



Systems Engineering Case Studies

Synopsis of the Learning Principles

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INTRODUCTION

The Department of Defense is exponentially increasing the acquisition of joint complex systems that deliver needed capabilities demanded by our warfighter. Systems engineering is the technical and technical management process that focuses explicitly on delivering and sustaining robust, high-quality, affordable solutions. Air Force leadership has collectively stated the need to mature a sound systems engineering process throughout the Air Force. Gaining an understanding of the past and distilling lessons learned that are then shared with others through formal education and practitioner support are critical to achieving continuous improvement.

This synopsis conveys the salient results of case studies focused on the application of systems engineering principles within various programs. Salient results are conveyed as learning principles to facilitate pedagogy. But these results are also useful to practicing engineers and managers as they apply systems engineering throughout a weapon system's life cycle. The reader is encouraged to delve into the details contained in the complete case study should a particular learning principle relate to a situation on your program.

Each learning principle is identified as follows:

(short name) / (learning principle number)

The short name key is as follows:

F-111 refers to the F-111 Systems Engineering Case Study

B-2 refers to the B-2 Systems Engineering Case Study

C-5 refers to the C-5A Galaxy Systems Engineering Case Study

GPS refers to the Global Positioning System Systems Engineering Case Study

HST refers to the Hubble Space Telescope Systems Engineering Case Study

TBMCS refers to the Theater Battle Management Core System Systems Engineering Case Study

Peacekeeper refers to the Peacekeeper Intercontinental Ballistic Missile Systems Engineering Case Study

A-10 refers to the A-10 Thunderbolt II (Warthog) Systems Engineering Case Study

GH refers to the Global Hawk Systems Engineering Case Study

KC-135 refers to the KC-135 Simulator Systems Engineering Case Study

The learning principle title is highlighted **green** if it contains information related to an application of systems engineering that one should consider adopting. The learning principle title is highlighted **yellow** if it contains information related to problems that should be avoided in the application of systems engineering.

Complete case studies are available on the Air Force Center for Systems Engineering website at [<http://www.afit.edu/cse>].

CASE STUDY LEARNING PRINCIPLES

B-2/1 Integration of the Requirements and Design Process

A key aspect of the implementation of the B-2 system engineering process was the integration of the SPO requirement's team with the contractor's 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.

B-2/2 WBS Task Teams and Functional Hierarchy

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 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.

B-2/3 Air Vehicle Reconfiguration

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 sections (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 crises 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.

B-2/4 Subsystem Maturity

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.

B-2/5 Risk Planning and Management

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.

C-5/1 Requirements

The process for developing and documenting the system performance requirements integrated the User (warfighter), planners, developers, and technologists from both the government and industry in a coordinated set of trade studies. It resulted in a well-balanced, well-understood set of requirements that fundamentally remained unchanged throughout the program.

C-5/2 Total Package Procurement Concept (TPPC)

The Total Package Procurement Concept (TPPC) employed by the government required a fixed-price, incentive fee contract for the design, development, and production of 58 aircraft. It included a clause giving Total Systems Performance Responsibility (TSPR) to the prime

contractor. TPPC was invented to control costs, but it was the underlying cause of the cost overrun and limited number of aircraft purchased under the original contract.

C-5/3 Weight Empty Guarantee

A Weight Empty Guarantee was included in the specification as a performance requirement and in the contract as a cost penalty for overweight conditions of delivered aircraft. The aircraft Weight Empty Guarantee dominated the traditional aircraft performance requirements (range, payload, etc.), increased costs, and resulted in a major shortfall in the wing and pylon fatigue life. The stipulation of a Weight Empty Guarantee as a performance requirement had far-reaching and significantly deleterious unintended consequences.

C-5/4 Independent Review Teams (IRTs)

The Air Force C-5 Systems Program Office employed Independent Review Teams (IRTs) to assemble national experts to examine the program and provide recommendations to the government. These problem-solving teams were convened to garner the best advice in particular technical areas: structure design and technology, and designs to achieve useful service life.

F-111/1 Requirements Definition and Management

Ill-conceived, difficult-to-achieve requirements and attendant specifications made the F-111 system development extremely costly, risky and difficult to manage.

F-111/2 Systems Architecture and Design Trade-Offs

F-111 Systems Engineering managers (both government and contractor) were not allowed to make the important tradeoffs that needed to be made in order to achieve an F-111 design that was balanced for performance, cost and mission effectiveness (including survivability) and the attendant risk and schedule impacts.

F-111/3 Communications and Systems Management

The F-111 suffered from poor communications between the Air Force and Navy technical staffs, and from over-management by the Secretary of Defense and the Director, Defense Research and Engineering, and it came under intense congressional scrutiny, which restricted the System Program Office (SPO) Director from applying sound systems engineering principles.

F-111/4 Validation and Verification

The F-111, like any complex weapon system development program which provides new war-fighting capability, had areas of risk or deficiency that came to light during RDT&E even though there was perceived low risk in the design. The F-111 development program introduced concurrency (overlap) between design validation/verification and production to

accelerate program schedules because there was an urgent need for the capability. However, technical problems uncovered in verification and validation led to costly retrofits and redesign of the production versions. The most notable technical problems during the F-111 development were inlet-engine compatibility, structural failures in the wing carry-through structure, and the introduction of the technically immature digital avionics system (call the Mark II) to replace the baseline analog avionics system.

F-111/5 Program Management

Cancellation of the Navy F-111B in 1968, after bi-service design was frozen in 1964 and production of the Air Force F-111A was well underway, had a lasting impact on the United States Air Force (USAF) F-111 performance and cost.

GPS/1 Programs must strive to staff key positions with domain experts.

From program management to systems engineering, to design, to the manufacturing and operations teams, the people on the program were well-versed in their disciplines, and all possessed a systems view of the program. While communications, working relationships, and organization were important, it was the ability of the whole team at all levels to understand the implications of their work on the system that was vital. Their knowledge-based approach for decision making had the effect of shortening the decision cycle, because both the information was understood and the base and alternative solutions were accurately presented.

GPS/2 The systems integrator must rigorously maintain program baselines.

The JPO retained the role of managing and controlling the system specification and, therefore, the functional baseline. The JPO had derived and constructed a mutually agreed-to set of system requirements that became the program baseline in 1973. While conducting the development program, the GPS team was able to make performance/risk/cost trade analysis against the functional baseline to control both risk and cost. The JPO was fully cognizant of the implications of the functional requirements on the allocated baseline because they managed the Interface Control Working Group process. Managing that process gave them first-hand knowledge and insight into the risks at the lowest level.

GPS/3 Achieving consistent and continuous high-level support and advocacy helps funding stability, which impacts SE stability.

Consistent, continuous high-level support provided requirements and funding stability. In this role, the OSD provided advocacy and sourced the funding at critical times in the program, promoted coordination among the various services, and reviewed and approved the GPS JPO system requirements. OSD played the central role in the establishment and survivability of the program. The GPS JPO had clear support from the Director of Defense Development, Research and Engineering (DDR&E), Dr. Malcolm Currie, and program support from the Deputy Secretary of Defense, Dr. David Packard. Clearly the services – particularly the Navy and the Air Force early on, and later the Army – were the primary users

and the eventual customers. However, each service had initial needs for their individual programs, or for the then-current operational navigation systems. Additionally, the Secretary of the Air Force provided programmatic support to supply manpower and facilities.

GPS/4 Disciplined and appropriate risk management must be applied throughout the lifecycle.

The GPS program was structured to address risk in several different ways throughout the multiphase program. Where key risks were known up front, the contractor and/or government utilized a classic risk management approach to identify and analyze risk, and developed and tracked mitigation actions. These design (or manufacturing/launch) risks were managed by the office who owned the risks. Identified technical risks were often tracked by Technical Performance Measures (TPMs), (e.g. satellite weight and Software Lines of Codes (SLOC)), and addressed at weekly chief engineer's meetings.

HST/1 Early and full participation by the customer/user throughout the program is essential to program success.

In the early stages of the HST program the mechanism was not well defined and the user community was initially polarized and not effectively engaged in program definition and advocacy. This ultimately changed for the better, even if driven heavily by external political and related national program initiatives. Ultimately, institutionalization of the user's process for involvement ensured powerful representation and a fundamental stake and role in the program requirements and requirements management. Over time, the effectiveness of "The Institute" led to equally effective user involvement in the operational aspects of system (deployment and operations) as well.

HST/2 The use of Pre-Program Trade Studies ("Phased Project Planning" in NASA parlance at the time) to broadly explore technical concepts and alternatives is essential and provides for a healthy variety of inputs from a variety of contractors and government (NASA) centers.

These activities cover a range of feasibility, conceptual, alternative and preliminary design trades with cost initially a minor, then later a major, factor as the process proceeds. For HST, several Headquarters and Center organizations funded these studies and sponsored technical workshops for HST concepts. This can promote healthy or unhealthy competition, especially when roles and responsibilities within and between the participating management Centers have not yet been decided and competing external organizations use these studies to further both technical and political agendas. Center roles and missions can also be at stake depending on political and or budgetary realities. The systems engineering challenge at this stage is to "keep it technical, stupid!"

HST/3 Provision for a high degree of systems integration to assemble, test, deploy and operate the system is essential to success and must be identified as a fundamental program resource need from early on (part of the program baseline).

For HST, the early wedding of the program to the Shuttle, prior NASA (and of course, NASA contractors) experience with similarly complex programs, such as Apollo, and the early requirement for manned, on-orbit servicing made it hard not to recognize this was a big SE integration challenge. Nonetheless, collaboration between government engineers, contractor engineers, as well as customers, must be well defined and exercised early on to overcome inevitable integration challenges and unforeseen events.

HST/4 Life Cycle Support Planning and Execution must be integral from day one (including concept and design phases) and the results will speak for themselves. Programs structured with real life cycle performance as a design driver will be capable of performing in-service better, and will be capable of dealing with unplanned, unforeseen events (even usage in unanticipated missions.)

HST likely represents the benchmark for building-in system sustainment (reliability, maintainability, provision for technology upgrade, built-in redundancy, etc.), all with provision for operational human execution of functions (planned and unplanned) critical to servicing missions. With four successful service missions complete, including one initially not planned (the primary mirror repair), the benefits of design-for-sustainment, or life cycle support, throughout all phases of the program, becomes quite evident. Had this not been the case, it is not likely that the unanticipated, unplanned mirror repair could have even been attempted, let alone be totally successful.

HST/5 For complex programs, the number of players (government and contractor) demands that the program be structured to cope with high risk factors in many management and technical areas simultaneously.

For HST, there was heavy reliance on the contractors (especially Lockheed (LMSC) and Perkin-Elmer (P-E) and they each “owned” very significant and unique program risk areas. In the critical optical system area, and with LM as the overall integrator, there was too much reliance on LM to manage risk in an area where P-E was clearly the technical expert. Accordingly, NASA relied on LMSC and LMSC relied on P-E with insufficient checks, oversight and independence of the QA function throughout. While most other risk areas were no doubt managed effectively, lapses here led directly to the primary mirror defect going to orbit undetected in spite of substantial evidence that could have been used to prevent this occurrence.

TBMCS/1 Requirements Definition and Management

The government did not produce a Concept of Operations, key operational performance parameters, or a system specification for the contractor. The contractor was responsible for generating a systems segment specification that had performance measures as goals, but not testable requirements. The government did produce a technical requirements document that defined a technical approach and levied certain standards on the contractor. There was no firm baseline for operational and system requirements from which the system could be built and tested. The requirements baseline was volatile up to system acceptance, which took place after TBMCS passed operational test and evaluation.

TBMCS/2 System Architecture

The system architecture was defined at too high a level, which had a tremendous impact on system design and development. The government's mandates for software reuse and use of commercial software products were often contradictory and problematic for the system development. The layered system architecture did support system evolution and migration to modern technologies.

TBMCS/3 System/Subsystem Design

The system and subsystem design was severely hampered by the complexity of legacy applications, misunderstanding of the maturity and complexity of commercial and third party software products, and a lack of understanding of how the system would be employed by the user.

TBMCS/4 System Integration

Systems and interface integration was highly complex. The system integration was very difficult because of the lack of detail in the system architecture and the mandate to use government-furnished equipment that was not necessarily compatible with commercial off-the-shelf products. Integrating third party software products was an arduous process and required extensive oversight. The external system interfaces were not managed and were often impossible to test at the contractor's facility.

TBMCS/5 Validation and Verification

The lack of a firm requirements baseline made validation and verification very difficult. The program was schedule driven and often ran parallel test processes without clear measures of success. Not being able to replicate the operational environment prior to acceptance test created severe problems.

Peacekeeper/1 Development commands must manage their technology base to optimize progress over several programs.

During this period of Intercontinental Ballistic Missile (ICBM) development, BMO was able to develop and manage a technology base development plan that spanned several programs. BMO and its predecessors began developing technologies with the Atlas system that continued through the Titan, Minuteman, Peacekeeper and Small ICBM. This included technologies such as solid rocket propellants, nozzle manufacture, liquid fueled engines, and guidance systems. The solid rocket motors on Peacekeeper were variants of the design used on Minuteman. These efforts were integrated with the Air Force laboratories, support contractors, system contractors and Systems Engineering/Technical Assistance (SE/TA) contractors. Thus, a Systems Program Office (SPO) was able to manage the technology development efforts for the next program so that the lessons learned from the previous

system could be applied and technology transition decisions could be made based on an intimate knowledge of the result of the technology development efforts.

Peacekeeper/2 The systems integrator must maintain rigorous control of these processes and all of the supporting contractors.

The USAF SPO was the lead integrator for the contractor team with the support of the Systems Engineering/Technical Assistance (SE/TA) contractor (TRW), which enabled the USAF to own the systems engineering process and missile specifications. The SPO also served as the configuration control authority for the specifications for each associate contractor and for the Interface Control Documents (ICDs) coordinating associate contractor deliverables.

The systems engineering role was split between the SPO, TRW as the SE/TA Contractor, Martin Marietta as the Assembly and Check Out (A&CO) contractor for the missile, and Boeing as the contractor for the basing equipment including A&CO.

- The SPO provided contractual authority and oversight and controlled the specifications and ICDs for each associate contractor. The SE/TA contractor (TRW) provided insight and advice to the SPO. The hands-on physical integration at the test sites and in the field was handled by the A&CO contractors.
- There were many ramifications including significant SPO and SE/TA manpower requirements. Perhaps the most important benefit was the ability of the Government and its SE/TA support to conduct both technical and business tradeoffs and then impose the results contractually without concern for overriding a prime contractor and the vastly more detailed insight into the execution of the program.
- As the lead, the Air Force had the right to overrule contractors and even to re-compete their products and services if required.

Peacekeeper/3 The systems integrator must maintain a rigorous systems engineering process.

The System Requirements Analysis (SRA) evolved during the previous Minuteman program and brought significant discipline to the systems engineering process through four key elements:

- (i) The Operational Requirements Analysis (ORA), which defined and allocated the technical requirements for the prime operational equipment for each associate contractor to include Technical Orders (TOs), training, and other activities which also indicated the requirements for Strategic Air Command (SAC) operational personnel.
- (ii) Test Planning Analysis (TPA) that developed the requirements and plans for testing including the Integrated Test Plan (ITP) by which all developmental and operational testing was planned leading up to and including flight testing and that developed the requirements for test facilities including those at Vandenberg AFB.

- (iii) Logistics Support Analysis (LSA) which developed the requirements for sustainability and for deliverable test equipment for both the depots and the field sites.
- (iv) Assembly and Check-Out (A&CO) Analysis which developed the A&CO requirements on the prime equipment as well as special equipment to accomplish A&CO in the field.

Peacekeeper/4 Investing in long term systems engineering and program management staff supports program success.

Key leaders in the program had one or more lengthy BMO assignments prior to Peacekeeper development or had other in-depth space related experience. The supporting staff had similar experience either as military officers with multiple space-related assignments, government civilians with lengthy tenure at BMO or as the SE/TA contractor with a staff of well-experience engineers, scientists, and support staff. While this situation was not unusual at the time, it seldom occurs in today's program offices.

The number and types of personnel assigned to the Peacekeeper program; high levels of knowledge, skill, ability, and experience of the personnel, and lengthy tenure assignment at BMO all contributed tremendously to the success of the program. These aspects reflect the importance of the Manpower, Personnel, and Training domains associated with Human Systems Integration (HSI) in the systems engineering process. While HSI was not a common term at the time of Peacekeeper development, many of the tenets of good HSI as we know it today were applied, particularly in these domains.

The engineering and advanced degrees held by most of the leadership were critical in enabling them to make informed decisions and manage their programs. The engineers were allowed sufficient time to learn missile systems, gain experience in all aspects and subsystems, and learn and practice the BMO Systems Engineering Process. This knowledge and experience, coupled with the major increase in manning numbers at that time, primed the program for success. The Air Force staff had the manning and expertise to carefully monitor subcontractors and actually participate in detailed reviews, allowing them to make all critical decisions for the best outcome of the Air Force.

Adequate manning, experiential learning, supportive work environment, hands-on experience, job rotation, mentoring, hand-picked staff, and staff education level (Manpower, Personnel, and Training characteristics) were key factors in the success of the Peacekeeper program.

Peacekeeper/5 System Requirements Definition must be completed prior to development to reduce program risk and cost.

The Peacekeeper System was developed to meet the perceived ICBM "vulnerability gap." A requirements debate centered on whether the Soviets had indeed improved accuracy to a point that silo-based systems were vulnerable to a first strike. The Peacekeeper provided a very highly accurate missile with ten warheads that provided increased offensive

capability—but could they be deployed in a mode that was relatively free from first strike annihilation? The Peacekeeper basing mode requirements analyses took place in a very public forum with intense input from non-traditional DOD sources. Unlike previous weapon systems (such as Minuteman) that developed a basing mode in a more classified environment with little public debate, the Peacekeeper system was studied intensely with several hundred different modes considered. While the missile requirements were essentially completed prior to development, the basing mode changed constantly during this development period. While the systems engineering analysis considered performance and survivability merits, a major portion of the analysis focused on regional and national economic and environmental considerations.

This Peacekeeper case study revealed the importance of adhering to a rigorous systems requirements analysis (SRA) process. This SRA process had started on previous programs at the BMO and produced a well trained engineering force that transparently used the SRA process on the Peacekeeper program. The study also demonstrated the importance of short and long term technology planning. BMO carefully invested resources in new and updated technologies with each new program, but only inserted them when they were technologically mature. This is similar to today's Technology Readiness Level (TRL) analysis and the concept of spiral development. The case study also highlighted the importance of developing system engineers and allowing them to progress through a variety of missile programs to gain expertise. Finally, all of these elements combined to allow BMO to successfully develop, produce and deploy a weapon system despite significant public debate and Congressional micro-management.

A-10/1 The system concept and preliminary design must follow, not precede, the mission analysis.

The A-10 would have been a very different aircraft had this principle been violated. The clear predilection within the Air Force at the time of needs definition was for fast multi-purpose aircraft. By concentrating on the Close Air Support mission, and focusing on key characteristics of that mission, the early A-X concept working group was able to discover what the critical performance parameters were that contributed to these characteristics. An example of this approach is how the group treated the key mission characteristic of responsiveness. While a contributor towards responsiveness can obviously be aircraft speed, the group understood that responsiveness was even more dependent on how close to the battlefield the aircraft could be based and maintained, how long the aircraft could loiter around the battlefield, and whether or not the pilot could easily communicate and coordinate with the ground troops they were supporting. The aircraft performance parameters were analyzed in terms of alternative design approaches and aircraft design parameters in areas of airframe and propulsion, avionics, armament, and survivability provisions. Once those design parameters were understood and traceable back to mission characteristics, the study group was able to evaluate candidate aircraft configurations in terms of mission and cost effectiveness. This front end application of Systems Engineering led to well understood requirements and provided a solid foundation with which to solicit contractor proposals and start a development program.

Part of the A-X concept from the beginning was a low ownership cost. While the A-10 did not meet its intended design-to-cost goal, the cost driven approach permeated all aspects of the design, development and production of the aircraft. The design was largely constrained to use "existing state-of-the-art" technology, avionics were kept to a minimal set necessary to accomplish the primary missions, and the design incorporated many features to reduce the maintenance and support cost for the aircraft. An example of this is the attention paid to reducing the cost associated with the ammunition, the majority driver for ownership cost of the gun system. The program paid more in the development effort (due to multiple ammunition subcontractors) to ensure a low production cost would be attainable when it came time for large competitive contracts for ammunition to support operational use.

A-10/2 Prototyping can be used to help manage technical and cost risk at the system, subsystem, and component level.

There are mixed feelings throughout the DoD with respect to prototyping, and in particular competitive prototype phases prior to full scale development. Most would agree that technical and life cycle cost risk can be partially mitigated by delaying costly commitment decisions for full scale development until after the basic design has been demonstrated and cost estimates have matured. The typical downside of this approach is that development costs rise and development schedules lengthen, and clearly this is what occurred as a result of the decision to use the competitive prototype phase for the A-X program. Some would argue that the additional development expense of these competitive prototype phases makes them impractical for large systems (e.g., bomber aircraft, ships). An example that can be taken away from the A-10 case study is how this can be done at the subsystem and component level. The gun system on the A-10 was considered to be risky, so a competitive prototype phase for the GAU-8/A program was run in parallel with that for the A-X aircraft. Further, the 30 mm ammunition was assessed as having both technical and cost risk, so competitive prototyping was used at the subcontractor level within the GAU-8/A program. With the expected ownership cost of the gun being driven by the ammunition cost, the intent was to have multiple qualified sources for ammunition by 1978 when a direct competitive contract would be let to procure ammunition for operational use. While the GAU-8/A program paid the development cost for this risk mitigation approach, a good gun system with relatively low operating cost was obtained as a result.

A-10/3 Clear lines of responsibility must be established to ensure successful integration, especially when multiple programs are involved.

The Air Force and the program office understood what the A-10 system integration risks were, and took steps to mitigate them. These risks were associated with the integration of a large caliber internal gun system, and the ammunition associated with the gun. The aircraft, the gun, and the ammunition were all parallel development efforts, and it was important that they all came together if the A-10 was to provide the capability the Air Force needed. The Air Force addressed this integration risk directly by how they set up responsibility for the various programs. Managerial responsibility for the GAU-8/A gun system was given to the A-10 program office, and the memorandum of understanding establishing this relation between the aircraft and gun program was later expanded to include the ammunition as well. The ammunition suppliers were established under a subcontract relation to GE, the prime contractor for the gun system. This made GE responsible for the total gun system and a

single program office responsible for the combined aircraft and gun system. While the Air Force did not establish this same type of relationship with the engine program, the TF-34 engine was already under development for another aircraft at the time the A-X program began. Further, the engine placement off the fuselage of the A-10 allowed for relatively easy integration with the airframe.

A-10/4 The government must ensure the contractor is able to “Walk the Talk” when it comes to production.

In reviewing the abilities of the contractor to execute the contract, the Air Force failed to identify a number of issues that might well have doomed the program to failure. Both before and after the awarding of the contract the company was in trouble. The government’s pre-award survey of Fairchild Hiller examined their capacity, capability and financial condition, but failed to recognize some of the risk elements and concerns that would be noted some 3 years later. Fairchild had failed to adequately invest in equipment and its workforce, and its management and organization had deficiencies. The Air Force made a number of recommendations that were followed, and the company was able to produce the aircraft; however, it ultimately put the company in a position from which it could not recover.

A-10/5 Successful design, development and production is not enough to sustain a system throughout its life cycle.

By most accounts, the A-10 was a well designed and well built aircraft. Its performance in Desert Storm certainly supports this claim. Prior to Desert Storm, however, the Air Force had committed to retiring the A-10 and this adversely affected the sustainment efforts for the aircraft. While the Air Force reversed the decision to retire the A-10 shortly after Desert Storm, it did not make the investments in maintenance and modifications that should have followed that reversal. Multiple sources noted systemic neglect of the inspection, maintenance, and attention to service life issues throughout the late 1980’s and most of the 1990’s. Required inspections were not conducted, early fatigue indications at Wing Station 23 and other locations were effectively ignored, and critical data regarding actual service life was no longer being obtained. This was further impacted by major disruptions to the sustainment program office as a result of the 1995 Base Realignment and Closure decisions. The program office reported 80% loss of experienced personnel due to the work transfer from McClellan to Hill AFB, and repeated turnover at the System Program Director and Chief Engineer level was equally problematic. The Air Force lost awareness of the structural health of the A-10 fleet, and the intended repair for the aircraft, which did not address the full scope of issues required to provide the required life extension, proved to be costly and ineffective in providing the required service life. The end result was a decision to manufacture new wings for all thin skin aircraft remaining in the fleet. Had the Air Force maintained awareness of the structural health of the A-10, the decision to re-wing could have been made earlier, possibly obviating the need for the wing components of the HOG UP program. This likely would have resulted in an overall cost savings and earlier operational capability for the re-winged aircraft.

A-10/6 “If the politics don’t fly, the system never will.”¹

The quote defining this Learning Principle is one of the heuristics from the text *The Art of Systems Architecting* by Mark Maier and Eberhart Rechtin. In that text the authors devote an entire chapter to “The Political Process and Systems Architecting”. Other heuristics from that chapter include:

- Affordability is decided by whichever side has the most votes;
- A strong, coherent constituency is essential;
- Technical problems become political problems;
- The best engineering solutions are not necessarily the best political solutions.

All of these heuristics can be applied in retrospect to the A-10 as it was beset with political fighting for the entire life of the program. Early on, internal Air Force politics made it difficult to pursue a specialized CAS aircraft when the majority of the service favored fast multi-purpose fighters. Later, it faced difficulties justifying its existence alongside the Army attack helicopters; however, it may have been the very existence of these advanced helicopter development programs that allowed it to overcome resistance to the CAS aircraft within the Air Force. Still later, the A-10 was forced to walk a tight line between those that wanted a simpler, lower cost aircraft, and those that didn’t want the A-10 because of its shortcomings at night and in adverse weather (brought about by a “lean” avionics package to keep costs down). Politics shaped the A-10 program structure, most notably in the adoption of a politically attractive competitive prototyping phase associated with both the A-X aircraft and the GAU-8/A gun. Congressional politics forced an additional competition with the A-7D even after the competitive fly-off between the YA-9 and YA-10, and attempted to force another show down with the Piper Enforcer. Finally, congressional politics attempted to derail redistribution of production required to address deficiencies associated with the Farmingdale NY plant. The proponents of the A-10 won some of these battles, and lost some as well, but persevered in cobbling together the “strong, coherent constituency” considered essential to the success of the program.

GH/1 While an “evolving requirements” strategy may be an excellent choice for a concept demonstration program, it is an unwise strategy for an EMD program.

Typically, a System Specification derived from the SRD is placed on contract at the beginning of EMD to establish the contractual basis for the subsequent design and verification activities and support the definition of the scope and cost of the development program. With the spiral development approach that was employed, there was no contractual System Specification at the start of Spiral 1 or Spiral 2 (each of which constituted significant EMD programs), just a draft SRD that contained top-level requirements. The intent was to evolve to the baseline technical requirements at the completion of EMD, thus providing the contractor with greater contractual latitude, similar to the ACTD program. However, at this point in the program, the user had specific performance requirements that needed to be met, and these were not necessarily consistent with available funding. The result was a choice of “the devil’s alternative”: either breach the program cost ceiling or fail to meet the user

¹ Maier, Mark & Rechtin, Eberhardt, *The Art of Systems Architecting*, 2nd ed., CRC Press, New York, 2002.

requirements. Not having a firm set of technical requirements also increased the program risk relative to requirements creep and baseline verification of engineering content. As a result, the program experienced a Nunn-McCurdy cost breach in excess of the 25 percent threshold during Spiral 2 (Block 20) of EMD.

GH/2 An overall systems engineering strategy must be defined as early as possible in a program and must be consistent with the acquisition approach and program needs.

During the ACTD phase, the contractor had a small systems engineering organization consisting of systems engineers located within each of the Integrated Product Teams (IPTs). The contractor integrated the systems engineering function partly into the technical management structure wherein some of the IPT leads were experienced in the systems engineering discipline. The Chief Engineer created this organization and chose the IPT leads based on leadership capability, interpersonal skills, and technical excellence in their area of expertise (systems engineering, design, analysis, manufacturing/assembly, logistics, cost, ground segment, communications, payloads, etc.) In this concept, the Chief Engineer was the individual with primary responsibility to define and execute the systems engineering process. At the start of EMD, the systems engineering function was largely integrated into the IPTs. About two years into EMD, the contractor reorganized, and the systems engineers were centralized into a Systems Engineering Integration Team (SEIT). The SEIT was viewed by the IPTs as a “non-value added” activity and “watch dog” that imposed workload that detracted from the IPT’s ability to accomplish required tasks. Consequently, the SEIT had very limited ability to successfully impact the conduct of the program. This is supported by the point that, when funding problems drove program cutbacks, systems engineering proved to be an easy target. As a result, the Spiral 2 effort was lacking in processes necessary to support the efficient completion of an EMD program.

GH/3 The more an acquisition strategy plans concurrency between developing the validated baseline and production, the higher the risk of future cost increases and schedule delays.

Before a program proceeds into production, there is a need that all participants understand how the product baseline, expressed in terms of performance capabilities and limitations, meets the functional baseline, expressed in terms of technical requirements. If this mutual understanding does not exist, then there is a significant risk that the user needs will not be met.

GH/4 The more complex the program, the more critical it is that an IMS links all aspects of the program, including the lower-tiered schedules.

The Spiral 1 EMD Statement of Work (SOW) required that the contractor create and maintain an IMS that showed interdependencies and critical paths. The contractor responded by creating a multitude of IMSs: one for each Spiral and one for each second tier IPT. The IMSs were independent of each other, did not address subcontracted efforts, and there was no single overarching IMS that integrated all the lower-tiered IMSs. The Global Hawk program was complex with multiple spirals occurring simultaneously, and few individuals, if any, knew how all the “pieces” fit together. The lack of a single, integrated schedule showing

overall program critical paths and interdependencies made it impossible for program management to truly assess the overall program status. In reality, no one knew how one schedule slip impacted another and whether someone else's critical path was being violated.

GH/5 Contractual programmatic and technical requirements must be clearly defined, understood, and executed by all parties to include the areas of airworthiness certification and software development and verification.

In order to avoid disputes between the contractor and Air Force customer, it is necessary to contractually define key programmatic and technical requirements. The contractual wording needs to be clear and unambiguous. Also, particular care needs to be taken to ensure that all parties share the same understanding of the requirements and that the requirements are executed in a timely fashion. This principle was violated in two key areas: airworthiness certification and software development/validation.

GH/6 Development testing must follow a disciplined engineering process or cost, schedule, and technical risks may be incurred.

The OSD assessment in support of the Nunn-McCurdy recertification concluded that the program development, test, and evaluation (DT&E) strategy was insufficient to reduce program risk and support knowledge-based decisions. Lower-level development tests were typically not used as a building block to system test, entry and exit criteria were typically missing, test planning and test procedures were inadequate, critical test parameters were often not verified, test assets were lacking, and systems were not assessed against their intended environment. In short, OSD concluded that the lack of a disciplined engineering approach to development testing was a contributor to the Nunn-McCurdy breach.

KC-135/1 Systems Engineering must translate program goals and objectives into clearly defined and verifiable system requirements, focusing on the entire life cycle.

Key elements of requirements allocation include early involvement by the support contractor with the aircraft systems prime contractor(s) to ensure simulator specific requirements are addressed. Because aircraft upgrades are identified by the KC-135 Program Office at Tinker AFB there are roadmap meetings held at Tinker where upcoming modifications to the KC-135 aircraft are discussed. The KC-135 ATS O&M contractor and the Training System Program Office at Ogden now are present to assess those modifications and ensure the ATS requirements are included in the early planning process.

KC-135/2 The Systems Engineering process must be structured to properly mitigate challenges generated by third-party Modification Contractors.

The KC-135 O&M contract states the prime contractor, FlightSafety, is responsible for meeting the overall performance requirements of the training system including trained students that meet Government standards. Competitive contracting for early OFT upgrades did not formally involve buy-in from the O&M contractor who retains ultimate responsibility for providing a "guaranteed" student to the Government. This was recognized and remedied in future contracts by involving the support contractor in a more disciplined manner to ensure

early involvement in the development effort. For example, the requirement for a Performance Work Statement (PWS) has evolved that identifies specific tasks to be accomplished by the KC-135 ATS prime in order to ensure training system requirements are identified at the ATS level and properly allocated to the various subsystems under development.

KC-135/3 Systems engineers must be responsible for ensuring that all stakeholders are involved during key decision technical planning and execution process reviews.

The KC-135 program requires a tailored set of formal reviews be held during the development phase that is based on the size and complexity of the modification program. These reviews ensure that the entire KC-135 ATS team is working to the same requirements, designing and developing the correct modifications, adequately testing the modifications and generating the appropriate courseware changes. The reviews employed throughout the modification development and verification efforts may include a Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), Test Readiness Review (TRR), Required Assets Available Review (RAAR) and In Process Reviews (IPR). KC-135 simulator reviews are structured to ensure that the KC-135 Simulator team has mutual expectations and understanding of requirements and that the contractor's proposed preliminary designs and program plan satisfies the development specification.

KC-135/4 Integrated logistics/maintainability support structure avoids parts obsolescence and diminishing manufacturer supply issues.

As with aircraft systems, training systems must also have detailed technical plans that integrate a logistics/maintainability support structure to ensure continued future operation. During each technical planning activity, systems engineering must be concerned with the total support of the system to assure its economic and effective operation throughout its life cycle. Logistics objectives for the program need to be included in these technical plans to ensure achieving stated readiness objectives such as system availability, programmed flying training throughput, establishment of Reliability and Maintainability performance requirements needed to support readiness objectives, and emphasizing logistics support considerations in all design trade studies.

KC-135/5 Simulator modeling data/modification requires verification and validation to ensure aircraft-like flying qualities.

AMC and FlightSafety personnel have also developed a test and evaluation process that promotes confidence that KC-135 simulator modifications "fly" like the KC-135 aircraft. Even though the systems integrating contractor and the Government quantitatively specify many requirements, the final evaluation of the training realism is still subjectively validated. In the end, the trainer model must be correct enough to allow training, which means it's a judgment call by the test crews and Air Force instructors about the system's "training value." The KC-135 ATS team has implemented an approach, which utilizes no more than one or two contractor instructor (FlightSafety) pilots and one Air Force instructor pilot to minimize extended test periods and facilitate reaching consensus on a modification's training value.