Economics of Human Systems Integration: The Pratt & Whitney F119 Engine

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Abstract

Human Systems Integration is a comprehensive management and technical approach for addressing the human element in weapon system development and acquisition. The primary objective of human systems integration is to integrate the human as a critical system element, regardless of whether humans in the system function as individuals, teams, or organizations. This discipline seeks to treat humans as equally important to system design as are other system elements, such as hardware and software.

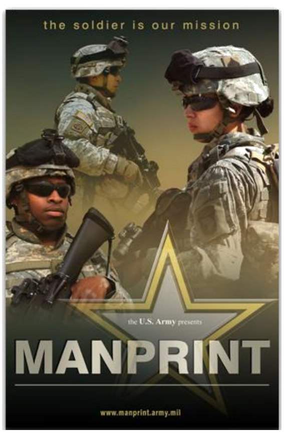
HSI has been defined by many stakeholders, particularly government agencies that advocate the "total system" approach, which incorporates humans, technology, the operational context, and the necessary interfaces between. The human considerations include the following nine domains: manpower, personnel, training, human factors engineering, environment, safety, occupational health, habitability, and survivability. This paper introduces one area of a larger research project, sponsored by the U.S Air Force, which seeks to develop an approach for determining what percentage of the overall systems engineering activity should be allocated to HSI in order to effectively consider these nine domains as part of the overall systems engineering effort. To determine the appropriate systems engineering effort needed for a program, we examine a case study that represents an exemplar outcome.

The Pratt & Whitney F119-PW-100 engine is an example of a US Air Force project that successfully employed HSI principles, even though it was not called HSI at the time, throughout its development in the 1980s. The engine powers the F-22 Raptor air superiority fighter aircraft and has been praised both for its performance and supportability. Although the successes of the F119 project are apparent, the effort spent specifically on HSI was not well documented, and this will be examined during the study. This paper first provides a brief background of HSI and relevant research in the field. We use previous work on HSI best practices to focus our case study on the activities most important to HSI success. Our case study shows that Pratt & Whitney adopted HSI principles and methods early in the development process in response to continued Air Force emphasis on Reliability, Maintainability & Supportability (RM&S). We also document the effort and resources Pratt & Whitney voluntarily put into HSI activities and explain how that effort led to reduced life cycle cost for the Air Force.

Current Practice of Human Systems Integration

Human Systems Integration (HSI) has its origins in the field of Human Factors Engineering (HFE), with which it is commonly confused. Human Factors is the science of understanding the properties of human capability and the application of this understanding to the design and development of systems and services. HFE is the field that Human Systems Integration grew from and continues to be one of its central elements. However, Human Systems Integration as it is practiced expands upon Human Factors Engineering by incorporating a broader range of human considerations over the system life cycle such as occupational health, training, survivability, etc.

The study of human performance can be traced to at least as far back as the industrial revolution, when technological advances and a need for greater efficiency drove research on how humans could best interact with machines. At the time, these efforts were known as Industrial Engineering. The challenges and requirements of industry leading up to the beginning of the 20th century grew significantly during the first and second World Wars. In response, the U.S. and UK both funded efforts to understand human impacts on performance. Modern work in Human Factors Engineering derives from the research done during this time period (Nemeth 2004).



Army MANPRINT	Navy HSI Branch	Air Force HSI Office
Established 1984	Formalized 1997	Formalized 2007
7 Domains	8 Domains	9 Domains
Deputy Chief of Staff, Army G1	CNO (N12)/ System Commands	Vice Chief of Staff, USAF

Figure 1. Comparison of U.S. military HSI programs (U.S. Army 2007) (U.S. Navy 2008a) (U.S. Air Force 2008a).

General Maxwell R. Thurman of the U.S. Army is credited with first recognizing the need to integrate HFE with other human domains early in the weapons system design process. In 1982, General Thurman directed that the Army's human factors program be expanded to include Manpower, Personnel Capabilities, and Training (MPT) issues. The result was the U.S. Army Manpower and Personnel Integration Program (MANPRINT), established in 1984, which continues to define the Army's HSI policy today (Booher 2003).

HSI initiatives have evolved in the civilian sector and in non-U.S. organizations as well. However, this report focuses on HSI in the U.S. military because it has had a greater impact on the case study presented.

Although the Army's MANPRINT program has existed since the early 1980s, HSI as a field continues to mature. DoD Instruction 5000.02, *Operation of the Defense Acquisition System*, mandates that HSI be implemented as part of system development and demonstration (Department of Defense 2008). Figure 1 summarizes the HSI programs of the U.S. military branches (the Marine Corps is represented within the Navy's HSI program). Due to HSI's multidisciplinary nature, its stakeholders within each of the branches span departments and hierarchical structure. The HSI programs in each of the services are responsible for policy guidance and for assessment of programs, but specific design and analysis efforts in each of the domains is contracted to military assets or private firms possessing those capabilities. Therefore, the differences in organization of each of the HSI programs is not an indication of less emphasis put on a particular domain, but rather reflect the differences in each branch's existing practices. The Air Force mandates addressing HSI concerns in all capabilities-based development documents in Air Force Instruction 10-601 (U.S. Air Force 2006). The Air Force defines HSI as "a comprehensive management and technical approach for addressing the human element in weapon system development and acquisition," (U.S. Air Force 2008b). It defines the 9 domains of HSI as:

> "***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, and 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 providing personnel with requisite knowledge, skills, and abilities to properly operate, maintain, and support a system.*
>
> ***Environment—****in the context of HSI, environment includes 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 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 dynamic) into systems design, to optimize human interfaces to facilitate human performance in training operation, maintenance, support and sustainment of a system,*" (U.S. Air Force 2008a).

Aside from domain differences, the HSI programs in each of the military branches fit into their larger organizational structures differently. The Army's MANPRINT program is part of Army G-1, the Deputy Chief of Staff responsible for Manpower and Personnel. The Director, Total Force Requirements Division (CNO (N12) is the resource sponsor for HSI (U.S. Navy 2008b). The Navy is unique in that systems are acquired by each of the Navy Systems Commands, which report to the Secretary of the Navy. Each system command therefore also has its own HSI requirements division. The Air Force's HSI Office is currently part of the Office of the USAF Vice Chief of Staff.

HSI Best Practices

Currently, budgeting for HSI in defense acquisition programs is assigned based on particular HSI activities expected to be performed during development. For example, budget may be set aside for iterative safety analyses or crewmember workload simulations, but no budget is designated for "HSI" in general. In this paper we seek to better understand how HSI fits into the larger systems engineering picture by evaluating how investment is allocated in the domains of HSI. The eventual goal is to understand the life cycle cost implications of doing good HSI and planning for it early in the development process.

In order to better understand the impact of early HSI investment on cost, we describe the development of the F119 turbofan aircraft engine, with a focus on HSI. To better frame our research, we reviewed previous work on case studies of HSI and identified patterns where best practices derived from these studies showed that certain activities and elements must exist in order for an HSI program to be effective.

Harold Booher's 1997 *Human Factors Integration: Cost of and Performance Benefits to Army Systems* examines four Army systems and the impacts of Human Factors Integration (HFI), a term used to describe specific methodologies for implementing HSI. The case studies provide an assessment of costs that were avoided due to HFI considerations throughout the development process. Some costs were estimated using historical data on mishaps and occupational health impacts. Other data was generated using models that simulated the effects of system use on humans. At the time, the leading model was a software package called Hardware vs. Manpower (HARDMAN III) (Booher 1997). HARDMAN III could assign specific tasks to simulated crewmembers and calculate the effort placed on each. The program could then make a recommendation as to the optimal crewsize of a system. Today's incarnation of HARDMAN is the Improved Performance Research Integration Tool (IMPRINT), a model developed by the U.S. Army Research Laboratory for use across the DoD. The four case studies performed in 1997 showed how HFI and MANPRINT had improved Army systems and resulted in significant cost avoidance. The analysis focused on modelling techniques that were applied early in the development process and estimated costs avoided using historical data.

In 2003, the *Handbook of Human Systems Integration* combined many of the lessons learned from the 1997 case studies with the experience of other researchers in the field. The result was a set of ten "principles" described as "crucial to effective HSI" (Booher 2003). These principles are show in Table 2.

Landsburg, et. al. (2003) performed their own case studies on mostly non-military examples of HSI from the Department of Transportation, the Federal Aviation Administration and the U.S. Coast Guard. They derived an 11-step "guide" to HSI best practice, based on the U.S. Navy's HSI practices. They also created a prioritized list of elements critical to HSI success, summarized in Table 3. Landsburg, et. al. concluded that the transportation organizations studied would have benefitted from the implementation of a top-level HSI program modelled after the Navy's program.

Table 2: The 10 Principles of Effective HSI (Booher 2003).

Top-level leadership
Focus on human-centered design (HCD)
Source selection policy
Organizational integration of all HSI domains
Documentation integration into procurement process
Quantification of human parameters
HSI technology
Test and evaluation/assessments
Highly qualified practitioners
Education and training program

Table 3: Prioritized List of Critical Elements for Successful HSI (Landsburg et. al. 2008).

Management and Organizational Commitment
User/stakeholder involvement
Education and awareness of all
HSI process ownership
Holistic, enabled view
Funding support
Documented and technically sound processes
Qualified personnel
Open collaborative environment
Practical applications based on sound human factors research

Booher consolidated detailed analyses of complex Army systems to create a direct link between HFI investment and cost savings. Landsburg et. al. chose instead to focus on a few isolated HSI successes and then develop recommendations from the practice of HSI in Navy acquisitions. In the course of our case study, we found that HSI success was dependent on the participation of both the Air Force and Pratt & Whitney, the developers of the F119.

For that reason, it was valuable for us to compare the results of our case to previous work. Other best practice work can be found in the U.S. Navy's *Human Systems Engineering Best Practices Guide* and the U.S. Army's *MANPRINT Handbook* (Beaton 2008) (U.S. Army 2005).

The Pratt & Whitney F119 Engine

Methodology

This paper documents HSI activities done during the development of Pratt & Whitney's F119 engine, which powers the $143M Lockheed Martin F-22 Raptor fighter aircraft (Drew 2008). The F-22 raptor fulfills the air superiority role in the Air Force by using a package of technologies to deliver "first look, first shot, first kill capability in all environments" (U.S. Air Force 2008c). 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.

Figure 2. The F-22 Raptor (Dunaway 2008).

We chose to do a case study because the engineers who worked on the F119 were available to be interviewed, although most have retired. In designing the study, we referenced Yin (2003), who lists five important components to case study design: "(1) a study's questions; (2) its propositions, if any; (3) its units of analysis; (4) the logic linking the data to the propositions; and (5) the criteria for interpreting the findings."

The case study was designed around three central research questions:

(1) How did Pratt & Whitney predict 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?

Since we sought to describe *how* the F119 became a best practice of HSI, we designed our study as a single-case descriptive study, as defined by Yin (2003). Our proposition was that HSI effort could be isolated from the larger systems engineering effort spent. We sought to analyze the early development of the F119, from concept development until major engineering and manufacturing development (EMD). Although HSI activities would continue to be important after EMD, the HSI activities that affected the design of the F119 largely occurred prior to EMD. The engineering organization responsible for HSI on the F119 at Pratt & Whitney was our unit of analysis.

Since historical data on specific costs associated with HSI activities was not available either because data was 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. In our interviews, we asked specifically about our proposition, creating a direct link between our data and our proposition. 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 from 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. 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).

The Air Force placed an emphasis on reliability and maintainability from the beginning of the ATF program as well as 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, Colonel John Reynolds, then director of JAFE, sent a memorandum to participants in the program, including Pratt & Whitney, asking them to consider that over 50% of 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 the previously built Pratt & Whitney F100 engine, which powered the Air Force's F-15 eagle. Developed in the 1970s, the F-15 was developed in direct competition with the Russian MiG-25, with air superiority in mind. Therefore, emphasis was placed on performance during the development of both the F-15 and F100. Unfortunately, the high performance of the F100 only resulted in more engine failures. The Air Force emphasized 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, GE 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 to 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 Human Systems Integration.

Pratt & Whitney conducted roughly 200 formal 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 and Yankel 2002).

Figures of merit were developed for the trade studies in order to define a consistent set of criteria to assess the trade studies on. 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, 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 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) at Pratt & Whitney, it dealt with EH&S within the organization itself and did not impact engine design. Habitability was also not factored into engine design.

Figure 3. Cutaway of the F119 engine (Pratt & Whitney 2003).

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 for 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 maintainers from the 5th percentile female and 95th percentile male as shown in Figure 4 (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% and depot level tools by 60%, with a 40% reduction in average tool weight,"* (Aronstein, et. al. 1998).

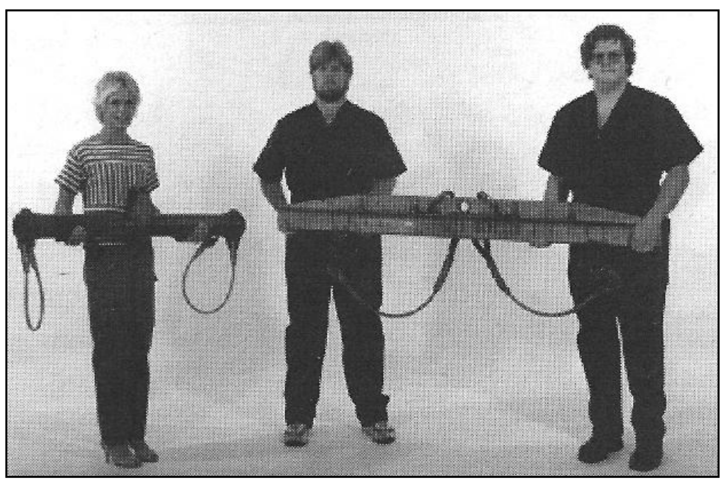


Figure 4. Tool design to accommodate maintainers. (Gillette 1994)

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 Integrated Product Development 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 like 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 was 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 their minds. 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 $2M a piece, while the cost of an engine was then about $7M) but allowed engineers to see whether their designs had really achieved maintainability goals. Engineers were asked to service LRU's 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 engineering and manufacturing development (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 30 times increase in total test hours over its predecessor, the F100 (Aronstein, et. al. 1998).

In 1991, both Pratt & Whitney and General Electric were awarded contracts worth $290 million to complete the engineering and manufacturing development (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% more test hours than General Electric (Aronstein, et. al. 1998).

GE 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 23rd, 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, then 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 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 2nd of 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).

Conclusions

In this case study, we sought to document an example of successful Human Systems Integration in order to inform a larger project on the economics of HSI. As a way forward, we will focus on identifying specific costs and efforts attributed to HSI. It was clear that HSI strongly influenced the development of Pratt & Whitney's F119 turbofan engine from design to engineering manufacturing and development. Some specific observations were:

(1) The Air Force's initial guidance to emphasize RM&S shaped the processes of Lockheed, Northrop Grumman, General Electric, and Pratt & Whitney.
(2) Pratt & Whitney was willing to spend significant effort on demonstrating the F119's RM&S features because it saw the Joint Advanced Fighter Engine competition as its last chance to stay in the military engine market.
(3) Pratt & Whitney was able to institutionalize HSI principles in two ways.
    a. It had a top-level leader who understood Air Force's needs for HSI and RM&S.
    b. It adopted the Integrated Product Team approach, which improved the design of the F119, and led to other formal procedures that ensured groups responsible for each of the domains of HSI had input on every major design or requirement change.

As a result of these observations, we conclude that the Air Force can continue to ensure HSI success across all of its programs by providing:

(1) Clear guidance as to the importance of HSI at the beginning of a program and clearly defined HSI requirements.
(2) An established process for design or requirement change request through an Integrated Product Development process.
(3) Contract incentives for contractors to demonstrate compliance with HSI requirements on contracts.

The case study showed that while Pratt & Whitney was responsible for the successful application of HSI during the design and development of the F119 engine, the company's actions were driven by Air Force policies and funding. Our next step is to isolate the life cycle cost impact of HSI to demonstrate the economic benefits of HSI on weapon systems.

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