THE F119 ENGINE: A SUCCESS STORY OF HUMAN SYSTEMS INTEGRATION IN ACQUISITION

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The Department of Defense recently mandated the incorporation of Human Systems Integration (HSI) early in the acquisition cycle to improve system performance and reduce ownership cost. However, little documentation of successful examples of HSI within the context of systems engineering exists, making it difficult for the acquisition community to disseminate and apply best practices. This article presents a case study of a large Air Force project that represents a successful application of HSI. The authors explore the influence of both the Air Force and the project contractor. Additionally, they identify top-level leadership support for integrating HSI into systems engineering processes as key to HSI success, reinforcing the importance of treating HSI as an integral part of pre-Milestone A activities.

Keywords: *Human Systems Integration, Systems Engineering, Acquisition Process, Human Factors Engineering, Integrated Product Development*

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HSI

Manpower

Personnel

Training

Environment

Safety

Occupational Health

Habitability

Survivability

Human Factors Engineering

optimize total system performance

Human Systems Integration (HSI) is defined as the "interdisciplinary technical and management processes for integrating human considerations within and across all system elements; an essential enabler to *systems engineering* practice" (Haskins, 2007). The primary objective of HSI is to integrate the human as a critical system element, regardless of whether humans in the system function as individuals, teams, or organizations. The discipline seeks to treat humans as equally important to system design as are other system elements, such as hardware and software.

Many stakeholders have attempted to define HSI, and the number and definitions of HSI domains vary by organization (Department of Defense [DoD], 2008). However, DoD guidance makes it clear that the ultimate goal of any HSI program should be to "optimize total system performance, minimize total ownership costs, and ensure that the system is built to accommodate the characteristics of the user population that will operate, maintain, and support the system" (DoD, 2008; Department of the Army, 2005; Department of the Navy, 2008). Since this article documents a case study of HSI practice within the Air Force, we provide the nine domains of HSI, as highlighted on the previous page.

Large defense projects require significant systems engineering effort that can quickly drive up costs. At the same time, defense projects typically have high requirements for survivability, safety, and other human considerations. As mentioned earlier, DoD is interested in HSI as a means of both reducing cost (Wallace et al., 2007), shortening acquisition cycles (Mack et al., 2007), and improving system performance (DoD, 2008). Published case studies and best practices have highlighted the technical and economic benefits of successful HSI practice (Booher, 1997; Landsburg et al., 2008). These studies and others have consistently emphasized the importance of taking HSI into consideration early in the *acquisition process*.

Although HSI evolved from the study of Human Factors, it expands upon the latter discipline by incorporating a broader range of human considerations such as occupational health, training, and survivability over the system life cycle. Depending on the particular definitions being used, the areas covered by Human Factors and HSI can overlap. The best way to understand the differences between the two terms is that HSI is at heart a subset of systems engineering. HSI work must take place in conjunction with systems engineering and applies to all the same acquisition phases. Historically, many engineers have tended to view human factors (and therefore HSI) as a means of identifying problems with a design, rather than as an enabler of good design (Harrison & Forster, 2003). Although HSI analyses in the later phases of acquisition are an important part of HSI success, the case study presented in this article focuses on the role and impacts of HSI in systems engineering throughout the acquisition life cycle.

Method

This case study documents HSI activities during the development of Pratt & Whitney's F119 engine, which powers the $143 million Lockheed Martin F-22 Raptor fighter aircraft (Drew, 2008). The F-22 Raptor (Figure 1) fulfils the air superiority role in the Air Force by using a package of technologies to allow pilots to "track, identify, shoot, and kill air-to-air threats before being detected" (Department of the Air Force, 2008b). Although the Air Force HSI Office was not formalized until 2007, much of the work done on the F-22 and F119 in the 1980s and 1990s spans the domains of HSI, making the F119 a best practice of HSI in the Air Force.

In designing the study, we followed Yin's (2003) approach for identifying five important components to case study design: 1) a study's questions, 2) its proposition, 3) its units of analysis, 4) the logic linking the data to the propositions, and 5) the criteria for interpreting the findings.

FIGURE 1. THE F-22 RAPTOR

Flying High. The Lockheed Martin/Boeing F-22 Raptor is a fifth-generation fighter aircraft that uses stealth technology. It was designed primarily as an air superiority fighter, but has additional capabilities that include ground attack, electronic warfare, and signals intelligence roles. The Raptor was first introduced into the U.S. Air Force in December 2005. Retrieved 2009 from *Inside AF.mil* [Web page] at http://www.af.mil/shared/media/photodb/photos/090123-F-2828D-942.JPG. *U.S. Air Force photo by Air Force Master Sgt. A. Dunaway (2008)*

The case study was designed around three central research questions:

1. How did Pratt & Whitney determine how much HSI effort would be needed?
2. How much did HSI effort eventually cost?
3. How did HSI fit into the larger systems engineering picture?

The first two of our research questions reflect our ongoing research on the economics of HSI. Discussion of this case study from the perspective of cost estimation can be found in Liu, Valerdi, and Rhodes (2009), and Valerdi and Liu (2009). In this article, we address the third research question.

Since we sought to describe *how* the F119 became a best practice of HSI, we designed our study as a single-case descriptive study. Our proposition was that HSI effort could be isolated from the larger systems engineering effort spent. Initially, we hoped to establish a quantitative relationship between HSI cost and systems engineering cost, but were also interested in identifying the critical factors that led to successful HSI implementation. Although our third research question was originally meant to better our understanding of HSI cost, we found in the course of our case study that the role of HSI in systems engineering is not well understood and would benefit from the documentation of a best practice.

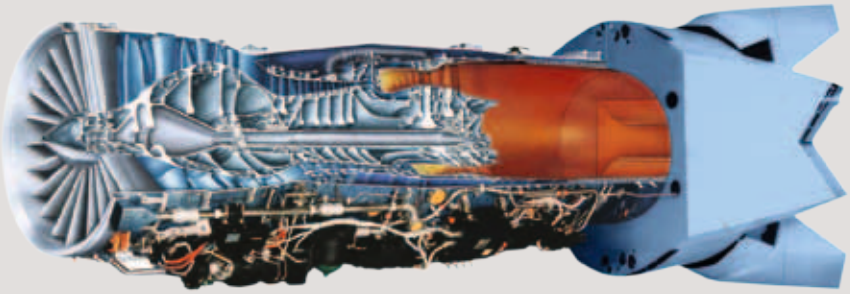
We sought to analyze the early development of the F119, from concept development until major engineering and manufacturing development (EMD). Our unit of analysis was the engineering organization responsible for HSI on the F119 at Pratt & Whitney. Since historical data on specific costs associated with HSI activities were not available either because data were not kept or the records could not be found, we depended on Pratt & Whitney employees familiar with the F119 to build an understanding of its development. We conducted a series of interviews with Pratt & Whitney engineers who were active in the development of the F119, in both technical and management roles. Based on our central proposition and research questions, our interviews focused both on life-cycle cost measurement as well as on systems engineering and HSI methodology. With this information, we were able to identify key HSI success factors. We concluded the case study by validating our results using existing literature on the F119 and the F-22 and by comparing the results of our interviews with multiple engineers.

EARLY AIR FORCE EMPHASIS ON RELIABILITY AND MAINTAINABILITY

The Defense Resources Board approved the creation of the Advanced Tactical Fighter (ATF) program in November of 1981 to create a military jet that would be able to guarantee air superiority against the Soviet Union. This fighter was meant to replace the F-15 Eagle, which had previously filled this role. A team composed of Lockheed, Boeing, and General Dynamics competed against Northrop Grumman to develop the fighter. In 1991, the

ATF contract was awarded to the Lockheed team's F-22, powered by Pratt & Whitney's F119 engine (Figure 2). Then-Secretary of the Air Force Donald Rice noted that an important consideration in the awarding of the contract was the fact that the F-22's engines offered superior reliability and maintainability (Bolkcom, 2007).

FIGURE 2. F119 ENGINE



Cutaway of Pratt & Whitney's (P&W) F119-PW-100 engine. Two F119-PW-100 engines power the Lockheed Martin F-22 Raptor, the U.S. Air Force's new stealth fighter. The F119 features a unique thrust vectoring nozzle, integrated stealth characteristics, and the capability to supercruise, or achieve Mach 1.5 without afterburner. Adapted from "Pratt & Whitney's F119 Engine Receives ISR Approval from USAF, Surpasses 4,000 Flight Hours, Demonstrates Unprecedented Reliability," Pratt & Whitney Press Release, September 16, 2002. Retrieved 2009 from http://www.pw.utc.com/Media+Center/Press+Releases/Pratt+&+Whitney's+F119+Engine+Receives+ISR+Approval+from+USAF,+Surpasses+4,000+Flight+Hours,+Demonstrates+Unprecedented+Reliability.

The Air Force placed an emphasis on reliability and maintainability from the beginning of the ATF program as well as throughout the Joint Advanced Fighter Engine program (JAFE)—the program to develop the engine for the ATF. In June of 1983, four general officers representing the Army, Navy, and Air Force signed a joint agreement in order to "emphasize to the DoD and defense contractor communities the critical importance of improving operational system availability by making weapon system readiness and support enhancement high-priority areas for all our research and development activities" (Keith et al., 1983). Later that year, the director of the JAFE program sent a memorandum to participants in the program, including Pratt & Whitney, asking them to consider that over 50 percent of the Air Force budget was then devoted to logistics, and that the problem would only worsen (Reynolds, 1983).

To address this increase in logistics cost and determine ways to develop creative solutions, the Air Force created the Reliability, Maintainability, & Sustainability (RM&S) program in 1984 (Gillette, 1994). Besides reducing life-cycle cost, the RM&S program also sought to address the reliability and durability problems that had plagued Pratt & Whitney's previous F100 engine, which powered the Air Force's F-15 Eagle. Developed in the 1970s, the F-15 was developed specifically to counter the Russian MiG-25. Therefore, emphasis was placed on performance during the development of both the F-15 and F100. Unfortunately, the high performance of the F100 meant that the engine was more prone to failure and downtime. By the 1980s, the Russian air superiority threat was no longer as pressing as when the F-15 was developed, and supportability was emphasized over performance. As a result, the Air Force wanted improved RM&S not only on the F119 engine, but on development of the F-22 as a whole. Specific supportability goals for the F-22 were announced as early as 1983 (Aronstein et al., 1998).

UNDERSTANDING CUSTOMER NEEDS

The F-22 engine competition was not the only instance in which Pratt & Whitney had competed with General Electric. Both companies had developed engines to power the Air Force's F-16 Fighting Falcon. In the end, General Electric provided the majority of engines for that platform. Pratt & Whitney saw success in the JAFE program as critical to the company's ability to continue to compete in the military engine market. For the F119 engine, Pratt & Whitney decided not only to meet the Air Force's RM&S requirements, but to emphasize designing for the maintainer throughout all aspects of the program. The company's approach exemplified the best practices of what is now known as HSI.

Pratt & Whitney conducted approximately 200 trade studies as contracted deliverables for the Air Force. Pratt & Whitney engineers also estimated they had conducted thousands of informal trade studies for internal use. These trade studies used evaluation criteria, including safety; supportability; reliability, maintainability, operability, and stability; and manpower, personnel, and training (Deskin & Yankel, 2002).

Figures of merit were developed for the trade studies to define a consistent set of criteria upon which to assess the trade studies. Pratt & Whitney engineers used these figures of merit to determine which engineering groups would participate in each trade study.

As is often the case in the development of complex defense systems, responsibilities for the various domains of HSI are distributed among many different organizations at Pratt & Whitney. Of the nine domains of HSI (see Table), seven were represented in Pratt & Whitney's engineering groups. Maintainability, Survivability, Safety, Training, and Materials were all engineering groups at Pratt & Whitney. Manpower, Personnel, and *Human*

TABLE. NINE DOMAINS OF HUMAN SYSTEMS INTEGRATION

Manpower	The number and mix of personnel (military, civilian, and contractor) authorized and available to train, operate, maintain, and support each system.
Personnel	The human aptitudes, skills, knowledge, experience levels, and abilities required to operate, maintain, and support a system at the time it is fielded.
Training	The instruction and resources required to provide personnel with requisite knowledge, skills, and abilities to properly operate, maintain, and support a system.
Environment	In the context of HSI, the conditions in and around the system and the concepts of operation that affect the human's ability to function as a part of the system, as well as the requirements necessary to protect the system from the environment (e.g., radiation, temperature, acceleration forces, all-weather ops, day-night ops, laser exposure, air quality within and around the system, etc.).
Safety	The application of systems engineering and systems management in conducting hazard, safety, and risk analysis in system design and development to ensure that all systems, subsystems, and their interfaces operate effectively, without sustaining failures or jeopardizing the safety and health of operators, maintainers, and the system mission.
Occupational Health	The consideration of design features that minimize risk of injury, acute and/or chronic illness or disability, and/or that reduce job performance of personnel who operate, maintain, or support the system.
Habitability	Factors of living and working conditions that are necessary to sustain the morale, safety, health, and comfort of the user population that contribute directly to personnel effectiveness and mission accomplishment, and often preclude recruitment and retention problems.
Survivability	The ability of a system, including its operators, maintainers, and sustainers, to withstand the risk of damage, injury, loss of mission capability, or destruction.
Human Factors Engineering	The comprehensive integration of human capabilities and limitations (cognitive, physical, sensory, and team dynamics) into systems design to optimize human interfaces and facilitate human performance in training, operation, maintenance, support, and sustainment of a system.

Factors Engineering were taken into account by the Maintainability group. Human Factors Engineering also impacted the Safety group. Occupational Health was considered by both the Safety group and Materials group, which dealt with hazardous materials as one of its responsibilities. While there was an Environmental Health and Safety (EH&S) group at Pratt & Whitney, it dealt with EH&S within the organization itself and did not impact engine design. Habitability was not an important consideration in the engine design.

TOP-LEVEL LEADERSHIP AND INTEGRATED PRODUCT DEVELOPMENT

The major requirements for RM&S came directly from the Air Force. The JAFE program in particular was intended to improve RM&S by "reducing the parts count, eliminating maintenance nuisances such as safety wire, reducing special-use tools, using common fasteners, improving durability, improving diagnostics, etc." (Aronstein et al., 1998). While General Electric made significant RM&S improvements to its F120 engine during this time period, Pratt & Whitney centered its competitive strategy on RM&S superiority.

During the Joint Advanced Fighter Engine competition, Pratt & Whitney participated in the Air Force's "Blue Two" program. The name refers to the involvement of maintenance workers in the Air Force—"blue-suiters." The program brought Pratt & Whitney engineers to Air Force maintenance facilities so that the engine designers could experience first-hand the challenges created for maintainers by their designs. Maintainers showed how tools were poorly designed, manuals had unclear instructions, and jobs supposedly meant for one person took two or more to complete safely.

Many of the features for which the F119 would come to be praised were a result of leadership commitment to HSI. Frank Gillette, the Chief Engineer of the F119, served in various leadership positions on the F119 project, eventually leading a team of over 900 engineers. In interviews with Pratt & Whitney employees familiar with the F119, Gillette was identified as a driving force behind ensuring buy-in to HSI principles.

When the Pratt & Whitney team returned from its Blue Two experience to work on the F119, Gillette captured the lessons learned from the site visits in a series of presentations. These presentations were then shown to every engineer on the F119 team. Gillette also established design ground rules based on the requirements of the maintainer.

One of the most important requirements for the F119 was that only five hand tools should be used to service the entire engine. All Line Replaceable Units (LRUs) would have to be "one-deep," meaning that the engine would have to be serviceable without removal of any other LRUs, and each LRU would have to be removable using a single tool within a 20-minute window (Gillette, 1994). Maintenance would have to be possible while wearing hazardous environment protection clothing. Maintenance tasks would

have to accommodate the heights of maintainers from the 5th percentile female to the 95th percentile male+ (Gillette, 1994; Aronstein et al., 1998). In addition:

> Built-in test and diagnostics were integrated with the aircraft support system, eliminating the need for a special engine support system. Lockwire was eliminated, and torque wrenches were no longer required for "B" nut installations. The engine was designed with built-in threadless borescope ports, axially split cases, oil sight gauges, and integrated diagnostics. Other improvements were a modular design…color-coded harnesses, interchangeable components, quick disconnects, automated integrated maintenance system, no component rigging, no trim required, computer-based training, electronic technical orders, and foreign object damage and corrosion-resistant. These advances were intended to reduce operational-level and intermediate-level maintenance items by 75 percent and depot-level tools by 60 percent, with a 40 percent reduction in average tool weight. (Aronstein et al., 1998)

These innovations were only possible using the *Integrated Product Development* (IPD) concept. Whereas on previous projects, engineering groups at Pratt & Whitney each worked in their own respective disciplines, under IPD teams of engineers from varying disciplines were able to provide design engineers with the perspectives they needed to see the full impacts of their design decisions.

CONTINUING ACCOUNTABILITY AND ENFORCEMENT OF HSI

Adoption of the IPD concept brought various stakeholders together early in the design process and ensured multidisciplinary input through design and development. As a matter of policy, whenever a design change needed to be made, the originating group would submit the change to be reviewed by a Configuration Control Board (CCB). CCBs were composed of senior engineers from multiple engineering groups. At CCB meetings, each group with a stake in a particular design change would explain the impacts of that change to the chair of the CCB, typically a design engineer. The chair would then weigh the different considerations of the design change and either approve/disapprove the change or recommend further analysis be done.

In instances when Air Force requirements needed to be changed, the originating group would submit a Component Integration Change Request (CICR), which would then be internally debated much as with design changes. CICRs were typically initiated when it was determined that a particular requirement might not be in the best interests of the customer or when one requirement conflicted with another. Once a CICR was finalized

internally by all of Pratt & Whitney's engineering groups, it was presented to the Air Force, which would then make the final decision on whether a requirement could be eliminated, modified, or waived.

The processes for design and requirement change ensured that the work of one group did not create unforeseen problems for another. However, change requests were typically made in response to problems that arose during development. Although reacting to and fixing these problems were important, it took proactive leadership to make sure HSI principles were being followed even when no problems were apparent.

Frank Gillette created several policies that ensured engineers kept RM&S considerations constantly in mind. All part design drawings were required to be annotated with the tools needed to service that part. This helped to achieve the goal of being able to service the entire engine with only five hand tools (in the end, the F119 required five two-sided hand tools and one other tool, sometimes described as 11 tools total).

Gillette also insisted on the development of several full-scale mock-ups of the F119. These mock-ups came at a considerable cost (over $2 million each, while the cost of an engine was then about $7 million) but allowed engineers to see whether their designs had really achieved maintainability goals. Engineers were asked to service LRUs on the mock-ups by hand to ensure that they were each indeed only "one-deep." When an LRU was shown to not meet that requirement, the teams responsible for those LRUs were asked to redesign them.

HSI EFFORTS LEAD TO COMPETITION SUCCESS

Leading up to the major EMD contracts awarded in 1991, Pratt & Whitney conducted 400 distinct demonstrations of the F119's RM&S features. The F119 also accrued over 110,000 hours of component tests and 3,000 hours of full-up engine tests, representing a thirtyfold increase in total test hours over its predecessor, the F100 (Aronstein et al., 1998). Pratt & Whitney was willing to spend significant effort on demonstrating the F119's RM&S features because the company had recently been beat out by General Electric in their competition to provide engines for the Air Force's F-16 Fighting Falcon, and therefore saw the Joint Advanced Fighter Engine competition as its last chance to stay in the military engine market.

In 1991, both Pratt & Whitney and General Electric were awarded contracts worth $290 million to complete the EMD phase of competition. The companies were given independence as to the number and types of tests that would be run on their engines, while the Air Force provided safety oversight. As a result, Pratt & Whitney chose to log about 50 percent more test hours than General Electric (Aronstein et al., 1998).

General Electric chose to emphasize the performance of its F120 engine over RM&S, though the F120 did meet the Air Force's RM&S requirements. The F120 was the world's first flyable variable cycle engine (Hasselrot &

Montgomerie, 2005). This meant that the F120 was able to change from turbofan to turbojet configuration to achieve maximum performance in multiple flight situations. The F120 was tested in both Lockheed's YF-22 and Northrop Grumman's YF-23 prototypes, demonstrating better maximum speed and supercruise than Pratt & Whitney's F119 in both cases (Aronstein et al., 1998). The dry weight of the F119 is classified, making it impossible to calculate its exact thrust-to-weight ratio. However, Pratt & Whitney advertises the F119 as a 35,000-lb thrust class engine, putting it into the same thrust class as the F120 (Gunston, 2007).

Despite the F120's superior performance in the air and higher thrust-to-weight ratio, on April 23, 1991, the Air Force chose the combination of Pratt & Whitney's F119 and Lockheed's YF-22 to be developed into the F-22. Pratt & Whitney had repeatedly demonstrated a better understanding of the Air Force's RM&S needs, investing more time and money into demonstrations and internal efforts than its competitor. It also avoided the increased risk of developing a variable cycle engine, at the time considered a relatively new and untested technology. By 1991, the Air Force's RM&S program was less focused on reducing downtime and more concerned with reducing life-cycle costs. Pratt & Whitney had presented a management plan and development schedule that the Air Force considered sensitive to their needs (Aronstein et al., 1998). On August 2, 1991, contracts worth $11 billion were awarded to Lockheed and Pratt & Whitney (Bolkcom, 2007), demonstrating the Air Force's commitment to HSI. Pratt & Whitney's portion was worth $1.375 billion alone (Aronstein et al., 1998).

KEY HSI SUCCESS FACTORS

The Air Force's early and continuing emphasis on RM&S was captured via requirements. Although dating back to 2003 the General Accounting Office (GAO, now the Government Accountability Office) was still advocating for more equal consideration of reliability and maintainability in requirements definition (GAO, 2003), our case study showed that the Air Force had already understood this principle a decade prior. The Air Force's initial guidance to emphasize RM&S shaped the design approach of all of its contractors.

The actions of both the Air Force and Pratt & Whitney were examples of combining top-level leadership's role within systems engineering practices. The Air Force set formal requirements and expected deliverable trade studies, but it also set early supportability goals, released memoranda explaining their intent, and funded programs to show Pratt & Whitney engineers actual maintenance conditions. In its own right, Pratt & Whitney embraced the IPD approach along with IPD's subordinate systems engineering processes, but also invested significant effort to develop mock-ups, conduct additional testing, and hold engineers accountable for RM&S standards.

As a result, we identify three factors as key to the success of HSI in the context of systems engineering in the F119 program:

1. Air Force policy to elevate the visibility of HSI
2. Pratt & Whitney's willingness to internalize HSI practices and enforce accountability for HSI
3. The integration of HSI and systems engineering in the early phases of the acquisition life cycle.

Conclusions

In this case study, we document an example of successful HSI. HSI strongly influenced the development of Pratt & Whitney's F119 turbofan engine from early in the acquisition life cycle through EMD.

Many traditional systems engineering activities also were clearly impacted. Conversations with Pratt & Whitney engineers indicated that by the time HSI requirements were integrated into the engine, the cost of specific HSI activities could no longer be distinguished from other systems engineering costs. In addition, Pratt & Whitney never had a formal organization responsible for all HSI considerations. Instead, responsibilities for HSI were spread between multiple engineering groups. The lack of a formal HSI group did not prevent the F119 from becoming a best practice of HSI. To the contrary, the fact that HSI considerations were tightly coupled to other systems engineering practices was one the project's major strengths.

This case study represents a first step toward establishing the role of HSI in the context of systems engineering. As more success stories are documented, the ability to disseminate best practices throughout the defense acquisition community will improve and will lead to reduced lifecycle costs and improved performance.

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The work presented in this article is part of a larger ongoing project to understand the economics of Human Systems Integration, focusing on cost estimation approaches and leading indicators. The authors have also produced a series of conference papers and a book chapter on this topic, which are cited in the reference section.

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