OF 4)